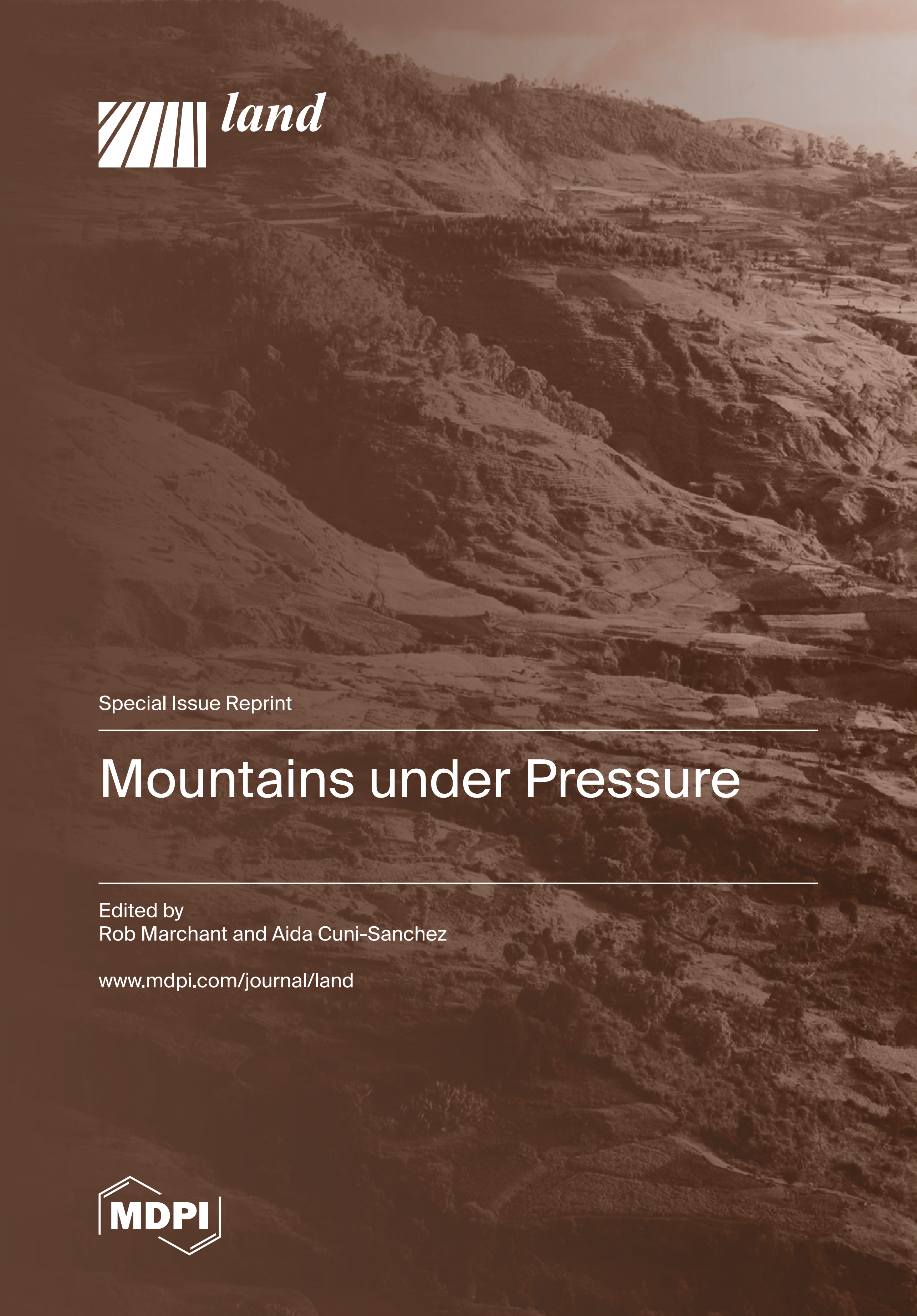

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Special Issue Reprint

Mountains under Pressure

Edited by
Rob Marchant and Aida Cuni-Sanchez

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Cover image courtesy of Rob Marchant

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About the Editors

Rob Marchant

Since conducting his PhD in southwest Uganda in 1995, much of Rob Marchant's research is focused in East Africa, where he has developed close collaborations with numerous university, NGO, UN and governmental institutions that have resulted in numerous joint projects, publications and continued professional and organisational development. In 2014, he was appointed as a member of the Scientific Leadership Council (SLC) for the Mountain Research Initiative, a multidisciplinary scientific organization that addresses global change issues in mountain regions worldwide. Rob Marchant continues to work across a number of mountain systems, unravelling their social and environmental histories so that the futures of mountains can be made sustainable.

Aida Cuni-Sanchez

Dr. Aida Cuni-Sanchez is an Associate Professor at the Norwegian University of Life Sciences and an honorary fellow at the University of York. She has a PhD in Environmental Sciences from the University of Southampton (UK) and a degree in Biology from the University of Barcelona (Spain). She has over 10 years of work experience in twelve countries in tropical Africa, where she has focused on tropical forest ecology, carbon stocks, indigenous knowledge and forest use by local communities and local communities' adaptation to climate change.

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Editorial

Special Issue Editorial: Mountains under Pressure

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Mountains are highly significant regions in the context of climate change and sustainable development; they are situated at the intersection of accelerated climate warming, changes in moisture regime and support a large population that depends on mountains for their livelihoods, either directly or indirectly (Adler et al., 2022 [1]). Montane forest and alpine ecosystems are rich in biodiversity and endemism (Rahbek et al., 2019 [2]) and are an important global carbon store (Cuni-Sanchez et al., 2021 [3]). Despite their importance and impact on multiple downstream communities, mountain ecosystems are increasingly threatened by climate change, population growth, and land-use change (Adler et al., 2022 [1]). Mountains provide an ideal natural laboratory to investigate the evolution of social–ecological systems, and to assess the current challenges and opportunities that this evolution has created (Thorn et al., 2021 [4]). Mountains have been centres of past development and conduits for the spread of crops, populations, and technologies. They were, and remain, a locus for cultural interaction, in many parts of the world through pastoral–agricultural–urban interactions over access to space and resources, particularly water. As outlined in the special Cross-Chapter on 'Mountains' of the latest IPCC report (Adler et al., 2022 [1]): 'Observed climate-driven impacts on mountain ecosystem services, agriculture and pastoralism are largely negative in most mountain regions through increased exposure to hazards such as droughts and floods, changes in the onset of seasons, the timing and availability of water, increasing pests and decreasing pollinator diversity. These impacts are challenging the adaptative capacity of mountain communities with knock on impacts at lower altitudes as drought induced degradation of rangelands and pastures and decreasing yields of important cash and subsistence crops such as maize, rice, tea and coffee, respectively'.

Amani et al. (2022) [5] and Kaganzi et al. (2021) [6] approach the topic of the impacts of climate change on mountainous socio-ecological systems, focusing on mountains in Africa that have limited long-term meteorological data. In addition to providing insight into their specific case studies, these manuscripts raise the much wider challenge of missing or incomplete basic data, such as data on climate or hydrology. The potential of indigenous and local knowledge to identify the impacts of climate change and formulate adaptation measures has been demonstrated and is being increasingly recognized (e.g., Petzold et al. 2020 [7]; Schlingmann et al. 2021 [8]). Both Amani et al.'s (2022) [5] and Kaganzi et al.'s (2021) [6] studies administered semi-structured questionnaires to smallholder farmers to identify their perceptions of climatic changes, the impacts of these changes in the biophysical domain, and the adaptation strategies already being used by these farmers. Whereas Kaganzi et al. (2021) [6] focused on two mountains in Tanzania (Mount Kilimanjaro and Udzungwa Mountains) Amani et al. (2022) [5] focused on two different ethnic groups living in the Itombwe Mountains in eastern DR Congo. The respondents in all these mountains reported numerous climatic changes beyond changes in rainfall and temperature, and impacts on their crops, livestock, and even human health. Farmers in these mountains

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were implementing several adaptation strategies, but several factors were constraining their adaptation options.

Garcia-Amorena et al. (2021) [9] also explore climate change impacts but focus on specific plant species: providing an analysis of the potential future distribution shifts of *Pinus hartwegii*, a tree species native to the very high altitudes of the mountains of Mexico, Eastern Central America, and Honduras. These authors combined satellite images, species distribution models, and connectivity analysis to disentangle the effects of climate change and anthropogenic land use change on the habitat availability for this species in Izta-Popo National Park in Mexico. Their approach proposes solutions to overcome the limitations of field-based observations in areas that are difficult to monitor or are unsafe due to ongoing conflict. Indeed, mountains often form the boundary between nations and can be the focus of conflict.

Beyond the impacts of climate change, invasive plant species are known to threaten mountain ecosystems. Canavan et al. (2021) [10] assessed the status of alien plants in South African mountains by determining the sampling efforts, species compositions, and abundances across the six major mountain ranges in South Africa. These authors showed that most alien species were woody plants with broad ecological tolerances and were characterised by long distance seed dispersal, contributing to the trend of woody plant encroachment across South African mountains. They also showed that more data are urgently needed for four of the six mountains they targeted. This is a common thread throughout the special issue—for the effective execution of informed decisions around ecosystem management, ecological restoration, and how to maximise the potential of nature-based solutions to deal with these challenges, we must have more data from mountain regions to make evidence-based decisions.

One of the key challenges for understanding mountain ecosystems and the impacts of their change is their sheer taxonomic diversity. This problem is particularly acute as resources for descriptive taxonomy and biodiversity inventories have substantially declined over the past decades, and they are also globally unequally distributed, which can result in a decline in the quality of biodiversity data, reducing the utility and reliability of inventories (Ahrends et al., 2011 [11]). The Andean forests support a strikingly high diversity of plants, making it difficult to understand the main drivers of species assembly. However, trait-based approaches can help overcome some of the challenges associated with high taxonomic complexity, providing insights into the main drivers of species coexistence. The roles of climate, soil fertility, and symbiotic root associations and how these shape the assembly of six of plants' functional traits (leaf area, specific leaf area, dry leaf matter content, leaf thickness, leaf toughness and wood density) are evaluated along an elevational gradient in the species-rich northwestern Andean forests of Colombia by Ochoa-Beltrán et al. (2021) [12]. The study shows how trait-based approaches can help in overcoming some of the challenges associated with high taxonomic complexity in the Colombian Andes; methods that could be applied to other highly diverse tropical montane forest ecosystems.

Land-use change is another major threat to both natural and cultural mountain landscapes. Three empirical studies from different continents (Africa, Asia and Europe) in this issue focus on this topic. Mpanda et al. (2021) [13] assess land cover dynamics in the Uluguru Mountains of Tanzania. They show an overall net increase in forest cover across the entire 25-year study period, which they attribute to a trend towards intensified tree-based farming systems. Qu et al. (2021) [14] investigate the spatio-temporal differentiation pattern in gully production following the expansion of agriculture in the Chinese Loess Plateau. They report shifts in the agricultural elevational area in the past 20 years; a common trait of many mountain areas driven by social and economic factors. Dax et al. (2021) [15] study the risk of land abandonment in mountain regions in Europe and show that this risk is three times higher in mountain areas than in non-mountain areas. These authors attribute this high risk to the high disparity in agricultural competitiveness between regions (at a fine geographical scale) and call for policy reform. Ehrlich et al. (2021) [16] also provide data on another important threat to mountain socio-ecological systems and more broadly to their functioning: population growth. They provide estimates for population changes in mountain regions between 1975 and 2015. They show that the global mountain population has increased from over 550 million in 1975 to over 1050 million in 2015, and that 34% of this growth is in mountain cities.

Given the importance of water resources, particularly as a connection between mountain and lowland communities, our Special Issue also includes two papers on water, one from an ecological and one form a social perspective. Sumner and Venn (2021) [17] conducted a quantitative systematic review and meta-analysis of the effects of an altered water supply on plants from high elevation ecosystems. They report that the responses to decreases in water supply appear to be related to the magnitude of the change in the water supply, the form of plants' growth and to the measured response attributes. Yu et al. (2021) [18] study the characteristics and challenges facing rural mountain settlements in southwestern China. They report that in their study area, 8.7% of rural settlements are situated in high-risk and medium risk areas and discuss the implications of their findings for both revitalisation activities and the site selection of rural mountain settlements.

Our Special Issue also includes two papers on cultural aspects. Laković et al. (2020) [19] investigate seasonal mountain settlements for summer cattle grazing (katuns) in the Kuči Mountain in Montenegro. Although these are now obsolete, the density of these settlements and the architectural and constructional characteristics show the high importance they had for the local population up until the last third of the 20th century. More broadly, this paper showcases the importance of taking a historical perspective for a greater understanding of change and the evolution of mountainous social-ecological systems. Wan et al. (2020) [20] investigate farmers' environmental perceptions in the Huanjiang Karst Mountain Area of China. Through a survey administered to 379 farmers following a government intervention policy to enhance the livelihood of mountain communities in this area, they report farmers' high satisfaction with their living space, average for their ecological space, but low for their farming production space.

Finally, three papers examine the impacts of more action-oriented approaches to developing sustainable mountain futures for people and biodiversity. Carbutt and Thompson (2020) [21] present insights into how new investments that build on the Long-Term Ecological Research (LTER) in South Africa can help to optimise catchment management through sound water policy. It is suggested that this new investment marks a renaissance period of global change research in South Africa, which takes greater cognisance of the social context. This diversity of initiatives will generate a more robust knowledge base from which to draw conclusions about how to better safeguard the well-being of people and biodiversity in the region and help balance livelihoods and environmental sustainability in complex, socio-ecological mountain systems. In addition to underlining the necessity of further data, there is also a need for new tools to visualise and connect science and practice. Giupponi and Leoni (2020) [22] introduce the VegeT: a tool to classify and inform the management of Seminatural Grasslands of the Italian Alps, through techniques such as the timing of pastoral mobilisation. Mackay-Smith et al. (2021) [23] present a framework for reviewing silvopastoralism in Oceania by comparing poplar (*Populus* spp.)—the most commonly planted silvopastoral tree in their study area—and the endemic kānuka (*Kunzea* spp.) tree. The insights from the research provide a formalised tool for reviewing and generating research priorities for silvopastoral trees and provides clear research directions for silvopastoral systems worldwide.

All the authors whose work comprises this Special Issue are engaged to bring new empirical insights to bear on these growing and important topics and ensure an evidence-based approach to finding solutions facing mountains throughout the world. Our aim in this Special Issue of Land is to showcase the breadth and depth of mountain research from around the world; the articles present the results of case studies from Central and South America, Europe, Africa, Asia and Oceania. We hope that the relevance and impact of this Special Issue on mountains transcends academia. Increasingly, practitioners, organisations, policy-makers, and managers charged with addressing the challenges of global change and finding solutions to crafting future sustainable pathways need information and data-based insights on the dynamics and changes in social-ecological systems to aid in the design and implementation of appropriate management strategies for the sustainable future of mountains, and this need is particularly acute in this United National International Year of Sustainable Mountain Development.

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Article

Climate Change Perceptions and Adaptations among Smallholder Farmers in the Mountains of Eastern Democratic Republic of Congo

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Abstract: The warming rates in many mountain areas are higher than the global average, negatively impacting crop systems. Little is known about the climatic changes which are already being observed in eastern Democratic Republic (DR) of Congo, due to the lack of long-term meteorological data. Local perceptions could help us to understand not only the climatic changes and impacts but also which adaptation strategies are already being used by local smallholder farmers. Semi-structured questionnaires were administered to 300 smallholder Bafuliru (n = 150) and Lega (n = 150) farmers living in the Itombwe Mountains. The respondents reported climatic changes and impacts, with the Bafuliru—living on the eastern drier slopes—reporting more changes and impacts. While the Bafuliru were implementing several adaptation strategies (e.g., increased irrigation and use of inputs, more soil conservation, more income diversification), the Lega were implementing very few, due to soft limits (access to inputs, markets, and information) and culture (less interest in farming, less capacity to organize into groups). The results highlight important differences in sociocultural contexts, even for one 'remote' mountain, calling for a more collaborative approach to adaptation planning and action.

Keywords: adaptation strategies; ethnicity; farmers; Itombwe Mountains; local knowledge; perceptions; wealth group

1. Introduction

It is increasingly recognised that in order to better understand the climatic changes observed and their impacts on the biophysical domain at local scales, local communities' perceptions of climatic changes can be used to complement meteorological data scarce areas [1,2]. Research on local knowledge can also help us to understand smallholder farmers concerns and priorities, offering new opportunities to better target climate change adaptation policies and development interventions that are more fitted to the local context(s) [1,3].

Smallholder farmers have addressed (or tried to address) the effects of climate change, including food shortages and reduced health and income, e.g., [4]. by implementing different measures, often classified as 'coping strategies'—when addressing the post-disaster damages—or as 'adaptation of strategies', when they are carried out before a hazardous climate event occurs [5]. Sometimes, though, approaches which start as coping strategies in exceptional years can become 'true' adaptation strategies for households or whole communities over time [5]. In general, smallholder farmers' adaptation strategies can be clustered into two groups: on-farm and off-farm strategies. The most common on-farm strategies are the maintenance of high agrobiodiversity—to spread the risk of crop failure among species which are susceptible to different climatic stresses—and soil or water conservation practices [6]. Two of the most prominent off-farm strategies are off-farm labour and membership in farmers' organisations (which can facilitate technical help or access to improved seeds, inputs, credit and subsidies; see [7]). A recent review of the adaptation strategies used by smallholder farmers in Tanzanian mountains reported over 20 adaptation strategies, and showed that wealthier households generally had more options for adaptation [8]. This is because wealthier households have greater access to land, greater resources to invest in irrigation or inputs such as improved seeds or pesticides, and even better access to information and technologies (e.g., [8]).

There is an increasing interest in understanding the limits of adaptation [9] or adaptation deficits [10], with recent work on mountain systems being focused on adaptation gaps [11]. The latter authors highlighted three components of adaptation gaps: exposure, realisation and coherence. While the first component refers to the gap between the magnitude of climatic exposure and the sum of all adaptation options, the second component refers to the gap between all of the adaptation options and actual adaptation action, and the third refers to the gap between actual adaptation action and the proportion of adaptations that are in alignment with established national or international goals, such as the Paris Agreement's Global Goal on Adaptation [11]. Adaptation gaps are context specific, and the realization gap can be particularly large in areas where social conditions (e.g., poor access to education, information or financial capital) inhibit adaptation, but other social conditions such as high social capital might foster a high adaptive capacity [11]. The Itombwe Mountains of DR Congo offer a unique opportunity for the investigation of adaptation gaps. Apart from high physical isolation and the distance to decision-making centers (urban cities), which contribute to socioeconomic and political isolation and marginalization [12], they are culturally complex systems. Cultural differences, related to ethnic differences, are known to affect adaptation, e.g., the adaptation gap might be smaller amongst cultures in which high levels of social capital foster adaptive capacity, while strong food preferences might constrain crop diversification (or staple crop change), and therefore adaptive capacity, as shown in Tanzania [8].

This article presents a case study in the mountain region of the Albertine Rift, which is a climatically complex region comprising bimodal and unimodal rainfall regime zones, with important rain shadow effects due to the highly variable topography [13] This region comprises the western branch of the East African Rift, covering parts of Uganda, DR Congo, Rwanda, Burundi and Tanzania. The climatic patterns of this region are poorly understood, due to (i) the unreliable rain gauge coverage over central equatorial Africa [14], and (ii) the disagreement among satellite rainfall products [13,15]. Satellite-based rainfall estimates have reported a drying trend for the Congo Basin (e.g., [16]), while research from western Uganda, which combined satellite and gauge-based rainfall estimates with farmers' perceptions, reported changes in seasons' lengths and wetting trends caused by increased rainfall during the rainy seasons [13]. Recent work from Mt. Kahuzi in eastern DR Congo, which also combined gauge-based rainfall estimates with farmers' perceptions, showed changing season lengths but reduced overall rainfall [4].

In the mountains of DR Congo, both on-farm and off-farm adaptation options are likely to be more limited. Recent work from Mt. Kahuzi showed that smallholder farmers were implementing only four on-farm strategies (improved seeds, new crops, irrigation, and increased farm size) and only two off-farm strategies (diversification into animal rearing, diversification into selling charcoal/timber) [4], with labour and membership in farmers' organisations not being cited. Indeed, many mountain communities continue to face socioeconomic difficulties that constrain their ability to enact their own locally appropriate responses to climate change [11]. This leads to persistent vulnerabilities and greater reliance on external actors and outside intervention [11], if such external actors are present.

This paper, focused on two smallholder farmer ethnic groups living in the Itombwe Mountains in eastern DR Congo (Bafuliru and Lega), aims to: (1) identify the changes in climate and their impacts on the biophysical system, as perceived by these farmers; (2) determine which strategies they are using to adapt to these climatic changes and their impacts; and (3) investigate adaptation gaps. We address the following research questions: (1) Have climatic changes and/or impacts been perceived by farmers, and do these differ between ethnic groups? (2) Have farmers used strategies to adapt to these impacts, and if yes, do these differ between ethnic groups or wealth groups? (3) Which adaptation gaps can be observed, do these differ between ethnic groups? This study contributes to the field with three novel aspects: (i) it is the first study to investigate how culture affects adaptation gaps in the Albertine Rift, (ii) it is the first study to document how wealth affects (or it does not) the adaptation strategies used by smallholder farmers in DR Congo, and (iii) it documents that climate change impacts have already been perceived by smallholder farmers in the Itombwe Mountains—a region for which meteorological data is unavailable. Our study provides a basis for better understanding the concerns and priorities of smallholder farmers' adaptation in mountain regions, offering new opportunities to better target climate change adaptation policies and development interventions.

2. Materials and Methods

2.1. Study Sites

We selected two farmer communities living in the northern part of the Itombwe Mountains (Mts) (Mt. Mohi 3475 m) (Figure 1), which are more easily accessible from Bukavu and are slightly less prone to insecurity due to rebel groups. The annual rainfall ranges between 1200 (the northeastern slopes) and 3000 mm yr^{-1} (the southeastern slopes) [17]. The Itombwe Mountains have a unimodal rainfall regime with a dry season between June and July (*Kipwa*), and a rainy season from mid-August to May (*Wakati ya vula*) [14]. Important climatic differences can be observed with increasing altitude (colder and wetter), with fog being a common feature at high altitudes (personal observation; see Figure S1 in the Supplementary Material). In Bafuliro villages, the soil is clay loam with very little fine, rounded quartz gravel, and is a very dark grey at a superficial depth (0–15 cm). This soil is haplic Cambisol (Eutric) [18]. In the middle altitudes in Mwenga, the soil is clayey-sandy and very fertile due to rocks of the Lukuga series [17].

The Itombwe Mts are part of the Albertine Afromontane Biodiversity Hotspot [19], and support globally important populations of Grauer's gorillas (*Gorilla beringei graueri*), eastern chimpanzees (*Pan troglodytes schweinfurthii*) and forest elephants (*Loxodonta cyclotis*) [20]. Most of the montane forest and alpine vegetation is now part of the Itombwe Nature Reserve, which was declared in 2006 but the boundaries of which were established in 2016 [21]. Insecurity (the presence of armed groups hiding in the forest) is high throughout the Itombwe Mts, and market access is limited in the eastern part due to poor road conditions and the greater distance to the Bukavu or Uvira urban centers (Figure 1).

Several ethnic groups live around the Itombwe Mts, with the Bafuliru and Lega being two important groups ones. The Bafuliru, of Bantu origin, are a small ethnic group of

250,000 people speaking Fuliiru, whose homeland is the Ruzizi plain in the northeast of the Itombwe Mts [22]. They are predominantly farmers, although they also own and raise cattle for milk and meat [22]. They are known for being the only highland Bantu people to be organized into a 'single, relatively small state', which is highly centralized [23].

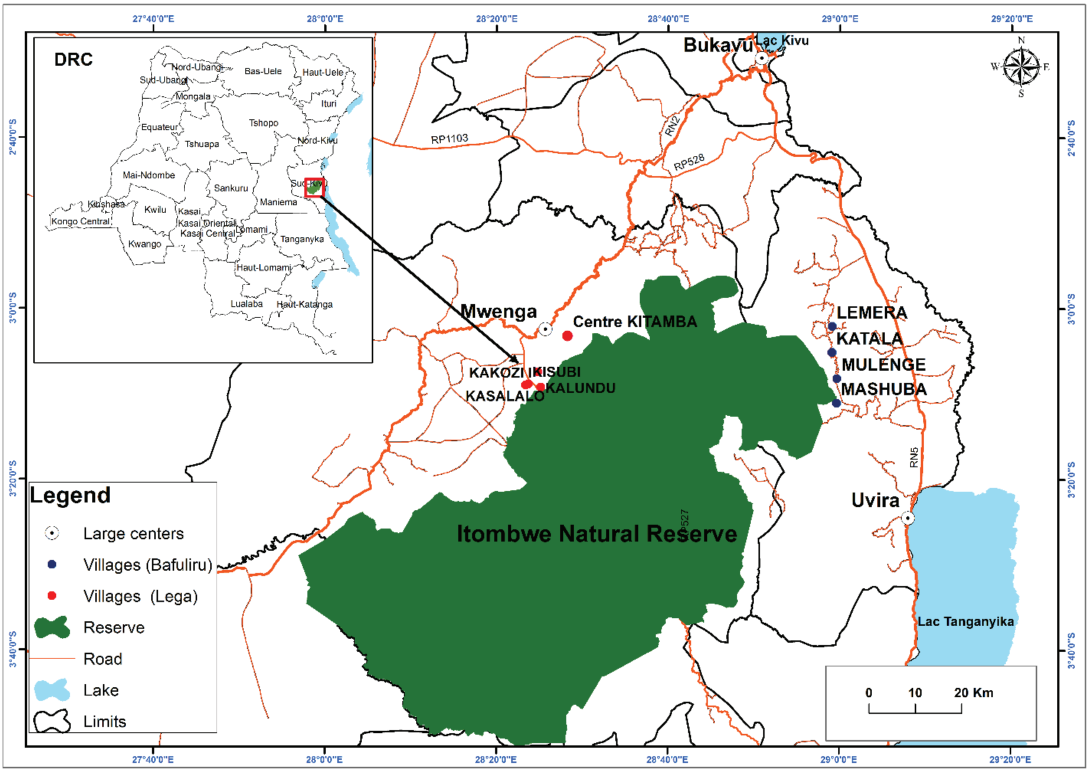

Figure 1. Study area with the location of the Lega and Bafuliru villages sampled.

The Lega (Rega or Barega), of Bantu origin, are a small ethnic group of 250,000 people speaking Kirega, whose homeland is the Mwenga territory, in the northwest of the Itombwe Mts [24]. The Lega traditionally lived by hunting and gathering, and were organised into small village groups, with no central authority. They were forced by the colonial administration to start farming in order to produce cassava and rice to feed the miners in the region [24]. In more recent years, the Lega have been increasingly engaged in panning for gold in the rivers and working in the iron ore mines of the region. The Lega are not engaged in cattle rearing, but they often engage in the pisciculture of *Tilapia nilotica*, e.g., fish ponds are often given as a bride price.

Both the Bafuliru and Lega practice small-scale rainfed subsistence agriculture, and cultivate cassava as a main staple food crop (both the roots and leaves are consumed). Farmers often intercrop cassava with maize, beans, amaranths and yam (especially the Bafuliru farmers). The use of tractors is limited due to the steep terrain and poor road infrastructure. Due to poor market access, there is no major cash crop. Examples of local farms can be seen in Figure S1 in the Supplementary Material. In the two local contexts, all of the local farmers are smallholders.

2.2. Data Collection

We administered a semi-structured questionnaire to 300 randomly selected household heads (n = 150 households per ethnic group) in four Bafuliru and four Lega villages (Figure 1), which represent a sample of 0.06% of the total population for each ethnic group (estimated at 250,000 people, see the previous section). In total, 150 households per ethnic group were considered an appropriate number, given the time and resources available for the research.

The questionnaires addressed household characteristics and assets, the climatic changes observed, the impacts in the bio-physical domain, and the adaptive strategies which were used to cope with or adapt to the observed changes (see the Supplementary Material). The methodological approach and the questionnaire used follow the guidelines of the project Local Indicator of Climate Change Impacts, a project focused on providing data on the contribution of local and indigenous knowledge to climate change research (see https://licci.eu/, accessed on 16 December 2021). The same approach (150 households per ethnic group, with a similar questionnaire) was used to survey smallholder farmers in Mt. Kilimanjaro in Tanzania [8].

The interviews were carried out in Swahili, and were facilitated by the first author between July and August 2021. All of the study participants were selected on a voluntary basis, and were first informed that the aim of the study was to better understand their everyday experiences and practices of climate change adaptation.

2.3. Data Analysis

The percentage of respondents was the main unit of analysis for each ethnic group (n = 150 per ethnic group). First, we explored the main patterns and differences between ethnic groups. Then, we explored the differences within the ethnic groups by pooling the respondents by wealth groups (poor, average, wealthy) based on a wealth index created from ten asset indicators [25,26]. The assets which varied most across households (over 25% of households did not own them) were weighted 0.25 greater than those which were more commonly found. Cross-tabulation tables and chi-square tests were used to determine the significant relationships between wealth groups and adaptation strategies, following [8]. We used the wealth group as an explanatory variable, and adaptation strategies as response variables. We used a significance level of $p < 0.05$. The Statistical Package for Social Science (SPSS) version 28 was used for all of the data analysis.

3. Results

3.1. Characteristics of the Smallholder Farmers Studied

An overview of the characteristics of the smallholder farmers studied can be found in Table 1. Notably, only five Bafuliru households were female-headed (there was no husband or male relative living in the household); these included average and poor households. In total, 51% of the Bafuliru respondents had never completed primary school (including both males and females). Only 13 Lega households were female-headed (there was no husband or male relative living in the household); these included average and poor households. In total, 49% of the Lega respondents had never completed primary school (including both males and females). For the Bafuliru, the ten assets considered in the wealth analysis were (in increasing order of being common): a motorbike (2% of the respondents), a farm >2 hectares (5%), >two chairs (17%), a mobile phone (26%), a solar plate (27%), >two cows (28%), a radio (36%), >two children attending primary school (41%), two containers of 20 liters of water (49%), and a machete (78%). In total, 95% of the Bafuliru respondents owned their home. Large animals referred to goats (43% of the respondents), cows (29%), or sheep (5%), no respondent owned a pig.

Table 1. Wealth analysis of the two ethnic groups (n = 150 Bafuliru, n = 150 Lega).

Bafuliru	**No Household**	**Adults (Mean ± std)**	**Farm (ha) (Mean ± std)**	**Large Animals (% Households)**	**Main Activities**	**Wealth Items**
Poor	n = 37	3.4 ± 2.7	0.48 ± 0.4	16%	100% farming	<2 items
Average	n = 95	3.9 ± 2.7	0.6 ± 0.6	63%	96% farming	2–6 items
Rich	n = 18	4.5 ± 2.1	1.3 ± 1.2	62%	94% farming	>6 items
Lega	**No household**	**Adults (mean ± std)**	**Farm (ha) (Mean ± std)**	**Large Animals (% households)**	**Main activities**	**Wealth items**
Poor	n = 35	3.5 ± 2.4	0.55 ± 0.6	6%	100% farming	<2 items
Average	n = 90	4.9 ± 2.7	1.2 ± 0.9	28%	99% farming	2–6 items
Rich	n = 25	5.9 ± 2.4	1.3 ± 0.8	76%	100% farming	>6 items

For the Lega, the ten assets considered in the wealth analysis were (in increasing order of being common): a concrete floor (5%), > two children attending primary school (20% of the respondents), a mobile phone (24%), a radio (28%), a pisciculture pond (29%), >two chairs (43%), two containers of 20 L water (45%), a solar plate (49%), and a machete (76%). In total, 94% of the Lega respondents owned their home. 'Large animals' refers to goats (22% of the respondents), pigs (10%) and sheep (9%); no respondent owned a cow.

3.2. Climatic Changes and Impacts

In general, the answers from the two ethnic group studied were in agreement with regard to both climatic changes and impacts (see Figures 2 and 3). Overall, respondents from both ethnic groups reported 12 changes in climate and seven impacts (Figures 2 and 3), with most of the changes and impacts being noticed by a larger number of Bafuliru respondents. The changes which were most often reported by both ethnic groups (>60% of the respondents) were changes in rainfall distribution (dry spells, showers) and interannual variability, and there being fewer foggy days and increased hailstorms (Figure 2). Most Bafuliru respondents also reported increased temperatures, a lower amount of rainfall, the late onset of the rains, less frost and more droughts (Figure 2). The impacts most often reported by both ethnic groups (>60% of the respondents) were reduced cassava yields, an increase in cassava mosaic disease (CMD), and reduced human health (Figure 3). The respondents related the reduced human health to a perceived increase in malaria prevalence (Bafuliru) or cholera (Lega). About 40% of the respondents of both ethnic groups also reported increased soil erosion and increased diseases of livestock. The Bafulriu respondents highlighted impacts on cattle (Figure 3), which the Lega did not as they do not own cattle.

3.3. Adaptation Strategies

In terms of adaptation strategies, the answers from the two ethnic group studied were not in agreement (Figure 4). Overall, the Bafuliru had implemented thirteen adaptation strategies and the Lega had implemented eleven, although for the Lega only four strategies were implemented by >20% of the respondents. The strategies most often used by the Bafuliru (>40% respondents) were the increased use of improved cassava (which is resistant to CMD), the increased use of pesticides (to address CMD), sowing seeds earlier, changing farm locations to be closer to streams (to benefit from the high water table), increasing the use of soil conservation techniques (to avoid the effects of dry spells during the rainy season), and increasing veterinary care for cattle (Figure 3). Some of the farmers also increased their farm size or used fertiliser (to compensate for lower cassava yields) (Figure 4). The increasing use of pesticides is considered an adaptation strategy by the farmers interviewed, as they link changing rainfall patterns (in particular more showers during the dry season) to an increase of cassava mosaic disease (CMD), and in order to acquire a minimum cassava yield (to feed the family) they have to use pesticide.

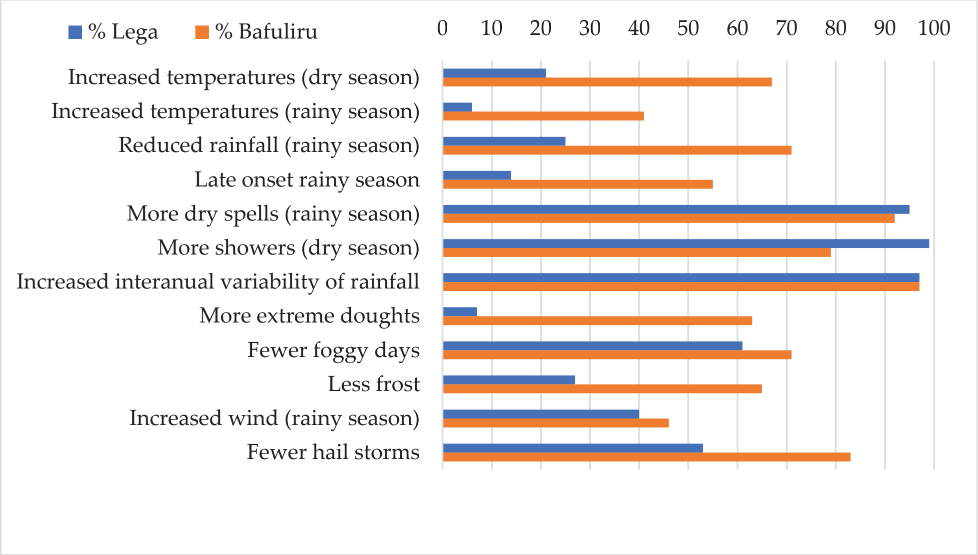

Figure 2. Perceived climatic changes per ethnic group (n = 150 Bafuliru, n = 150 Lega).

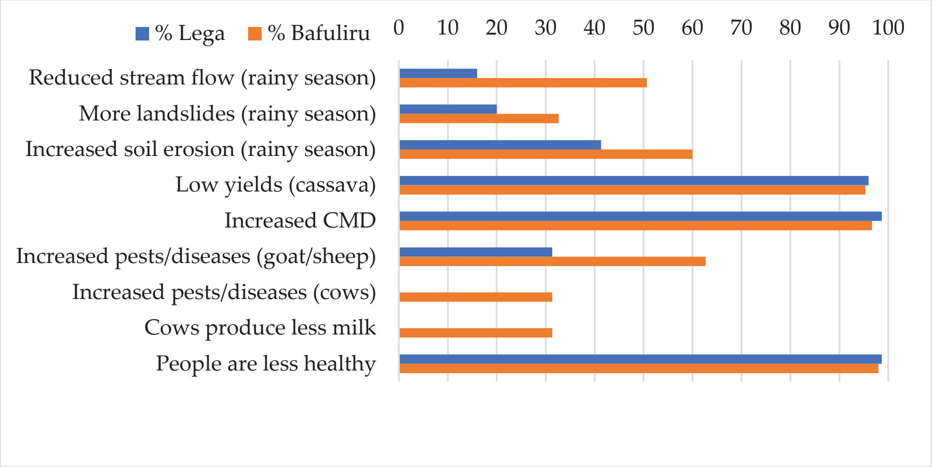

Figure 3. Perceived impacts per ethnic group (n = 150 Bafuliru, n = 150 Lega). CMD: cassava mosaic disease.

The strategies most often used by the Lega (>40% respondents) were the increased use of improved cassava, and sowing seeds earlier (Figure 4). Pesticides are difficult to find in any shop in Lega villages, and soil conservation is not widespread due to the more gentle slopes in Lega villages (compared to those of the Bafuliru).

Very few Bafuliru or Lega farmers diversified their livelihoods (e.g., animal rearing, growing and selling vegetables) to obtain other food products or cash to buy food and compensate for lower cassava yields. Notably, labour was only mentioned by one Lega respondent. Only one of these adaptation strategies—improved cassava—had been initiated by external actors, i.e., a local Non-Government Organization (NGO) (Figure 4).

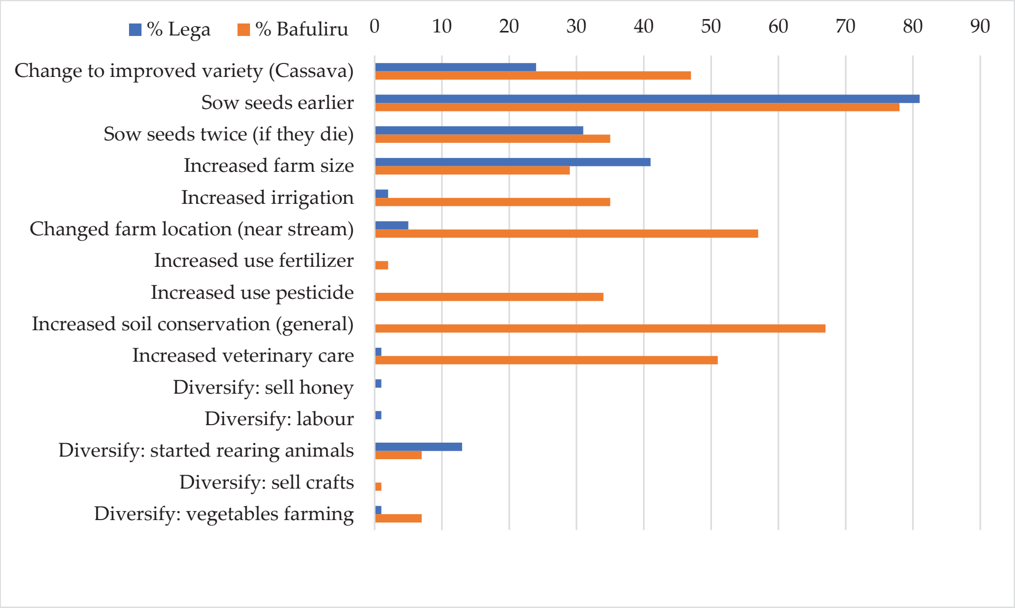

Figure 4. Adaptation strategies used per ethnic group (n = 150 Bafuliru, n = 150 Lega). Diversion ditches are the most common soil conservation technique used by the Bafuliru.

3.4. The Effects of Wealth

Among the Bafuliru, there were some significant differences across wealth groups. The wealthier households increased the use of improved cassava, sowed seeds twice (if they die due to a dry spell during the rainy season) or used veterinary care (Table 2), which would be expected given that financial means are needed to implement these strategies (e.g., to buy seeds again if they die). Contrary to our expectations, irrigation (with manually made canals) and soil conservation techniques were practiced by a similar percentage of households across the Bafuliru wealth groups—even if wealthier households should have greater financial means to pay for labour to implement these. Among the Lega, there were no significant differences across wealth groups (Table 2), probably because only four strategies were implemented by >20% of the respondents (see Figure 4).

Table 2. Differential adaptation responses by wealth groups among the Bafuliru (n = 150) and the Lega (n = 150). '%' refers to the percentage of respondents within a wealth group. Bold values and * indicates significant differences across the wealth groups at $p < 0.05$, using cross-tabulation tables and chi-square tests.

Bafuliru	Rich (%)	Average (%)	Poor (%)
Change to improved variety (cassava) *	**33.3**	**31.6**	**8.1**
Increased irrigation	33.3	35.8	35.1
Changed farm location (near stream)	55.6	55.8	59.5
Sow seeds earlier	94.4	76.8	73.0
Sow seeds twice (if they die) *	**50.0**	**40.0**	**16.2**
Increased use fertiliser	0.0	2.1	2.7
Increased use pesticide	50.0	34.7	24.3
Increased use soil conservation	61.1	66.3	73.0
Increased use veterinary care (cows) *	**27.7**	**31.5**	**5.4**
Increased use veterinary care (goat/sheep) *	**50.0**	**28.4**	**10.8**

Table 2. *Cont.*

Bafuliru	Rich (%)	Average (%)	Poor (%)
Diversify: sell crafts	0.0	1.1	0.0
Diversify: vegetable farming	16.7	5.3	5.4
Diversify: started rearing animals	5.6	8.4	2.7
Lega	**rich (%)**	**middle (%)**	**poor (%)**
Change to improved variety (cassava)	16.0	11.1	8.6
Increased irrigation	4.0	2.2	0.0
Changed farm location (near stream)	12.0	4.4	0.0
Sow seeds earlier	88.0	81.1	74.3
Sow seeds twice (if they die)	36.0	32.2	22.9
Increased use veterinary care (goat/sheep/pig)	8.0	0.0	0.0
Diversify: honey	0.0	2.2	0.0
Diversify: vegetable farming	0.0	2.2	0.0
Diversify: labour	0.0	1.1	0.0
Diversify: started rearing animals	12.0	12.2	14.3

4. Discussion

4.1. Climatic Changes

The results indicate that climatic changes have already been perceived by smallholder farmers in the Itombwe Mts, and that in general, these perceptions do not differ between ethnic groups. Overall, respondents from both ethnic groups reported changes in rainfall distribution within and between years, reduced fog and hailstorms but increased strong winds during the rainy season. Most Bafuliru respondents also highlighted increased temperatures and the reduced duration and amount of rainfall during the rainy season. Most likely, these small differences in perceptions observed are related to diverging local climates on different sides of the Itombwe Mts chain. Although field measurements of rainfall and temperature are unavailable [17], based on the vegetation patterns the northeastern side (which the Bafuliru inhabit), it is drier than the northwestern side (which the Lega inhabit) (see [19]). Therefore, it is most likely that small changes in temperatures or rainfall are more pronounced in the areas which are drier and hotter. The overall agreement between Bafuliru and Lega perceptions of climatic changes support the notion that different ethnic groups inhabiting nearby areas report similar changes in climate (e.g., [4]).

The climatic changes reported by the Bafuliru and Lega generally agree with the changes reported by farmers around Mt. Kahuzi [4] and Bukavu [27], who noted increased temperatures, shorter and less rainfall during the rainy season, the increased occurrence of dry spells and strong winds during rainy season, and more rain showers during the dry season. Compared with other studies in mountains in the Albertine Rift region, increased temperatures were also reported by farmers in the Rwenzori Mountains (Uganda), while a late (or unpredictable) onset of the rainy season was also reported in Kibale National Park (NP, Uganda) and Volcanos NP (Rwanda) [28,29]. Overall reduced rainfall was reported from Kibale NP, as in our study, but increased rainfall—mostly due to fewer but heavier precipitation events—was reported in the Rwenzori Mountains [29,30]. Reduced rainfall was also reported by farmers in Mt. Kilimanjaro and the Udzungwa Mountains in Tanzania (see [8]).

Likewise, in our study, the farmers around Mt. Kahuzi also reported less fog and fewer hailstorms [4]. The farmers in Mt. Kilimanjaro and the Udzungwa Mountains also reported reduced fog [8], while Mt. Elgon in Uganda (which is not in the Albertine Rift region) reported increased hailstorm frequency [31]. Most studies on farmers' perceptions of climatic changes do not investigate fog or hailstorms, even if both can have important impacts on crop yields, e.g., fog can extend the length of the growing season for beans [32] while hailstorms can destroy crops. In summary, our study highlights that smallholder farmers report numerous climatic changes beyond rainfall and temperature, as highlighted by other authors (e.g., [4]). In areas where no meteorological data are available, local perceptions can help us to understand local climates and impacts [1,2].

4.2. Impacts

Similarly to the climatic changes, the results indicate that in general, the perceptions of impacts do not differ between ethnic groups. Overall, respondents from both ethnic groups reported a reduction in cassava yields, an increase in CMD, and reduced human health, while the Bafuliru also mentioned reduced health for cattle and an increase in soil erosion and floods. Because the Lega do not own cattle, they could not report such changes. With regard to an increase in soil erosion and floods, the area where the Bafuliru live might be more prone to floods and soil erosion during intense rains, because of steeper terrains next to the Rusizi floodplain. Farmers in Mt. Kahuzi also reported increased soil erosion and floods [4], which they related to both climatic changes and increased deforestation in the area where they lived. In this study, some Bafuliru also mentioned local deforestation as a potential driver of increased soil erosion. Increased soil erosion associated with heavy rains was also reported by local famers living around Volcanos NP, and increased floods and landslides were reported in Mt. Elgon [28,31].

In Mt. Kahuzi, about 60% of the farmers reported reduced cassava yields, and that goats were now less healthy [4]. Reduced cassava yields were not reported by other studies in the mountains of Uganda, Rwanda or Tanzania, but cassava is not the main staple crop on such mountains. However, the farmers on such mountains also reported reduced crop yields, which they linked to climatic changes, e.g., maize and beans [8]. CMD is known to be the principal constraint of cassava production in sub-Saharan Africa [33,34]. Beyond climatic changes, new strains and certain agronomic practices are favourable to the virus' spread [35]. In our study area, the participants linked an increase in showers during the dry season to increased disease prevalence. Given that cassava is the source of food and income for about 70% of the population in DR Congo—not just in mountain areas—CMD represents an important threat to food security in this country [35]. The integration of farmers' perceptions of drivers of crop disease could open pathways towards potential solutions for the increased spread of this disease. As highlighted by Labeyre et al. [36], the increased integration of farmers' knowledge can complement the limited scope of current agricultural research on the impacts of climate change, which is focused on a small number of cereal crops.

With regard to cattle health and reduced milk production, such impacts have been reported in other mountains, e.g., in northern Kenya [32] or Mt. Kilimanjaro [8]. In Kenya, reduced cattle health and milk production were related to reduced fodder availability and quantity, which were in turn related to changing rainfall patterns. In this study, the Bafuliru farmers also linked it to reduced fodder availability in the area, and increased diseases such as foot-and-mouth disease. As highlighted by other authors (e.g., [37]), local perceptions can help identify impacts that may be largely overlooked by government and development agencies. The integration of farmers' perceptions of drivers of cattle disease could also help to address such challenges.

4.3. Adaptation Strategies, Wealth, and Adaptation Gaps

Contrary to perceptions of climatic changes and impacts, large differences were observed between the Bafuliru and the Lega, with the Bafuliru implementing several adaptation strategies, and the Lega implementing fewer. The Lega mostly sowed seeds earlier, sowed seeds twice if they died, increases their farm size (to compensate for lower yields), used improved cassava varieties (which were resistant to CMD) and increased veterinary care for goats—all of which were cited by farmers in Mt. Kahuzi [4]. Notably, sowing seeds twice if they die could be perceived as a 'coping mechanism', rather as an adaptation strategy, as it is a mechanism which is often constrained by the availability of enough resources (seeds or cash to buy seeds again). Several factors might explain why Lega implemented fewer adaptation strategies. First, market access is limited for the Lega; therefore, there is a limited availability of inputs (e.g., pesticide) and room for selling crop surplus, vegetables or crafts (therefore, there is no motivation to diversify into such strategies). Second, the environmental context is different to that of the Bafuliru: the terrain is less steep (there is less need for soil conservation techniques) and rainfall is generally more abundant (there is less need for irrigation). Third, culture is also likely to explain some differences, as Lega do not place a high value on farming (as a livelihood activity defining identity or social status), but they place higher value on, e.g., pisciculture or hunting.

All of the adaptation strategies mentioned by the Bafuliru have been reported by previous studies, such as in Mt. Kahuzi [4] or elsewhere in the Albertine Rift. For example, changing planting dates, soil conservation practices, irrigation and agroforestry were mentioned by farmers in the Rwenzori Mountains [29]. An important difference with other studies is the fact that only one Lega mentioned labour as a livelihood diversification option. This can be explained by the limited availability of labour jobs—such as engaging in tea plantation, timber plantation, transporting goods in a market town, or being a shop assistant in market town—in the study areas. Furthermore, diversifying into off-farm activities such as mining, timber harvesting, or charcoal production—strategies mentioned in Mt. Kahuzi [4]—were not cited in our study as adaptation strategies. However, diversifying into mining is common among the Lega, but this is mostly driven by economic motivations, and it is not considered a climate change diversification strategy.

In our study, wealth had an effect on the adaptation strategies used amongst the Bafuliru but not the Lega. Numerous studies have documented that wealthier households generally have more options for adaptation, as they have greater access to land, and greater resources to buy inputs such as improved seeds or pesticides, to pay for irrigation, or even to access information and technologies (e.g., [8]). However, our findings show that wealth effects are not so straight-forward. For the Lega, due to their disconnection from markets, wealthier households were not able to implement more strategies, highlighting how important it is to consider the local socioeconomic context(s), not just wealth.

With regard to the three components of adaptation gaps (exposure, realisation and coherence) [11], the main difference between ethnic groups is realization. It could be argued that exposure (the gap between the magnitude of climatic exposure and the sum of all of the adaptation options) is similar for both groups, as both ethnic groups live in the same mountain and report similar climatic changes and impacts. For coherence, the gap between actual adaptation action and the proportion of adaptations that are in alignment with 'national or international' established goals, it could also be argued that it is similar for both groups, as both are located in the same political context, i.e., DR Congo. However, realization (the gap between all adaptation options and actual adaptation action) is different, as the Bafuliru are using more adaptation strategies compared to the Lega. Both soft limits (access to inputs, markets, and information) and culture (less interest in farming, less capacity to organize into groups) seem to explain the differences in the realization gap.

4.4. Limitations and Future Research

Our study approach has some limitations. First, we only studied four villages per ethnic group. In our study area, biophysical or socioeconomic differences across the villages of one ethnic group are rather limited (e.g., market access or the presence of external change agents). However, it is possible that by including more villages, different adaptation strategies could be identified. We also only focused on two ethnic groups living around the Itombwe Mts, but there are others, including, e.g., the Banyamulenge, for whom cattle rearing is the main livelihood activity. In order to obtain an overview of the adaptation options in these mountains, future research should consider the different ethnic groups. As highlighted by [38], the exchange of knowledge not just between local farmers and scientists but also among different communities and mountains could be vital in order to devise efficient adaptation. Furthermore, although we interviewed female respondents, most of the female respondents were married. Future work should also investigate adaptation options for female-headed households. Last but not least, we should acknowledge that we focused on climatic changes as the main challenge to farmers' livelihoods. However, other drivers of change are likely to act synergistically with climatic change, constraining adaptation options, including insecurity, as we further discuss below.

The results highlight important differences in sociocultural contexts, even within one 'remote' mountain, calling for more a collaborative approach to adaptation planning and action. In order to address soft limits, the smallholder farmers we studied need external support, together with greater implementation resources. External support should focus on mutual learning among actors, in order to ensure the sustainability of the adaptation strategies implemented (e.g., [39]). One option for this 'isolated' mountain context is to foster social capital, e.g., in parts of the Andes, farmers' organizations provide an alternative to non-existing government support [40]. The Lega, who seem to show weaker social capital, might need more support than the Bafuliru to enhance organization. In order to address hard limits (infrastructure, insecurity, and the technical solutions available), external support is also needed. Accessibility to markets depends on the infrastructure and transport system in a region, which can make farm-households more vulnerable if they are inadequately developed [41]. Although there have been numerous attempts to tarmac the N2 national road between Bukavu and Mwenga (the main town among the Lega studied), none of them have been successful. Apart from improving roads and the mobile phone network—which can, e.g., facilitate access to microcredit—increased security from the rebel groups present in the Itombwe Mts, who control illegal mining sites [42], would also be beneficial, as farmers would be more keen to invest in strategies which can only benefit farmers in the mid-term (e.g., investment in irrigation infrastructure, agroforestry, and cash crops). More scientific research is also needed on climate change impacts on cassava. Beyond CMD, whitefly, brown streak disease, and cassava mealybug are predicted to be major challenges to this crop in the future [43]. We also recommend the urgent establishment of several meteorological stations around the Itombwe Mts, in order to help understand local microclimates, monitor climatic changes, and help prepare detailed weather forecasts, which could help, e.g., to advise farmers on planting dates.

5. Conclusions

This study aimed to investigate climate change perceptions and adaptations among smallholder farmers in the Itombwe Mountains of eastern DR Congo. The results show that numerous climatic changes and impacts have already been perceived by farmers, and that these perceptions do not differ between ethnic groups. The results also show that farmers have used up to 13 adaptation strategies, and that the adaptations differed between ethnic groups due to soft limits and culture (less interest in farming, less capacity to organize into groups).

Overall, apart from helping to understand the effects of culture (ethnicity) and wealth on adaptation, our findings on climate change perceptions and the adaptation strategies used by the Bafuliru and Lega smallholder farmers of the Itombwe Mountains in eastern DR Congo contribute to filling in the data gap on indigenous adaptation strategies used in Central Africa [44]. This is key information which will be needed if the IPCC is to better integrate indigenous knowledge in this continent (e.g., [44,45]).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11050628/s1, Figure S1. Top left: fog as a common climatic feature at high elevations. Top right: example of a farm with cassava intercrop with beans. Bottom left: example of weeds left to dry out and act as soil cover to maintain soil moisture. Bottom right: examples of farms on steep slopes (terracing is not common in both study areas).

Author Contributions: Conceptualization, G.I., A.C.-S. and B.R.; Methodology, R.K.A. and A.C.-S.; Data gathering, R.K.A. and R.B.; Formal analysis, R.K.A., G.I. and A.C.-S.; Writing—original draft preparation, R.K.A., B.R., G.I., N.Z.-C. and A.C.-S.; Revisions: R.K.A., G.I. and A.C.-S. All of the authors reviewed the final draft of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and approval were received for this study from the Ethics Committee of Integrated Management of Tropical Forests and Lands' Department of Ecole Régionale Post-universitaire d'Aménagement et Gestion Intégrés des Forêts et Territoires Tropicaux (ERAIFT).

Informed Consent Statement: Informed consent was obtained orally from all of the subjects in the study.

Data Availability Statement: The data that support the findings of this study is available for scientific purposes from first author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

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Article

The Alien Plants That Threaten South Africa's Mountain Ecosystems

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Abstract: The six major mountain ranges in South Africa support critically important ecosystem services—notably water production—and are rich in biodiversity and endemism. These mountains are threatened by detrimental land uses, unsustainable use of natural resources, climate change, and invasive alien plants. Invasive alien plants pose substantial and rapidly increasing problems in mountainous areas worldwide. However, little is known about the extent of plant invasions in the mountains of South Africa. This study assessed the status of alien plants in South African mountains by determining sampling efforts, species compositions and abundances across the six ranges in lower-and higher-elevation areas. Species occurrence records were obtained from three databases that used various approaches (roadside surveys, citizen science observations, focused botanical surveys). Most mountain ranges were found to be undersampled, and species composition assessments were only possible for two ranges. The majority of abundant alien plants in both the lower- and higher-elevation areas were species with broad ecological tolerances and characterised by long distance seed dispersal. These prevalent species were mostly woody plants—particularly tree species in the genera *Acacia*, *Pinus*, and *Prosopis*—that are contributing to the trend of woody plant encroachment across South African mountains. We suggest improved mountain-specific surveys to create a database which could be used to develop management strategies appropriate for each mountain range.

Keywords: alien species; biological invasions; citizen science; elevation; species abundance; tree invasions; woody plant encroachment

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1. Introduction

The mountains of South Africa support critically important ecosystem services—notably water production [1,2]. Through orographic influence, mountains trap moisture, providing surface and groundwater that is essential for downstream agriculture and the persistence of major urban and industrial centres [3]. The topographic complexity of South African mountains and their distribution across a strong climatic gradient in the region has resulted in diverse ecosystems and high local endemism [4–6]. This biodiversity is critical in supporting the livelihoods of rural local communities that are often poorer and more marginalised [7], and are therefore directly reliant on natural resources, such as for agriculture and traditional medicine [8,9]. Yet montane areas are under threat from detrimental land-uses, unsustainable use of natural resources, climate change, and invasive alien plants [10–13]. The establishment of alien plants in particular poses a substantial and continuously increasing problem in driving ecosystem changes and biodiversity loss in mountains [14]. This threat has not been adequately acknowledged in South Africa, and most mountain ranges are understudied [15]. Canavan et al. [13] highlighted that mountains remain areas of low priority for alien plant management and are generally considered to be largely resilient to invasion.

In the last two decades, research focused on mountain invasions has expanded worldwide [14,16,17]. Global reviews reveal a pattern of declining alien plant richness with increasing elevation [17–20]. This pattern has been attributed to a number of different mechanisms, including the introduction of alien species predominantly to low elevations, coupled with environmental filtering as species spread towards higher elevations [21], and limited propagule pressure [22]. Although mountains generally support fewer invasive alien plants than lowlands, there is clear evidence that alien plants are more frequently establishing at higher elevations, and are becoming an increasing threat in these areas [16,23]. South Africa has relatively good records on the extent of alien plant invasions compared to many other countries, partly due to investment into large nation-wide initiatives such as the Working for Water programme (WfW) [24]. Yet, as in most areas of the world, this research has largely not been extended into higher-elevation mountain areas [25,26]. There is, however, growing evidence that alien plants are becoming more prevalent in the country's mountains. For example, it is estimated that over 170 alien plants have invaded the Maloti-Drakensberg [27], and a further 23 species have been identified as emerging invaders [28]. Within the same mountain range, Turner [15] found that the number of alien plants along the Sani Pass more than doubled during a decade (2007 to 2017). Road networks extending into montane areas are facilitating the establishment of alien plants beyond their elevational barriers and present sustained propagule pressure [26,29]. This threat has not been matched with appropriate expansion of mountain research and alien plant management interventions in South Africa.

Pauchard et al. [16] proposed a three-pronged global research agenda aimed at improving the understanding of plant invasions in mountain environments: (1) detection and analysis of invasion patterns at multiple scales; (2) experimental studies of invasion drivers; and (3) assessment of the impacts caused by alien species and their conservation implications. This paper addresses the first of these proposed research needs for South Africa—the documentation of patterns. Forming appropriate management programmes to protect mountain ecosystems will rely on improved understanding of the spread and occurrence of alien plants [17]. We assess the current status of alien plants in South African mountains by examining the sampling effort achieved in currently available species occurrence databases, the merit of existing alien plant sampling techniques, and assessing alien plant assemblages in terms of composition and abundances across mountain ranges and elevations (low- and higher-elevation).

2. Data and Methods

2.1. Delineating Mountain Ranges and Their Characteristics

Mountain areas were demarcated using a combination of Topographical Positional Index (an algorithm used to measure topographic slope positions and to automate landform classifications) and roughness surfaces [13,30]. These were used to produce six mountain area polygons in ArcMap 10.3 namely: the Western Great Escarpment (WGE); the Eastern Great Escarpment (EGE); the Southern Great Escarpment (SGE); Sub-tropical/Tropical Cuestas (TC); the Central Griqualand Mountains (CGM), and the Cape Fold Mountains (CFM) (Figure 1). From this, elevational gradient and vegetation types were determined across all six ranges using Schulze [31] for elevation and Rutherford et al. [32] for vegetation types.

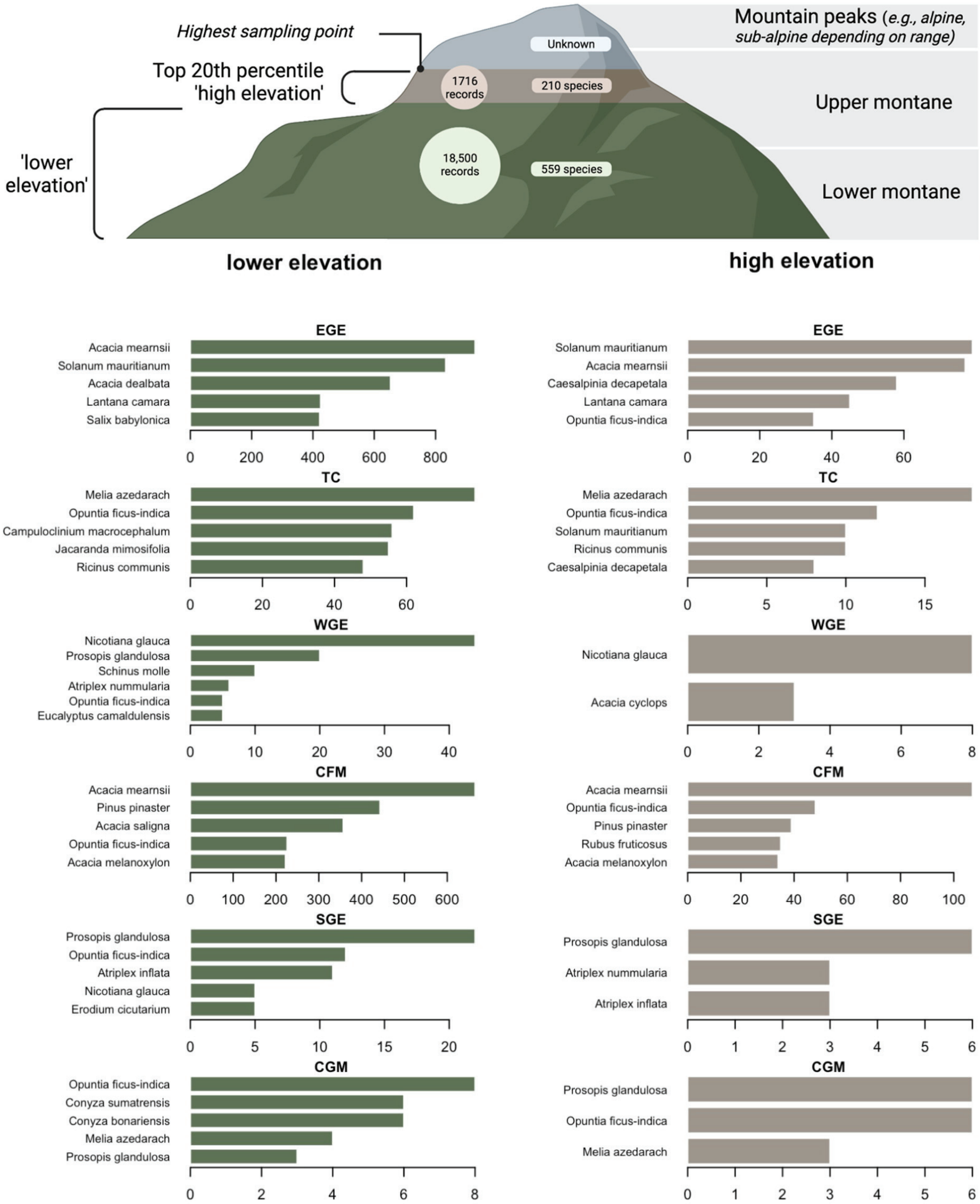

Figure 1. The top five most abundant alien plants recorded in each range in South Africa using SAPIA, iNaturalist and Great Escarpment Data (GED) databases. The high-elevation areas represent the upper 20th percentile elevational area in each range from the highest point recorded in the databases. The maximum elevation (highest peak) and high-elevation delineation for each range was—WGE: 1719 m, 1469 m; TC: 1868 m, 1528 m; EGE: 3446 m, 1651 m; SGE: 1784 m, 1451 m; CGM: 1605 m, 1355 m and CFM: 2064 m, 1667m. The lower elevational area reflect the entire mountain range below the designated high-elevation area. Figure created using BioRender (https://biorender.com/, accessed on 10 October 2021).

2.2. Sampling Effort

Sampling effort was assessed by performing a systematic literature review of all floristic surveys that include records of alien plants in South Africa's mountains. Alien plants were defined as species considered not native to the country and therefore "extralimitals" (species that are native to parts of South Africa but invasive in others) were not considered. Google Scholar [33], Scopus [34], ScienceDirect [35], Web of Science [36] and Taylor and Francis [37], databases were used. Furthermore, literature was obtained through searching bibliographies of papers and reports. There was no temporal constraint on journal publication date in the search. In September 2021, the following search terms items were included, 'floristic OR vegetation survey' AND 'South African mountains'; invasive OR weed OR alien AND plant species AND 'South African mountains'. Surveys were included if they stated GPS coordinates for all alien plant records to allow mountain area records to be extracted or were solely focused within the six mountain ranges of South Africa. After searching, the results were collated across databases and the title and abstract were used to select studies based on our criteria.

Three additional databases were included, as they are known to the authors to contain comprehensive records of alien plant occurrences—the Southern African Plant Invaders Atlas [38], iNaturalist [39] and the Great Escarpment Biodiversity Research Programme data mobilisation (hereafter referred to as GED) [40]. SAPIA is the best source of data on the distribution of alien plants in South Africa [24,41]. SAPIA was established to collate data on the distribution, abundance and habitat types of alien plants growing outside of cultivation in southern Africa [38]. iNaturalist is one of the largest online citizen science initiatives for naturalists, hosting about 50 million verifiable observations of 300,000 different species globally [42], and is an increasingly utilised resource for alien plant distribution in South Africa [43,44]. For this study, iNaturalist records were downloaded directly from the website and filtered for being verifiable, re-search grade, and alien plant species to South Africa (downloaded on 24/08/2021). The GED was a focused botanical survey (2005–2014) across two mountain ranges and is one of the most comprehensive publicly available mountain surveys [40].

Surveys that were carried out across more than one mountain range and contained GPS coordinates for all alien plant occurrences were analysed further. For these databases, alien plants recorded within the mountain layers were selected out in ArcMap10.3. All records of alien plants were included regardless of their invasive status (naturalised, casual etc.). The retention of all point observations may result in the inclusion of some duplicate records across the databases (duplicates were removed within each database). However, methods to avoid this duplication (i.e., removal of records of the same species within a grid-cell) would significantly reduce the dataset and retract from the aims of the paper including assessment of plant abundance.

The list of all species from each database was cleaned, updated and corrected; species names were checked for synonyms using the Plants of Southern Africa database (POSA) [45] and any revision of names were updated. When a species was not listed in POSA, the Plant List [46] was used to verify taxonomy. The native range for each species was determined using the Plants of the World Database [45] and was visualised using the 'maps' package in R [47]. For mapping, the ranges were generalised to the country-level (e.g., BrazilSouth to Brazil) and to update geopolitical boundaries (e.g., Czechoslovakia to Czech Republic and Slovakia). From this, 25 species were removed from the lists as they were noted to be alien; however, they have a native range within parts of South Africa (Table S1).

To assess sampling deficiencies on estimates of alien plant richness, we performed two analyses. Firstly, to assess whether sampling effort varies between mountain ranges we plotted the cumulative number of alien plant records and cumulative species richness over time for each of the six mountain ranges. Separate curves were plotted for each mountain range for records originating from the surveys to determine whether sampling effort variation between mountain ranges was linked to database (collector) bias. Secondly, we assessed whether sampling effort has varied between databases. A focused botanical survey within a specific montane area (GED) was compared to two nation-wide surveys within the same geographical area. The cumulative number of alien plant records and cumulative species richness were plotted within the timeframe of the GED surveys. We then investigated whether there were taxonomic biases between databases by calculating the unique alien plant species within each family.

2.3. Species Composition

Alien plant assemblages were defined here according to Rouget et al. [48], who determined that invasive alien plants in South Africa cluster into distinct suites of species according to broad environmental conditions. Alien plant assemblages were assessed to determine how these species compositions varied between mountain range, databases and elevation (100 m intervals). To visualise how alien plant assemblages vary between mountain ranges, databases and elevation (100 m intervals), model-based unconstrained ordination was employed using the 'boral' R package [49]. A Bayesian hierarchical correlated response model was fit to the species-abundance matrix for the EGE and CFM ranges only. The remaining ranges had insufficient records for the analysis. The model uses latent variables to account for residual correlations between alien plant species. Thereafter, multivariate generalised linear models (MvGLM's) were used to test for the effect of mountain range, database and elevation on plant assemblages using the 'mvabund' package in R [50]. To do so, the 'manyglm' function was used to model the multivariate species abundances as the response variable, with mountain range (CFM, EGE), database (SAPIA, iNat) and elevational bands specified as categorical fixed effects. Likelihood-ratio tests (hereafter 'LRT') and pit-strap bootstrapping were used to compute P-values, using 999 bootstrap replicates, to assess the statistical significance of fixed effects.

Univariate GLM's were performed to determine which individual plant species accounted for any observed differences in plant composition between mountain ranges and elevation, using pit-strap bootstrapping to compute adjusted p-values corrected for multiple testing and correlations between species [50]. All GLM's were specified using a negative binomial distribution to account for mild overdispersion in preliminary models specified with a Poisson distribution and the strong mean-variance relationship present in the dataset. All statistical analyses were performed in R ver. 4.0.3. [51].

2.4. Species Abundance

The most abundant alien plants were determined for each range. To determine the species that have established in the highest elevational areas, each range was delineated into the highest-elevation areas (referred to as "high elevation") and then the adjacent lower-elevation areas (referred to as "lower elevation") (Figure 1). The highest elevational areas within mountain ranges generally have unique vegetative and climatic conditions that define the alpine and sub-alpine zones [52]. These distinct mountain zones are often differentiated by determining shifts in species composition and climatic conditions with elevation [16,53]. However, this could not be performed for this study for two reasons. Firstly, species composition assessments were not possible for all ranges due to a lack of alien plant records. Secondly, alpine and sub-alpine areas are only found within the EGE and CFM ranges respectively. Consequently, the highest areas of each range were categorised by demarcating the upper 20th percentile using the highest elevation point. When using the highest peaks for range as the upper limits, there were no alien plant records across all six ranges. The upper limit was therefore set as the highest elevational point that was taken during surveying for each range (see Figure 1). High-elevation areas were then defined as the upper 20th percentile from this high-elevation point and low-elevation areas were defined as the lower adjacent 80th percentile elevation. The five most abundant alien plants were then outlined for the highest and lower elevation areas for each range.

3. Results and Analyses

3.1. Delineating Mountain Ranges And Their Characteristics

The six major mountain ranges in South Africa were determined using the topographical positional index and roughness surfaces (Figure 2). Compared to mountains globally, South African mountains do not have particularly high absolute elevations, with a maximum elevation of 3446 m at the Mafadi peak in the EGE (the EGE reaches its highest point at 3482 m in Thabana Ntlenyana, Lesotho) (Figure 3). Overall, the EGE has the highest elevations in South Africa (with many points > 3000 m), while—of the other mountain ranges—only the CFM exceeds 2000 m (the highest point being Seweweekspoort Peak, 2325 m, in the Klein Swartberg); the WGE, SGE, TC and GCM are all < 2000 m (Figure 3). Elevational difference is more important for our purposes than absolute elevation, as the former provides the basis for determining surface area for invasion potential, and climatic partitioning and related potential invasion envelopes.

The WGE, EGE and SGE all form part of the same passive continental margin from the break-up of Gondwana, while the TC, CGM and CFM have diverse, ancient orogenies. Within these ranges, there is a strong effect of latitude on mountain vegetation—from temperate south to tropical north—and in terms of rainfall seasonality—from both south to north, and east to west [5,32,54]. A total of 443 vegetation types occur within these ranges according to Rutherford et al. [32] (Figure 3 and Table S2). The WGE—comprising the arid to hyper-arid Richtersveld and Namaqualand—has 36 vegetation types. The EGE—comprising the mesic grassy-dominated escarpment from the Sneeuberg to the Wolkberg—has 438 vegetation types. The SGE—comprising the arid Hantam–Roggeveld and Nuweveldberge—has 17 vegetation types. The TC—comprising mesic savanna-dominated hogsbacks in the far north—has 30 vegetation types. The CGM—comprising arid savanna—has seven vegetation types. The CFM—comprising fynbos-dominated folded mountains systems in a winter-rainfall region—has 139 vegetation types.

3.2. Sampling Effort

A total of 29 studies were found to include alien plant surveys within the mountains of South Africa (Table S3, references [55–75] are cited cited in the supplementary materials). Ten of these surveys focused only on recording alien plants. Most research has involved botanical surveys of specific mountain ranges with the aim of recording plant diversity and therefore focus has been on species richness rather than abundance. Most records of alien plants therefore came from lists produced during these botanical surveys. Only three databases include the GPS coordinates for each alien plant occurrence and covered more than one mountain range—SAPIA, iNaturalist and the GED (see Table 1 for comparison between databases).

A total of 570 alien plant species were recorded across all six mountain ranges, with 20,216 occurrence records across all three databases (SAPIA, iNaturalist and GED) (Table S4). Origins are from a wide range of countries, with China and Mexico being the source countries for the largest number of introduced taxa (Figure 4 and Table S4). The native ranges of 68 of the species were not included, as they were not represented in the POWO database. Most records were taken within the lower elevations of each range (18,500 total records) compared to the highest areas (1716 total records). The EGE and CFM had the greatest number of occurrence records, and also the highest density of sampling per area (Figure 2). The SGE and WGE had the fewest occurrence records per area (Figure 2).

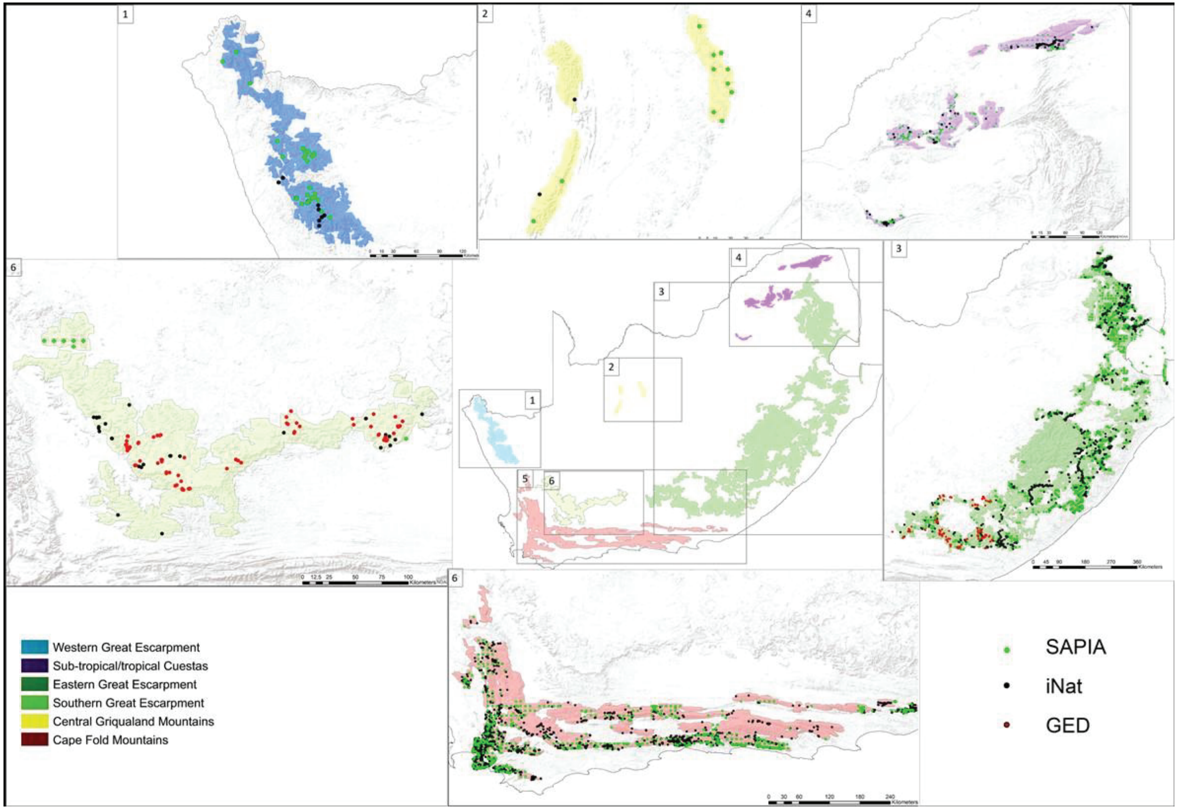

Figure 2. The six major mountain ranges in South Africa (adapted from Canavan et al. [13]), showing sampling effort across the six mountain ranges. The occurrence points for each alien plant record for all three databases is shown: SAPIA—the Southern African Plant Invaders Atlas, iNat—iNaturalist and the GED—the Great Escarpment Data.

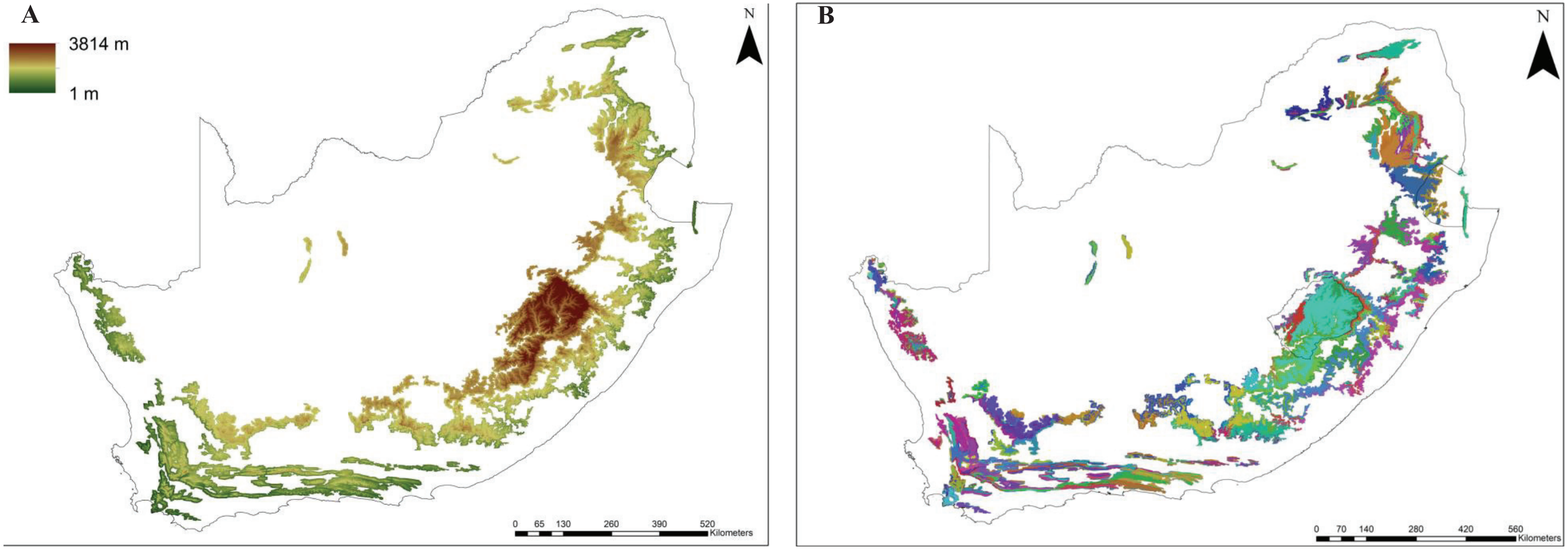

Figure 3. (**A**). The elevational gradient (metres) across the mountains of South Africa. (**B**). The vegetation types within South African mountains: EGE—438; TC—30; CGM—7; SGE—17; WGE—36, CFM—139 vegetation types according to Rutherford et al. [32] (see Table S2 and Figure S1 for vegetation type information).

Table 1. The three databases used to determine alien plant species occurrences in montane areas of South Africa.

Database	Total Records in SA	Total Species Richness in SA	Total Alien Plant Records in Mountain Areas	Percent of Records in Mountain Areas	Total Species Richness in Mountains	Observers	Methodology	Level of Botanical Verification	Spatial Scale	Temporal Scale	Funding Dependent	Alien Specific	Source
SAPIA *	80,226	969	18,278	26%	588	710	Nation-wide roadside survey, initially at the quarter degree scale, later using precise coordinates	High	National	1979–2018	Yes	Yes	Henderson and Wilson [55]; SAPIA Atlas [38]
iNaturalist *	59,704	554	1472	3%	239	9816	Citizen science observations	Medium to high	Global	2008–present (continuously updated)	No	No	Nugent [43]
GED	N/A	N/A	466	100%	160	3	Botanist focused plant surveys	High	Regional	2005−2014	Yes	No	Barker [40]

* SAPIA downloaded March 2018, iNaturalist downloaded 24 August 2021.

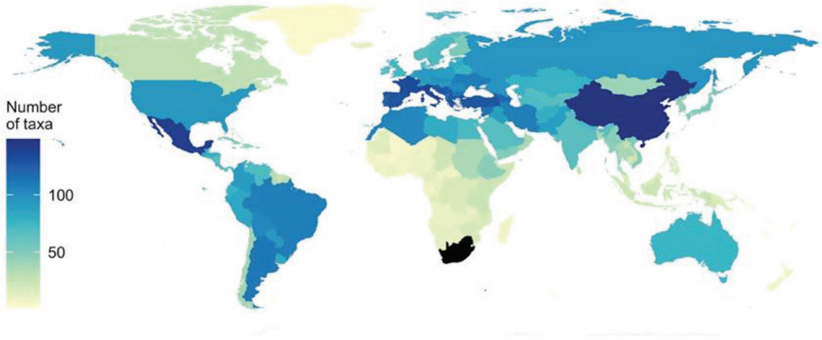

Figure 4. The native range distributions of the alien plants present within the six mountain ranges of South Africa (Table S3).

The nation-wide sampling effort for SAPIA and iNaturalist across all six mountain ranges revealed that all ranges have sampling deficiencies (Figure 5). The species accumulation curves for all mountain ranges did not reach an asymptote indicating that species richness of alien plants is not fully documented. Both the total number of records and alien plant richness are higher in SAPIA than iNaturalist. The occurrence data for the WGE, SGE and CGM is scarce and for both databases there has been little increase in numbers of records over time.

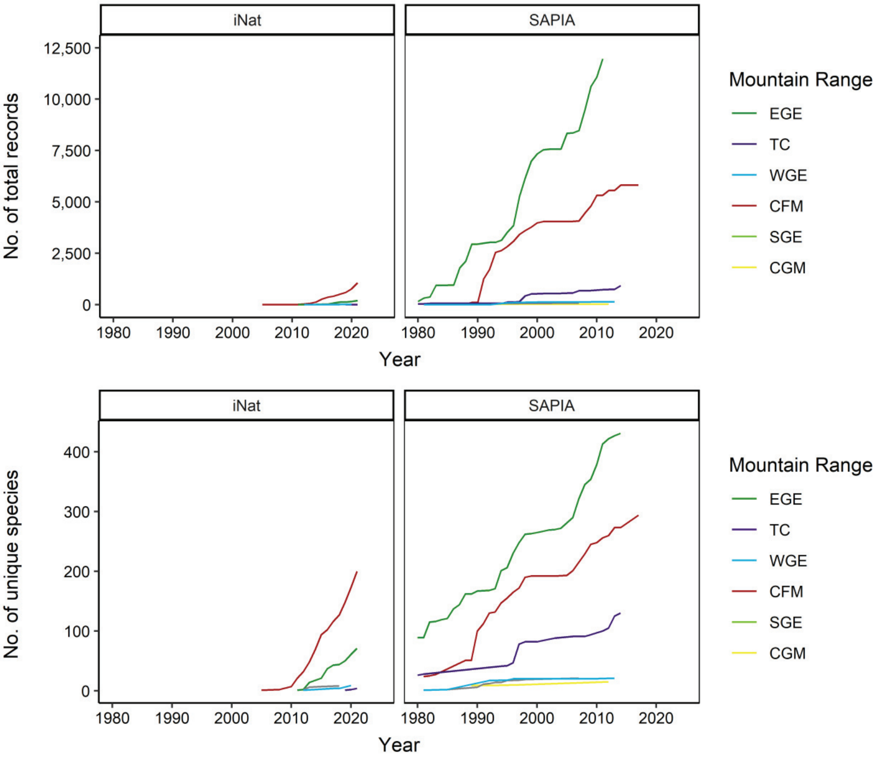

Figure 5. Species accumulation curves showing the number of records over time and the cumulative number of unique species recorded for iNaturalist and SAPIA databases for each mountain range across South Africa.

In assessing how sampling effort varied between the databases, the GED was found to have more effectively recorded the alien plants within the geographical area surveyed (Figure 6). A total of 160 alien species were recorded during the GED surveys over the nine-year sampling period, while SAPIA and iNaturalist combined recorded only 87 alien species with more than double the number of records over their full sampling periods (1994–2014, 2012–2014 for SAPIA and iNaturalist respectively). Species accumulation curves for the GED approached an asymptote, indicating that species richness was well documented (Figure 5). Within this surveyed area, a total of 41 plant families were recorded across all three databases, with 15 families being uniquely recorded in the GED (Table S3). The GED recorded 83 unique species (one of these being a new record for South Africa, *Sisymbrium runcinatum* (Brassicaceae)), with the Poaceae representing the most number of species (Figure 6). iNaturalist contributed only two unique species (Figure 6).

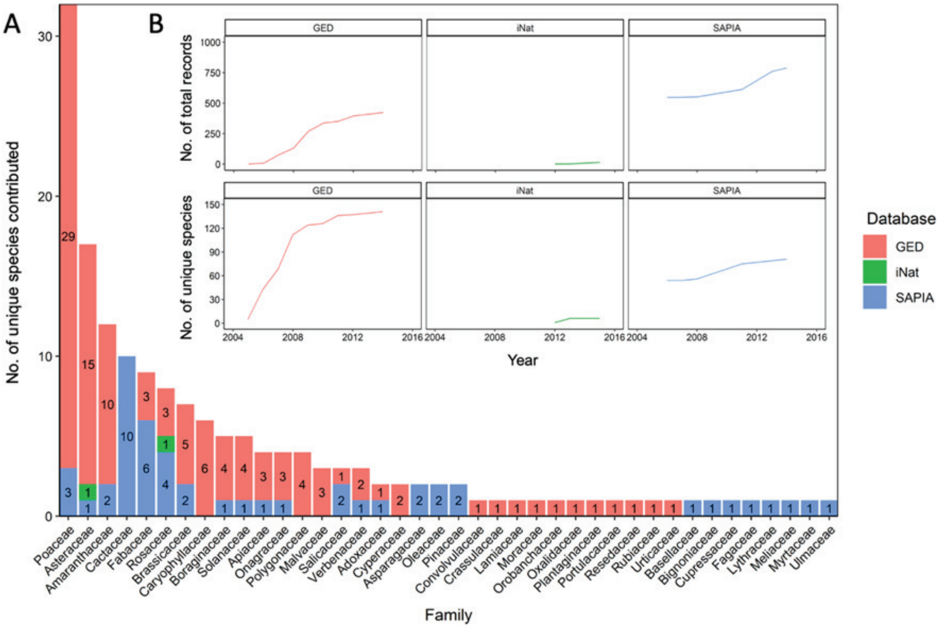

Figure 6. (**A**) The number of unique species recorded in each plant family across the three databases—Great Escarpment Data (GED), iNaturalist (iNat), South African Plant Invaders Atlas (SAPIA) (see Table S4 for all species recorded). Families are ordered by highest species richness from left to right. (**B**) Species accumulation curves showing the number of records over time and the cumulative number of unique species recorded for the GED, iNat and SAPIA. All records for each database are within the geographical range of the GED surveys (see Figure 3 for geographical area).

3.3. Species Composition

Species composition was only assessed for two ranges—the EGE and CFM. The remaining ranges had insufficient records to allow for meaningful species composition comparisons. There was significantly different species composition between the EGE and CFM mountain ranges ($X^2 = 2872$, d.f. = 1, $p < 0.01$), the two databases (iNaturalist and SAPIA) ($X^2 = 5045$, d.f. = 1, $p < 0.01$) and with elevation ($X^2 = 12{,}015$, d.f. = 17, $p < 0.01$). Univariate hypothesis tests determined which species were accounting for these differences (Table S4). For example, two species (*Hakea sericea* (Proteaceae) and *Pinus pinaster* (Pinaceae)) were found to drive the differences in elevation across the mountain ranges (Table S5); both species are largely restricted to lower elevations. There were 32 alien plants that were found to vary according to the mountain ranges where they were largely found to occur within one range. For example, *Cotoneaster pannosus* (Rosaceae) was only found within the EGE. Sixty-nine plant species were found to vary according to the databases.

3.4. Species Abundance within Each Range

The higher elevation areas did not encompass the highest peaks of each mountain range due to a lack of records—and yet there were still very few records within these delineated areas (210 alien plant species, 1716 records) (Figure 1). The CFM had the greatest number of records in the higher elevation areas (above 1667 m) (Figure 1). Woody plant species made up the majority of the most abundant species in all ranges (Figure 1 and Table S6, references [76–83] are cited in the supplementary materials). The species found in the higher elevational areas were largely a subset of the most abundant species found in the lower elevational areas (70% of alien plants in high-elevations areas had abundant lower elevation populations) (Figure 1). For example, in the TC mountain range, *Melia azedarach* (Meliaceae) is the most abundant alien plant in both the lower and high-elevation areas. A majority of the most abundant species in both higher- and lower-elevation areas were frost tolerant and occur across a range of climatic zones (Table S6). All the species have capacity for long distance seed dispersal, with birds and water being the main vectors for spread (Table S6).

4. Discussion

Research on biological invasions in the mountainous areas of South Africa has been hampered by the lack of reliable baseline data for temporal studies, and sampling bias due to limitations of conducting surveys in challenging, inaccessible terrain [15]. This study has confirmed this and has highlighted major gaps in knowledge relating to alien plant distribution in South Africa's mountains. There has been an uneven sampling effort of alien plants across the country, and most surveying has been focused within the CFM and EGE. Higher elevation areas had considerably fewer alien plant records than adjacent lower elevation montane areas. All mountain ranges have sampling deficiencies, and the true extent of alien plant invasions is thus poorly known.

The SAPIA database contributed the most alien plant records, however these surveys are largely restricted to roadside observations. Such surveys capture only part of the spectrum of plant invasions in mountains and do not provide a true reflection of invasions across entire landscapes [25]. As such, data for the less accessible higher-elevation areas in the interior of South Africa are especially scarce. The surveying techniques of the GED and iNaturalist databases offer improved records as observers are often on foot and able to access entire landscapes, for example on hiking trails. At present, iNaturalist has contributed few occurrence records for most ranges, but this citizen science shows promise. For example, in the CFM where most iNaturalist observations were made, the number of occurrence records equated to more unique species compared to SAPIA (ratio of about 5:1 and 20:1 number of occurrence records to number of unique species for iNaturalist and SAPIA respectively). iNaturalist is a relatively new platform and has not yet been widely adopted. However, with increased public awareness, its use is likely to grow. Outreach campaigns for iNaturalist that are supported by easy-access communication channels have been found to be effective at obtaining new observations [84]. Overall, the GED surveying was most efficient at recording alien plants, supporting the need for focused botanical surveys and trained taxonomic experts. Yet, there has been a decline in field collection surveys in mountain areas in recent decades [85]. Continued support for such surveys will be highly valuable and will greatly improve the records for each range in South Africa.

Given the unique environmental conditions and vegetation types across different mountain zones, it was anticipated that the highest elevation areas would be invaded by different alien plant assemblages compared to lower adjacent areas. Evidence for this has been found in studies of high-elevation mountain areas in South Africa. For example, in the Maloti-Drakensberg in the EGE, surveys have found specific species becoming more abundant or even restricted to higher elevation areas such as *Cotoneaster*, *Pyracantha*, and *Rubus* spp. [13,28,29,52,86]. However, due to the lack of records found across all the databases, the overall extent of invasion on South Africa's mountain peaks is unknown. Instead, the higher-elevation areas delineated here were below the mountain peaks, and the most abundant alien plants were found to be largely a subset of species that occur in the adjacent lower-elevation areas. This uniformity across elevations is in contrast to the native plant communities in these montane areas that are highly varied according to elevation and the environmental conditions across these landscapes (Figure 3); there are elevation-related vegetation differences particularly for CFM and EGE, as the relative elevation differences are the most ecologically significant in South African mountains: the CFM has a matrix of macchia/sclerophyllous-dominated vegetation (proteoid, ericoid, restioid, up to three to four m tall at maturity) that gives way to sub-alpine dwarfed forms of these >2000 m; similarly, the Maloti-Drakensberg in the EGE shows stratification, with C_4-grassland and evergreen forest mosaic <1800 m (montane zone), giving way to mixed C_4–C_3 sub-alpine grassland and sclerophyllous thickets (1800–2800 m), which in turn is replaced by alpine tussock grassland and ericoid shrubland >2800 m. The other mountain ranges show less discrete vegetation partitioning, but in general there is a trend of woody habitats prevalent at lower elevations transitioning to thinner woodland or pure sourveld grassland with increasing elevation. Most of the alien plants can however establish across a range of climatic conditions—and transgress these discrete native vegetation patterns—and have the ability for long-distance seed dispersal primarily by birds and water. It is likely that vertical dispersal of seeds is occurring whereby birds are carrying seeds into higher elevation areas and then water runoff moves the seeds downhill to establish populations in adjacent lowland areas. Vertical seed dispersal towards higher or lower altitudes is one of the critical processes for plant migration; for example, birds have contributed to the uphill seed dispersal of *Cerasus leveilleana* (Rosaceae) and *Prunus grayana* (Rosaceae) in two mountain ranges in Japan [87]. This pattern is consistent with global mountain studies whereby species that are reaching higher elevations are generally species from lowland invasions with broad ecological ranges and with the greatest capacity to adapt to novel conditions [14,21,22,88].

The unique characteristics within a mountain range will generally shape a distinctive assemblage of alien plants [89]. This was found to be the case for the EGE and CFM mountains, where the species compositions of alien plants were found to be significantly different between the ranges. This variance is likely a reflection of their distinct environmental conditions, including climate—which has been found to have the greatest impact on the composition of invasive alien plants in South Africa [48]. The CFM and EGE occur in different climatic and vegetation types, being predominantly within the Fynbos and Grassland biomes, respectively [32]. In addition, their histories of human influence have contributed to the extent and types of alien plants present. The CFM have had much greater exposure to anthropogenic disturbance (international trading through the Cape trade route since 1652) [90], whereas most areas in the EGE have had relatively recent exposure (from the late 1700s in the south and from c. 1850 in the north) [91]. While species composition assessments were not possible for the remaining mountain ranges, the variance determined in their most abundant species indicates the likelihood of distinct alien plant assemblages.

The most abundant species in all ranges were largely woody species, showing a pattern of woody plant encroachment (WPE). Woody plant encroachment is becoming more prevalent in the region. For example, over the past three decades, 7.5 million km^2 (55%) of non-forest biomes in sub-Saharan Africa have had significant net gains in woody plant cover [92]. While there is clear evidence of WPE in South Africa's mountains, it is also important to recognise that surveys, particularly SAPIA, have been biased towards this group [38]. The majority of alien plants in alpine areas globally have been found to be herbaceous species, as these areas generally support low-growing shrubs and grasses [11,52]. Alexander et al. [17] found that most alpine alien plants were in the families Poaceae, Asteraceae, Caryophyllaceae, Fabaceae, and Brassicaceae, in order of abundance. Floristic surveys in the Maloti-Drakensberg have supported this, with Poaceae and Asteraceae contributing the most invaders [27]. It is likely that herbaceous and (particularly) grass species [93] have been undersampled in South Africa's mountains. This was evident through the inclusion of the focused botanical GED surveys where there were considerably more unique species and families recorded, most of which were herbaceous and grass species. The experience of the botanists conducting these surveys allowed for the detection of plant families that are often difficult to identify taxonomically. For example, the invasive alien grass, *Nassella trichotoma* (Poaceae), was only recorded in the GED survey. This species is considered a morphologically cryptic species in South Africa as it is very similar to certain native grasses, which means that populations often go unnoticed [94]; such "cryptic" alien plants are not easily amenable to citizen science efforts (such as iNaturalist) and require specialist searches (e.g., Sylvester et al. [93]).

The bias towards the recording of woody plants is also a reflection of their disproportionate impacts in these ecosystems [11]. Although the spatial combinations of vegetation communities in South African mountains is complex [32], most montane areas in South Africa (particularly the higher-elevation areas) are open, tree sparse habitats structurally dominated by graminoids (grasses, sedges, and restios) in the wetter mountains, and shrubs in the drier mountains; only the TC and CGM have spatially dominant natural woody elements at higher elevations (e.g., *Protea* and *Faurea* woodland communities in the TC) [52,95]. When large alien invasive trees and shrubs plants establish in these ecosystems, there is often a major shift in their proportion of the plant biomass compared to native species. According to the biomass-ratio hypothesis, ecosystem properties are driven by the traits of dominant species in the community, and these are generally those with the greatest biomass [96]. Woody plant encroachment therefore has the ability to transform these ecosystems [52,95]. One of the most concerning consequences of this is a change to the hydrology of the water sources that can lead to greatly reduced water availability [97].

At present, management of alien plants in mountains is also primarily focused on woody species, with particular investment on species of the *Acacia*, *Hakea* and *Pinus* [88,98]. Unfortunately, because of the costs of control, and the logistical challenges in managing the biomass, especially relating to fire—the control of invasive woody species is more challenging compared to other invasive alien plants [99]. Additionally, in mountain regions, alien species, including trees, often grow on steep slopes and in dangerous terrain where conventional control methods are difficult, expensive, and carry high risk to personal safety [100]. Management of alien plants in South Africa is currently largely coordinated through the WfW programme, which works in partnership with local communities [101]. For species growing in upper catchments and in rugged terrain, the programme has specifically developed "high-altitude teams" [102]. These teams only reach a fraction of the areas requiring management. Due to such difficulties, WfW has also supported the development of The Northern Temperate Weeds programme, which aims to use biological control to target some of the problematic alien plants in mountain regions [100]. However, this programme will only be able to offer solutions for a select few alien species. Effective management thus remains a major challenge in mountain regions in South Africa, which is only exacerbated by the lack of concise data. Until suitable data are obtained, we suggest an area-based management approach whereby management efforts are prioritised in areas where the greatest impacts occur now or are projected to occur in the future [103].

5. Conclusions

Mountains are one of the few ecosystem types where proactive management of alien plant species may still be possible [88]. However, in South Africa, convincing funding bodies to invest in alien plant management will require comprehensive knowledge of the identity and distribution of the most problematic species. The outlook for improved detection and analysis of alien plant patterns is promising, with expanding local research and greater opportunities for local actors to collaborate with global networks. The Afromontane Research Unit of the University of the Free State is facilitating the expansion of this work through partnerships with international groups such as the Mountain Invasion Research Network (MIREN) [104]. Based on the findings of this study, it is recommended that these initiatives expand an alien plant inventorying, targeting understudied ranges (e.g., SGE and CGM) and employing focused botanical surveys to allow for fine scale sampling with GPS-recorded localities. In addition, the use of iNaturalist presents a cost-effective way to further enhance alien plant records and outreach campaigns that highlight mountain areas are likely to be beneficial. This would provide the means to begin establishing a comprehensive national mountain database on alien plants to guide strategic planning at regional and national levels.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land10121393/s1, Table S1: Plant species removed from lists due to erroneous inclusion in databases as alien species to South Africa; Table S2: The vegetation types across the six mountain ranges in South Africa according to Rutherford et al. [32]. Table S3: Mountain surveys that have been conducted across the six mountain ranges in South Africa; Table S4: The alien plant species found across all databases—SAPIA, iNaturalist and the Great Escarpment Data (GED); Table S5: Univariate hypothesis tests for alien plant differences between databases (SAPIA and iNaturalist), mountain ranges (Eastern Great Escarpment and Cape Fold Mountains) and elevation. Highlighted values indicate significant differences ($p < 0.01$); Table S6: The most abundant alien plants found across all six mountain ranges in South Africa (see Figure 1). Figure S1: Legend of vegetation types across the six mountain ranges in South Africa (see Figure 3). Vegetation types not included in the map had very restricted geographical ranges (see full list of vegetation types in Table S2).

Author Contributions: All authors conceived the idea of the study. K.C. led the writing with input from G.F.S., S.C., O.G., G.D.M., V.R.C. and D.M.R.; G.F.S. performed the statistical analyses and plotted the results; S.C. led data curation and visualisation; O.G. performed the literature review; G.D.M. produced the maps and supervised the project. All authors have read and agreed to the published version of the manuscript.

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Article

Plant Responses to Changing Water Supply and Availability in High Elevation Ecosystems: A Quantitative Systematic Review and Meta-Analysis

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Abstract: Climate change is expected to lead to changes to the amount, frequency, intensity, and timing of precipitation and subsequent water supply and its availability to plants in mountain regions worldwide. This is likely to affect plant growth and physiological performance, with subsequent effects to the functioning of many important high-elevation ecosystems. We conducted a quantitative systematic review and meta-analysis of the effects of altered water supply on plants from high elevation ecosystems. We found a clear negative response of plants to decreases in water supply (mean Hedges' g = −0.75, 95% confidence intervals: −1.09 to −0.41), and a neutral response to increases in water supply (mean Hedges' g = 0.10, 95% confidence intervals: 0.43 to 0.62). Responses to decreases in water supply appear to be related to the magnitude of change in water supply, plant growth form, and to the measured response attribute. Changes to precipitation and water supply are likely to have important consequences for plant growth in high elevation ecosystems, with vegetation change more likely be triggered by reductions than increases in growing season precipitation. High elevation ecosystems that experience future reductions in growing-season precipitation are likely to exhibit plant responses such as reduced growth and higher allocation of carbohydrates to roots.

Keywords: alpine; mountains; climate change; experimental manipulations; PRISMA; precipitation; drought; vegetation

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1. Introduction

Along with temperature, water availability is one of the most important abiotic factors determining the fundamental niche of plant species. In high elevation ecosystems, steep changes in aspect, slope, and soil depth greatly affect the soil water that is available to plants [1,2]. Plants vary in their traits associated with water use strategies such as specific leaf area (SLA), rooting depth, and the ability to endure very low water supply [3]. Over soil moisture gradients, this gives rise to distinct communities from wet meadows to xeric slopes across relatively short spatial scales [1,4]. Variation in plant water status can also affect plant susceptibility to temperature extremes; a key factor limiting plant growth and productivity in high mountain ecosystems [5]. Water-limited plants may be able to withstand lower temperatures and avoid lethal ice formation within cells [6]. Conversely, well-watered plants may have better capacity to mitigate heat stress via transpiration [7]. Variation in response to altered precipitation patterns will likely have important consequences for productivity [8] and susceptibility to other environmental stressors [9].

Ongoing climate change is having profound effects on precipitation and subsequent water supply and availability in high elevation ecosystems. In many mountain ecosystems, annual precipitation is expected to increase [10–13] which is likely to be brought about by more frequent and more intense precipitation events, with associated changes in seasonality [12,14]. In contrast, in other mountain areas, summer precipitation is projected to decline [12] with increases to the length and magnitude of drought events [14]. Simultaneously, earlier melting and evaporation of snow, driven by increasing spring temperatures, may also contribute to severe drying over the summer months [15–17], even if precipitation sums do not indicate changes in overall average precipitation. Changes to soil water availability are likely to alter key physiological processes in plants and may exacerbate the effects of other climate factors that are changing simultaneously, such as warmer [18] or more extreme temperatures [7,19], increased CO_2 and nitrogen deposition [20]. Altered soil water availability may also affect productivity and community stability in high mountain ecosystems [21] which may have consequences for a range of ecosystem functions including carbon storage, nutrient cycling, and water regulation [15]. In addition, altered soil water availability may have important consequences for plant responses to disturbance events, such as fire [22] and grazing [23].

Our current understanding of the responses of high elevation plants to changes in water availability may be inferred from various approaches. These include direct observations of vegetation change correlated with historical changes in precipitation regimes [24], occurrence of plant functional traits relating to water use among biomes [25], via transplant experiments using individual plants or communities across environmental gradients [26,27], or by observing plant community responses to disturbance events such as drought [28]. These kinds of approaches take advantage of interannual or site variation in soil moisture but risk confounding changes with other factors that are likely to covary across space and time such as temperature. Experimental manipulations carried out in the field, glasshouse or laboratory can alter single or multiple environmental conditions to causally link changes in water supply with plant responses, providing an important tool for understanding the physiological mechanisms underpinning plant responses to altered moisture regimes. Experiments that manipulate water supply typically aim to either induce or ease water-limitation among target plants in relation to a control group, while in other studies, the seasonality of precipitation is varied, without altering the cumulative total of water inputs. While the aims and duration of experiments vary, basic measurements of plant growth (e.g., biomass, leaf number, plant height), and physiological performance (rate of photosynthesis, functioning of photosystem II) are often reported. Hence, combined results from precipitation modification studies can lead to meaningful insights regarding the responses of high-elevation plants to changing moisture regimes.

Here, we undertake a quantitative systematic review and meta-analysis to synthesize the current knowledge on plant responses to altered water availability in high-elevation ecosystems, and to examine plant responses to increases and decreases in water supply. For the purposes of this study, a high-elevation plant or community are those belonging to high mountain, high elevation, alpine, sub-alpine, or montane environments. We focus on high elevation plants as they are considered among the most vulnerable to climate change, as high elevation species show high rates of endemism compared to lowland plants which can occupy broader latitudinal belts [16].

In this systematic review and meta-analysis, we synthesize the literature regarding high elevation plant response to modified water supply. Specifically, we ask

1. Do growth forms vary in their response to altered water supply?
2. Is the nature of the response consistent across experimental settings?
3. Do mature and immature life history stages respond differently to altered water supply?
4. How do the responses of measured attributes vary in relation to altered water supply?
5. Are plant responses related to the magnitude change in water supply?

Overall, we expect varying responses among plant growth forms to both increases and decreases in water supply. Forbs and graminoids, which tend to access water from relatively shallow soils compared to woody taxa, are expected to show stronger responses to decreased water supply, and stronger responses are expected in immature than mature plants.

2. Materials and Methods

2.1. Systematic Review

We focussed our literature search on published research that generated empirical data on the responses of high elevation plants globally, to changes in water supply and water availability. We searched three major electronic databases—ProQuest, Web of Science, and Scopus on 27 May 2019, of peer-reviewed primary literature using combinations of search terms relating to plants and precipitation. The literature search was conducted for English language articles only. No constraints were put on year of publication.

Search String Used in Systematic Literature Review

(alpine OR "sub alpine" OR "high mountain*" OR "high elevation*" OR alps OR montane) AND (plant* OR shrub* OR grass* OR herb* OR forb* OR graminoid* OR vegetation) AND (drought* OR irrigation OR "water restrict*" OR "soil moisture" OR moisture OR rainfall OR water supply OR water OR "water deficit*" OR drier OR dry*) AND (experiment* OR manipulat* OR shelter OR "rain out" OR treatment).

We also used the reference lists of relevant articles to look for additional articles that matched our search criteria. Our search returned 5570 articles. After screening titles and abstracts, we found 270 articles to be appropriate for inclusion in the systematic review. This was reduced to 129 articles after examining the full texts of each study (Supplementary Materials, Figure S1). Consequently, a second search of the same electronic databases was conducted on 25 March 2021 for primary literature published since the original search, using the same search string. This search returned 390 studies, of which 22 were included in the systematic review.

As our review was focussed on high-elevation mountains specifically, we did not include "tundra", "Arctic", or "Antarctic" search terms. We did not originally intend to include tree species in our review, hence the terms "forest" and "treeline" were not used. However, the search string returned several articles which focussed on treeline, subalpine and montane tree species and these were included, if they also satisfied our other criteria.

For the purposes of this study, we define the term "article" as a peer-reviewed scientific journal article, and a "study" is nested within an article. For example, an article will comprise multiple studies if it includes multiple precipitation treatment conditions or sites. In situ studies commonly use precipitation differences to describe treatment conditions, while laboratory or glasshouse experiments typically use differences in volumetric soil moisture, or watering frequency. We use the term "water supply" to broadly encompass all the terms relating to water available to plants.

To ensure that we only included articles in the review specifically related to the responses of plants of high elevation ecosystems to changes in water supply, we used two levels of screening. At the first level of screening, we read titles and abstracts, excluding articles that did not satisfy at least two of the following criteria: (1) a focus on plants; (2) a focus on high elevation, montane or alpine environments; and (3) a measure of plant response to either an increase or decrease in water supply. Full text pdf format files were obtained for all the articles that passed the first level of screening. At the second level of screening, we read entire articles, excluding those that did not include any of the following: original research focussed on responses of plants to changes in water supply or water availability, or those that contained empirical data, provided statistical analyses of data, or had been entirely published in English. We did not include review and meta-analysis articles, book chapters, government reports or grey literature. At each level of screening, we recorded the number of articles identified and the number of studies included and excluded according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement [29].

2.2. Meta-Analysis

The meta-analysis focussed on a subset of the studies included in the systematic review that imposed an experimental change to water supply (increase or decrease) in relation to a control group. For in situ experiments, control groups were typically defined as plants or plots receiving ambient water levels while in ex situ experiments, control groups were defined as plants receiving unlimiting water. We excluded articles that altered the timing of precipitation, amount of snow accumulation, as well as articles which utilised natural environmental conditions including natural climatic events or soil moisture gradients due to the lack of clear control groups.

We focussed on studies that reported changes in physiological performance, growth, and abundance indices to changes in water supply and water availability. These response variables included photosynthetic rate, quantum yield of PSII (Fv/Fm), above-ground biomass, below-ground biomass, root:shoot ratio, heat resistance, freezing resistance, species richness, and percent cover. For studies that included freezing resistance, the sign of the effect sizes was reversed to aid interpretation, such that a decrease in freezing resistance would return a negative result and an increase would return a positive result. For simplicity, we categorised "growth rate", "height", "number of leaves" and "above-ground dry weight" all as "above-ground biomass".

For inclusion in our meta-analysis, studies had to have provided sufficient information to derive means, standard deviations, and sample sizes. These summary statistics were either taken directly from tables reported in Results or Supplementary Materials, or extracted from figures using the *metaDigitise* package [30] in R. Studies that did not provide sufficient data to calculate effect sizes (e.g., reported model co-efficients and standard errors, not means and standard deviations or standard errors) were excluded from the meta-analysis. To reduce complications from interacting abiotic factors, only the data relating solely to changes in water supply were included in the meta-analysis. Studies that investigated additional biotic factors including grazing, trampling, and plant competition were included in the meta-analysis when it was clear that those biotic conditions were likely to occur at the sites investigated in the study (e.g., grazing is likely to occur at a study site in some seasons/years). We allocated studies to magnitude groups based on irrigation inputs described in the methods. For the precipitation increase dataset, when it was not possible to calculate percentage difference between treatment and control groups, studies were described as applying a "supplemental" irrigation treatment magnitude.

In in situ studies, plants or plots receiving ambient precipitation were treated as control groups and compared to plants or plots receiving either a reduction or increase in ambient precipitation levels. In ex situ studies, plants receiving low-stress, well-watered conditions were treated as control groups and compared to treatment groups that received reduced water supply. Sample sizes typically corresponded to the number of individuals, or number of plots used in the data analysis for each response variable reported. If repeated measurements were provided for a given site or species (e.g., above-ground biomass measured across multiple years), we averaged data to calculate pooled means and standard deviations.

We used the "escalc" function in the *metafor* package [31] in R to calculate standardized mean differences (Hedges' g) [32] between treatment and control. This summary measure controls for bias in studies with small sample sizes by adjusting for variation in study effort. Negative values indicate a negative response to water supply modification (e.g., reduced biomass in plots with decreased water supply), whereas positive values indicate a positive response to modifications in water supply.

We split studies into those that increased and those that decreased precipitation relative to controls and performed separate analyses on each dataset. We used multilevel models to analyse variation in effect sizes, with the *metafor* package. We included random effect terms for species, family, article identity and study identity (studies nested within articles) to account for non-independence between effect sizes from the same species, family, article and studies within articles. We fitted seven models containing different combinations of article, species, taxonomic family and study identity and ranked these models using Akaike's Information Criterion (AIC) to identify the appropriate random effect structure. We assessed whether broad taxonomic patterns were present in the data by fitting a model with family as the explanatory variable. For each model, we considered predictor variables significant when the 95% confidence intervals did not overlap zero.

Study Heterogeneity and Publication Bias

To test for the level of variation between study effect sizes in each meta-analysis (separate water supply increase and decrease datasets), and to interpret whether the variance was due to heterogeneity between studies or due to sampling error, we calculated a Q heterogeneity test (I^2) using *metafor*. Higher I^2 values indicate that a higher proportion of the total variance between effect sizes can be attributed to heterogeneity between studies, rather than to chance [33]. To test for publication bias in our datasets, we used two different methods. Firstly, we constructed funnel plots and inspected them visually for asymmetry; and secondly, we conducted Egger's regression tests for funnel plot asymmetry. Funnel plots display effect size estimates of individual studies and their corresponding precision. In the absence of publication bias (that significant results are more likely to be published than non-significant results), studies with high precision will be plotted near the average, and studies with low precision will be scattered either side of the average to resemble an inverted funnel shape [34]. Funnel plot asymmetry provides an indication that significant results are more likely published than non-significant results [34].

3. Results

3.1. Systematic Review

Our systematic review produced 147 articles investigating changes to water supply and/or water availability in high mountain plant species, with a sharp increasing trend of publications per year since 2000 (Figure 1). Studies included in the systematic review were carried out in 19 countries; however, the majority of these occurred in Europe, Asia and North America (41%, 34% and 18%, respectively) with Oceania and South America representing 4% each (Figure 1). The most represented plant families investigated amongst these studies were Poaceae (19%), followed by studies investigating plant communities (13%), Pinaceae (12%), Asteraceae (11%), and Fabaceae (9%), with 33 additional plant families representing the remaining 36%.

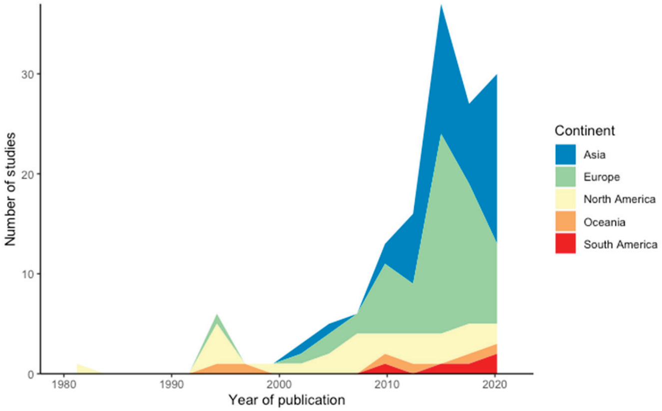

Figure 1. Number of studies in the systematic review dataset ($n = 147$) published per continent, per year. Different coloured bands are cumulative within years and are stacked: thicker colour bands represent more cumulative publications for that continent in a given year.

The majority of studies (81%) focussed on individual species rather than plant communities (12%). Overall, seeds, immature and mature plants from 262 species across 40 families were assessed in studies that measured plant response to changes in water supply.

Studies mainly concentrated on decreases in water supply (60%), as opposed to increases in water supply (38%), while few compared natural conditions (e.g., wet versus dry sites or years) (2%) (Figure 2). Mostly, articles focussed on experimentally manipulating water supply in a single direction (either an increase or decrease), though a total of 20 articles (out of 147 included in the systematic review) applied both increases and decreases to water supply compared to controls. Water supply reduction studies were equally carried out in situ or within controlled environments (e.g., growth chambers) (41% each), while water supply increase studies were overwhelmingly carried out in situ (91%) (Figure 2).

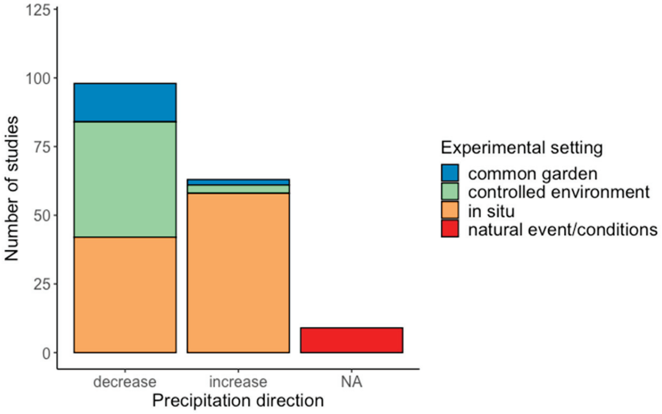

Figure 2. The direction of precipitation treatments included in the systematic review, grouped by experimental setting.

Water supply reduction studies were typically carried out between 1–6 months (50%) and 1–3 years (22%) (Figure 3), whereas the most common duration in studies that increased water supply was 1–3 years (64%) followed by 1–6 months (24%) (Figure 4). Water supply reduction studies focussed mostly on mature plants (63%), with immature and seed life stages comprising 33% and 4%, respectively (Figure 3). In contrast, most water supply increase studies were focussed on mature plants (91%), with immature life stages (9%) less represented (Figure 4).

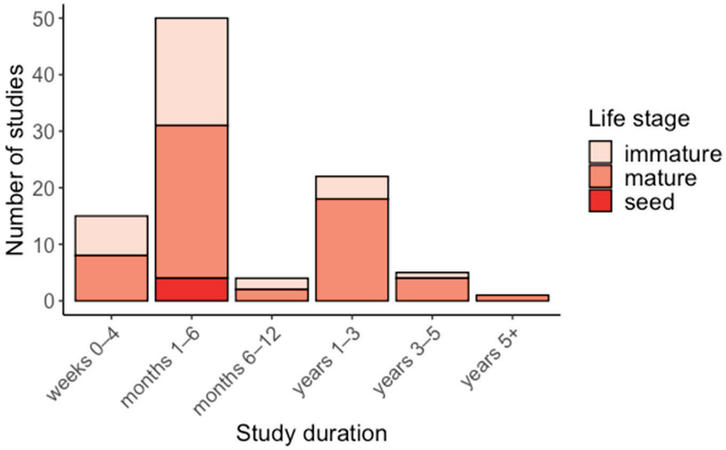

Figure 3. Duration of water supply reduction studies, grouped by life stage.

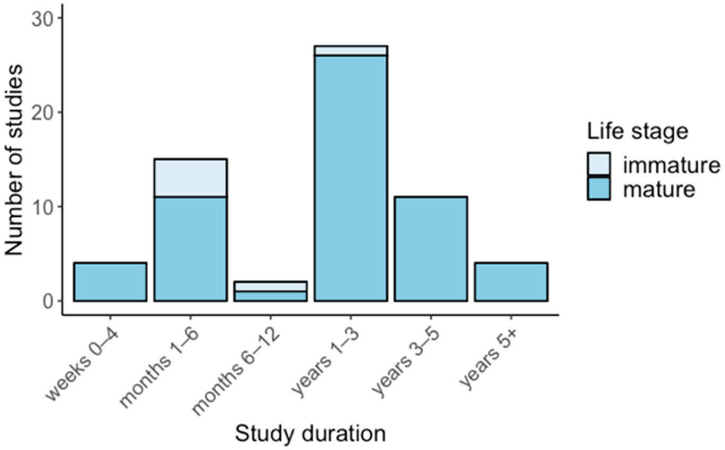

Figure 4. Duration of water supply increase studies, grouped by life stage.

3.2. Meta-Analysis

For the meta-analysis, we analysed 647 effect sizes, of which 491 involved water supply decreases and 156 involved water supply increases. For the water supply decrease dataset, the best global model had "species" and "study" nested within "article" as random effects (Supplementary Materials, Table S1). The best global model for our water supply increase dataset included "species" and "article" as random effects (Supplementary Materials, Table S2).

Sites from articles included in the meta-analysis were located predominantly in the northern hemisphere including Europe, North America, and Asia (Figure 5) across a range of climate groups, though most were concentrated within temperate and arid climates.

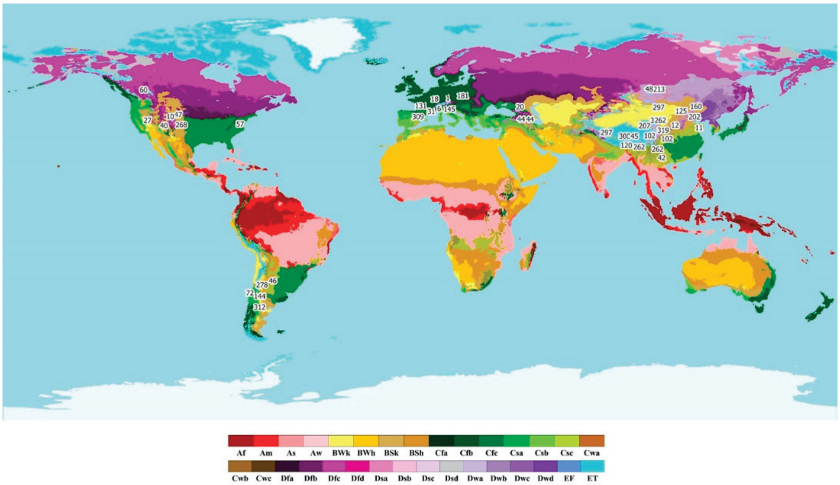

Figure 5. Köppen–Geiger climate map showing study site locations from articles included in the meta-analysis. Numbers correspond to article numbers. Colour scale refers to Köppen–Geiger climate classification criteria (Main climates: A: equatorial, B: arid, C: warm temperature, D: snow, E: polar; Precipitation: W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, m: monsoonal; Temperature: h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, F: polar frost, T: polar tundra).

3.2.1. Modification of Water Supply In Situ

Typically, in situ studies employed rainout shelters to apply water supply reduction treatments ($n = 20$). These structures consisted of a transparent roof situated above vegetation plots to exclude varying amounts of natural precipitation, with control plots receiving ambient precipitation. Studies that increased water supply to plants in situ typically did this by applying water manually ($n = 16$), through irrigation systems ($n = 4$), or passively using proportional collection funnels ($n = 3$). In addition, some studies that compared both increases and decreases in precipitation to ambient controls collected the rain excluded by rainout shelters and redistributed to plots to create a water surplus treatment ($n = 9$).

3.2.2. Modification of Water Supply Ex Situ

Typically, ex situ studies conducted in controlled environments used plants that were well-watered as control groups. This was achieved either by using high watering frequencies, or by maintaining a predetermined high level of volumetric soil moisture or field capacity. These were typically compared to plants which were watered less frequently ($n = 3$), with less water ($n = 2$), were not watered at all (dry down) ($n = 8$) or were maintained at a predetermined lower level of volumetric soil moisture ($n = 1$) or field capacity ($n = 5$). Studies conducted in common gardens used rainout shelters ($n = 3$) and the dry down method (1) in water supply decrease treatments, and compared well-watered plants to lower levels of volumetric soil moisture ($n = 2$) and field capacity ($n = 2$) in water supply increase treatments.

3.2.3. Water Supply Decreases

For the reductions in water supply dataset, the mean effect size (Hedges' g) was −0.75 (95% CI: −1.09 to −0.41), thereby demonstrating an overall negative effect on plant responses (Figure 6; Supplementary Materials Table S3). Under a decrease in water supply, trees (Hedges' g: −1.22, 95% CI: −1.91 to −0.53), graminoids (Hedges' g: −0.73, 95% CI: −1.19 to −0.27), forbs (Hedges' g: −0.51, 95% CI: −0.96 to −0.07) and communities (Hedges' g: −0.71, 95% CI: −1.21 to −0.22) had similar negative effect sizes and CIs that overlapped each other (Figure 6), while shrubs (Hedges' g: −0.66, 95% CI: −1.38 to 0.06) and legumes (Hedges' g: −0.20, 95% CI: −0.78 to 0.38) had weakly negative effect sizes. There were similarly strong negative effects amongst immature (Hedges' g: −0.80, 95% CI: −1.28 to −0.33) and mature (Hedges' g: −0.70, 95% CI: −1.19 to −0.22) life stages, with CIs that overlapped each other. Experiments conducted in situ (Hedges' g: −0.72, 95% CI: −1.34, −0.11) and in controlled environments (Hedges' g: −0.85, 95% CI: −1.34, −0.36) had significantly negative effect sizes with overlapping CIs, and those conducted in common gardens were weakly negative (Hedges' g: −0.56, 95% CI: −1.31 to 0.19).

All measured response attributes had negative mean effect sizes except for root:shoot ratio which was positive (Hedges' g: 0.66, 95% CI: 0.33 to 0.99), and heat resistance which was weakly positive (Figure 6). Rate of photosynthesis had the strongest negative response (Hedges' g: −1.65, 95% CI: −1.99 to −1.31), followed by above-ground biomass, percent cover, species richness, below-ground biomass and quantum yield PSII, all with CIs not overlapping zero (Figure 6). The CIs overlapped for most response variables, although the rate of photosynthesis and root:shoot ratio had the most negative and positive mean responses, respectively (Figure 6).

Studies that reduced water supply by a magnitude of 0–20% showed a weakly negative response with CIs that overlapped zero (Hedges' g: −0.43, 95% CI: −0.91 to 0.06) (Figure 6). In comparison, studies that reduced water supply by 21% or more all showed strong negative responses, with CIs that overlapped each other. Studies with magnitudes of 61–80% had the strongest negative response (Hedges' g: −0.109, 95% CI: −1.53 to −0.65), followed by those that decreased by 81–100% magnitude, 41–60% magnitude, and 21–40% magnitude (Figure 6).

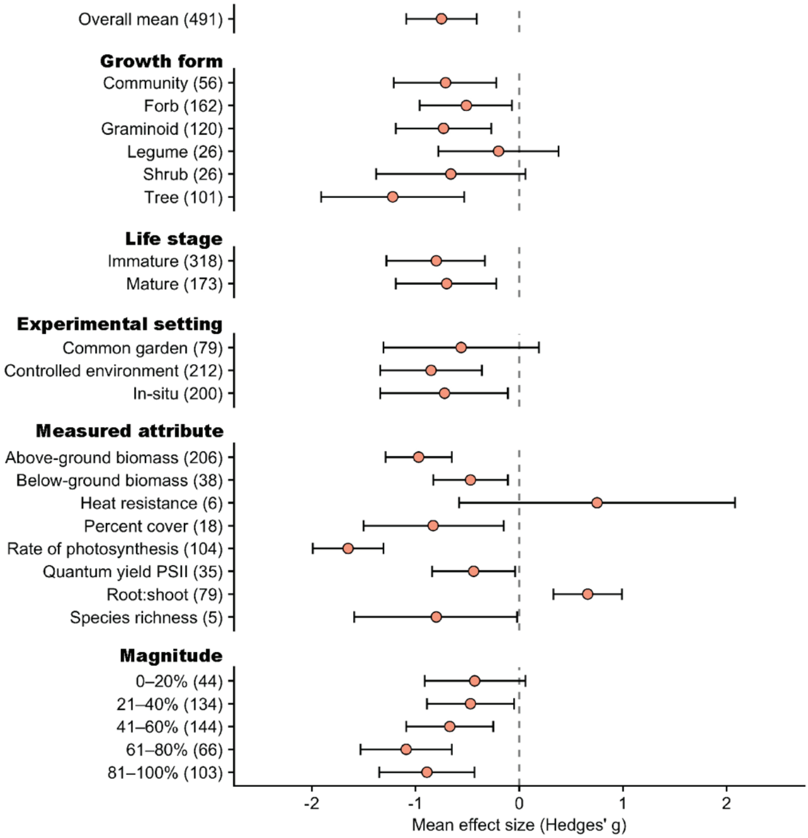

Figure 6. Mean effect sizes (Hedges' g) and 95% confidence intervals for the effect of reductions to water supply on high elevation plants according to growth form, life stage, experimental setting, response variable measured, and treatment magnitude. Sample sizes for each predictor variable are represented in parentheses.

3.2.4. Water Supply Increases

The mean effect size (Hedges' g) for the increases in water supply dataset was 0.10 (95% CI: −0.43 to 0.62) indicating essentially neutral plant responses (Figure 7; Supplementary Materials Table S4). Under an increase in water supply, only graminoid (Hedges' g: 0.18, 95% CI: −0.45 to 0.81) and tree (Hedges' g: 0.34, 95% CI: −1.13 to 1.82) growth forms showed positive responses, though both CIs overlapped zero (Figure 7). Studies that investigated communities, forbs, or legumes all showed essentially neutral responses. In contrast, shrubs showed weak negative response (Hedges' g: −0.53, 95% CI: −1.39 to 0.33), though this is likely driven by freezing resistance being the main response variable measured in shrubs (60%) which showed a strong negative response (Hedges' g: −1.45, 95% CI: −2.57 to −0.33). Other response variables including above-ground biomass, below-ground biomass, percent cover, rate of photosynthesis, quantum yield PSII, and species richness all showed weak positive responses, with CIs overlapping zero (Figure 7).

Studies that increased water supply by supplemental watering, or experimentally increased water supply by magnitudes between 0–20%, 21–40% and 101–120% all showed weakly positive responses, with overlapping CIs which also overlapped zero (Figure 7). Studies that increased water supply by a magnitude of 41–60% showed an essentially neutral response (Hedges' g: 0.00, 95% CI: −0.58 to 0.90).

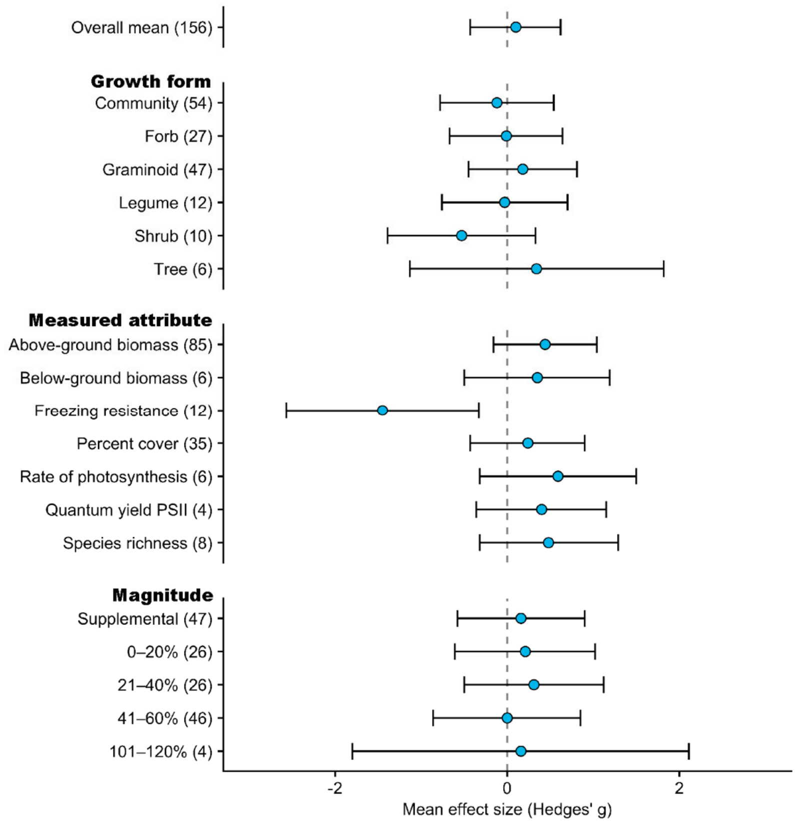

Figure 7. Mean effect sizes (Hedges' g) and 95% confidence intervals for the effect of increases to water supply on high elevation plants according to growth form, response variable measured, and treatment magnitude. Sample sizes for each predictor variable are represented in parentheses. Only predictor variables with sample sizes equal to or greater than 4 are shown.

3.3. Publication Bias and Heterogeneity

We detected evidence of publication bias amongst the studies reporting reductions in water supply, but not those reporting increases in water supply (Supplementary Materials, Figure S2). Egger's tests confirmed funnel plot trends, for the water supply increase data set ($z = 1.0111$, $p \geq 0.05$), and for the water supply decrease dataset ($z = -9.2470$, $p < 0.0001$). While we detected and removed outliers from the water supply decrease dataset, the Egger's test was still significant ($z = -22.5508$, $p \leq 0.0001$), suggesting a strong signal of publication bias in the decrease in water supply dataset, which indicates a tendency for more negative results to be published than positive ones.

The heterogeneity test returned an I^2 value of 81% for the water supply decrease dataset, and an I^2 value of 72% for the water supply increase dataset. These values indicate moderate to substantial heterogeneity, which justifies the inclusion of moderators to explain the variation in our datasets.

4. Discussion

We aimed to determine how plants of high-elevation environments respond to varying water supply. From our meta-analysis, it is evident that reductions in water supply are largely met with negative plant responses, while increases to water supply stimulate some positive, although weaker plant responses. We found the strength of responses to altered water supply among differing life forms/plant groups such as graminoids, trees, legumes, shrubs, and forbs, to be highly variable. The number of studies that measure plant responses to changing water supply in high elevation and high mountain ecosystems is rapidly increasing, though a strong geographic bias towards the northern hemisphere remains. In addition, there appears to be an over-representation of mature plant responses compared to those from early life history stages which are considered critical in the maintenance of plant populations, and especially vulnerable to the effects of a changing climate [35,36].

4.1. Decreases in Water Supply

We predicted that, overall, negative responses of high elevation plants to decreases in water supply were likely, given that all plants slow their growth in response to declining water potentials in their leaves [37,38]. Negative responses among high-elevation plants were evident when water supply was reduced by at least 21% and generally became stronger with increasing magnitude. However, the strength of response to decreases in water supply also appears to be associated in part with plant growth form. Woody and herbaceous plants differ fundamentally in root architecture (rooting depth and lateral spread) [39]. Herbaceous taxa concentrate a high proportion of their root biomass in the upper parts of the soil [39] and are generally considered to be more prone to episodic soil water shortages [4]. Our data support this effect, with graminoids and forbs showing strong negative responses to decreasing water supply, while shrubs showed only weak negative responses. During periods of drought, root biomass in herbaceous species has been shown to quickly decrease as a result of mortality, and the inhibition of root production [40]. By comparison, woody plants tend to be deeper rooting and are considered less susceptible to fluctuations in near-surface water availability [39]. It should be noted, however, that the grasses which comprise the majority of our graminoid dataset are typically soft-leaved, C3 species and are not representative of Poaceae in all high elevation ecosystems. While high elevation C4 grasses are rare, they will likely exhibit higher drought tolerance than typical cool-season C3 grasses [41]. Indeed, alpine plants from mountains which experience summer droughts are considered to have elevated desiccation tolerance [6]. Similarly, giant rosettes from high tropical mountains may also withstand long periods of soil drought due to their capacity to store water in well-developed pith [42].

Contrary to assumptions based on maximum rooting depth, the treeline and subalpine trees amongst the studies in this dataset showed strong negative responses to decreased water supply. Similarly, immature plants, considered more vulnerable to unfavourable conditions [36], showed similar responses to mature plants. Generalisations regarding “deep” and “shallow” rooting responses to drought, may be less applicable in high elevation ecosystems. At high elevations, soils can be very shallow and plants typically have shallower roots with higher root densities in the upper, warmer soil layers [43]. Shallow roots, which are highly sensitive to water fluctuations, show almost equally fast turnover rates among herbaceous and woody plants [44], and can show similarly negative responses to reductions in precipitation [40].

4.2. Increases in Water Supply

Most growth forms showed neutral responses to increases in water supply, with graminoids and trees showing weakly positive responses. A meta-analysis of field experiments in the Arctic also found largely insignificant responses to increases in precipitation among most plant functional groups [45]. In contrast, Wu et al. [46] found high sensitivities among both woody and herbaceous plants to increased precipitation, and that cold-climate ecosystems were more responsive than warm-climate ones. Additional precipitation during the growing season can ease moisture limitations and stimulate plant growth [46]. We expected the strength of plant responses to reflect water supply magnitude; however, there was no discernible pattern amongst magnitude groups. This may indicate that the plants under ambient precipitation or soil moisture conditions were not experiencing water limitations. With increasing annual precipitation, plant productivity becomes less sensitive to inter-annual variability in precipitation [47]; therefore, low sensitivity may simply reflect a higher proportion of plants from mesic sites in our dataset. Indeed, while comprising high levels of taxonomic diversity [48,49] there is a notable paucity of studies in the literature and within our dataset, from mountain regions with Mediterranean or tropical climates. Extrapolation of plant responses from our meta-analysis to these regions must be conducted with caution. Given summer drought is the main abiotic factor constraining plant establishment in Mediterranean-type ecosystems [50], increases in water supply may trigger responses that contrast significantly with mesic-climate mountains. Alternatively, the outcomes of plant responses to water supply increase may reflect experimental design. All studies focussing on precipitation increases were conducted in situ where increased precipitation was typically applied to experimental plots using sprinklers [51,52] or by diverting rainfall from passive rainout shelters [53]. Studies rarely reported soil moisture at varying depths, yet these methods of water application potentially only recharge the surface soil layers. Consequently, taxa with deep roots may not be able to exploit small additions of supplemental watering typical of these types of field experiments, compared to shallow-rooted taxa.

4.3. Plant Growth, Biomass Accumulation and Plastic Responses

Plant growth over the active growing season, measured as increases in above-ground biomass, is clearly sensitive to water availability in high elevation plants, with significant responses to decreases in water supply. The most effective allocation of biomass to above-ground and below-ground tissue depends on resource availability [54], hence plasticity in the partitioning of carbohydrates can facilitate adjustments to changing environmental conditions [55–57]. For instance, the allocation to root growth was enhanced when drought-tolerant *Anisodus tanguticus* was placed under water stress [56]. Higher resource investments in root compared to shoot biomass reduces the detrimental effects of water limitations as a large root network improves a plant’s ability to access to water and nutrients [58], and reduced investment in above-ground biomass reduces the evaporative demand to the plant [59]. By comparison, crown density significantly increased in fast-growing *Pinus sylvestris* when water supply was increased [60]. It is considered more likely, however, that fast-growing species can alter morphological traits such as biomass allocation more rapidly than slow growing and stress-tolerant species [61]. By comparison, plants prone to seasonal water-shortages can maintain robust physiological functioning even though they show low plasticity in water-related morphological traits [62–64]. Indeed, while morphological plasticity is a strategy that may help plants cope with changing soil water availability, plants may use alternative strategies to adjust to varying water availability.

It is often assumed that slow-growing species should exhibit greater physiological plasticity than morphological plasticity as it is considered a less expensive alternative to plants [63,65,66]. Reversible physiological adjustments (acclimations) to varying water supply are likely common among inherently slow growing high elevation plants [67]. Indeed, photosystem II performance and rate of photosynthesis were highly sensitive to reductions in water supply. Some plants have the capacity to rapidly facilitate stomatal closure and reduce photosynthesis rates in response to the declining water potential of their leaves [38]. Conservative responses to water limitations can occur relatively quickly in wild plants. These may depend upon several physiological factors such as hydraulic conductivity, growth and photosynthetic rates, and water use efficiencies [68]. For example, when watering ceased, net photosynthetic rate and gas exchange decreased significantly within a matter of days in high elevation grass species [69]. Thermal tolerance also appears to respond to varying water supply, with a reduction in plant tolerance to freezing observed when water supply was increased. This reaction is possibly linked to a de-acclimation response typically associated with increasing temperatures and photoperiod during the onset of the growing season [70]. However, despite showing similarly fast gas exchange responses to water stress, populations of several grass species survived longer if they had smaller leaves [69]. Indeed, traits such as smaller leaves and greater water use efficiency are selected for in dry conditions as they reduce water loss during periods of low water availability [71]. Physiological trait plasticity may provide an advantage to high elevation plants during periodic fluctuations in soil moisture, though it may not confer a fitness advantage where long, dry periods prevail.

4.4. Effects of Altered Water Supply on Community Composition

While short-term experiments are useful in providing a snap-shot of plant species responses to either increases or decreases in soil moisture, longer-term experiments (5+ years) conducted in situ can provide insight into responses at the community-level. Shifts in community composition, particularly long-term fluctuations in abundance, are likely to arise with ongoing changes to precipitation and water supply. Abundance of rarer or infrequent species may increase due to the relaxation of water limitations [72], or decrease through intensified interspecies competition and susceptibility to water limitations [26]. Plant responses to altered climate factors can be largely idiosyncratic [73], and may vary depending on the combinations of climate factors that are changing. While we did not include studies in our meta-analysis that combined additional abiotic factors with changes to precipitation, it is important to note that complex interactions between abiotic and biotic factors exist that are well known to affect overall plant responses. Altered precipitation had a stronger effect on community biomass in the Tibetan Plateau when warming was simultaneously applied [18]. Indeed, plant responses to altered water availability may be amplified by other climatic and abiotic factors that are changing, such as increased CO_2 [74] and increased nitrogen through atmospheric deposition [75]. In some instances, nitrogen availability may ameliorate the effects of drought [76], which could partly explain the weak response amongst N-fixing legumes to decreased water supply in our dataset. Plant growth enhanced by increased precipitation may also be counterbalanced by subsequent increases in herbivory [77], or through increases in concurrent environmental stressors such as UV-B radiation [78]. Alternatively, multiple resource limitations can co-limit the growth or survival of seedlings, or amplify the susceptibility of plants to environmental stressors such as drought [79]. Interactive effects must be more routinely included into studies to account for this complexity.

5. Conclusions

Overall, results from our meta-analysis suggest that high elevation plants show variable responses to water supply, which is projected to change with ongoing climate change. High elevation plants included in our study tended to show stronger responses to water reductions than to water increases, contrasting with previous meta-analyses across terrestrial ecosystems [46]. This likely indicates that water is not a strong limiting factor for high elevation plants and communities included in our dataset, though it is important to note that our dataset is strongly mesic and northern hemisphere biased. Plant responses are likely to differ in plants from mountainous regions with a Mediterranean-type climate (characterised by hot and dry summers) which were underrepresented in our study. Different responses to varying water availability among plant functional groups may lead to changes in the cover and abundance of certain plant groups or species, with flow-on effects for the structure and functioning of high mountain plant communities. Plant responses may also be compounded or offset by simultaneous rising temperatures, and the increasing intensity and frequency of extreme events such as heatwaves, droughts, and fires. Physiological and morphological plant responses to varying water supply inform us about the mechanisms behind plant responses to the climate drivers that are changing. It is increasingly important, however, that experiments are applied under realistic settings which represent forecasted precipitation scenarios including changes to the frequency, magnitude, and timing of precipitation, combined with interactions with other drivers of global change. Current understanding of the effects of altered water supply on plants from high elevation ecosystems is limited to predominantly northern-hemisphere mesic mountains. Despite being exceptionally biodiverse, mountains with Mediterranean and tropical climates are severely underrepresented within the literature, and future research should aim to balance this bias.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land10111150/s1, Figure S1: PRISMA diagram showing the literature search and exclusion process using the search terms above. Numbers in parentheses indicate the number of articles included or excluded at each step, Figure S2: Funnel plots for datasets used in the null model of the water supply decrease (a) and increase (b) datasets. The x-axis shows observed outcome of effect size (Hedges' g) and the y-axis shows the standard error. Note, outliers with observed outcomes <-54 have been removed from the decrease dataset funnel plot. Table S1. Model selection table of Multivariate Meta-analysis models explaining variation in Hedges' g in the water supply decrease dataset, their Δ Akaike Information Criterion. Table S2. Model selection table of Multivariate Meta-analysis models explaining variation in Hedges' g in the water supply increase dataset, their Δ Akaike Information Criterion. Table S3. Estimates of Hedges' g for each moderator variable within the water supply decrease dataset. Table S4. Estimates of Hedges' g for each moderator variable within the water supply increase dataset.

Author Contributions: Conceptualization, E.S. and S.V.; methodology, E.S. and S.V.; formal analysis, E.S.; data curation, E.S.; writing—original draft preparation, E.S.; writing—review and editing, S.V.; supervision, S.V.; project administration, E.S. and S.V.; funding acquisition, S.V. All authors have read and agreed to the published version of the manuscript.

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Plant Trait Assembly in Species-Rich Forests at Varying Elevations in the Northwest Andes of Colombia

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Abstract: Andean forests are home to a strikingly high diversity of plants, making it difficult to understand the main drivers of species assembly. Trait-based approaches, however, help overcome some challenges associated with high taxonomic complexity, providing insights into the main drivers of species coexistence. Here, we evaluated the roles of climate, soil fertility, and symbiotic root associations on shaping the assembly of six plant functional traits (leaf area, specific leaf area, dry leaf matter content, leaf thickness, leaf toughness, and wood density) along an elevational gradient in the species-rich northwestern Andean forests of Colombia. The two main axes of the correspondence RLQ analysis explained 95.75% of the variability. The first axis was associated with the leaf economic spectrum, while the second axis with the tradeoff between growth and survival. Furthermore, the fourth corner method showed that both regional (climatic variables) and local factors (soil fertility, symbiotic root associations, and light distribution) played a key role in determining plant trait assembly. In summary, our study emphasizes the importance of considering both individual size and local factors to better understand drivers of plant trait assembly along environmental gradients.

Keywords: functional traits; environmental drivers; mycorrhizas; fourth corner; RLQ; Andean forests

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1. Introduction

Andean forests represent the greatest hotspot of diversity on Earth [1,2], as well as one of the regions most threatened by deforestation and climate change [3–6]. To assure effective forest conservation in this endangered ecosystem, an improved understanding of the mechanisms determining species assembly along elevational gradients is needed [7]. One meaningful approach, which has helped to identify the underlying mechanisms shaping forest structure and function along environmental gradients, is the use of functional traits [8–10]. In particular, functional traits can circumvent challenges associated with high taxonomic complexity, such as is present in tropical Andean forests, thereby shedding new insights into the main drivers of species coexistence [1,11].

Leaf traits have been previously used to identify plant adaptation across the functional economic spectrum along elevational gradients [12–16]. Along elevational gradients, a handful of studies conducted in tropical forests have found that species at lower elevations tend to have acquisitive characteristics mainly due to greater temperature as well as higher availability of light and nutrients [12,15,17]. On the contrary, species at high elevation tend to have conservative characteristics due to constraints in resources availability [12,14,15,17]. Other factors, such as vapor pressure deficit and solar radiation, are also known to be important drivers of leaf trait variation among plant communities [18,19].

Additionally, wood-specific gravity (g cm^{-3}), hereafter called wood density, has shown to be an efficient trait to characterize the tradeoff between hydraulic safety and efficiency, which determines plant resistance to embolisms [20–23]. This trait has also shown to be a good proxy for the life history of tropical tree species [24,25]. In general, acquisitive species have lower wood densities, due to lower investment in tissue construction and hydraulic safety, while conservative species have high wood densities to protect from hydraulic or biomechanical damage [20,26–31].

The functional composition of tropical forests also changes across strata due to a systematic reduction in light availability from canopy to understory [32,33]. For example, in the presence of low light availability, plant species favor conservative water and nutrient use and high light capture [34,35]. In contrast, in the light-exposed canopy, plant species typically have a positive correlation between photosynthetic rate and resource allocation [35,36]. Another important yet often overlooked determinant of tree fitness and community assembly at a local scale are symbiotic root associations (e.g., mycorrhizae and nitrogen-fixing bacteria) [37]. These associations can enhance plant nutrient availability as well as modify plant responses to environmental constraints such as water or light limitation [38–42].

In this study, we aimed to assess the main drivers of plant trait assembly along elevational gradients in the northwestern Andean forests of Colombia. We evaluated the relative roles played by climate, soil fertility, and symbiotic root associations on shaping the assembly of six functional traits (leaf area, specific leaf area, dry leaf matter content, leaf thickness, leaf toughness, and wood density) in nine one-hectare plots along an elevational gradient spanning 2850 m. Furthermore, we evaluated the local effect caused by differences in resource availability (e.g., light) between large trees (diameter at breast height-DBH $\geq$ 10 cm) and small trees (1 $\leq$ DBH < 10 cm). We hypothesized that: (i) Functional assembly gradually changes from acquisitive to conservative strategies along the elevation gradient in the northwestern Andean forests of Colombia. (ii) Climate variability overrides soil fertility and symbiotic root associations as a determinant of plant trait assembly, and iii) plant trait assembly between large and small trees has a differential local response to changes in light availability.

2. Materials and Methods

2.1. Study Area

The study area is located in the northwest region of Colombia between 5°50′ and 7°78′ North and 74°61′ and 77°67′ West. This region encompasses an elevational gradient highly variable in terms of climate, and soils. We established nine permanent monitoring 1 ha (100 m × 100 m) plots between 50 and 2900 m asl (Figure 1). The distance between plots ranged from 22.1 to 271.7 km. In Colombia, the Andean region contains only approximately 20% of its original natural cover, primarily due to historical deforestation [43]. Plots were randomly located within protected forest fragments without considering previous criteria in terms of floristic composition, structure, climate, or soils. We did, however, ensure that the location of plots was at least 100 m away from any forest edge (see supporting information).

2.2. Tree Species Abundance (L Matrix)

In each 1 ha plot (100 m × 100 m), all trees with a diameter at breast height (DBH) $\geq$ 10 cm (hereafter referred to as large trees) were mapped and tagged. Likewise, shrubs and small trees with 1 cm $\leq$ DBH < 10 cm (hereafter referred to as small trees) were tallied in a 0.16 ha subplot (40 m × 40 m) located near the center of each plot (Figure 1). Voucher specimens were collected for each potentially unique species in each plot. We collected vouchers in all cases in which there was any doubt as to whether an individual plant was the same species as another individual that was already collected within the same plot. Taxonomic identifications were made by comparing the specimens with herbarium material and with the help of specialists in particular plant groups. All of the vouchers are kept at the University of Antioquia’s Herbarium (HUA). The plants that were identified at the level of genus and family were classified as morphospecies based on differences in vegetative character morphology. We used the function *correctTaxo* from *BIOMASS* R package [44] to standardize the taxonomic name using the Taxonomic Name Resolution Service (TNRS). We built a community matrix ($n \times p$) with species abundance information, where sites are in rows and species in columns (hereafter referred to as L matrix).

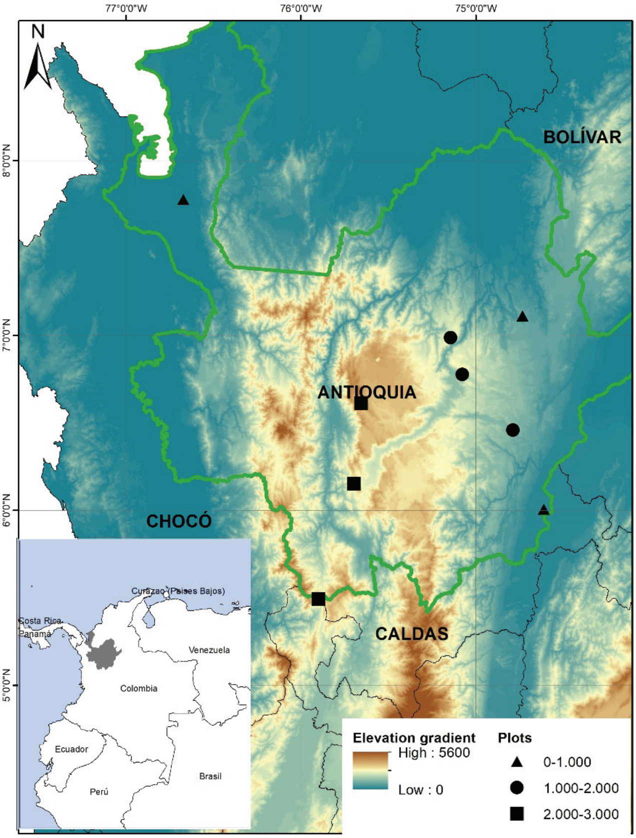

Figure 1. Plot locations in the northwest Andes in Colombia. The symbol shape and the colors represent the change in the elevational gradient.

2.3. Environmental Variables (R Matrix)

We used climatic and edaphic information to characterize each plot. Each environmental variable was included in an $n \times m$ matrix, where sites are in rows and environmental values in columns (hereafter R matrix). Climatic data were downloaded from Worldclim version 2.1. (1970–2000) with a resolution of 30 arcsec–1 km (Table S1) [45]. The climatic variables are mean annual temperature (MAT °C), temperature seasonality (T.s), mean annual precipitation (PP mm), precipitation seasonality (P.s), solar radiation (Srad in kJ m^{-2} day^{-1}), wind speed (Wind in m s^{-1}), vapor air pressure (VAP in Kpa), and vapor pressure deficit (VPD in Kpa). VPD was calculated as the difference between saturated vapor pressure and VAP. The soil variables assessed were pH, calcium (Ca in meq per 100 g soil), magnesium (Mg in meq per 100 g soil), potassium (K in meq per 100 g soil), phosphorus (P in ppm), and organic matter (OM in %) (Table S2). We used the mean concentration per plot calculated from 25 composite soil samples taken in each 20 × 20 m quadrant in the 1 ha plot (Figure S1). Soil samples were analyzed in the Biogeochemical

Analysis laboratory of the Department of Forest Sciences at the Universidad Nacional de Colombia-Medellin.

To incorporate the potential contributions of symbiotic root association (SRA) in explaining plant trait assembly along the elevational gradient, individuals were assigned an SRA status either as arbuscular mycorrhizal (AM), ectomycorrhizal fungi (EcM), or nitrogen-fixing bacteria (Nfix) based on the genus- or family-level designations provided in [46]. We chose these two taxonomic levels to increase the ability to provide SRA assignments to the dataset; this choice is supported by the fact that SRA is largely conserved at the genus and family level [47,48]. Here, we restricted matches for our genera and families to only those present in North and South America in the compiled list of [46]. Any genus or family lacking symbiotic root assignment was manually checked and, when possible, assigned SRA based on primary literature searches. We used the above information and L matrix (tree species abundance matrix) to calculate each SRA proportion as the ratio between the abundance of individuals with EcM, AM, or Nfix associations and the total number of individuals in each plot.

2.4. Trait Sampling (Q Matrix)

In the nine plots, we assessed six morphological traits: leaf area (LA), specific leaf area (SLA), leaf dry matter content (LDMC), leaf thickness (LT), leaf toughness (Lth), and small branches' wood density (WD), following the methodology proposed in the "New handbook for standardized measurement of plant functional traits worldwide" [49] (see supporting information). LA is associated with plant fitness to compete for light and to regulate water balance [50,51]. SLA and LDMC represent the tradeoff between resource acquisition, plant productivity, and carbon storage [50,52]. LT and Lth are related to adaptations to harsh climatic conditions and herbivory defenses [49,50]. Finally, WD primarily represents the tradeoff between survival and growth [25] and hydraulic safety–efficiency [49,50].

We took samples of five mature leaves from five different individuals per plot. For rare species, the samples were taken in as many individuals as possible, reaching a sampling effort of 76% of the morphospecies registered in the study area. In total, we sampled 2765 individuals belonging to 1099 morphospecies. To assess WD, we took one sample from one mature branch per individual. The size of the samples was around 2–3 cm in diameter and 10 cm long. Since for some species within the plot, it was not possible to measure directly the WD due to the small size of the individuals and the lack of mature branches (approximately 18% of the individual sampled), the missing values were filled hierarchically. First, the missing WD values per individual were assigned based on the average value of the same species in other plots. If the value was not available at the species level, the value by either genus or family was applied.

We selected light-exposed leaves when possible. However, we excluded those species that had either small individuals with few leaves/branches or were out of reach due to height. Fresh weight, leaf thickness (LT), and leaf toughness (LTh) were measured in situ, while the other traits were measured in the lab. The data were organized in a $p \times s$ trait matrix, where the rows have the s trait's mean value per species and the columns the p species (hereafter referred to as the Q matrix). To build this matrix, we used the species with information on all six traits, which correspond to 1086 morphospecies. LA, SLA, LT, and Lth were log-transformed to reduce the bias on trait distributions [53].

2.5. Data Analysis

We used the Pearson correlation coefficient to assess the correlation between the community weighted mean (CWM) of each trait weighted by species abundances in each plot, as well as the environmental variables and elevation. Elevation was used here as a valid surrogate for temperature ($r = -0.99$).

To assess plant trait assembly in the northwestern Andean forests of Colombia, we used correspondence analysis RLQ and fourth corner analysis [54–56]. The correspondence analysis RLQ and fourth corner analysis are two alternative methods that integrate information stored in the R matrix (sites × environmental characteristics), L matrix (sites × species abundance), and Q matrix (functional traits × species). The RLQ is a multivariate method that reduces the variability of the three matrices (RLQ) by applying ordination procedures [54]. The RLQ enables visualization of the structure of the three matrices by assigning scores to species, samples, traits, and environmental variables along orthogonal axes. The RLQ analysis was performed using the *RLQ* function. The fourth corner analysis is a multivariate permutation test that relates the R, L, and Q matrices to generate a matrix with association scores [55]. This analysis was run employing the *fourthcorner* function. Both analyses were performed using the *ade4 R* package [57]. The significance of the associations obtained from both methods, RLQ and fourth corner analysis, was tested by applying the permutation procedure in the matrix L by samples and species separately and then combining those outputs (model 6: a combination of the outputs of models 2 and 4) [58]. We used this model since it allows determination of the influence of both traits and environmental variables in the community assembly, as well as fixes the level of type I error [59]. Furthermore, we performed a high number of permutations (49,999 times) to minimize the occurrence probability of a multitesting issue and reporting of a false correlation caused by the large number of environmental variables [59].

To assess our first research hypothesis, which aimed to differentiate and identify functional groups along the elevational gradient, we applied the k-means method using the *kmeans* function available in the *stats* R package [60] to the two first trait orthogonal axes derived from the RLQ analysis. The optimal number of clusters was estimated with the elbow method, which minimizes the within-cluster sums of squares using the *fviz_nbclust* function available in *factoextra* R package [61]. We compared the distribution of each functional group per trait with the RLQ structure to determine the position of each functional group along the conservative–acquisitive leaf/wood-density economic spectrum. Significant differences between functional groups (FG) were calculated using the Tukey Honestly Significant (Tukey HSD) test. To assess the second hypothesis, we used the fourth corner analysis to test for the correlation between each trait and climatic ($n = 11$) and edaphic variable ($n = 11$). Individual correlation between each trait and each environmental variable was tested by permuting the n sites and the p species, using model 6. Finally, to test the third hypothesis, we repeated the same analysis (fourth corner) using the two tree cutoff sizes: only large trees (DBH $\geq$ 10 cm) and only small trees (1 cm $\leq$ DBH $<$ 10 cm). Thus, the fourth corner analysis was employed to analyze the influence of the climatic and edaphic variables on determining trait functional assembly according to tree size cutoff (large and small trees).

3. Results

3.1. Patterns of Change with Elevation

Eight out of the 17 variables evaluated showed a significant correlation with elevation. OM and AM were positively associated, while MAT, VAP, VPD, Srad, Mg, and Nfix were negatively associated (Figure S2). Regarding functional traits, when we included all individuals (DBH $\geq$ 1 cm), we found a negative relationship between the community weight mean of LA/SLA with elevation, and a positive one with LT (Figure 2 and Table S3). The significant trait–elevation relationship differed when the analysis was carried out separately by tree cutoff size categories. Overall, LTh significantly increased only for large trees, while LA decreased for small trees. LT was also statistically significant, in both large and small trees (Figure 2).

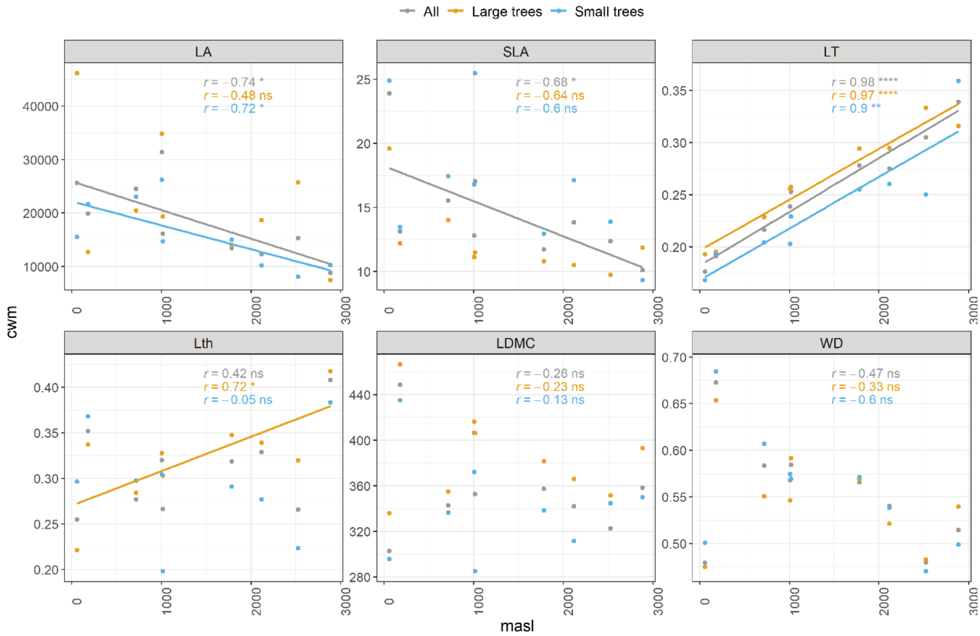

Figure 2. Relationship between traits CWM and elevation in the northwest Andes of Colombia. LA: leaf area (mm^2), SLA: specific leaf area ($mm^2\ mg^{-1}$), LDMC: leaf dry matter content ($mg\ g^{-1}$), LT: thickness (mm), Lth: toughness (N mm), and WD: wood density ($g\ cm^{-3}$). Gray: all individuals (DBH $\geq$ 1 cm), orange: large individuals (DBH $\geq$ 10 cm), blue: small individuals (1 cm $\leq$ DBH < 10 cm). Not significant (ns), 0.05 (*), 0.01 (**), 0.001 (****).

3.2. Definition of Functional Groups

According to the k-means and elbow methods applied on the RLQ scores, we found five main functional groups (FG) along the elevational gradient in northwestern Andean forest (RLQ permutation test: model 2, *p*-value: 0.00106 and model 4, *p*-value: 0.00002) (Figure 3 and Table 1). The first functional group (FG1; red) was characterized by low WD/LDCM and intermediate SLA. Some representative species were *Miconia acanthocoryne*, *Ladenbergia macrocarpa*, and *Miconia micropetala*. The second functional group (FG2; orange) was characterized by high SLA, but thin soft leaves with low dry matter content in their leaf and woody tissues, with respect to the mean values within the study area. Some representative species were *Allomaieta pancurana*, *Allomaieta hirsuta*, and *Piper urabaensis*. The species of this group were primarily located in low elevations with warm weather and relatively fertile soils (Figure S3). The third functional group (FG3; yellow) was characterized by high WD and LDMC, and was located along the entire elevation gradient, being more representative of areas with high MAT, VPD, and high presence of N-fixing root associations (Figure S3). Some representative species were *Palicourea angustifolia*, *Matayba arborescens*, and *Tapirira guianensis*. FG3 fell within the acquisitive second half of the leaf/wood-density economic spectrum. The fourth functional group (FG4; purple), as well as FG 3, had high WD and LDMC, but this latter group had more conservative foliar traits (higher LT / Lth and low SLA), and was primarily located between middle and high elevations. FG4 belonged to the conservative extreme of the leaf/wood-density economic spectrum. Some representative species were *Matudaea colombiana*, *Billia rosea*, and *Eschweilera antioquensis*. Finally, the fifth functional group (FG5; blue) was characterized by high LDMC, LT, and Lth. FG5 was located at high elevations and at the conservative extreme of the leaf economic spectrum, but lower WD (Figure 3). Some representative species were *Miconia multiplinervia*, *Schefflera trianae*, and *Tibouchina lepidota*.

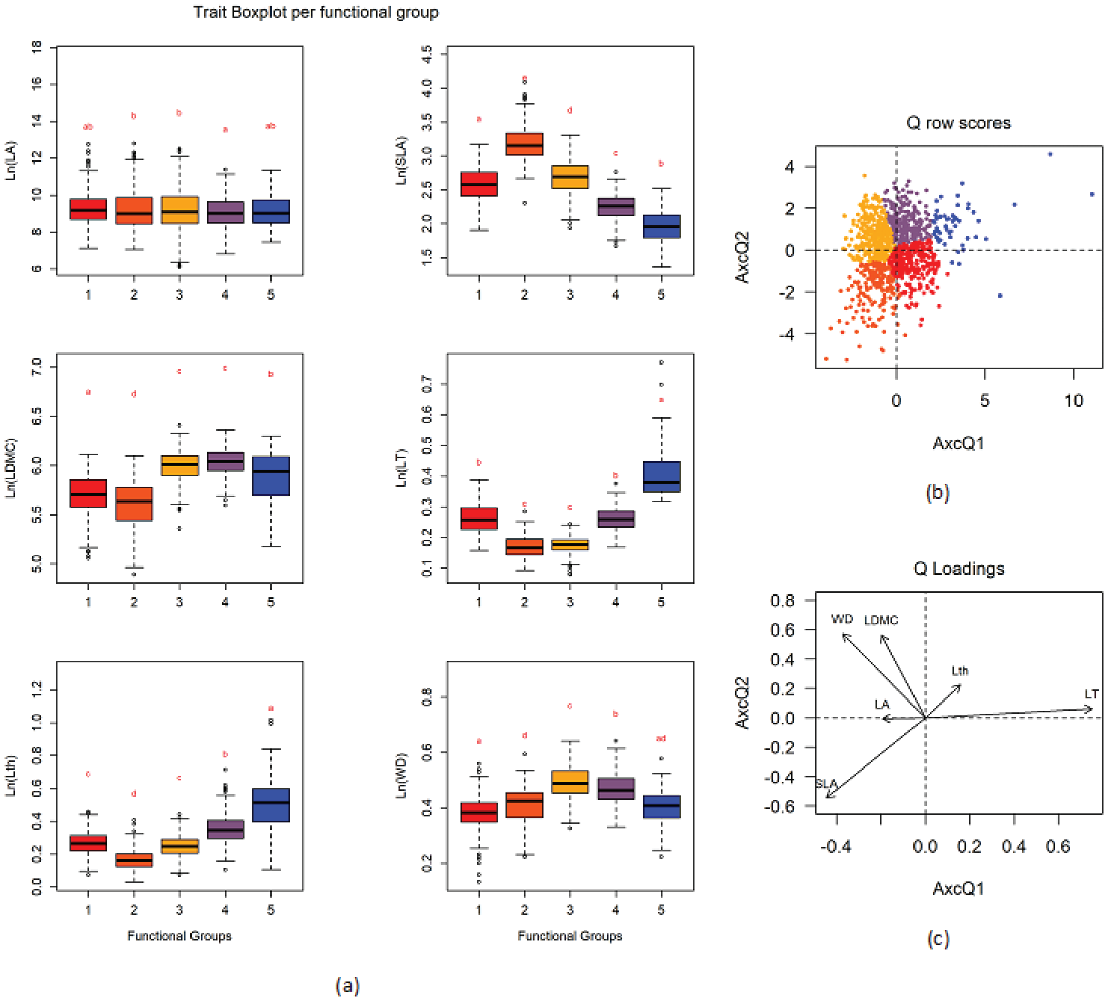

Figure 3. (**a**) Boxplot of trait per functional group resulting from the k-mean analysis. Tukey's test estimated the significant mean differences with a 95% confidence level. (**b**) Species clustering according to K-mean results (Q row scores). (**c**) Traits lineal combination (Q loadings). LA (leaf area-mm^2), SLA (leaf specific area-mm^2 mg^{-1}), LDMC (leaf dry matter content-mg g^{-1}), LT (leaf thickness-mm), Lth (leaf toughness-N mm), and WD (wood density-g cm^{-3}).

Overall, the five main functional groups were placed along the first two RLQ orthogonal axes, which explained most of the trait–environment relationships (total explained inertia 95.76%; see Table 1). The first axis was associated with the leaf economic spectrum, while the second one with the tradeoff between growth and survival (hereafter referred as to growth). However, the wood density did not follow any systematic trend along elevation (Figure 2).

Table 1. RLQ Statistics. Each Ax represents the first five orthogonal axes with their respective Eigenvalues (Eig), projected inertia (Eig %), and cumulative projected inertia (%) (Accumulative). The two first orthogonal axes decomposition with their covariance (covar), R matrix variance (sdR), Q matrix variance (sdQ), and Q-R correlation (corr). Outputs of the permutation test, which alternative hypothesis is "greater" and *p*-value is estimated as: (number of random values equal to or greater than the observed one + 1)/(number of permutations + 1).

Total Inertia: 4,16					
	A × 1	**A × 2**	**A × 3**	**A × 4**	**A × 5**
Eig	3.23	0.75	0.13	0.03	0.01
Eig %	77.66	18.10	3.04	0.84	0.27
Acumulative	77.66	95.76	98.81	99.65	99.92
Eigenvalues Decomposition					
	Eig	**covar**	**sdR**	**sdQ**	**corr**
1	3.23	1.80	2.48	1.22	0.59
2	0.75	0.87	1.44	1.39	0.43
Permutation Test (Randtest)					
	Test	**Obs**	**Std. Obs**	**Alter**	***p* value**
1	Model 2	4.16	3.98	greater	0.00006
2	Model 4	4.16	15.26	greater	0.00002

3.3. Traits–Environment Relationship for Different Cutoff Tree Sizes

When all individuals (DBH $\geq$ 1 cm) were included, the fourth corner analysis revealed that other explanatory variables different from climate, such as abiotic (e.g., soils) and biotic factors (e.g., SRA), were also important drivers of plant trait assembly. Water vapor (VAP) and vapor pressure deficit (VPD), positively influenced traits associated with photosynthetic rates (SLA and LA) and resistance to embolism (WD). However, MAT, VAP, and VPD were negatively associated with leaf thickness (LT). Other relevant variables were symbiotic root associations with both mycorrhizal types as well as nitrogen-fixing bacteria. The results showed that greater EcM association enhanced leaf toughness (Lth), while increased AM association decreased SLA. An increase in N-fixing association was also positively associated with WD and LDMC, but negatively with LT. Finally, there was a negative correlation between soil Mg concentration and LT (Figure 4).

The fourth corner analysis on large (DBH $\geq$ 10 cm) and small tree (1 cm $\leq$ DBH < 10 cm) categories produced partially differentiated environment–trait correlations. The gradient of MAT and VAP highlight the acquisitive/conservative leaf spectrum and a positive relation with WD. However, increases in MAT differentiated between increases in SLA for large trees and increases in LA for small trees. Large trees were influenced by other climatic variables than MAT and VAP, such as Wind, Srad in SLA, and T.s in WD. An increase in Mg was positively associated with SLA but negatively with LT in large trees. On the contrary, an increase in OM, likely associated with a reduction in N availability, was positively associated with an increase in LT in small trees. Finally, SLA was negatively associated with AM association in large trees but with increased EcM association in small trees. N-fixing association was mainly positively associated with LA and WD in small trees (Figure 5a,b).

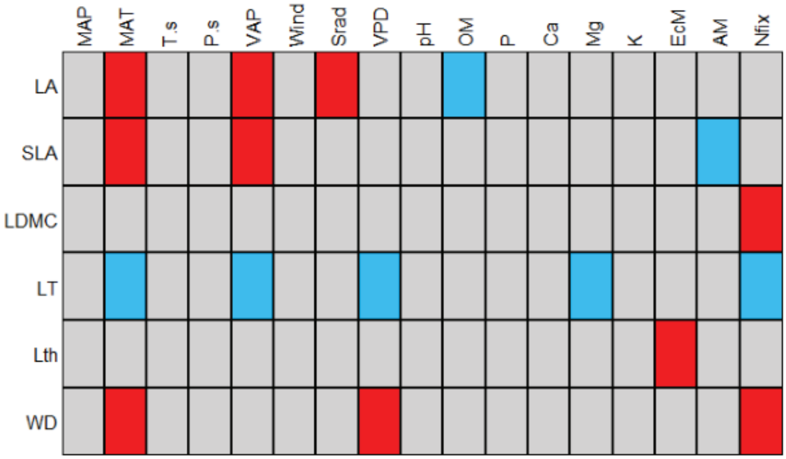

Figure 4. Fourth corner analysis for all individuals (DBH ≥ 1 cm). Red cells represent a positive correlation and blue ones a negative correlation ($\alpha \leq 0.05$). Traits: LA (leaf area), SLA (leaf specific area), LDMC (leaf dry matter content), LT (leaf thickness), Lth (leaf toughness), and WD (wood density). Environmental factors: MAT (mean annual temperature), MAP (mean annual precipitation), T.s (temperature seasonality), P.s (precipitation seasonality), VAP (water vapor pressure), Wind (wind speed), SRad (solar radiation), VPD (vapor pressure deficit). Edaphic variables: pH, soil nutrients (Ca, K, Mg, and P), OM (organic matter content), EcM (ectomycorrhizal fungi), AM (arbuscular mycorrhizal fungi), and Nfix (Nitrogen-fixing bacteria).

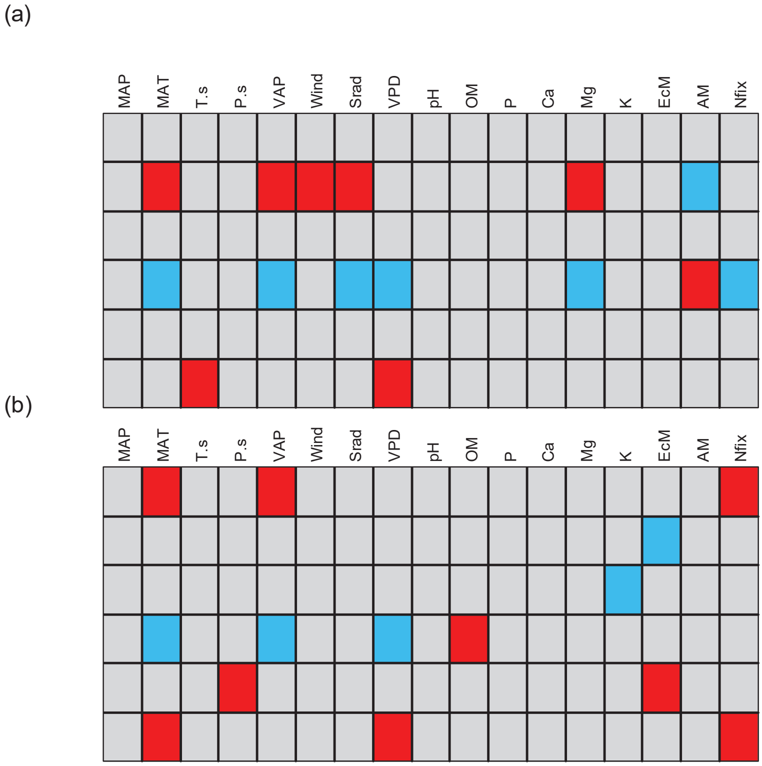

Figure 5. Outputs of the fourth corner analysis for large trees (**a**) and small trees (**b**), Cells in red

represent a positive correlation and blue a negative one ($\alpha \leq 0.05$). Traits: LA (leaf area), SLA (leaf specific area), LDMC (leaf dry matter content), LT (leaf thickness), Lth (leaf toughness) and WD (wood density). Environmental factors: MAT (mean annual temperature), MAP (mean annual precipitation), T.s (temperature seasonality), P.s (precipitation seasonality), VAP (water vapor pressure), Wind (wind speed), SRad (solar radiation), VPD (vapor pressure deficit). Edaphic variables: pH, soil nutrients (Ca, K, Mg, and P), OM (organic matter content), EcM (ectomycorrhizal fungi), AM (arbuscular mycorrhizal fungi), and Nfix (Nitrogen-fixing bacteria).

4. Discussion

In this study, we found environmental heterogeneity as a key driver of plant community assembly in the wet tropical forests of the Northwest Andes. The climatic variation, together with soil fertility and symbiotic root associations, shaped plant trait assembly along the elevational gradient (Figure S2). Five main functional groups were distinguished along the conservative/acquisitive spectrum. Furthermore, the environment–trait relationships partially differed according to plant size (small vs. large trees) as well as the position across forest strata (understory vs. canopy, respectively). Taken together, our study shows that a combination of local-scale factors, such as microclimatic variation, soil fertility, and symbiotic root associations within forests, along with regional climatic heterogeneity, drives plant adaptation and species coexistence along tropical elevational gradients.

4.1. Functional Groups

The distribution of functional groups shifted from an acquisitive strategy in lowlands, characterized by thin leaves with low dry matter content per area (FG2), to a conservative one in highlands, which was characterized by thick and resistant leaves with high dry matter content per area (FG4 and FG5) (Figure S3), in concordance with other studies [12,14,16]. Plant adaptation to environmental heterogeneity along the elevational gradient was mainly associated with two functionally independent axes. On one hand, the first RLQ axis represented the aforementioned leaf economic spectrum, in which plants have developed mechanisms of protection against physical/biological hazards by increasing LT and Lth at lower temperature but increasing SLA and LA to improve their photosynthetic efficiency in warmer lowlands [12,30,62,63]. On the other hand, the second RLQ axis represented a growth tradeoff, which was positively correlated with LDMC and WD. The growth tradeoff highlights the capability of plants to acquire and store resources, and thus, to accumulate carbon [64–66]. Although the wood density did not show a clear pattern along elevation, our results agree with other studies in tropical lowlands that have demonstrated a positive correlation with low fertility [67]. However, our findings suggest a still unexplored relationship between WD and the association with nitrogen-fixing bacteria, which could support the positive correlation observed between WD and nitrogen accumulation in species with low growth rates [68] in the understory.

4.2. Drivers of Plant Trait Assembly

In contradiction to our second hypothesis, we found that soil environmental heterogeneity and symbiotic root associations were both significant drivers of plant trait plasticity and adaptation in wet tropical Andean forests along with climatic variation. The relevant climatic variables in our study area were MAT, VAP, VPD, and Srad, which favored SLA but reduced LT. A decrease in SLA but an increase in LT with the decline in temperature has also been reported in similar studies on tropical elevational gradients [14,69], confirming the expected tradeoff between increasing photosynthetic efficiency at low altitudes and an increase in defenses against harsher climatic conditions in the highlands [62,63]. A decrease in the evaporative demand at higher elevations may also regulate the foliar accumulation of mobile nutrients [15], as was revealed in our study for N (here understood as an increase in organic matter) and Mg. Although our study area did not present limitations due to water since they are humid forests, our analysis highlighted that in environments with a high vapor pressure deficit (low altitudes), plants increased their WD, likely as a strategy to avoid cavitation [70].

Soil fertility also played a major role in shaping trait assembly along elevational gradients [71]. Both Mg and OM were negatively and positively correlated with elevation, respectively. The negative correlation between magnesium in soils and leaf thickness emphasizes the importance of Mg concentration in leaves to enhance photosynthesis [72,73]. Alternatively, the negative correlation between leaf area and organic matter points to N limitation in high/cold elevations [74–76], which has been associated with low decomposition and soil mineralization rates [36,37,75]. Conversely, in our study area, phosphorus did not correlate significantly with any functional trait, which indicates that, in this region, P was not limiting for trait development [16]. This lack of correlation may be due to the high variability in P concentration along the elevation gradient (Figure S2 and Table S2) [77] or the relative young age of the Andean soils that supposes a low limitation of phosphorus [74,77].

In the whole plant community (DBH $\geq$ 1 cm), our findings suggest contrasting roles among symbiotic root associations in promoting plant growth. Nitrogen-fixing associations were more prevalent at low altitudes, while mycorrhizal (AM and EcM) associations were more abundant at high altitudes, with EcM associations largely constrained to higher elevations (Figure S2). The positive relations between N-fix associations with WD and LDMC suggests a primary role of this symbiosis in enhancing plant carbon assimilation in areas that contain higher availability of nutrients. However, as shown below, this trend was consistent only for small trees (Figure 5b), suggesting that N-fixing associations may enhance carbon accumulation mainly in the earlier stages of development of shade-tolerant species. In contrast, the higher abundance of AM and EcM associations in sites with lower temperatures (Figure S2) was mainly associated with conservative traits (low SLA or high Lth). This may reflect greater reliance of these plants on these symbiotic associations to ensure sufficient nutrient acquisition under harsher environmental conditions [37,78–80].

4.3. Traits–Environment Relationship for Different Tree Size Cutoff

When we split the whole dataset into large (DBH $\geq$ 10 cm) and small trees (1 cm $\leq$ DBH < 10 cm), our results showed only partial differences in the extent to which the explanatory variables differentially determined plant trait assembly. MAT and VPD correlated positively with LA in small trees and SLA in large trees. Small trees need to increase leaf area to increase light interception to out shade their neighbors [36]. Increases in specific leaf area in large trees aim to enhance photosynthetic efficiency [51]. Only in large trees, wind speed and solar radiation, which are promoters of boundary layer conductance [72], were positively correlated with the SLA. Finally, temperature seasonality was significantly associated with WD for large trees, while mean annual temperature was with small trees. In large trees, a greater WD has been shown to be an effective strategy to resist droughts and water shortage mainly triggered by the increase in temperature [67,81]. However, for small trees, the increase in WD seems to respond to slow-growing shade-tolerant species that tend to accumulate carbon [68].

Regarding soil fertility, K and Mg have been found to be associated with the harvest of light and the photosynthetic efficiency of plants [63,72,73]. Mg had a more significant influence on large trees (high SLA y low LT), while K influenced small trees, highlighting the prevalence of carbon assimilation (high LDCM).

In conclusion, our study emphasizes the importance of considering small individuals and local factors, such as soil fertility and symbiotic root associations, to better understand the drivers of plant trait assembly along complex environmental gradients. Likewise, we emphasize the utility of using leaf and woody traits to improve our understanding of the main drivers of plant assembly in species-rich tropical forests along elevational gradients.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land10101057/s1, Table S1. Climatic values per plot in the northwestern Andean mountains, Colombia. Table S2. Soil values per plot in the northwestern Andean mountains, Colombia. Table S3. Community Weight Mean (CWM) of the six traits (LA, SLA, LT, LTh, LDMC, and WD). Figure S1. Sample plot design diagram. Figure S2. Correlation between elevation and environmental variables. Figure S3. Distribution of the functional group abundance along elevational gradient and plot of the first two RLQ axes with the environmental variables. Plot establishment and trait sampling. Methods used to calculate leaf and woody traits.

Author Contributions: A.O.-B.: data preparation, analysis, and writing of the manuscript. J.A.M.-V.: data collection, data preparation, and processing. P.G.K.: collaboration in writing and editing. B.S.-N.: data collection and suggestions to improve the quality of the manuscript. A.D.: data collection, analysis, writing, and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The datasets generated and analyzed during the current study are not publicly available. The data employed for the analysis are available from the AD on reasonable request.

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Combining Remote Sensing and Species Distribution Modelling to Assess *Pinus hartwegii* Response to Climate Change and Land Use from Izta-Popo National Park, Mexico

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Abstract: A detailed analysis of distribution shifts in *Pinus hartwegii* Lindl. is provided across time for Izta-Popo National Park (México). Combining satellite images, species distribution models, and connectivity analysis we disentangled the effect of climate change and anthropogenic land use on the habitat availability. Twenty-four Maxent habitat suitability models with varying complexity were combined with insights on vegetation and land cover change derived from two Landsat satellite images at 30-m resolution from 1993 and 2013. To evaluate effects of climate change on Izta-Popo's *P. hartwegii* forest, projections for future climatic conditions (averaged for 2050 and 2070) were derived using two General Circulation Models under three Representative CO_2 concentration pathways (RCPs). Calculated fragmentation and connectivity indexes (Equivalent Connected Area and Probability of Connectivity metrics) showed significant habitat loss and habitat fragmentation that weakens *P. hartwegii* dispersion flux and the strength of connections. Projections of future climate conditions showed a reduction of *P. hartwegii* habitat suitability as populations would have to migrate to higher altitudes. However, the impact of anthropogenic land use change documented over the 20 years masks the predicted impact of climate change in Izta-Popo National Park.

Keywords: model complexity; model validation; Landsat; satellite data; species distribution models; connectivity; fragmentation; Maxent; land-use change

1. Introduction

Studies over the last three decades have shown that land change and climate changes produce major impacts on biological systems across many scales [1]. The work by Foden et al. [2] provides an overview of this exponentially developing field of climate change vulnerability assessment of species to choose effective conservation strategies. However, there is an ongoing challenge to reduce uncertainties on the quantification of climate change and land use impacts, particularly in heterogeneous areas or those more intensively affected, typified in mountain ecosystems [3,4]. Usually, in these areas, species' inventories are incomplete and climate models are inaccurate due to the lack of meteorological stations at high altitudes [5]. Here, the combination of the widely accessible remote sensing data with field-based climate change impact models can be used as an alternative approach to improve land use and climate change vulnerability assessment of ecosystems.

Species Distribution Models (SDM) can be used to forecast climate change impacts on species' distributions [6–8]. SDM are based on modeling the potential distribution of a species by establishing algorithms between (1) field observation points as a current species distribution proxy, and (2) their current associated environmental conditions as predictor variables [9,10]. This correlative approach, often conducted at a 1-km^2 scale, considers climate as the dominant environmental factor defining the "fundamental ecological niche" of a species' distribution [11]. Such correlations can be projected to future climate conditions associated with different anthropogenic scenarios, to evaluate habitat suitability impacts. This approach is strongly dependent on the different algorithms used, the selection of predictor variables, and the quantity and quality of the input data used to construct the models [12–15]. Maxent, the modeling technique employed here, uses the principle of maximum entropy on presence-only data to estimate the relative suitability of habitat in the study area [16,17]; this can overfit the training data, making transferability unreliable [18]. To control overfitting, parallel to choices on function settings and the number of explaining variables, Maxent uses a β regularization parameter that relaxes the suitability functions to lie within an interval around the empirical mean rather than matching it exactly [17]. The pre-selected features, explaining variables and β-parameter, define the complexity level of each Maxent model as quoted on the "number of parameters" [16].

To compare the different model selections, their predictive ability must be evaluated, ideally with independent observations [19]. However, due to the lack of such data, validation is performed by dividing the presence data set into a 'calibration' and a 'validation' data set [20].

Biased or incomplete field data are common due to environmental, economic, or security handicaps (as in this case study), where data are not collected across the environmental range, in more inaccessible areas, or from conflict zones, respectively. These issues combine to result in an incomplete picture of the realized niche [11,21]. Using alternative sources of presence data would benefit the calibration and validation modeling processes, especially in remote areas that house an important part of the world biodiversity. Here, Remote Sensing Data (RSD) stands out as an alternative low-cost and independent data to cross-validate SDM, while furthermore informing about habitat structure changes through time at a complementary spatio-temporal scale, accounting for biological interactions and human activity [9,11].

Satellite spectral information (RSD) in combination with attributes obtained from inventory plots is a growing research field to investigate ecosystem functioning and to detect plant assemblages or ecosystem properties' changes in time that complement in situ terrestrial monitoring approaches [22,23]. Multi-spectral biophysical estimates of vegetation have been used to map large areas of forests [24] or to assist forest surveys for stratification and post-stratification field sampling [25]. The continuous advances on multi- and hyper-spectral approaches and techniques to obtain biophysical estimates at higher temporal and spatial resolution [26–28] in parallel increasing quality and accessibility of in situ observations [29] open new horizons in biodiversity studies [30]. However, few studies integrate RSD with SDM, and usually they are limited to the inclusion of RSD estimates as explanatory variables to calibrate SDM; this handicaps the possibility to project such models under future scenarios due to the absence of RSD estimates in future conditions [31–33].

In areas where a lack of data field information exists, RSD have been proven to provide valuable and complementary information in landscape structure (i.e., disruption of the landscape patters, resulting in habitat loss, habitat fragmentation, and connectivity) at broad scales [34–39]. Importantly, habitat loss and fragmentation due to anthropogenic land use change is a major ecological concern that might result in a decrease of habitat availability and reachability (i.e., the amount of habitat and capacity to move among habitat patches) that can lead to habitat isolation, decrease of genetic diversity, and population decline or local extinctions [40–42].

Connectivity analyses have shown a great utility and effectiveness to guide conservation efforts to preserve and restore habitat connectivity in a cost-effective way, e.g., [43,44]. These studies normally focus on characterizing ecological networks in order to quantify functional habitat changes along time and providing explicit information about the most important areas for genes and species to move [43,45]. Recently, some studies have highlighted the contribution of RSD to derive more accurate connectivity predictions with a large potential to support the best-informed conservation plans, e.g., [40,42].

In this work, we show a framework for habitat evaluation across time to overcome limitations of field-based data by integrating RSD, correlative distribution models, and connectivity metrics. First, the climate change effect on *Pinus hartwegii* Lindl. habitat suitability was tracked by the projections of Maxent models to future climate conditions on Izta Popo National Park. Second, the variation of *P. hartwegii* habitat distribution and its connectivity observed on the land cover variation during a 20-year interval (tracked by RSD) were investigated. Our results help a spatially explicit understanding of *P. hartwegii* distribution under climate change, giving support to develop management recommendations for its conservation.

2. Materials and Methods

2.1. Species and Study Area

The re-sprouting 30-m-tall *P. hartwegii* is found naturally in Mexico, Guatemala, and Honduras mountain summits, between 2300 to 4300 m above sea level (m a.s.l.) [46,47] (Figure 1), making it an ideal candidate to explore modeling challenges on mountain areas. The main range of the species is found in México, where *P. hartwegii* dominates forest up to the tree line ~4000 m a.s.l., forming pure stands above 3000 m a.s.l. [48]. At present, the 1:125,00 INEGI vegetation map only provides for rough limits' distribution of the *p. hartwegii* target species [49]. Species' occurrence information can be found from the Mexican Forest Inventory [48,50] and from the Atlas of the world's conifers [47].

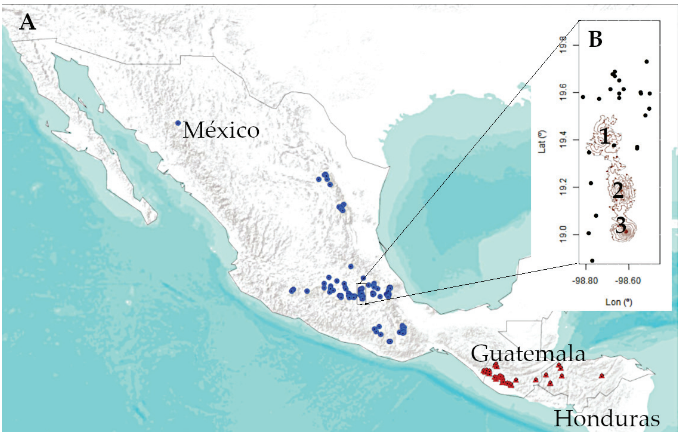

Figure 1. *P. hartwegii* occurrence data. (**A**): Mexican National Forest Inventory (Green dots); World's Conifer Atlas [47] (Yellow dots). (**B**): Available meteorological stations [51] (Black dots) on the topographic map of Izta Popo National Park (lines ranging from 3600 to 5400 m a.s.l. every 200 m). 1: Tláloc (4120 m a.s.l.); 2: Iztaccíhuatl (5230 m a.s.l.); 3: Popocatépetl (5452 m a.s.l.).

Ranging from 3600 to 5480 m a.s.l., and covering an area of 39,819.09 ha, the Izta-Popo National Park hosts two of the three highest volcanoes in Mexico (Figure 1). This area provides for key environmental services (e.g., water, timber, carbon storage) to Morelos, Puebla, and downstream Mexican states. The climate is characterized by 928 mm mean annual rainfall, with September being the wettest month (185.6 mm) and February the driest (6.9 mm). The monthly mean temperature is 14.5 ± 5.4 °C. January with 10.8 °C and May with 16.2 °C are the coldest and warmest months, respectively [48].

Following Rzedowski's classification of the Mexican vegetation in 1978, three vegetation zones have been distinguished in Izta-Popo National Park; these are strongly dependent on the altitude and orientation [48]. On the most hygrophilic areas of the basal belt (below ~3700 m a.s.l.), a Pino-Oyamel (i.e., *Pinus hartwegii* Lindl.—*Abies religiosa* Kunth Schltdl. et Cham.) mixed forest can be found. *Pinus ayacahuite* Ehrenb. ex Schltdl. and *P. montezumae* Lamb. are found on more xerophytic areas, up to this ~3400 m a.s.l. Above this altitude a second vegetation zone is formed by *P. hartwegii* monospecific forests alternating with altitudinal pastures that dominate above ~4000 m a.s.l. (third vegetation zone). From ~4500 m a.s.l., glaciers inhibit the establishment of permanent vegetation. More vegetation types can be found in the areas surrounding Izta-Popo National Park, below 3600 m a.s.l., where *Pinus montezumae-Stipa* spp. or *Pinus leiophylla-Stellaria cuspidate* associations grow [52].

2.2. Remote Sensing-Based Maps

To analyze the spatial variation of *P. hartwegii* habitat between 1993 and 2013, two Landsat Satellite images were acquired on 5 June 2013 (Sensor 8, Path 26, Row 47, Id: LC80260472013156LGN00) and on 2 September 1993 (Sensors 5, Path 26, Row 47, LT50260471993053AAA04) from the United States Geological Survey [53]. The 30-m resolution images were geo-referenced and atmospherically and geometrically corrected with ground control points using ENVI 4.5 Software (C Exelis Visual Information Solutions, Boulder, Colorado). The images were classified to create supervised vegetation maps of the National Park, for which seven classes were previously defined following Rzedowski (1978) [52] (Table 1).

Table 1. Predefined classes were previously defined following Rzedowski (1978) [52] to classify the satellite images.

Class	Description
Pine forest	Areas dominated by *Pinus hartwegii*
Pino-Encino-Oyamel forest	Mixed formations dominated by *P. hartwegii*, *Pinus ayacahuite* Ehrenb. ex Schltdl., *P. montezumae* Lamb., *Quercus crassifolia* Benth., *Quercus laurina* M. Martens & Galeotti, and *Abies religiosa* Kunth Schltdl. et Chamy
Urban zones	
Crops	
Pastures	Areas dominated by *Festuca* spp., *Camalagrostis tolucensis* Trin. ex Steud., *Agrostis tolucensis* Kunth., and *Juniperus montícola* Martínez
Clouds	Clouds and glaciers
Shadows	

The 1993 images were classified by means of the Mahalanobis' Mínimum distance supervised algorithm, with 70 % of the area ground-truthed [54,55]. The ground-truthing data set was obtained from random polygons selected on Quickbird and Ikonos Satellite images assessed with four field observations obtained in the Western slopes of the Tláloc, Iztaccíhuatl, and Popoctépetl (Figure 1, Table S1) from September 2011–March 2012 (given the significant social unrest in the area and consequent risk of sampling at that time, no more field observation points were visited). The same polygons were used as field-based training areas to classify the 2013 Landsat images.

The accuracy of the 1993 and 2013 classification maps were quantified with the 30% remaining ground-truth for each map (16,345 and 9753 pixels, respectively). The accuracy was assessed with the confusion matrix (matrix indicating accordance of the classified pixels with the ground-truth) and the Kappa's Statistic (a proxy of the difference between the confusion matrix with a random accordance between the classified map and the ground-truth [55]). All maps were created using the ArcMap 10.1 software [56].

2.3. Changes in Habitat Availability

To assess *P. hartwegii* habitat changes from 1993 to 2013 in the National Park, we calculated the relative variation of the total habitat (dA):

$$dA = (A_{2013} - A_{1993})/A_{1993}, \tag{1}$$

where A_X is the area occupied by the *Pine forest class* the year $_X$. A connectivity analysis was performed based on the graph theory [57] as applied by, e.g., [39,43]. Probabilities for every existing link between patches (p_{ij}) were calculated using two median dispersal distances (19.1 and 52.1 m) to capture the most common range of dispersal variability of pine seeds [58–61]. Those were obtained from a negative exponential function with a probability value of 0.5 [62].

The change of the total reachable habitat for *P. hartwegii* (i.e., connected area) was quantified by the relative difference on the Equivalent Connected Area (44) between 1993 and 2013:

$$dECA = (ECA_{2013} - ECA_{1993})/ECA_{1993}, \tag{2}$$

calculated for the different pine seed dispersal distances. The Equivalent Connected Area (4), which is obtained from the Probability of Connectivity index (3), represents the size of a hypothetical and unique patch with the same area than the overall reachable habitat for the species in the entire landscape [45,63,64]:

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \cdot a_j \cdot p_{ij}^{*}}{A_L^2}, \tag{3}$$

$$ECA = A_L^2 \cdot \sqrt{PC}, \tag{4}$$

where PC is the Probability of Connectivity index, i and j are the source and destination nodes (i.e., habitat patches), a_i and a_j are their attributes (habitat area), n is the total number of patches, ECA is the Equivalent Connected Area, A_L is the maximum landscape attribute, and p^*_{ij} is the probability of connection between patches i and j (considering both direct dispersal or through intermediate stepping stones) [63].

Additionally, the contribution of the different habitat patch to the overall connectivity was portioned into three components [64]:

$$dPC = dPC_{intra} + dPC_{flux} + dPC_{conn}. \tag{5}$$

The intra fraction measures the amount of habitat existing within a particular patch. The flux fraction quantifies how much dispersal flux a patch is expected to receive or produce. Connector fraction (conn) measures the role of a patch as connecting an element or stepping-stone.

All calculations were performed in Conefor 2.6 [65], using habitat area as patch attribute.

2.4. Species Distribution Models

Twenty-four SDMs were fitted for present climate conditions with Maxent software [16,66], combining two sets of current occurrence data (sets 1 and 2) and different complexity by varying the climatic variables, the features allowed in the modeling process, and β-multiplier [17,67].

One hundred *Pinus hartwegii* natural occurrences (data set 1) from the Mexican Forest Inventory that benefit from an *ad-hoc* design inventory [50] were used to account for the species' current presence. To account for a wider ecological native range of *P. hartwegii* [68], 43 herbarium occurrence records from Guatemala and Honduras [47] were added to the Mexican data to construct the models (Figure 1). Occurrence coincidences in 1-km pixels were aggregated, and ecological outliers were discarded after performing non-metric multidimensional scaling (NMDS) ecological analysis of their annual and seasonal related precipitations and temperatures [69] (Figure S1).

Current climate data for the 1960–1990 period at 30-arc-second (~1 km) resolution were downloaded from the WorldClim 1.4 database [51,70], which provides 19 bioclimatic variables (Table 2) that account for annual trends, seasonality, and extremes in climate that have been reported to act as limiting environmental factors for many organisms [70]. The ecological space of *P. hartwegii* was defined by 10,000 background points randomly selected in (1) México and (2) Mexico, Honduras, and Guatemala [16] to build all the models.

Table 2. Wc. V: WorldClim v1.4 climatic variables and their descriptions [51,70]. S1, S2: The two climatic variable sets used to calibrate the model.

Wc. V	Description	S1	S2
BIO 01	Annual Mean Temperature		X
BIO 02	Mean Diurnal Range (Mean of monthly: max temp—min temp)		
BIO 03	Isothermality (BIO2/BIO7) (×100)		
BIO 04	Temperature Seasonality (standard deviation ×100)		
BIO 05	Max Temperature of Warmest Month	X	X
BIO 06	Min Temperature of Coldest Month	X	
BIO 07	Temperature Annual Range (BIO5-BIO6)		
BIO 08	Mean Temperature of Wettest Quarter	X	
BIO 09	Mean Temperature of Driest Quarter	X	X
BIO 10	Mean Temperature of Warmest Quarter		
BIO 11	Mean Temperature of Coldest Quarter		
BIO 12	Annual Precipitation	X	X
BIO 13	Precipitation of Wettest Month		
BIO 14	Precipitation of Driest Month		
BIO 15	Precipitation Seasonality (Coefficient of Variation)	X	X
BIO 16	Precipitation of Wettest Quarter		
BIO 17	Precipitation Driest Quarter		
BIO 18	Precipitation of Warmest Quarter	X	
BIO 19	Precipitation of Coldest Quarter		X

The selection of climatic variables was based on expert ecological analysis (i.e., stepwise selection following physiologically relevant criteria) [7] among the less correlated variables (Pearson $r < 0.75$; variance inflation factor < 5) [71,72]. The following options of feature classes provided by Maxent were included in the analysis: “auto-features” (that allow the inclusion of thresholds and hinge features due to physiological limits) and “LQP” (i.e., only linear, quadratic, and product features). Finally, three different β-multipliers, which Maxent uses to control the allowed model complexity, were set: $\beta = 0$ (no complexity control), $\beta = 5$ (to minimize the complexity of the model), and $\beta = 1$ [67].

The models were calibrated with 70% of the occurrence data, after a random selection for set 1 and set 2 data points. The remaining 30% were reserved to perform a non-independent validation [19]: each model was evaluated through the AUC statistic (Area Under the receiver operating characteristic curve), which informs about the ability of the model to discriminate between species’ presences and absences [21,73]. To account for the goodness of fit and the model complexity, the AICc (Akaike Information Criterion corrected for small sample sizes) was also calculated [17,74].

Due to the absence of other available independent data to validate the models, remote sensing data were used as an alternative to evaluate the habitat suitability models. Validation was performed by calculating the Pearson correlation coefficient between the habitat suitability values predicted by each Maxent model in each pixel and the corresponding *P. hartwegii* occupation percentages calculated from the 2013 RSD-based map ($r_{\text{HS-PO}}$). To calculate *P. hartwegii*’s surface occupation at 1-km resolution, the original 30-m *P. hartwegii* pixeled map was converted to relative percentage occupation on a 1-km^2 map.

Validation of the habitat suitability models with the RSD-based map was graphically counter-checked with the usual data-partitioning method to visualize agreements between $r_{\text{HS-PO}}$ and AIC. A detailed description of the modelling process can be found in Table S2, following the ODMAP v1.0 standardized protocol for reporting SDM [75]

2.5. Climate Change Impact on P. hartwegii Distribution

As a baseline, the present realized niche (the niche occupation index (NOI)) of *P. hartwegii* was calculated as the percentage occupation of the suitable area (as calculated from the model with best $r_{HS\text{-}PO}$ and AIC performance). Present species' occupation was derived from the 2013 *P. hartwegii* RSD-based map.

To evaluate *P. hartwegii* habitat suitability changes under different future human-developing scenarios in the study area, the Maxent models were projected to the corresponding climate conditions. We used the reproduction of future climatic conditions from two Earth System Models (ESMs) with three representative CO_2 Concentration pathways (RCP2.6, RCP4.5, and RCP8.5.): NorESM1-M y MPI-ESM-MR [76–78]. Among the available ESMs, these were selected after proving to perform well in the region when reproducing present and future climate conditions (see Figures S2 and S3) [79,80]. The values of the bioclimatic variables for the future scenarios were obtained from the WorldClim database for the periods 2050 (2041–2060) and 2070 (2061–2080). This database provides 1-km spatial resolution, after following a delta change-factor approach to downscale the original 2.5° cell size provided by the ESMs for each RCP [81]. To evaluate the sensitivity of *P. hartwegii* to the forecasted climate change, percentage variations of habitat suitability (HSV) between the present (2013) and the future climate conditions (2050 and 2070) were calculated [82,83].

To calculate NOI and HSV indexes, the suitability maps were converted into binary maps (0: non suitable pixel; 1: suitable pixel) with different suitable thresholds [84,85]. To account for permitted commission and omission errors, four different thresholds were utilized [71,85]: (1) the "Maximum test sensitivity plus specificity" Maxent threshold option (that predicts as absences the 10% of the inventoried presences with the most extreme environmental values), (2) the "10 percentile training presence" (that includes the 90% of the occurrences on the suitable areas), (3) 0.25 habitat suitability threshold, and (4) 0.5 habitat suitability threshold.

Changes in *P. hartwegii* habitat suitability for the future scenarios were counterchecked with the observed changes on land use from 1993 to 2013, to balance climate change impacts relative to the observed anthropogenic landscape fragmentation.

3. Results

3.1. Remote Sensing Data

The classification of the 1993 and 2013 Landsat images provided a vegetation map of the study area (Figure 2), with a 0.64 and 0.81 Kappa's statistic, respectively. The 2013 confusion's matrix showed that the errors were mainly due to confusions between *P. hartwegii* and the Pino-Encino-Oyamel mixed forest (19.02% and 18.14% misclassified pixels, respectively), and between urban and crop lands (24.60% urban misclassified pixels). The errors on the 1993 vegetation map were due to misclassifications among Pine, Pino-Encino-Oyamel, and pasture classes (19.5, 16.2, and 40.2), and among urban, crops, and snow classes (59.2, 39.8, and 20.5 misclassification percentages).

The 1993 and 2013 vegetation maps show the existence of two large habitat patches of *P. hartwegii* surrounding the Tláloc and Iztaccíhuatl-Popocatépelt volcanoes (Figure 2). In 1993, the pine forest occupied 58.80% of the National Park, in contrast to 50.59% in 2013, which corresponds to a habitat loss of 14.1%. However, when the connection between patches is taken into account (i.e., Equivalent Connected Area), a reduction of the reachable habitat up to 59.7% and 56.3% was observed for dispersal distances of 19.1 m and 52.7 m, respectively.

Simultaneously, at the expense of the *P. hartwegii* forest type, habitat increases from 16.57% to 23.42% were detected in the mixed pine forest (Pino-Encino-Oyamel) between 1993 and 2013. This pattern is clearly visible in the surrounding areas of the Popocatépetl volcano, although the area covered by clouds in the south for the 2013 image could be over-enhancing the effect of such change in this area. (Figure 2). Other noticeable changes observed in landcover during this period were related to pastures and crop lands (from 23.54% to 20.32% cover). Surrounding the Iztaccíhuatl volcano, the observed *P. hartwegii* tree-line decrease on the Western slope between 1993 and 2013 was compensated by an altitudinal gain on the Southern slope (Figure 2).

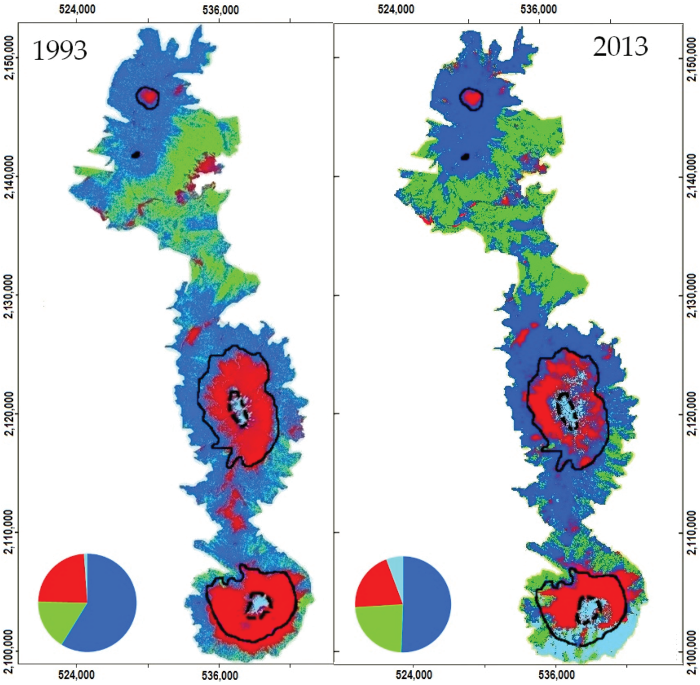

Figure 2. The 1993 (**left**) and 2013 (**right**) Izta-Popo's RSD classified maps, with indication of the percentage distribution of each class (cheese diagram). **Blue**: Clouds. **Red**: Pastures and croplands. **Dark blue**: Pine forest (*Pinus hartweggii-Muhlenbergia macrorura*). **Green**: Pino-Encino-Oyamel mixed forest (*Pinus patula-Quercus crassipes*; *Pinus patula-Quercus laurina*; *Abies religiosa*). Continuous line: 4000 m a.s.l.; dotted line: 4800 m a.s.l.

Regarding the importance of the individual patches to maintain the overall connectivity (dPC), the habitat patches showed a higher density in the north compared to the south of the study area (Figure 3).

When analyzing the ways that patches contributed to maintain the overall connectivity, marked differences in the role of patches were observed in the 20-year span. Besides observing the loss of some connections between patches, a noticeable decrease of the intrapatch connectivity was observed in 2013. Conversely, the contribution of patches as elements of dispersal flux (dPC_{flux}) and connector elements (dPC_{conn}) increased in 2013, a trend that is more evident with 52.72-m dispersal distance (Table 3).

Table 3. Decomposition of dCP (intra, flux, and connector) for the varying dispersal distances D (meters) and years (yr) (5).

Yr	D (m)	dPC_{intra}	dPC_{flux}	dPC_{conn}
1993	19.1	98.79	1.03	0.18
1993	52.72	95.76	3.47	0.76
2013	19.1	94.81	4.67	0.52
2013	52.72	77.29	17.80	4.91

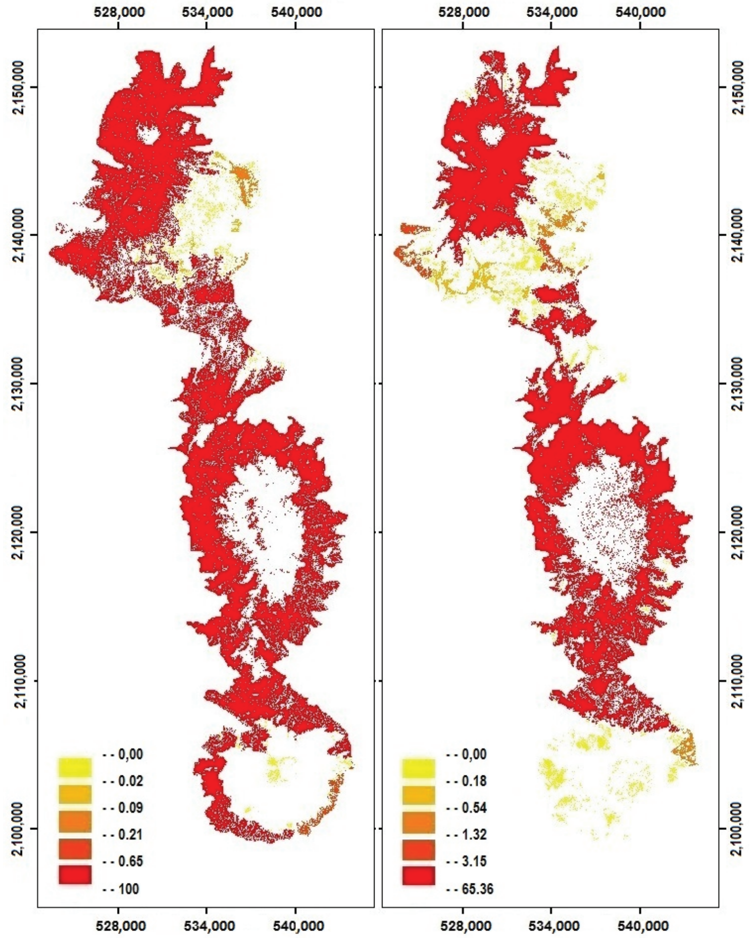

Figure 3. The dCP Values (5) for 1993 (**left**) and 2013 (**right**) calculated on the *P. hartwegii* remote sensing data-classified habitats, with a dispersal distance of 52.72 m.

Additionally, a relative decrease of dA = −14.15% (1) was observed on *P. hartwegii* habitat between 1993 and 2013. The relative variation of the total reachable habitat between 1993 and 2013 (dECA = −59.7% and −56.3% for dispersal distances of 19.10 and 52.72 m, respectively) and (2) evidenced the levered effect of the anthropogenic habitat fragmentation on the habitat loss.

3.2. *P. hartwegii* Habitat Suitability Models

After aggregating duplicated data, removing outliers and poorly georeferenced data, and performing the non-metric multidimensional scaling ecological analysis (Figure S1), 97 *P. hartwegii* natural occurrences from the Mexican Forest Inventory were used in the analysis as data set 1. The additional herbarium data from Honduras and Guatemala comprised 121 occurrences and were used as data set 2 (Figure 1A). As independent variables to explain the occurrence data, two sets of WorldClim climatic variables were selected after correlation and expert-based analysis (Table 2).

The standard cross evaluation of the 24 fitted Maxent models showed similar AUC values above 0.98. Small differences were observed between the models calibrated with the Mexican data set (0.9805 to 0.9888 AUC) and the models performed with the world's distribution data set (0.9919 to 0.9942 AUC) (Table 4). Focusing on the RSD-based validation index ($r_{HS\text{-}PO}$) of the models differing only from the occurrence data set, better models were also observed on those calibrated with Mexican data (data set 1).

Table 4. Characterization of the different distribution models. Model Id.: Identification number of the model). Occ: Occurrence data (97 Mexican occurrences. 24 Guatemala and Honduras occurrences). *n*: number of independent variables included in the model. Features: features classes allowed in the modeling process. L.Q.P: Linear, quadratic and product features. β: Maxent β-multiplier. AUC: Area Under the receiver operating characteristic curve. AIC: Akaike Information Criterion corrected for small sample sizes. *p*: number of parameters of each model. $r_{HS\text{-}PO}$: Spearman correlation between habitat suitability values (HS) and the percentage occupation (PO) of *P. hartwegii* on the 2013 satellite derived map. Shadowed in gray: best and worst model $r_{HS\text{-}PO}$ model. Bold: best models.

Model Id.	Occ.	*n*	Features	β	AUC	AIC	*p*	$r_{HS\text{-}PO}$
1	121	7	Auto-features	0	0.981	-	159	0.180
2	121	7	Auto-features	1	0.986	3274.54	33	0.395
3	121	7	Auto-features	5	0.986	2908.33	14	0.403
4	121	7	L.Q.P	0	0.988	2846.66	12	0.443
5	**121**	**7**	**L.Q.P**	**1**	**0.988**	**2839.50**	**10**	**0.446**
6	121	7	L.Q.P	5	0.988	2858.54	8	0.421
13	121	6	Auto-features	0	0.981	-	140	0.233
14	121	6	Auto-features	1	0.988	2960.42	28	0.363
15	121	6	Auto-features	5	0.988	2868.96	9	0.330
16	121	6	L.Q.P	0	0.988	2867.29	12	0.357
17	121	6	L.Q.P	1	0.989	2861.54	7	0.343
18	121	6	L.Q.P	5	0.989	2868.03	6	0.321
7	97	7	Auto-features	0	0.994	3071.03	79	0.340
8	97	7	Auto-features	1	0.994	2369.42	18	0.213
9	**97**	**7**	**Auto-features**	**5**	**0.994**	**2257.98**	**11**	**0.325**
10	97	7	L.Q.P	0	0.994	2276.60	14	0.351
11	**97**	**7**	**L.Q.P**	**1**	**0.993**	**2322.88**	**9**	**0.397**
12	97	7	L.Q.P	5	0.993	2279.90	8	0.381
19	97	6	Auto-features	0	0.992	2688.57	69	0.240
20	97	6	Auto-features	1	0.992	2282.71	18	0.153
21	97	6	Auto-features	5	0.992	2279.01	8	0.225
22	97	6	L.Q.P	0	0.993	2284.95	11	0.342
23	97	6	L.Q.P	1	0.992	2313.13	9	0.285
24	97	6	L.Q.P	5	0.992	2333.28	5	0.265

The AIC, considering both the complexity (number of parameters) and the goodness of fit of the models, showed varying penalization when using different combinations of occurrence data sets and complexity (Table 4).

The models' performance with the world's occurrence data set (set 2), after removing the most complex model, showed AIC ranging from 2839.50 to 3274.54 (Table 4). When removing the three models with AIC higher than 3000, an inverse relationship trend can be seen between AIC and the RSD-based validation index ($r_{HS\text{-}PO}$) (see Figure S4). Model 5, which was performed with seven climatic variables (see weights in Table S2), LQP features, and β-multiplier =1, resulted to be the best model among those performed with the set 2 of *P. hartwegii* occurrences (see Table 4). When comparing the choices to perform the models, the auto-feature option had the worst performance compared to the models restricted to only linear, quadratic, and products relationships (L.Q.P.). However, within the auto-feature selection, the models improved when restricting complexity (β = 1 or 5) and reducing the independent climatic variables to six.

Similarly, the AIC ranged from 2257.98 to 3071.03 on the models performed with the *Mexican data set* (set 1) (Table 4). In this case, the best model differed when taking AIC or $r_{HS\text{-}PO}$ into consideration (being models 9 and 11 the best ones, respectively). Better models were those performed with seven independent variables and two choices to control the complexity of the model: no mathematical control (i.e., auto-features) but maximum control with β-multiplier (β = 5), or mathematic relationships restricted to L.Q.P with an intermediate β-multiplier control (β = 1). Parallel to the world's occurrence data set, an inverse trend between both validation parameters (AIC and $r_{\text{HS-PO}}$) was observed on the Mexican data set, after removing the most complex models with an AIC > 3000 (Figure S4).

The three best models (5, 9, and 11), the ones performed with the world's occurrence data set, L.Q.P. features, and intermediate β control (=1), showed better $r_{\text{HS-PO}}$ correlation ($\geq$0.40) than the one performed with auto-features compensated with β = 5 and the occurrence data restricted to Mexico. The worst model derived from the RSD-based validation index was model 20, which, surprisingly, did not show a poor AIC (Table 4). This model was performed with the most restricted occurrence data and climatic variables, auto-features, and an intermediate β control. Within the best model (model 5), the weights of the climatic variables showed Bio 5 (Maximum temperature of the warmest month) to be the most important variable, with 94.4% contribution in the worst model (See Table S2). However, the best model showed other temperature variables to complement Bio 5 information with an additional 15.8% of model performance.

3.3. Projections to Present and Future Climate Conditions

Projections of *P. hartwegii* habitat suitability to present climate conditions of the best and worst RSD validated models (models 5 and 20; Figure 4B,C) showed contrasting agreements with the 2013 RSD-based *P. hartwegii* occupation map (Figure 4A). This reinforces the importance of calibrating models with different complexity, followed by a validation process best performed with independent occurrence data. Model 5 (Figure 4B) showed a high *P. hartwegii* habitat suitability except for the valley between Tláloc and Iztaccíhuatl volcanoes and the Iztaccíhuatl and Popocatépetl summits. No inferences can be made from the visual disagreements between the 2013 RSD occupation map and the model 5 habitat suitability projection on the Popocatépetl southern slope (bottom of Figure 4A), as this part of the satellite image was covered with clouds (see Figure 2, right).

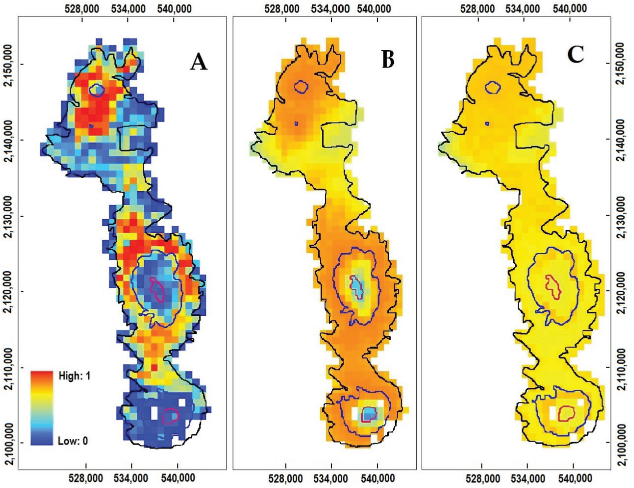

Figure 4. (**A**): The 2013 Remote sensing data-based map of *P. hartwegii*'s occupation (each pixel ranging from 0 to 100% occupation). (**B**,**C**): *P. hartwegii*'s suitability projections for current climatic conditions of models 5 and 20, respectively. Map lines: Izta-Popo National Park limit (black), 4000 (blue) and 4800 m a.s.l. (red).

As the baseline, niche occupation index (NOI) varied between 47.81% and 49.28% depending on the different threshold options for present climate conditions. The worst, 47.81%, occupation index was performed with 0.5 probability threshold, while for 0.25, a

10-percentile presence (10p), maximum training sensitivity plus specificity (max), and NOI between 49.08 and 49.28 were observed.

Projections of model 5 to 2050 future climate conditions showed an increased *P. hartwegii* habitat suitability in Izta Popo National Park, however, decreasing its suitability as the CO$_2$ emission scenarios worsens (from RCP 2.6 to RCP 8.5). The decrease in habitat suitability is clearly observed on the lowest areas, somehow counterbalanced with increases in the summits of the National Park. Projections to 2070 show the same pattern, although with worse suitability values (Figure 5).

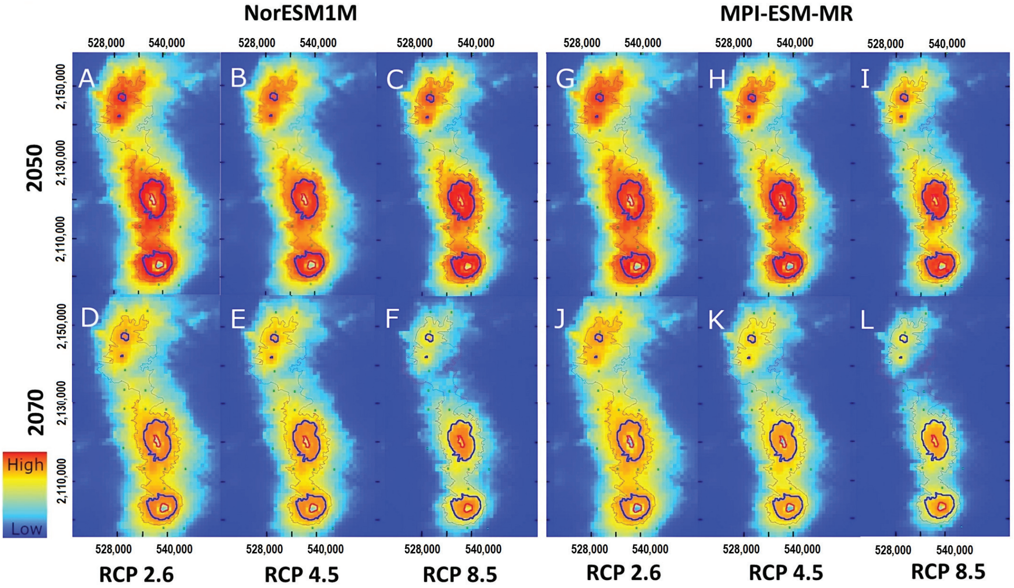

Figure 5. Izta-Popó's habitat suitability of *Pinus hartwegii* as projected by model 5 (Table 4) for 2050 (upper file) and 2070 (lower file), and future climatic conditions as modeled by NorESM1-M (**A**–**F**) and MPI-ESM-MR (**G**–**L**). Three different CO$_2$ Concentration pathways (RCP) were used: RCP 2.6. (**A**,**D**,**G**,**L**); RCP 4.5 (**B**,**E**,**H**,**K**); and RCP 8.5 (**C**,**F**,**I**,**L**). Map lines represent 3000 (brown-fine line), 4000 (blue), and 4800 (red) m a.s.l.

Focusing on the 0.5 suitability threshold and 2050, habitat decreases from 5.94% to 23.19% were observed in the Habitat Suitability Variation index (HSV) for the varying scenarios. The remaining threshold options did not show any significant variation for the 2050 projections. The 2070 projections showed relevant increases in habitat losses in every different threshold except for "Maximum test sensitivity plus specificity", which remained flat (Table S3). The 0.5 threshold showed habitat losses from 6.35% (RCP 2.6) to 43.74% (RCP 8.5). Between the two climatic models, MPI-ESM-MR showed higher climate change impact on the *P. hartwegii* habitat suitability, except for RCP 2.6, where similar values were observed (Table S3).

4. Discussion

The integration of RSD, SDMs, and connectivity metrics provide a powerful tool to assess the impact of climate change and anthropogenic land conversion that are the main drivers impacting biological systems [1]. Although the use of RSD to generate predictor variables is becoming more common in SDM, its potential as a validation tool in areas with poor field data remains relatively unexplored. Furthermore, RSD can be particularly valuable to assess ecological networks, by quantifying habitat connectivity levels and characterizing priorities to maintain connectivity.

4.1. The Use of Remote Sensing Data to Validate Species Distribution Models

The use of RSD to validate vegetation models and identify vegetation types has been useful at large scales (e.g., 0.5° resolution) [86]. However, its use to validate SDM at higher scales (e.g., 1-km^2 resolution) is rare, as identifying species from remote sensing data is not straightforward. First experiences to identify individual tree species confirmed the high value of RSD, thanks to the increasing availability of higher-resolution images at high frequency [28,87,88]. Parallel efforts to generate ground data [50] provide fundamental knowledge to get better accuracy on RSD-based maps [22]. As RSD classification maps are assessed by "ground-truthing" [55], obtaining accurate field data is key to getting accurate species distribution maps. This is particularly relevant in areas with steep environmental gradients with corresponding high vegetation cover diversity, such as mountain areas. In these zones, ecological data are usually biased towards lower altitudes, whose limitations are added to constraints of climatic models that are usually based on few stations at low altitudes (e.g., see available meteorological stations for the study area in Figure 1B) [33,89].

In our case study, due to the monospecific forests of *P. hartwegii*, the presence maps at 1-km resolution obtained from the 1993 and 2013 RSD can be used with good confidence (Kappa's index > 0.6) [90]. The 0.81 accuracy of the 2013 map makes it a valuable map to assess the effect of the different calibration options on the predictive ability of the fitted *P. hartwegii* habitat suitability models. Although the Kappa's accuracy of the 1993 remote sensing map is relatively lower (0.64), its errors are majorly attributed to misclassification of urban, crop lands, pastures, and snow classes. This map, however, is used only to evaluate land use fragmentation and connectivity changes.

4.2. Species Distribution Modeling

The higher RSD-based validation index $r_{\text{HS-PO}}$ shown by the models run with global presence data set compared with those run with the Mexican data (0.38 ± 0.05 vs. 0.29 ± 0.07; Table 4) agrees with previous studies that conclude that performing habitat suitability models with the species' full ecological range achieve better results in model calibration [5,67,68]. This is best observed on the environmental envelopes (NMDS) performed on both data sets; these show how *P. hartwegii* environmental conditions from Guatemala and Honduras complement the climatic spectrum provided by the Mexican occurrences (see e.g., Annual precipitation in Figure S1B). This conclusion supports the recommendations made by other authors to perform environmental envelope analysis, ensuring the meeting of the niche space assumption (i.e., full range of abiotic conditions are contained) [9,67].

Secondly, the trends observed in the RSD-based model assessment and the AIC agree with previous studies that indicate that models with intermediate complexity are more robust [17,67]. In this case study, the best models were achieved either by relaxing the Maxent β complexity ($\beta > 0$) or alternatively reducing the allowed function features (to L,Q,P).

Regarding the number of explanatory variables to fit the models, we followed the advice of many authors who recommend a previous stepwise selection of those variables to avoid the negative effects of auto-correlation [67,91–93]. In our study area, key climatic variables regarding the duration and amplitude of cold and dry seasons [7] and leaving more variables in the model produced slightly better models.

The small differences observed in AUC for the different Maxent models, compared with the contrasting AIC and RSD-based validation indexes, could be a consequence of using the same data for training and validating the model, which could be partially solved using a spatial data-partitioning method to train and validate the model [20,71]. The small difference in AUC also agrees with other studies that state that AUC ignores the goodness of fit of the models and provides very high values when the extension of the species' distribution is much smaller than the geographical area of the study [21,90].

In contrast, the RSD-based validation method proposed in this study has advantages over AUC and AIC, as it emerges from a completely independent data source and can compare the accuracy of models independently using varying calibration options (data sets, geographical amplitude, backgrounds) [21,94]. The coincidence of the best model as selected from the RSD validation index and the AIC from those fitted with the world's data set stands as evidence of the validity of the proposed remote sensing-based validation method.

4.3. Impact of Cover Change on Habitat Availability and Reachability

The noticeable *P. hartwegii* forest decrease (14.15%) observed from 1993 to 2013 aligns with anthropogenic impact [95,96]. To analyze the effect of this loss in the habitat connectivity, the dispersal ability of the species (a key functional element joining pairs of nodes [57]) needs to be estimated. However, dispersal capability is a complex process that depends on many factors (e.g., tree density, location, seed production, dispersal, fecundity, and establishment) [59] that remains largely unexplored in plants [58,60,61]. Although specific data on the species' movement should ideally be used, the two dispersal distances here considered to cover the most common range of dispersal ability in other *Pinus* species [58–61] showed similar declines of *P. hartwegii* habitat connectivity from 1993 to 2013 (56.3–59.7%). This dramatic decrease suggests a loss of key habitat patches for the ecological functionality of the species. The decrease of each patch contribution over the probability of connectivity index (dPC_{intra}) along the studied time period suggested that the species lost large habitat patches (that provided significant amount of intrapatch connectivity in 1993). Consequently, the ecological network shifted in 2013 to a greater reliance on the remaining patches as a connecting stepping stone (dPC_{conn}) and as patches receiving or producing dispersion (dPC_{flux}). This pattern of habitat loss and fragmentation may jeopardize the flux and the strength of connections to other patches, raising the question of the capability of isolated patches to maintain populations with low dispersal capacity, such as those associated with *P. hartwegii* [97]. Habitat change is more acute in the north and south of the National Park (Figure 2), with a remarkable connectivity drop between the Tláloc and Iztaccíhuatl summits (Figure 3), where the remaining fragments cannot compensate for the decrease of connectivity and the increasing patchiness of the populations. These findings document that the conservation of specific habitat patches can be critical to maintain habitat functionality and that management efforts should focus on their conservation.

4.4. The Impact of Climate Change

As a baseline, a niche occupation index (NOI) between 47.81% and 49.28% (i.e., habitat occupation of its suitable area) in 2013 documents the limitations to occupy all areas that are abiotically suitable for *P. hartwegii*. Anthropogenic impact, demography, and dispersal constraints, together with biotic interactions, stochastic events, and historical aspects, are among the responsible factors [9,90].

Illegal logging evidenced even during fieldwork and the extensive cattle industry [98,99] point to anthropogenic impacts as a main driver of the observed landscape fragmentation from 1993 to 2013 (see Figure 3). The contrasting increase of the mixed pine forest at the expense of *P. hartwegii* monospecific forest could be a response of its intense extraction and its natural replacement by other species (e.g., *Pinus patula* Schiede ex Schltdl. & Cham., *Quercus crassipes* Bonpl., *Quercus laurina* Bonpl., *Abies religiosa* (Kunth) Schltdl. & Cham.) to provide further challenges. At the upper tree line, pastures can replace *P. hartwegii* forest under such uncontrolled logging as observed in the Western slope of Iztaccíhuatl volcano (Figure 2).

In line with numerous studies that show an altitudinal and latitudinal shift of species' ranges in response to past and forecasted climate changes [100–103], the projections to future climate conditions show a clear tendency of *P. hartwegii* to migrate up-slope (Figure 5). The observed tendency is visible when comparing the habitat suitability under present (Figure 4B) and future climate conditions (Figure 5) between the Tláloc and the Iztaccíhuatl volcanoes, and above 4000 m a.s.l., which project a clear reduction of the habitat suitability in 2070.

Although the quantification of the total loss of suitable area is highly dependent on the threshold used to transform a continuous map into a binary map (see HSV index in Table S2) [85], it gives evidence of the worrying effect of the greenhouse effect as RCP become more extreme; e.g., up to a 32–43.7% of habitat loss was observed in the 2070 projections using the 0.5 threshold option. This tendency aligns with the observed and modeled climatic shifts [79,80], which show increases of maximum and minimum temperatures of up to 3.2 °C by 2085 (Figure S2). The essential temperature dependency of habitat suitability models in mountain environments (see Table S2) continues to be a concern under warming global climates.

Challenges related to deforestation, fire, and climate change have already been pointed as being critical in Mexico [98]. Several projects have been launched by the Mexican Government and wider partnerships to assess the value of the Izta Popo ecosystem services and to ensure the wider sustainability of the National Park [99]. The specific Payments of Environmental Services Schemes put forward (i.e., voluntary transaction in which a user buys a specific ecosystem service [98], or the planting of 300,000 *P. hartwegii* seedlings above 4000 m a.s.l. in Izta-Popo [104]) are good examples of responses at a National level to preserve the ecosystem and associated services threatened by land use and forecasted climate change evidenced by this study. Other actions aimed to adapt ecosystems to climate change (e.g., assisted migration of pine for successful colonization [99]), could benefit from the connectivity analysis presented here to focus ecological restoration in key areas.

5. Conclusions

To overcome limitations of field-based observations in areas that are difficult to monitor or unsafe areas, the incorporation of RSD with SDM can be a useful tool to assess vegetation change. RSD have been incorporated into the modeling procedure as an independent validation tool to test SDM performance.

The contrasting geographical projections of the *P. hartwegii* habitat suitability modeled to present conditions point out that during the modeling process there are important decisions to be made. Contrary to other validation methods, using RSD offers the advantage to evaluate different models independently.

Anthropogenic pressures on the Izta Popo National Park have led to a reduction of *P. hartwegii* forest cover and a drastic drop in its connectivity from 1993 to 2013. During these 20 years a significant number of critical elements for connectivity have disappeared, forcing a shift of the ecological network of the species to rely on weaker connections between habitat patches. Undertaking a detailed node analysis could determine the priority areas that conservation would ensure the habitat connectivity maintenance.

There is a reduction of *P. hartwegii* habitat suitability under climate projections for 2050 and 2070 parallel to an upslope shift in its altitudinal range. This trend, which is more acute as CO_2 scenarios worsen, can results in the split of the 2013 continuous suitable area of the species into separate patches. Climate change impacts aggravate the anthropogenic fragmentation process that the National Park suffered from 1993 to 2013, with impact on ecosystem services (water supply, carbon storage, diversity conservation, etc.). These shifts on *P. hartwegii* ecosystem ultimately impact on the livelihoods of the communities that live around the Izta Popo National Park as well as down-stream communities and the wider nation.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land10101037/s1, Figure S1: Non-Multidimensional Scaling, Figure S2: validation of Earth System Models, Figure S3: climate projections of coupled Earth System Models, Figure S4: model performances, Table S1: field observations coordinates, Table S2: weights of the explaining climatic variables in the best and worst modes, Table S2: ODMAP v1.0 standardized protocol of the species distribution modelling process [75], Table S3: Habitat Suitability Variation indexes.

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Data Availability Statement: The data created in this study are available within the article and in supplementary material at https://www.mdpi.com/article/10.3390/land10101037/s1. Third party free data was obtained from WorldClim (available at [51,78]), and GloVis (available at [53]). Restrictions apply to the availability of presence data, that are available with the permission of CONAFOR [50] and A. Farjon [47].

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Local Perceptions of Climate Change and Adaptation Responses from Two Mountain Regions in Tanzania

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Abstract: Mountain environments and communities are disproportionately impacted by climate change. Changes in temperature are greater than at lower elevations, which affect the height of the cloud base and local rainfall patterns. While our knowledge of the biophysical nature of climate change in East Africa has increased in the past few years, research on Indigenous farmers' perceptions and adaptation responses is still lacking, particularly in mountains regions. Semi-structured interviews were administered to 300 farmers on Mount Kilimanjaro (n = 150) and the Udzungwa Mountains (n = 150) in Tanzania across gender and wealth groups. Respondents in both mountains reported not only changes in rainfall and temperature, corresponding with meteorological data, but also a greater incidence of fog, wind, frost, and hailstorms—with impacts on decreased crop yields and increased outbreaks of pests. The most common adaptation strategies used were improved crop varieties and inputs. Wealthier households diversified into horticulture or animal rearing, while poorer households of Hehe ethnicity diversified to labour and selling firewood. Despite being climate change literate and having access to radios, most respondents used Indigenous knowledge to decide on planting dates. Our findings highlight how context and culture are important when designing adaptation options and argue for greater involvement of local stakeholders in adaptation planning using a science-with-society approach. Place-based results offer generalisable insights that have application for other mountains in the Global South.

Keywords: farmer; Chagga; gender; East Africa; local knowledge; Kilimanjaro; Hehe; Udzungwa; wealth groups

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1. Introduction

Mountains cover 30.5% of all land [1] and contain 23% of the Earth's total forest cover [2,3]. Mountains are home to 10% of the world's population—expected to grow to 736–844 million by 2050 [4]. Mountains provide benefits to almost half of the world's human population [3] and provide a range of ecosystem services and goods that are an important source of future agrobiodiversity, medicine, and associated poverty alleviation and sustainable development at local, regional, and international levels [5].

African mountains cover some 3 million km^2—most of which are in the north-western, central, and eastern regions [6]. These mountains are critical water towers, supplying water and associated economic value to the surrounding lowlands. For instance, in East Africa, Mount Kilimanjaro provides water to the 3.8 million people who live within the Pangani Basin [7], which is used for hydroelectricity, irrigated agriculture, fishing, and domestic use, among other purposes [8]. The Drakensberg supplies most of the water to Southern Africa, while several countries in West Africa depend on water resources from the Fouta Djallon Highlands [6]. African mountains are centres of biodiversity and endemism due to their topographical variation and ruggedness [5]. Tropical forests in African mountains are also vitally important carbon stores [9]. Most African mountains are characterised by intensive land use, averaging between 33 and 500 persons/km^2, compared to 15 persons/km^2 in the lowlands [10]. This is particularly the case in tropical African mountains which have favourable environmental conditions for agriculture, in contrast to the generally much dryer surrounding lowlands [6]. For instance, the Ethiopian Highlands is home to 90% of the population and 93% of the cultivated land in the country [10]. Moreover, African mountains have critical social–cultural value as Indigenous heritage landscapes [11,12], holding 40 of the UNESCO world heritage sites and biosphere reserves with associated tourism and recreation value [13]. For the purpose of this paper, we use the global mountain typology as defined by UNEP-WCMC (i.e., at a 1 km resolution, mountains as consisting on having a slope $>2°$ or local elevation $\geq$300 m, greater than 300 m, including an isolated basin plateau $\geq$25 km [14])—because it is the most robust definition of mountains of our study area in the Eastern Arc Mountains of Tanzania—covering an area of 48,000 km^2 and with an upper limit of 2636 m asl [15].

African mountains and their communities are highly impacted by climate change and experience more rapid changes in temperature than lower elevations because the rate of warming is amplified with elevation [16]. Particularly important are warming effects such as a rising cloud base or reduced overall cloud incidence because clouds can be a critical source of water in mountain tropical forests [17]. Changes in climate are pronounced in East Africa, where high-resolution climate projections for Africa indicate the region is likely to experience increased mean annual temperatures and rainfall seasonality [18]. Fewer but heavier rainfall events adversely affect plant growth, while higher temperatures accelerate evapotranspiration [19]. For instance, recent droughts, floods, and delays of rains have led to crop damages, failure, and chronic food shortages [20,21].

Two iconic mountains impacted by climate change in Tanzania are Mount Kilimanjaro and the Udzungwa Mountains. The latter is located in the globally recognised Eastern Afromontane biodiversity hotspot [22–25]. The glacier that lines the volcanic crater of Mount Kilimanjaro has shrunk and could disappear by 2033, with impacts on water availability, seasonality, amount of runoff, and quality due to the release of heavy metals including mercury and other legacy contaminants currently stored in the glacier [7]. In the Udzungwa Mountains, climate change has negatively impacted the reproductive fitness of plant and animal species, leading to upslope migration of species and changes in the structures of freshwater and foraging communities—with knock-on effects on predator–prey relations [4].

In the face of climate change, agricultural and pastoral communities are adapting to changes. However, people's adaptive capacity to deal with these pressures is often compromised in the mountains due to remoteness and economic marginalisation coupled with inadequate extension services, poorly developed infrastructure, and high dependence on natural resources for water, energy, and food requirements [26]. Meanwhile, in many African mountains, as the human population has grown, land has become scarcer, deforestation has intensified, and soil fertility has declined—resulting in severe land degradation, land use conflicts, and declining productivity [10]. Habitat areas are shrinking, increasingly fragmented and overharvested for building material, fuel, and food [27], while species are threatened with extinction [28].

A growing body of literature in the last decade recognises the importance of local perceptions of climate change impacts on social–ecological systems, particularly in meteorological data-scarce areas [29–32]. Another body of literature evidences the synergistic mitigation and adaptation co-benefits of nature-based solutions in agricultural landscapes while counteracting ecological degradation and biodiversity [33]. Scholars argue that local communities' knowledge and worldviews, including 370 million Indigenous people worldwide [34], are critical to understanding, evaluating, and developing more effective, locally tailored adaptation options [29,30]. The necessity of diverse knowledge systems in climate change research—particularly related to past, present and future change in the face of uncertainty—has been established in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [31,32]. Given this increasing recognition of the value of Indigenous knowledge, the IPCC has dedicated a chapter in the AR7 to capture societal perspectives on climate change around the world [35–38].

However, the historical and contextual complexities underpinning Indigenous people's knowledge, experiences, and impacts on livelihoods of climate change is largely overlooked, and the IPCC has been late to appreciate the value of these insights [39]. The existing literature on farmers perceptions of climate change shows that climatic change risks can be mediated through demographic factors, such as assets, gender, access to information and affiliation to cooperatives, and farmland characteristics, such as elevation, irrigation availability, and agricultural services [39,40]. However, relatively few studies have documented changes in African mountain regions and ensuing adaptive strategies [41,42]. In this paper, we use 'adaptive strategies' to refer to (i) strategies that evolved to manage climate shocks impacts ex-post (sometimes called 'coping strategies') and (ii) strategies which evolved to reduce overall vulnerability to climate shocks (sometimes called 'true adaptive strategies'). While there are multiple ways of categorising adaptation [43,44] we do not differentiate between both types as some strategies which start as ex-post interventions in exceptional years can become 'truly' adaptation strategies for households or whole communities over time [45]. It could be argued that some 'adaptive strategies' mentioned here are related to other non-climatic stresses, as we mention in the Discussion Section 4.

Comparing the cases of Mount Kilimanjaro and the Udzungwa Mountains in Tanzania, this study aims to better understand the perceived changes, impacts, and adaptation responses of farmers in East African mountains. Objectives are to: (1) identify observed climate change and their impacts on streamflow, landslides, soil erosion, agricultural production, and human and livestock health; (2) evidence local farmers' adaptation strategies; (3) investigate different adaptation responses according to farmer characteristics of wealth and gender; and (4) understand how other factors such as climate change literacy, membership in farmers' associations, or labour availability support or hinder adaptation. Due to the predominance of agriculture-based livelihoods and historical sedentary settlements and culture, throughout the paper, we refer to our respondents as 'farmers', but we acknowledge that individuals may have multiple livelihood strategies.

Overall, in agreement with several previous studies, we call for greater integration of Indigenous knowledge and experience in international mechanisms and instruments [46]. Such instruments include not only the IPCC [39] but also the International Science-Panel on Biodiversity and Ecosystem Services, the UN Convention on Biological Diversity (CBD) articles 8(j) and 10(c), as well as the UNESCO and CBD Secretariat Joint Programme of work on the linkages between biological and cultural diversity. Greater efforts are needed to strengthen transdisciplinary engagements and dialogue between Indigenous people, extension agents, scientists, and policymakers to explore synergies and complementarities of different knowledge systems, create opportunities for innovation, experiment with novel methods to advance understandings, and co-produce knowledge [46]. A more integrative, participative approach that combines local perceptions with meteorological data and remote-sensing products [47] will likely improve the identification and selection of meaningful and more robust adaptation options.

2. Materials and Methods

2.1. Study Sites

We studied two mountain systems in Tanzania because they represent a range of characteristics and wider social–ecological changes likely to be found in other mountain regions in sub-Saharan Africa. Both mountains are home to unique ethnic communities characterised by fast-growing populations, climate risks, transformations in agricultural practices, land and water systems, and shifts in regulatory contexts. Case studies thus offer broad regional coverage, which provides the rationale for generalising and scaling place-based results.

Mount Kilimanjaro (5895 m asl) has a bimodal rainfall regime with long rains (*masika*) starting from March to May, and short rains (*vuli*) from October to December. Rainfall and temperature change with increasing elevation. At about 1600 m asl, the mean annual rainfall is 2000 mm and temperature ranges between 15 and 30 °C [48]. Vegetation also changes with increasing elevation: from savannah (700–1000 m asl), submontane forest (1000–1800 m asl), montane forest (1800–3000 m asl) to alpine (above 3000 m asl) [49]. Most of the upper montane forest and alpine zones are now part of Mount Kilimanjaro National Park (declared in 1973) and UNESCO World Heritage Site (declared in 1987). As per Tanzania National Park's (TANAPA) policy, only non-consumptive activities are allowed within the park boundaries. However, given that local communities were previously allowed consumptive activities in the Kilimanjaro Forest Reserve (now part of the National Park), some women are permitted to collect dead stems for firewood within a half-mile strip next to the park boundary on the southern slopes (personal observation, 2020). Water that originates from the National Park is used not only for cultivation on the mountain slopes but also for irrigated rice, maize and tomato farms in the lowlands, flower cultivation around Arusha and hydropower plants at Nyumba ya Mungu and Hale and Pangani Falls [50].

The Chagga, of Bantu origin, are the largest ethnic group living on the southern slopes of Mount Kilimanjaro [49]. The Chagga home garden agroforestry system (intercropped trees with food cash crops) in the submontane forest zone, which dates to the seventeenth century, is considered one of the most productive areas of Tanzania [27,49]. As such, the Moshi District has a high population density—which in 2012 was 3409 people/km^2 compared to a national average of 67 km^2 [51]. The traditional system uses gravity-fed irrigation canals (*mifongo*) in the dry season, where customary agreements determine where water is channelled to plots via furrows for specified durations. Farms at higher elevations use a traditional terracing technique (*matuta*).

Apart from green banana (plantain, the preferred stable food), coffee, and yams, which are cultivated throughout the year, farmers also grow maize and beans during the long rains. At higher elevations, farmers also cultivate beans and green leafy vegetables during the short rains. Apart from farming, the Chagga keep livestock (mostly cattle). Dairy is an important part of their diet, dung is used as manure, and cattle has important social value (e.g., used as a dowry) [44]. Livestock is mostly kept in stables, but a few people graze them outside. However, both the agroforestry system and irrigation systems are disappearing gradually due to market changes (e.g., low coffee prices, industrial logging of conifer plantations, tourism), climate change, and other environmental challenges (e.g., land and water scarcity) [27].

The Udzungwa Mountains (2576 m asl) has a bimodal rainfall regime in the wetter southern slopes, but the north-western part has a unimodal rainfall regime with most rainfall falling from March to May (c. 1400 mm/a) [45]. Here, vegetation also changes with increasing elevation from savannah to submontane and montane forest and grasslands above 2500 m asl. Most remaining montane forest is part of the Udzungwa Mountains National Park (declared in 1992). As per TANAPA's policy, since 2011, only non-consumptive activities are allowed in the park [52]. However, there is evidence of some illegal extraction of firewood, amongst other activities such as encroachment and poaching [53].

On the north-western slopes of the Udzungwa Mountains, the Hehe or Wahehe, of Bantu origin, are the dominant farmer ethnic group [54]. The Hehe also use the terracing system (*matuta),* gravity-fed irrigation canals (*mitaro* or *mifereji*), and a soil conservation technique using small ditches (*mifereji*).

During the long rains, farmers grow food crops of maize, beans, and millet, and cash crops such as Irish potatoes at higher elevations and onions and ground nuts at middle to lower elevations. Green banana is not commonly grown by the Hehe. Farmers often store cash crops in communal storage facilities for sale during April and May, when food supplies in cities are low and prices of such crops are high [45]. Apart from farming, some Hehe keep livestock (mostly goats and pigs) which are usually grazed in open areas and along roads. Yet, local farming livelihoods are increasingly challenging to sustain due to climate change, combined with ex situ land acquisition, commercial agricultural, tourism, and infrastructural investment in the Kilombero Valley [55].

2.2. Data Collection

We first conducted a literature review to assess the state of evidence of climate change impacts and adaptation in mountains, with a focus on mountains. Studies that were included in the review and were coded were qualitatively assessed for quality following [56], i.e., —the data collection methods were thoroughly explained, 2—the sample size was well explained, 3—qualitative/quantitative analytical methods were clear and rational, 4—results and conclusions were logically derived, and 5—confounding factors were considered and explained. In each study area, we used the same approach. First, exploratory focus group discussions were conducted with four to five elders in four villages: two villages located at higher and two at lower elevations (Figure 1). These discussions were used to design the semi-structured questionnaires and build rapport. We interviewed elders that have been living in each area for several decades and could potentially report a larger number of climatic changes and impacts. Then, we administered semi-structured questionnaires to 150 randomly selected household heads using purposive sampling (50% male, 50% female) in the same villages. Questionnaires addressed household characteristics and assets, perceived changes in climate and impacts on the biophysical environment in their lifetime, and adaptation strategies used to cope with or adapt to observed changes (Supplementary Material A). The questionnaire protocol followed the guidelines of the project Local Indicator of Climate Change Impacts ([56] Available online: https://licci.eu/ (accessed on 12 September 2021)). Interviews were carried out in Swahili and were facilitated by two of the co-authors in November and December 2020. On Mount Kilimanjaro, all villages studied have gravity-fed irrigation canals (*mifongo*), but the number of households using irrigation varies, as well as community constructed reservoirs (*ndiva*) for domestic purposes in the wet season and water tanks and Moshi Urban Water Supply and Sanitation in the dry season. In only two of the villages studied (Foo and Kokirie), farmers use terracing (*matuta*). All four villages studied use gravity-fed irrigation canals (*mitalo* or *mifireji*), soil conservation technique (*mifereji*), and the terracing system (*matuta*).

2.3. Data Analysis

The percentage of respondents was the main unit of analysis for each mountain. First, we explored the main patterns and differences between communities. Second, we reported the effects of village elevation by pooling respondents into the four different villages sampled. Third, we explored the effects of gender by pooling respondents into two gender groups. Fourth, we explored the effects of wealth by pooling respondents into three groups (poor, average, rich). A wealth index was created from 10 asset indicators [46,57]. In each mountain, assets that were owned by <25% of the households were weighted 0.25 greater than those more commonly found (Supplementary Material B). Following this, paired t-tests were used to assess significant differences between genders, while cross-tabulation tables and chi-square tests were used to determine significant relationships between wealth groups and adaptation strategies. We used wealth group as explanatory variable and adaptation strategies as response variables. We used a significance level of $p < 0.05$. The Statistical Package for Social Science (SPSS) version 27 was used for all data analysis.

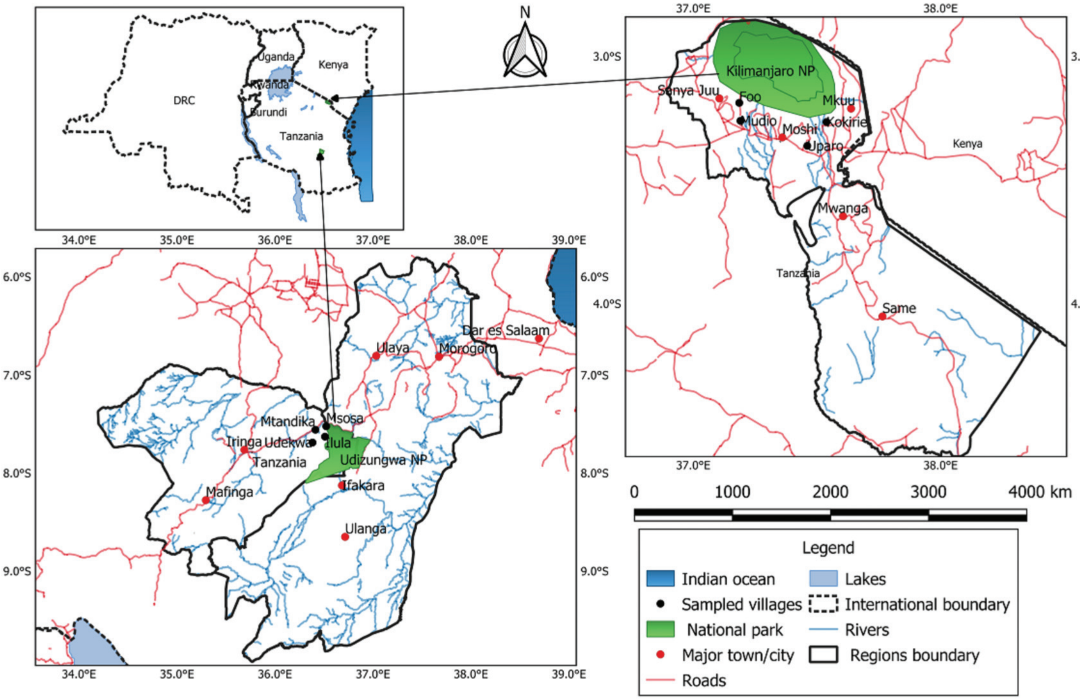

Figure 1. Map of Tanzania (top left inset) showing the locations of the two national parks. The sampled villages for Udzungwa are situated in the Rufiji River Basin, while sampled villages for Mount Kilimanjaro are situated in the Pangani River Basin. In each study site, four villages were sampled. Villages sampled in the Udzungwa Mountains were Udekwa (1013 m asl; 7°41′14.64″S 36°23′1.68″E), Mtandika (570 m asl; 7°33′19.08″S 36°23′48.48″E), Msosa (596 m asl; 7°32′31.56″S 36°30′7.56″E), and Ilula (1370 m asl; 7°37′34.32″S 36°30′35.64″E). Villages sampled in Mount Kiliminjaro were Foo (1694 m asl; 3°11′27.96″S 37°13′40.44″E), Uparo (1426 m asl; 3°21′34.92″S 37°27′41.04″E), Kokirie Mamba (1630 m asl; 3°15′46.44″S 37°32′17.16″E), and Mudio (1083 m asl; 3°15′1.8″S 37°11′22.92″E).

3. Results

3.1. Climatic Changes and Impacts

Most respondents (≥70%) on both mountains reported increased temperatures during the dry and the rainy seasons and a reduction in the number of frost days (Figure 2). Most respondents (≥70%) on both mountains also observed a reduction in the duration and amount of rainfall and fog during the long rains and an increase in dry spells and strong winds. Most respondents reported decreased stream flow and fewer hailstorms, and increased rain showers during the dry season. One main difference between the two sites were reports of increased extreme events, particularly floods and droughts: more respondents on the Udzungwa Mountains reported these compared to Mount Kilimanjaro (80% vs. 30%, respectively). However, more respondents on Mount Kilimanjaro reported an increased number of landslides (45% vs. 5%). In the two high-elevation villages on Mount Kilimanjaro, respondents also noted that the amount and duration of the short rains had changed. This was described by a female leader in Foo as follows: 'Vuli (short rains) have become unreliable. Sometimes there is too little rain to grow crops, and sometimes these rains are so long that they end up destroying the crop'.

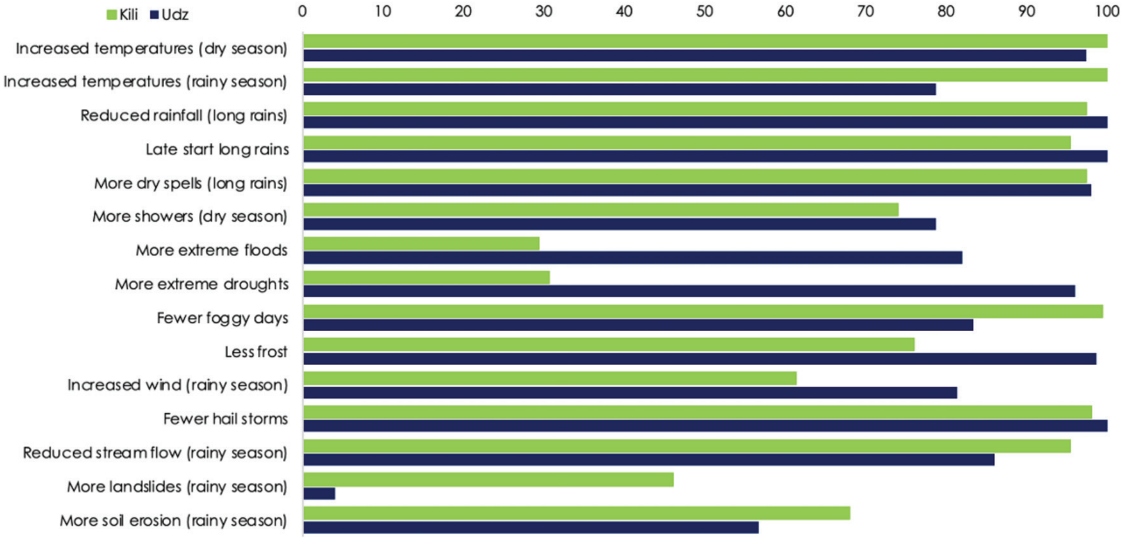

Figure 2. Observed changes in climate and impacts in the physical domain in terms of percentage of respondents in each mountain (n = 150 on Mount Kilimanjaro, n = 150 on the Udzungwa Mountains). On the Udzungwa Mountains, long rains refer to the only rainy season found on the north-western slopes. We did not specifically ask every respondent on Mount Kilimanjaro about the short rains, so these are not included in Figure 2.

Within each mountain, few differences were observed between villages at different elevations. On Mount Kilimanjaro, the main differences were that fewer respondents in Mudio (the lowest-elevation village) reported increased rain showers during the dry season, while more respondents in Kokire Mamba reported more landslides. In the Udzungwa Mountains, more respondents in Udekwa reported increased soil erosion (Supplementary Material C).

Respondents in both mountains reported reduced crop yields and an increase in crop pests and diseases, but the percentage of respondents varied for the different crops, being greater for maize, beans, coffee, and green banana (Figure 3). On Mount Kilimanjaro, respondents reported the most harmful crop pests as including *viwavi jeshi* (fall armyworm), which feeds on the stem and leaves of maize; *kishori* or *mnyauko* (fusarium wilt of banana), which dries the leaves of green banana and coffee; *kimamba* (green scale *coccus viridis*), which coils green leaves for beans and coffee; and *kimatira* and *uwiwi* (coffee berry borer), which attacks the fleshy berry surrounding the coffee kernel. On the Udzungwa Mountains, the most harmful pests were *viwavi jeshi* (fall armyworm) and *michilizi* (yellow striped virus), which affect maize by stunting the growth of panicles and flowers or causing the plant to be sterile; *fangasi* (rust), which, in beans, results in stunted growth; and *utitiri mwekundu* (red spider mites) and *vipekecha majani* (leaf miner), which, for onions, sucks the plant sap, grinds the leaves, and feeds on the plant tissue. Farmers noticed changes in pest incidence with increased temperature, which created favourable environments and changed ecological niches. For instance, farmers observed *wadudu chawa* (thrips) increased in abundance on onion leaves when there is little rainfall and high temperatures. Respondents on both mountains reported reduced milk production and an increase in cattle diseases, but more respondents reported these on Mount Kilimanjaro—probably as a larger percentage of respondents in this mountain own cattle, and milk production is an important component of the diet and culture of the Chagga. Surrounding the Udzungwa Mountains, more respondents reported increased diseases amongst goats. In both mountains, respondents said human health was adversely affected by climate change impacts (Figure 3).

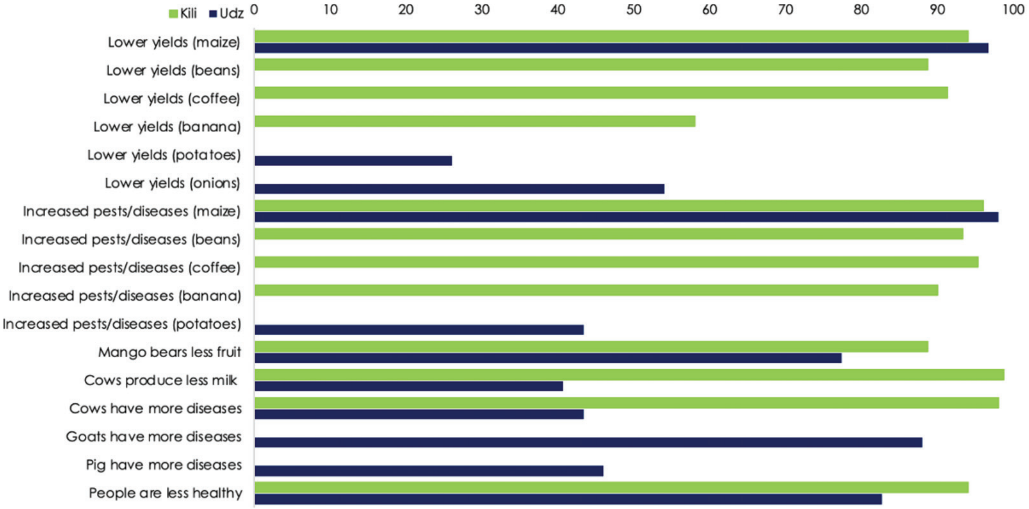

Figure 3. Observed impacts in the biological domain regarding percent of respondents in each mountain (n = 150 on Mount Kilimanjaro, n = 150 on the Udzungwa Mountains). Coffee and green bananas are not cultivated in our study area of Udzungwa Mountains. Although Irish potatoes, onions, pigs, and goats are grown by some farmers on Mount Kilimanjaro, we excluded these in the questionnaire on Mount Kilimanjaro as they are not widespread.

On Mount Kilimanjaro, the main differences across villages were that fewer respondents in Foo (the highest elevation village) reported decreased yields for green bananas (Supplementary Material C). On the Udzungwa Mountains, only respondents at high elevation villages (Ilula and Udekwa) reported reduced yields for Irish potatoes. Lower elevation villages were not involved in such farming activities.

3.2. Adaptation Strategies

The main adaptation strategies in both mountains were modifying farming or animal rearing. To adapt to climate changes, most farmers shifted to using improved crop varieties (mostly banana, maize, and beans)—preferring traits to improve disease, pest and drought resistance, early maturing, and high yield, depending on the context (Figures 3 and 4). This could be in part because in the past decade, agricultural extension programmes and research institutions have introduced several improved varieties of seeds. Respondents also mentioned increased use of soil conservation techniques, chemical fertilisers, and pesticides. Changing farm location, increasing farm size, and irrigation uptake were mentioned by more respondents on the Udzungwa Mountains than on Mount Kilimanjaro—where there is high population density. However, respondents highlighted that agrochemical use could lead to air and water pollution, while irrigation can lead to soil salinisation. Only around the Udzungwa Mountains did farmers cite changing crop species (e.g., from maize to drought-resistant millet), although there is some resistance due the shortage of seeds, food preferences, and the fact that maize has historically been planted. Notably, farmers on Mount Kilimanjaro reported sowing seeds later in the planting season, while around the Udzungwa Mountains, farmers sowed them earlier. In both study areas, farmers sowed seeds twice in one season when needed. Interestingly, most study participants mentioned changing planting dates.

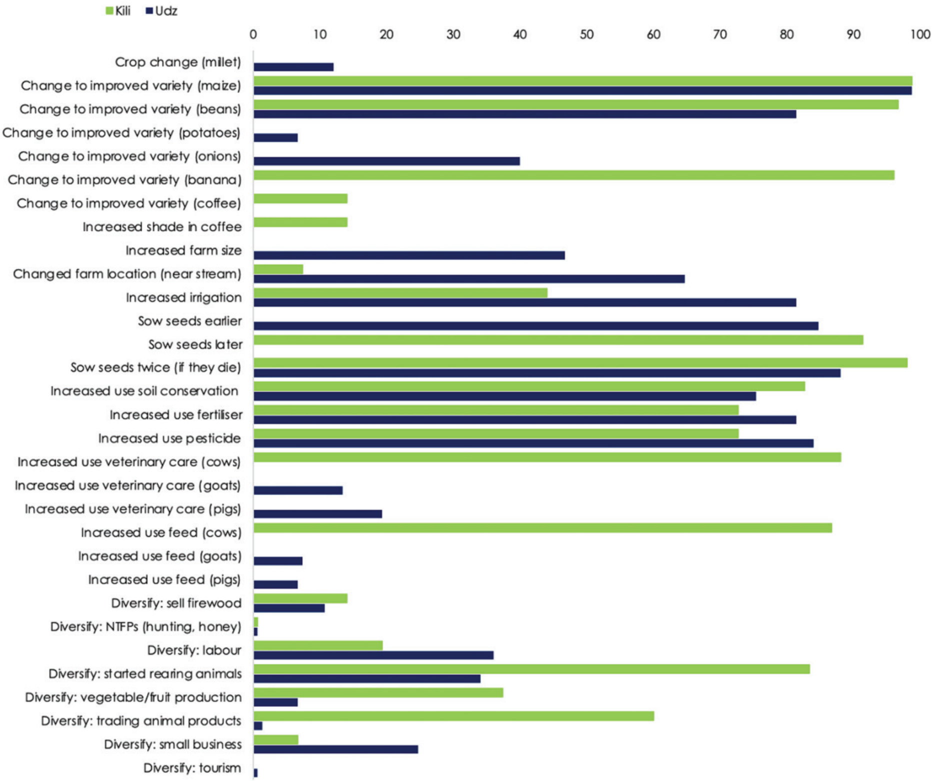

Figure 4. Adaptation strategies used by study respondents (%) (n = 150 on Mount Kilimanjaro, n = 150 on the Udzungwa Mountains). Coffee and bananas are not cultivated in our study area of the Udzungwa Mountains. Although Irish potatoes, onions, pigs, and goats are grown by some farms on Mount Kilimanjaro, we excluded these in the questionnaire on Mount Kilimanjaro as they are not widespread. NTFPs: Non-timber forest products.

On Mount Kilimanjaro, most farmers reported increased use of veterinary care and supplementary feed for cattle, while on the Udzungwa Mountains, a few respondents mentioned an increased use of veterinary care for goats and pigs. On both mountains, diversifying livelihoods was also cited, with increasing animal rearing or vegetable production being the most cited on Mount Kilimanjaro and casual labour employment or animal rearing being the most cited on the Udzungwa Mountains. In both regions, some respondents turned into firewood collection and trade, and some started small businesses (Figure 4). Across mountains, less than 30% use information from extension officers or radio (<30%) on when to sow seeds—even though most respondents in both mountains have a radio (Supplementary Material B). Instead, most farmers still used personal observations (e.g., observing when certain plants bloom before the long rains start or when certain birds sing).

Some differences were observed on Mount Kilimanjaro regarding village elevation. For example, fewer people in Uparu reported increased use of pesticides or fertilisers, and more respondents in Mudio (the lowest-elevation village) reported increased vegetable and fruit production and the trade of animal products. In the Udzungwa Mountains, only respondents in Ilula reported using improved varieties of Irish potatoes. In addition, increased use of pesticides and fertilisers was lower in Udekwa, and more respondents in Ilula reported increased use of veterinary care for pigs (Supplementary Material C).

3.3. Differentiated Adaptation Responses by Wealth and Gender

On Mount Kilimanjaro, wealth had a significant effect on five adaptation strategies. Wealthier households had a significantly higher adoption of the following adaptations: increased irrigation (63.3%), increased use of fertilisers (91.8%), increased use of pesticides (89.8%), increased vegetable farming (63.3%), and trading animal products (77.6%) (Table 1). Around the Udzungwa Mountains, wealth had a significant effect on nine adaptation strategies, including four of those also affected by wealth in Mount Kilimanjaro (Table 2). Poorer households had a significantly higher adoption of the following adaptations: diversify to sell firewood (18.8%), diversify to labour (46.9%) and diversify to rearing animals (20.3%). Interestingly, a major difference between the adaptations of the Hehe compared to the Chagga was that a greater number of poor than wealthy households had diversified to labour (46.9% vs. 10.7%) and selling firewood (18.8% vs. 7.1%). Gender was not significantly associated with adaptation responses (see results in Supplementary Material D).

Table 1. Adaptive strategies used by each wealth group on Mount Kilimanjaro (% respondents within wealth group). * Significant differences across wealth groups at $p > 0.05$, using cross-tabulation tables and chi-square tests.

Adaptive Strategies	Rich (%)	Average (%)	Poor (%)
Change to improved variety (maize)	100.0	97.6	100.0
Change to improved variety (beans)	98.0	97.6	94.7
Change to improved variety (green banana)	91.8	97.6	100.0
Change to improved variety (coffee)	20.4	12.2	5.3
Increased shade in coffee	20.4	11.0	10.5
Changed farm location (near stream)	18.4	1.2	5.3
Increased irrigation	63.3 *	41.5 *	5.3 *
Sow seeds later	95.9	87.8	94.7
Sow seeds twice (if they die)	98.0	97.6	100.0
Increased use of soil conservation	89.8	74.4	100.0
Increased use of fertiliser	91.8 *	68.3 *	42.1 *
Increased use of pesticide	89.8 *	70.7 *	36.8 *
Increased use of veterinary care (cows)	91.8	89.0	73.7
Increased use of feed (cows)	91.8	86.6	73.7
Diversify: sell firewood	22.4	9.8	10.5
Diversify: labour	20.4	22.0	5.3
Diversify: started rearing animals	85.7	85.4	68.4
Diversify: vegetable/fruit production	63.3 *	29.3 *	5.3 *
Diversify: trading animal products	77.6 *	53.7 *	42.1 *

Table 2. Adaptive strategies used by each wealth group on Udzungwa Mountains (% respondents within wealth group). * Significant differences across wealth groups at $p > 0.05$, using cross-tabulation tables and chi-square tests.

Adaptive Strategies	Rich (%)	Average (%)	Poor (%)
Crop change (millet)	10.7	15.5	9.4
Change to improved variety (maize)	100.0	100.0	96.9
Change to improved variety (beans)	89.3	86.2	73.4
Change to improved variety (potatoes)	14.3	8.6	1.6
Change to improved variety (onions)	78.6 *	36.2 *	26.6 *
Increased farm size	57.1	46.6	42.2
Changed farm location (near stream)	89.3 *	63.8 *	54.7 *
Increased irrigation	96.4 *	82.8 *	73.4 *
Sow seeds later	71.4	84.5	90.6
Sow seeds twice (if they die)	92.9	89.7	84.4
Increased use of soil conservation	89.3 *	79.3 *	65.6 *
Increased use of fertiliser	100.0 *	79.3 *	75.0 *
Increased use of pesticide	100.0 *	82.8 *	78.1 *
Increased use of veterinary care (goats)	21.4	15.5	7.8
Increased use of veterinary care (pigs)	17.9	27.6	12.5
Diversify: sell firewood	7.1 *	3.4 *	18.8 *
Diversify: labour	10.7 *	36.2 *	46.9 *
Diversify: started rearing animals	17.9 *	56.9 *	20.3 *
Diversify: vegetable/fruit production	10.7	1.7	0.0

3.4. Other Factors Supporting or Hindering the Adoption of Adaptation Strategies

In terms of factors supporting adaptation, farmers associations help provide loans to buy food or seeds or offer financial help to diversify income or start a small business. Approximately 51% of farmers are members of farmer organisations (i.e., 56% on Mount Kilimanjaro and 46% on Udzungwa). These are mostly women's or loan associations. When asking about the use of climate information, farmers indicate they access information from radio, television, or church. Most male and female Chagga and Hehe respondents had some schooling, more Chagga than Hehe listen to a radio on a daily basis, while 99.3% and 98.6%, respectively, understood the term 'anthropogenic climate change'. However, respondents explained that they do not trust the predictions from meteorological agencies because they feel the information given is not useful, which was described by a leader in a Uparo village in Kilimanjaro as due to the fact that the 'Two-day predictions from the radio are too short notice to prepare the fields'. This hinders the use of climate information to inform land management decision making.

Factors that hinder adaptation relate predominantly to land tenure and ownership rights, labour availability, high initial investment costs for adaptation, and limited technical skills for new practices. Food preferences further influence decisions to diversify crops. For instance, some Chagga avoid cassava and sweet potato because these crops are perceived as a 'hunger food'.

4. Discussion

4.1. Climatic Changes and Impacts

Our study provides evidence of how Indigenous communities can provide insights on the climatic changes already observed on mountains for a wide range of climate variables beyond rainfall and temperature (e.g., fog, rain showers, hailstorms), as shown by other studies [37–39]. If fog is expected to change considerably due to predicted increased temperatures and raising cloud base in African mountains [17,58] and few meteorological stations record such variables, local peoples' perceptions of change could be used to better understand non-precipitating changes in moistures impacts on crop and fodder production.

In general, the climatic changes reported by farmers in this study agree with previous studies on climate change perceptions in Tanzania's mountains [27,45,48,59–63], but we investigated more variables than previous studies (Table 3 and references therein). For instance, increased temperatures, reduced duration and amount of rainfall, and more dry spells during the long rains were reported by previous studies on Kilimanjaro, Pare, Uluguru, Usambara, and Udzungwa mountains and the Southern Highlands. However, in the Udzungwa Mountains, the early onset of the rainy season was noted instead of a later onset of rainfall—which we report here. Decreased stream flow was previously reported in both mountains [27,45,59,61,64,65]. An increase in extreme droughts was not identified in previous studies on Mount Kilimanjaro, although it was cited in the Pare and Udzungwa Mountains. An increase in wind strength during the rainy season was previously mentioned in the Pare Mountains [64], but not on Mount Kilimanjaro and the Udzungwa Mountains. While our study participants in both mountains reported important changes in fog, only one previous study recorded this change in the East Usambaras [66]. Some of the differences between this and previous studies in the same mountains could be related to local topography or climatic conditions (e.g., villages in ridges being more exposed to wind) [67]. The fact that some previous studies were conducted a decade ago might also explain differences across our and previous studies—if some phenomena have intensified in recent years.

As highlighted by [30,68], tapping into the detail of the climatic changes perceived by local communities allows researchers and practitioners to better understand the nuances of climate impacts on farmer livelihoods and ensuing locally acceptable adaptation decisions. For example, both dry spells during the rainy season or showers during the dry season can negatively affect maize yields, but fog can be a source of moisture for seed germination [58].

The perceived changes in rainfall and temperatures reported by farmers agree with available meteorological data. On Mount Kilimanjaro, rainfall measurements at three different elevations indicate a significant reduction in annual rainfall up to 2004 [68]. However, a recent re-analysis for Kilimanjaro airport showed no significant trend for the period 1973–2013, except for increased rainfall in March but reduced rainfall in April [69], which was also noted between 2001 and 2019 [59]. Respondents suggested this may be due to the late onset of the long rains. Differences in perceived and observed change could also be related to the fact that Kilimanjaro airport is located between 30 and 80 km from the villages sampled—further emphasising the need to capture local perceptions, particularly on mountains where the environment vary significantly over short distances. Available meteorological data also indicate increased temperatures [69,70], in agreement with farmer's perceptions. We did not have access to meteorological data from the Udzungwa Mountains as the only meteorological station in the region is located at much lower elevations.

Regarding impacts in the biophysical domain, only some of the impacts mentioned by our study participants have been reported by other studies. Surprisingly, lower yields for green banana and beans were not mentioned in previous studies on Mount Kilimanjaro, although the latter was reported in the Pare Mountains and [71] reported maize pests in Kilimanjaro. Several Chagga respondents highlighted that organisations should help ensure the productive yield of their preferred staple crop (green banana), which could be considered a cultural keystone species [72], as most instead focus on coffee.

Regarding livestock, previous studies in Tanzania's mountains did not report decreased milk or increased diseases, but these were reported from other locations in Tanzania [73]. A study in the mountains in northern Kenya [58] mentioned reduced fodder availability due to increasing droughts and related weak health of animals.

Previous studies on Mount Kilimanjaro did not mention reduced human health due to climate changes, but this was noted in the Udzungwa Mountains. Reasons related to increasing temperatures influencing the prevalence of waterborne diseases (cholera, typhoid, dysentery, malaria, and amoebic diseases) where there is limited potable water, as suggested by [74] for the Kilombero district and reported by [43]. Non-climatic factors could also affect health, such as reduced stream flow, upstream pollution, and river farming leading to deposition of agrochemicals in watercourses. We were unable to investigate the nuances of reduced human health, and thus future work is clearly needed in this area that combines medical data with insights from communities [75,76].

Table 3. Climatic changes and impacts as reported by other studies on farmers' perceptions in Tanzania's mountains. (H: Highlands). [1] [63]; [2] [48]; [3] [27]; [4] [59]; [5] [45]; [6] [60]; [7] [61]; [8] [62]; [9] [42]; [10] [60]; [11] [60]; [12] [4]; [13] [76]; [14] [77]; [15] [65]; [16] [32]; [17] [66].

	Kili 1	**Kili 2**	**Kili 3**	**Kili 4**	**Udz 5**	**Udz 6**	**Udz 7**	**Uluguru 8**	**Usam 9**	**Usam 10**	**Usam 11**	**Pare 12**	**Pare 13**	**Pare 14**	**SH 15**	**SH 16**	**SWH 17**
Increased temperatures (General)			×	×	×		×	×					×	×	×	×	×
Increased temperatures (dry season)			×		×										×		
Increased temperatures (rainy season)			×											×			
Changes in rainfall patterns (General)	×		×	×	×	×	×	×		×	×	×	×	×	×	×	×
Reduced rainfall (long rains)			×	×	×		×	×				×	×	×	×		×
Late start long rains				×		×				×		×		×			×
Early start long rains					×												
More dry spells (long rains)					×					×		×	×				
More showers (dry season)										×							
Hazards, Fog and wind (General)			×	×	×	×	×					×	×		×	×	×
More extreme floods						×										×	×
More extreme droughts					×								×		×		×
Fewer foggy days																	
Less frost															×		
Increased wind (rainy season)												×			×		×
Fewer hail storms																	
Reduced stream flow (rainy season)			×	×	×		×								×		×
More landslides (rainy season)																	
More soil erosion (rainy season)						×									×		
Lower crop yields		×		×	×	×	×				×		×	×	×	×	×
Lower yields (maize)		×			×	×							×	×			
Lower yields (beans)													×				
Lower yields (coffee)		×		×													
Lower yields (banana)																	
Lower yields (potatoes)						×											
Lower yields (onions)																	
Increased pests/diseases (maize)					×											×	
Increased pests/diseases (beans)					×												
Increased pests/diseases (coffee)				×													
Increased pests/diseases (banana)																	
Increased pests/diseases (potatoes)																	
Mango bears less fruit																	
Cows produce less milk																	
Cows have more diseases																×	
Goats have more diseases																	
Pig have more diseases																	
People are less healthy					×											×	

4.2. Adaptation Strategies

Previous work on Tanzanian farmers' adaptation to climate change (Table 4) highlighted that a combination of strategies is often used, including, inter alia, agricultural extensification, intensification, livelihood diversification, pooling of resources and labour, and migration [78]. On Mount Kilimanjaro, farmers changed the crop they planted. This is similar to studies in drier parts of Tanzania, where farmers increase the cultivation of sweet potatoes and cassava in dry years (or following a 'bad' year for maize) [20,78]. Coffee farmers grow shade trees to adapt to heat stress, a strategy previously undocumented for Mount Kilimanjaro but recorded in the Jimma Mountains, Ethiopia [77]. In the Usambara Mountains, increased use of agroforestry was cited for non-coffee crops [42], but this was not mentioned by our study participants. Others switched to vegetable or fruit production. Agricultural extensification was only used by some respondents surrounding the Udzungwa Mountains, but not in the southern slopes of Mount Kilimanjaro. This may be in part due to higher land scarcity coupled with high population density in the latter site.

Farmers also changed animal rearing practices as they intensified the use of veterinary care. This was previously undocumented for Mount Kilimanjaro but was mentioned in the mountains of northern Kenya [58].

Although most adaptation strategies focused on modifying farming practices, livelihood diversification was also cited, i.e., selling firewood, establishing a small business, and providing labour—most of which had been mentioned in previous studies. The sustainability of these strategies requires further investigation, especially collecting and selling firewood. Several other authors have highlighted the increased degradation of forests in the Eastern Arc Mountains (which includes the Udzungwa Mountains) [79]. Remarkably, very few households mentioned harvesting or trading non-timber forest products, which is different from previous studies in other African mountains [52]. This may be attributed to: the fact that we studied communities whose predominant livelihood activity is agriculture, fear of reporting illegal actions, changes in law reinforcement in the national parks, growing electrification, the fact that national park authorities in 2019 launched a household tree planting initiative to overcome firewood availability [80], or because the agroforestry farming system in Kilimanjaro has lowered firewood demand among villagers. In contrast to other studies across sub-Saharan Africa [81–83], we did not find evidence of migration due to climate change. Nevertheless, people are likely to migrate for other reasons such as education, lifestyle aspirations, and seasonal or permanent employment.

4.3. Differentiated Adaptation Responses by Wealth and Gender

We found that wealthier households used more inputs (e.g., irrigation, fertilisers, pesticides) and diversified commodities produced (e.g., horticulture, trading animal products), similar to other studies (e.g., [31]). However, we found one difference to previous work: in Udzungwa, poorer households used labour as diversification, but not in Mount Kilimanjaro. Most Chagga have invested in educating their children—some of which now work in urban areas and send remittances—which could explain why some do not engage in labour. Notably, even poor Chagga households are relatively wealthier than poor Hehe households in terms of assets—for example, owning a radio.

Table 4. Adaptation strategies reported by other studies on farmers' perceptions in Tanzania's mountains. (H: Highlands; NTFPs: Non-timber forest products) ^{1} [63]; ^{2} [48]; ^{3} [27]; ^{4} [59]; ^{5} [45]; ^{6} [60]; ^{7} [61]; ^{8} [84]; ^{9} [42]; ^{10} [60]; ^{11} [60]; ^{12} [35]; ^{13} [76]; ^{14} [78]; ^{15} [28]; ^{16} [85]; ^{17} [66].

Mountain	**Kili 1**	**Kili 2**	**Kili 3**	**Kili 4**	**Udz 5**	**Udz 6**	**Udz 7**	**Uluguru 8**	**Usam 9**	**Usam 10**	**Usam 11**	**Pare 12**	**Pare 13**	**Pare 14**	**SH 15**	**SH 16**	**SWH 17**
Crop change (millet)						x					x					x	x
Change to improved variety	x								x	x							
Change to improved variety (maize)						x					x					x	
Change to improved variety (beans)																x	
Change to improved variety (potatoes)														x			
Change to improved variety (onions)																	
Change to improved variety (banana)																x	
Change to improved variety (coffee)																	
Increased shade in coffee				x													
Increased farm size						x	x				x						
Changed farm location (near stream)						x					x		x	x	x		
Increased irrigation	x	x			x		x	x	x	x			x		x	x	
Sow seeds earlier																	
Sow seeds later									x							x	
Sow seeds twice (if they die)										x							
Increased use soil conservation	x	x				x		x	x	x	x					x	
Increased use fertiliser		x				x			x	x	x						
Increased use pesticide		x			x	x					x		x				
Increased use veterinary care (cows)																	
Increased use feed (cows)																	
Diversify: sell firewood																x	
Diversify: NTFPs (hunting, honey)																	
Diversify: labour	x											x				x	
Diversify: started rearing animals						x				x	x					x	
Diversify: vegetable/fruit production	x														x	x	
Diversify: trading animal products																	
Diversify: small business																x	
Diversify: tourism																	
Diversity: seasonal migration to cities	x											x					

Interestingly, gender did not influence perceptions of climatic changes, impacts, or adaptive strategies. This is in contrast to other studies in African mountains such as Mount Elgon, Uganda [85], where important differences between male and female respondents were reported. The explanation for this may be related to the fact that today, the distinction in gender-based roles in Chagga and Hehe societies is starting to blur and that education and access to information in our study areas are becoming more accessible to women. On the other hand, it could be argued that lack of differences is related to the fact that we interviewed few female-headed households (9.7%), resulting in a reporting bias (Supplementary Material B). Future work should explore the adaptive strategies of poor female-headed households in more detail, e.g., see [86].

4.4. Other Factors Supporting or Hindering the Adoption of Adaptation Strategies

Despite being climate change literate, most farmers in both mountains still rely on their own observations to judge the timing and quality of the coming growing season. Some farmers mentioned that the signs they used are not as accurate as they once were. These findings were also observed by [59,87], who showed climate variability could undermine farmers' confidence in their existing knowledge and practices and hinder farmers' ability to plan and manage new pests.

An important factor that can support adaptation is membership in farmers organisations. Organisations help farmers access loans to, for instance, buy improved seed varieties, buy agrochemicals, irrigate, and employ soil conservation techniques, as shown in many other studies [57,88–90].

Similar to [42,90], we found that ongoing demographic shifts and out-migration to urban centres means labour availability (e.g., to maintain irrigation canals or terraces) is another growing challenge for farmers left behind in rural origins. This trend is situated amidst the larger context, where Tanzania is currently experiencing a dramatic movement in labour out of agriculture to higher-return sectors. Meanwhile, commercial farms are increasingly claiming a prominent role and competition over land and water is growing [90]. Compounding these factors is the widening inequality associated with the coronavirus pandemic. Health and economic pressures intersect with climate shocks, and farmers have been among those that have borne the brunt—struggling to sell their produce with plunged consumer demand and changing export markets in Tanzania [91].

4.5. Limitations and Future Research Avenues

Our study has limitations and points towards future research avenues. First, we acknowledge that the sample size of 300 households and 4 villages per site is not statistically representative of the entire population. Nevertheless, we believe that the trends observed are likely to be found in the larger population in these and other mountain regions in the Global South. Future research should consider more villages, a larger population, and more ecological and social contexts. Second, future work should sample female-headed households more exhaustively. Third, future longitudinal research could study local perceptions across different seasons and years. Nevertheless, as our study was conducted in 2020, which was a relatively wet year [92], we argue that perceptions of reduced rainfall are not necessarily related to the particular year but are more representative of a wider trend. Fourth, future research should consider the influence of other intrinsic and extrinsic factors, such as beliefs and intentions of individuals and households [93], access to market, extension services, crop insurance, infrastructure, other farming inputs, land transactions and consolidation measures, as well as agricultural policies [84].

5. Broader Implications for Policy and Practice

Our findings have five major implications for policy and practice.

First, climatic changes are already perceived by local communities on Mount Kilimanjaro and the Udzungwa Mountains, which agree on reports by farmers in other mountains in Tanzania and East Africa. Notably, our participants reported a larger number of changes and impacts. In mountain regions where complex topography and terrain causes different local climatic conditions [18], local insights based on long-term verified patterns should be used to test how models and their underlying hypotheses are built [94], particularly in meteorologically data-scarce regions or at fine geographic scales, as highlighted by other authors [31,58,95]. Capacity-building among national and regional meteorological departments and sustained interactions between diverse stakeholders can help increase the use of climate information while addressing issues of trust and reliability on the forecasts [96,97].

Second, local farmers utilise a range of adaptation strategies, some of which have evolved over long periods of time, and others which are in response to new emerging patterns [98]. To assess the scalability, sustainability, and replicability of adaptation strategies, each strategy should be evaluated depending on the technical, social, biophysical, infrastructural, economic, and regulatory contexts, communications, stakeholder involvement, and barriers such as financial, human, social labour, land, and access to rapid credit [56,99,100]. Policy interventions can build the adaptive capacity of high mountain communities by supporting social learning and farmers' ability to experiment [96,101], expand their social networks, access external support for nontraditional adaptations, and internally reflect on their adaptation practices [98].

Third, despite widespread climate change literacy, farmers prefer to use personal observations over meteorological forecasts. This highlights the need to tailor forms of dissemination to local needs in terms of timing (e.g., farmers indicated a 2-day forecast was too short notice to start preparing their fields), format (e.g., cost-effective radio communication; advice given by extension workers) [80], and spatial resolution (e.g., farmers suggested forecasts were too coarse to deal with farm-level decisions)—as shown by [102] in the case of rural farmers in West Africa. There is a need to ensure credible communication procedures of forecasts [103].

Fourth, our results show differences in adaptive responses according to wealth groups. Numerous studies have documented how wealthier households generally have more options for adaptation [31]. However, overall, our findings show that the story is not so simple. There is a need to consider wealth when designing adaptation interventions within and across study sites, as some wealthier households might have fewer options than poorer households. In light of growing inequality—particularly during the coronavirus pandemic—and wider transformations in Tanzanian society, policies should carefully consider how wealth from subsistence and commercial farming and mixed sector off-farm income can be reinvested in locally produced, employment-intensive goods and services to reduce inequality, secure the livelihoods current and new workers, and drive intensification [90]. Better international cooperation and faster development action is needed to limit the loss of traditional knowledge in mountain farming communities [2,104].

Fifth, previous research has shown how many well-intended national policies for adaptation have prioritised large-scale infrastructure solutions or technocentric quick fixes. Such approaches typically fail to reach mountain communities, overlook the vital importance of context, and mobilise communities' profound attachment to nature from cultivating parcels of land on mountain slopes for centuries [27,65,105]. To identify promising future adaptation pathways, we recommend the use of a 'science with society' participative, transdisciplinary approach [104], an iterative process that brings together actors to engage in knowledge co-production. Appreciating cultural values helps build trust between local peoples and other agencies and provides a closer understanding of differentiated climate hazard exposure, vulnerabilities, risk, and resilience [19].

Nationally, insights are relevant for realising the plans of the Southern Agricultural Corridor of Tanzania public–private partnership's vision to introduce climate-smart practices to farmers, boost agricultural productivity, food security, environmental sustainability, and reduce poverty—particularly in the Kilombero cluster, which will influence the Udzungwa Mountains [56]. Results can inform Tanzania's National Adaptation Programme of Action– which explicitly mentions Mount Kilimanjaro, the Eastern Arc and Southwestern highlands, but not the Udzungwa Mountains [106]. Internationally, results can inform ongoing processes to secure the resilience of Indigenous peoples living in mountains: not least of which are the Sustainable Development Goal 2 on Zero Hunger (target 2.3.2), Goal 3 on health and well-being, Goal 4 on education (target 4.5.1), and Goal 5 on gender equality and the need to 'leave no one behind'. Results also have relevance for Agenda 2063—and targets of climate-proof investments (aspiration 1.7); ensuring local people are appropriately consulted in landscape planning (aspiration 6); and that citizens are healthy, well-nourished, educated, and strong (aspiration 1.3).

6. Conclusions

This study shows how local communities' perceptions can be used to identify the nuances of the climatic changes and impacts already observed in mountain regions. It also illustrates how farmers are using a wide range of adaptation strategies, most of which focus on modifying farming practices and how wealth affects adaptation options. Understanding the local context is important in mountain regions [107], but some of the key considerations of the Chagga and Hehe (e.g., effects of wealth on adaptation) can help inform policy and practice in other mountains in Africa and beyond where such climate change risks are likely to be the most acute.

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Article

Analysis of the Spatial Variations of Determinants of Gully Agricultural Production Transformation in the Chinese Loess Plateau and Its Policy Implications

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Abstract: Exploring the gully agricultural production transformation and its influencing factors is of considerable significance to the evolution of the human–land relationship and multifunctional transformation of gully agriculture in the context of new development. This paper tries to reveal intensive land use under the background of population contraction in the Chinese Loess Plateau and its transformation trend by defining the gully agricultural production transformation (GAPT). Given the representativeness of land-use change in the loess hilly and gully region (LHGR) was taken as a case study, and ArcGIS spatial analysis techniques and geographically and temporally weighted regression model (GTWR) were used to detect the spatio-temporal differentiation pattern and influencing factors. The results show that: (1) GAPT shifts from the high elevation area of 1000–1300 m to the low elevation area of <1000 m, and the transformation process remains within the range of slope 0–20° and topographic relief between 40 m and 180 m. (2) GTWR coupled with time non-stationary and spatial heterogeneity has a better fitting effect, which verifies its applicability in the study of GAPT. Social and economic factors were the main driving forces of GAPT in Yan'an City in the past 20 years, and they were increasing year by year. (3) The spatial-temporal distribution of the driving factors of the agricultural production transformation in Yan'an City is different. The intensity of the population factor and the slope factor is always in the dominant position, and the high value distribution area of the land average GDP factor forms a funnel-shaped pattern of "core edge" in the north and the central and western regions, and its changes tend to "flow" to the core. (4) The gully agricultural production transformation can reflect the general law of rural land use transition in gully areas, and thereby provide policy ideas for gully development. Overall, this study's content can provide scientific guidance for the sustainable development of gully agriculture and the revitalization of watershed and land consolidation in gully areas.

Keywords: gully agricultural production transformation; rural development; sustainable land use; geographically and temporally weighted regression; gully land consolidation

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1. Introduction

The Loess Plateau is a special region integrating agriculture from farming areas to pastoral areas, ecologically fragile areas, and economically poor areas in China. Over a long period of time, the irrational use of local resources has caused vegetation degradation, soil erosion, and severe land productivity reduction [1,2], reflecting the contradiction between ecological protection and economic development, and a key area connecting precise poverty alleviation and Rural Revitalization [3]. Ecological protection, human land system coordination, and sustainable development are always the basic propositions of high-quality development in the Loess Plateau [4,5]. The loess hilly and gully region (LHGR) is characterized by undulating hills and gullies, and its unique geographical characteristics have shaped a distinctive rural man land system [6]. In the process of social and economic development and urbanization, the loess hilly and gully region has suffered from the dual disturbance of natural ecology and human activities. With the implementation of the Grain for Green Project (GGP) and Gully Land Consolidation (GLC), the regional vegetation has been significantly improved, and the contradiction between people, food, and land has been gradually eased, the transformation and development trend of rural man land system in the loess hilly and gully region is obvious [7].

Since the reform and opening up, the operation characteristics of the rural man land system in the LHGR can be summarized into three stages: sloping agriculture stage, vegetation construction stage, and gully agriculture development stage. The process has involved the extensive planting and low income of agricultural production and then the sustainable saving of production practice, and the overall trend of transformation to modern agriculture [8,9]. At present, the related research on the rural man land system in the LHGR mainly focuses on the perspective of new types of business entities, ecological governance and industrialization, focusing on the spatial form of the core elements (settlement and land use) of the rural man land system [5,10,11], typical patterns [12–14], evolutionary process [15,16], dynamic factors and mechanisms [17,18].

Human activity in the Loess Plateau has a long and complicated history of more than a thousand years of human settlement [19]. In the new period, there is a shortage of high-quality cultivated land in the rural areas of the LHGR, the development space of construction land in the valley is limited, the ecological restoration of the gully region coexists with the rural decline, the slow development of the gully countryside and the "rural disease". Five problems, including high-speed non-agricultural transformation, over-fast aging, deep poverty, severe fouling of soil and water environment, and increasingly hollowing land management of the countryside, are more prominent, and the development of the rural human-earth system in the LHGR urgently needs to be reconstructed [20,21]. With the continuous development of Metrology geography and human-earth system science, the research on the evolution of the human-earth system is constantly updated and in-depth, and the mutual feed and correlation between system elements are emphasized. The dynamic analysis of the system and the model methods such as GWR, ESDA, geodetector, and other model methods has been paid attention to by the academic circles [22,23], gradually embedding spatial factors into the system model to reveal the driving mechanism of the system factors.

The Loess Plateau can be divided into geomorphic zones on the basis of geologic structure and topography. However, terraces have often been built on the slopes of loess Liang or Mao to create fields for agriculture, and check dams have been constructed in gullies and valleys [24]. The evolution of the gully man land system with gully farmland as the core has both temporal and spatial attributes. The changes in temporal and spatial geographical location will cause changes in the relationship or structure among variables [25]. The non-stationarity of time (lag effect) needs to be included in the scope of the model. At the same time, the spatial and temporal dimensions should be included in the driving force analysis model. It is of great significance to explore the spatiotemporal characteristics and laws of the driving forces of rural land conversion. The rural man land system in the LHGR is a system with different spatial changes in nature, economy, and environment. Its focus is more dependent on the agricultural production of the gully farmland unit [26].

In this context, this research focuses on the evolution of the rural man-land system with gully farmland as the core. The key point is to analyze the temporal and spatial relationship between people and land in the system, and integrate it into a framework to explore farmland changes and the spatio-temporal influence mechanism, explore "cure" approaches, and prescribe the right prescriptions to consolidate the effects of the Grain for Green Project and Gully Land Consolidation, thereby contributing to rural revitalization and regional sustainable development.

In view of this, this paper intends to select 30 Landsat TM/OLI data in four periods of 1995–2000, 2000–2005, 2005–2010, 2010–2018, and apply the CART decision tree classification algorithm for remote sensing image interpretation to obtain the corresponding time series of gully farmland change information, realizing the identification of gully farmland and the driving force analysis of gully farmland spatio-temporal evolution, analyzing its influence mechanism. Thus, it provides a scientific reference for the sustainable development of gully agriculture and the revitalization of watershed in the Chinese Loess Plateau, especially in the LHGR. Implications for rural development policy related to land consolidation would be also addressed.

2. Theoretical Analysis

2.1. A Theoretical Model for Gully Agricultural Evolution in Gully Areas

Since the economic reforms and open-door policy were initiated in 1978, the agricultural development in the LHGR has generally experienced three stages: the traditional sloping agriculture stage, transition stage, and modern gully agriculture stage. Firstly, in the traditional sloping agriculture stage, the agricultural production was mainly on the slope, and sloping farmland was the primary source of production in the regional agricultural production system. Due to the relatively high altitude, the agricultural production was large-scale planting and little harvesting, and the land use was extensive. Secondly, with the large-scale GGP implemented in 1999, the sloping land was converted to farmland, and the scale of the area continued to decrease. The slope farming was gradually withdrawn, and vegetation replaced the sloping farmland. The surface transformed from “yellow” to “green”, and agricultural production has now shifted from high-altitude slopes to low-altitude gully. The living spaces also gathered from high-altitude areas to low-altitude areas, and the gully had become the key area for the production and living in the LHGR. Thirdly, in order to develop the agricultural production in the gully, the GLCP’s “consolidation of the gully to protect the ecology and creating land to benefit the people’s livelihood” was implemented, achieving the coordinated development of ecology and production (Figure 1). In addition, through the GLCP, the comprehensive agricultural production capacity was improved, and the integration of “three industries” and the development of agricultural conservation were promoted [21,27].

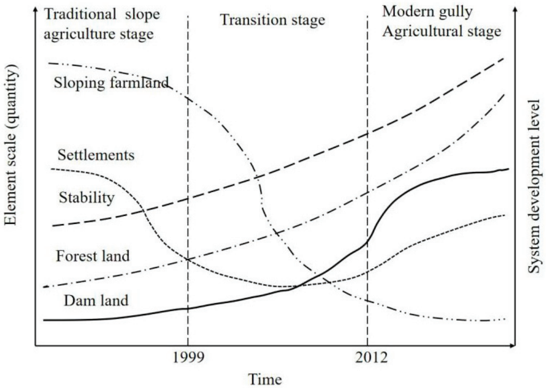


Figure 1. The evolution theoretical model of the gully agricultural production development.

2.2. The Evolution of the Gully Agricultural in the LHGR

Since 1999, the Grain for Green Project (GGP) in the LHGR, especially the Gully Land Consolidation (GLC) project in 2012, the gully rural human–land relationship has changed subtly), gradually shifting from the traditional sloping agricultural system to new gully agricultural systems; the agricultural system of the LHGR is transforming. The core of this transformation is to achieve the “win-win” goal of ecological and economic benefits, and mainly manifested in two aspects: food crop production of the gully farming system and ecological conservation of the gully forestry system in the LHGR. Thus, changes in land use patterns correspond to the transformation of functional effects driven by economic and social development and innovation that are compatible with the stage of economic and social development [20,28]. The traditional farming system in the LHGR is centered on the main production of food crops. As time goes by, the gully watershed becomes the distinctive land use pattern of the gully area. Adapting to the stage of social and economic development, agricultural production gradually transforms from extensive development and utilization of land expansion to intensive utilization under an ecological economy. The goal of this study is to deconstruct the multiple elements of the agricultural production system in gully areas from the perspective of farmer subject and regional production space and type change, evaluating the interaction mechanism that drives changes in the human–land relationship in the LHGR.

3. Materials and Methods

3.1. Geography of the Study Region

The loess hilly and gully region of Yan'an City is located in the center of the Loess Plateau, with a total area of about 18,729 km^2. It is the combination of the middle and upper reaches of the Yellow River Basin and the northern agro-pastoral region, covering eight districts and counties in the north-central part of Yan'an: Baota District, Yanchang County, Ganquan County, Ansai District, Yanchuan County, Zichang County, Zhidan County, and Wuqi County (Figure 2). The topographical conditions of the study area are complex, with crisscrossing ditches, streams, slopes, beams, and ridges, and the topography is very typical. Since 1999, as the first batch of pilot areas for the Grain for Green project and Gully Land Consolidation, this area has taken the lead in realizing the transformation of the surface color from "yellow" to "green" and the production space from "sloping" to "gully". In the context of urban-rural integration and the high-quality development of the Yellow River Basin, it is typical and representative to carry out the research on the characteristics and mechanism of gully farmland transformation in the loess hilly and gully region of Yan'an City [29].

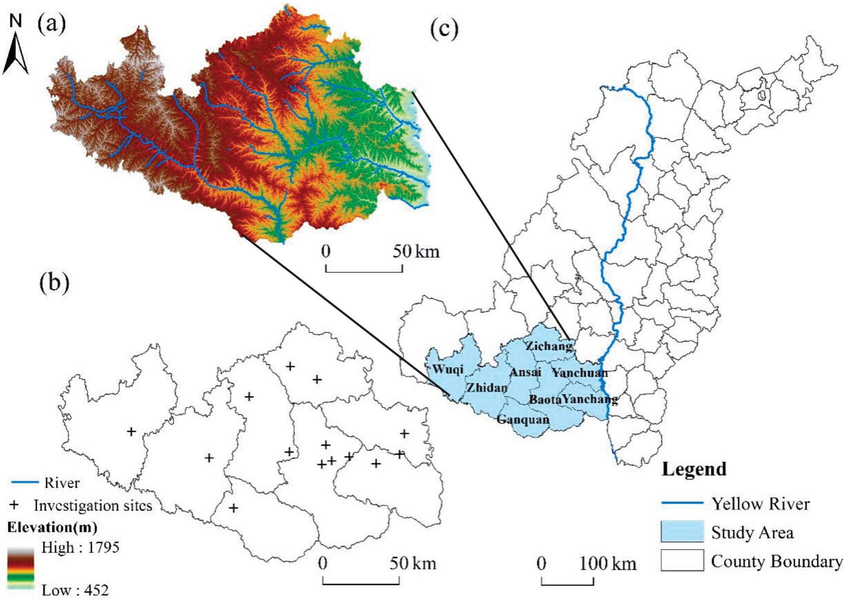


Figure 2. Location and investigation sites of the study area. (**a**) shows the digital elevation map of the study area, (**b**) shows the distribution of investigation sites in the study area, and (**c**) shows the loess hilly and gully region.

3.2. Data Sources and Processing

The data used in this study are mainly divided into two categories: remote sensing data and socio-economic data. The socio-economic data were mainly obtained through field surveys, field interviews, and statistical yearbooks. Field interviews mainly include four dimensions: natural ecological dimension, farmers' livelihood source and improvement dimension, agricultural planting and development dimension, ecological landscape, and environmental safety dimension. The remote sensing data originated from the United States Geological Survey (USGS) during 1995–2018 (http://glovis.usgs.gov/) and Landsat image data with a spatial resolution of 30 m from 1995 to 2018 were selected as the basic data for extracting gully farmland. The land use types were interpreted by referring to the classification method of CAS's resource and environment information database in 2018 (http://www.resdc.cn/). Besides, the crop vegetation grew luxuriantly from April to October, and the identification accuracy of the image was higher than in other months. After testing, the accuracy of the land-use types was over 85%.

The 30 m resolution digital elevation data in 2018 (http://www.gscloud.cn/), Google Earth images and high-resolution land classification data were used as training samples and verification basic data. Additionally, the selected vector road network data come from Open Street Map website in 2018 (http://www.openstreetmap.org), and the socio-economic data come from the Yan'an Statistical Yearbook and field investigation, and the socio-economic data was spatialized based on ArcGIS 10.4.

3.3. Research Methods

3.3.1. CART Decision Tree Algorithm

The classification methods such as artificial neural networks (ANN), decision trees (DT), and support vector machines (SVM) are widely used in the classification of remote sensing images [30]. Among them, the decision tree classification method can effectively excavate the spectral characteristics of the image and can solve the problem of the overlap of the remote sensing image spectrum to a greater extent. The commonly used algorithms in the DT decision tree classification method are: C4.5, CART, ID3, etc. [31], and the CART algorithm uses the Gini coefficient of the balanced distribution of income in economics as the criterion for determining the optimal test variable. The formula is as follows:

$$\text{Gini (D)} = 1 - \sum_{i=1}^{n} {p_i}^2 \tag{1}$$

In the formula, D is the data set, n is the classification number, and p_i is the distribution probability.

Compared with other decision trees, the model of the CART decision tree is simple. The classification threshold is determined by training samples, and the decision tree is automatically established (Figure 3). Therefore, it is less affected by other factors, and the recognition accuracy is higher.

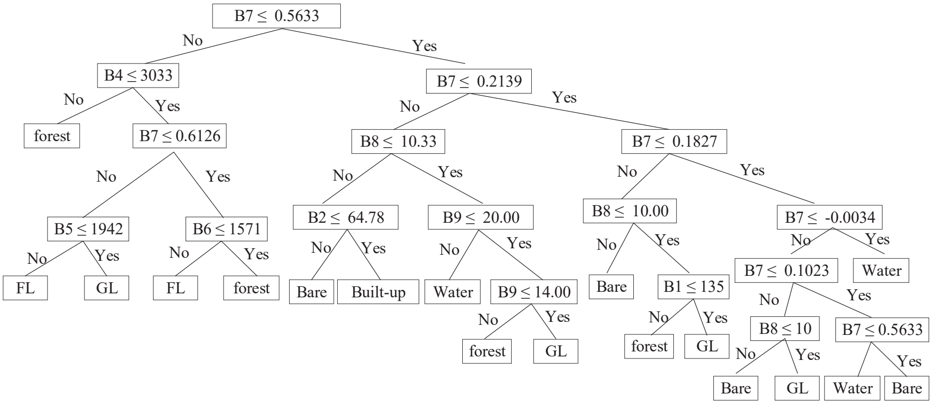


Figure 3. Decision tree classification process. Note: B1–B8 respectively correspond to the 8 bands of the composite image.

3.3.2. Gully Farmland Classification

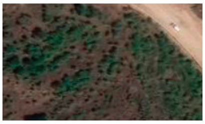
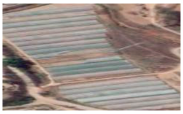
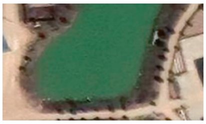
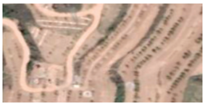
Gully farmland can also be called "dam land" (Figure 4), which is a new form of agricultural production land of different types (Table 1) [32]. The identification rule of gully farmland is as follows: Step 1: The range of farmland in 2018 is extracted as the background data of gully farmland, and then the pixel (T) of other years is obtained based on the change of the range of the farmland. Besides, the suspected gully farmland range with the specific research period (1995–2018) is obtained based on the above judgment. Step 2: Based on the range of gully farmland in year (t-1), and the overlapping part of the suspected gully farmland in year (t-2) and the suspected gully farmland in year (t-1) is extracted again. This part is judged to belong to the range of gully farmland in year (t-2). Step 3: According to this method, the range of gully farmland in a continuous sequence of prescribed years is obtained.

Gully farmland landscape

Typical gully remote sensing image Local remote sensing image The overall landscape

Figure 4. Gully farmland landscape in loess hilly and gully region.

Table 1. Reference standards of GUFL types.

GUFL Types	Identification Standard	Sources	Interpretation Reference
Type I FFZ	The EFZs are neatly concentrated with darker colors and patterns, the rationale is dotted and the individual is clear.	QuickBrid (0.48 m)	
Type II GV	There are certain roads and buildings around, the GVs regular rectangles with the same width, high reflectivity can be distinguished.		
Type III PF	The PF individuals are relatively regular polygons and the colors are mainly dark green.		
Type IV GP	The GPs are green in the growing season, and the rest are yellowish-brown in strips.		
Type V ML	The EFs are distributed in strips, the individuals show ladder-like shape, and the single row is a large width.		
Type VI T	There are signs of consolidation in cultivated land, T individuals are distributed in strips, with fine texture and narrow width.		

Note: Fruit forest zones (FFZ); Greenhouse vegetables (GV); Pond farming (PF); Grain planting (GP); mulberry leaves (ML); tobacco (T).

3.4. Modified Binary Logistic Regression Model

Binary logic regression is a valuable tool to analyze the relationships between dependent variables and independent variables, which is widely used in the analysis of land use driving forces [33–35]. Furthermore, spatial autocorrelation between land use transfer probability and land use types with adjacent grids couples to modify the deficiency of simple logical regression analysis. Comprehensively considering the spatial representation and driving factors difference and combining with the actual situation in the LHGR, 21 indicators of four driving factors are selected. According to the relevant research experience and the actual situation of the development in the LHGR, this paper attempts to comprehensively select the factors that affect the development of gully agriculture from different dimensions aspects: nature, social economy, and humanities. Among them, including socio-economic (SE), hydrothermal condition (HC), natural background (NB), and location condition (LC) (Table 2). Overall, the analytical principle of the driving mechanism is to explore the main driving factors of gully farmland change under the existing social-ecological background, and the time limit of each index is 2018.

Table 2. The driving index of GAPT.

Indicator Types	**Indicator Names**	**Unit**
Socio-economic (SE)	Population density (POP T_1)	People/km
	Gross domestic product (GDP T_2)	Yuan
	Main roads density (MRD T_3)	1/km
	Primary industry employment rate (PIER T_4)	%
	Urbanization rate (UR T_5)	%
	Per capita fiscal revenue (PCFR T_6)	Yuan/People
	Primary production change rate (PPCR T_7)	%
Hydrothermal condition (HC)	Mean annual temperature (MAT T_8)	°C
	Average annual precipitation (AAP T_9)	mm
	Accumulated annual temperature (AAT T_{10})	°C
Natural background (NB)	Elevation (ELE T_{11})	m
	Slope (SLOP T_{12})	°
	Terrain relief (TR T_{13})	1
Location condition (LC)	Distance to county cities (DTC T_{14})	km
	Distance to township (DTT T_{15})	
	Distance to national road (DTNR T_{16})	km
	Distance to main highways (DTMH T_{17})	km
	Distance to provincial road (DTPR T_{18})	km
	Distance to county road (DTCR T_{19})	km
	Distance to main railways (DTMR T_{20})	km
	Distance to river (DTR T_{21})	km

3.5. Geographically and Temporally Weighted Regression Model

Unlike the widely used Geographically and temporally weighted regression (GWR) model, which only takes spatial variation into account when estimating an empirical relationship [36], GTWR captures spatio-temporal heterogeneity based on a weighting matrix referencing both spatial and temporal dimensions. In this study, a GTWR model was fitted using the following structure:

$$Y_{\mathrm{i}} = \beta_0\left(X_i^t, Y_i^t, T_i\right) + \sum_m \beta_m\left(X_i^t, Y_i^t, T_i\right) X_{im} + \varepsilon_i \tag{2}$$

where: Y_i is the value of monitoring site i; (X_i, Y_i) represents the central coordinates of monitoring site i; β_0 denotes the intercepts at a specific location (X_i, Y_i) and year T; and β_1–β_m are the location-time specific slopes for 1-m, respectively. ε_i is the error term for sample i.

4. Results

4.1. Spatial Distribution Characteristics of GAPT

The center of gravity coordinate migration of gully farmland in 1995–2018 is shown in Figure 5. From 1995 to 2000, the migration direction of the gully farmland in the study area tended to the northwest of the region as a whole. After 2000, the center of gravity of the gully farmland showed a divergent distribution trend of migration to the surroundings. In the past 20 years, the gravity center of gully farmland moved northward, among which, Wuqi County, Baota County, and Ansai County have high consistency in migration direction. The migration direction of gully farmland in Baota County is always northward, while Wuqi County and Ansai County move southeast. The spatial conversion intensity of the gully farmland in Ganquan County and other counties is relatively intense, and the migration direction remains unchanged before 2005, and gradually expands to the opposite direction after 2005. In other counties, the direction of change in the stages of gully farmland is divergent, and the overall characteristics are relatively insignificant (Figure 5).

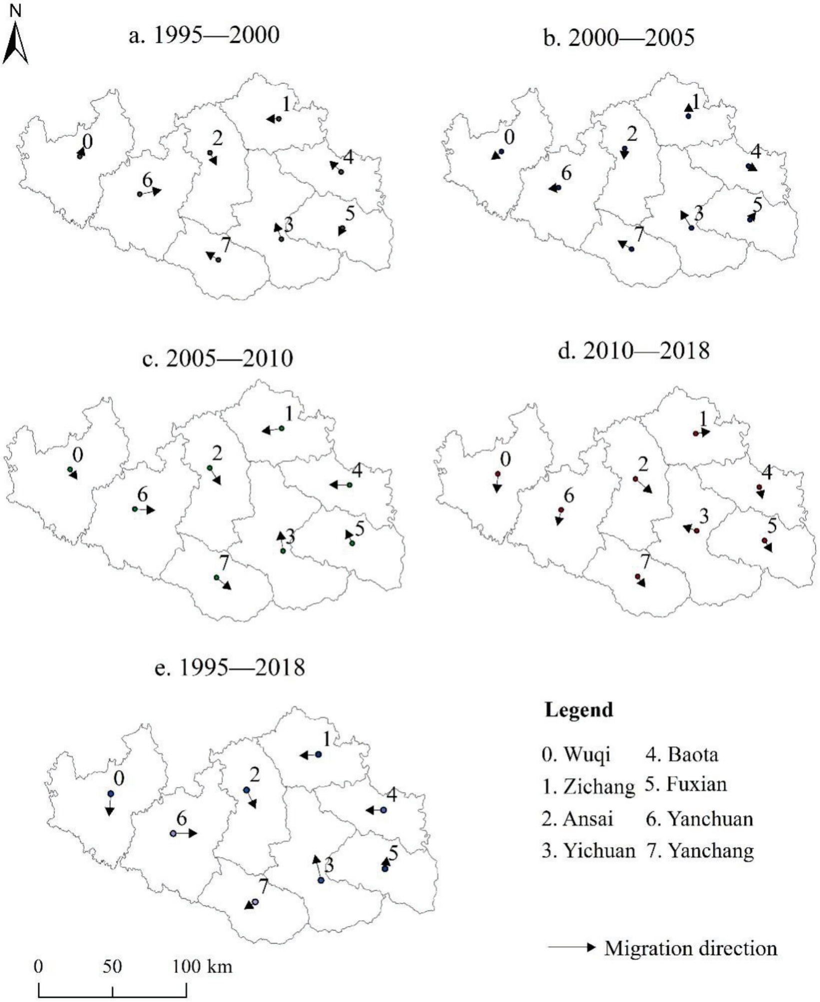


Figure 5. The center of gravity coordinate migration of gully farmland in districts of Yan'an City.

The spatial distribution characteristics of different types of gully farmland are shown in Figure 6. The growth of the gully farmland is mainly distributed in the relatively gentle low-altitude flat dam area, including elevation (700–1300 m), terrain relief (40–180 m), and slope (0–20°). The growth of oilseeds (IV), mulberry leaves (V), and tobacco leaves (VI) were negatively correlated with the distance between rivers, county roads, and provincial roads, and the increase was mainly within 5 km from rivers and 18 km from provincial roads. In general, the influence of the regional centers of townships on the cultivation of gully farmland was more significant than that of the regional centers of districts and counties. There was a strong market location orientation between economic fruit forest (I) and greenhouse vegetables (II), which was more manifested as agglomeration within the township, showing a "bottom-up" market location-oriented law.

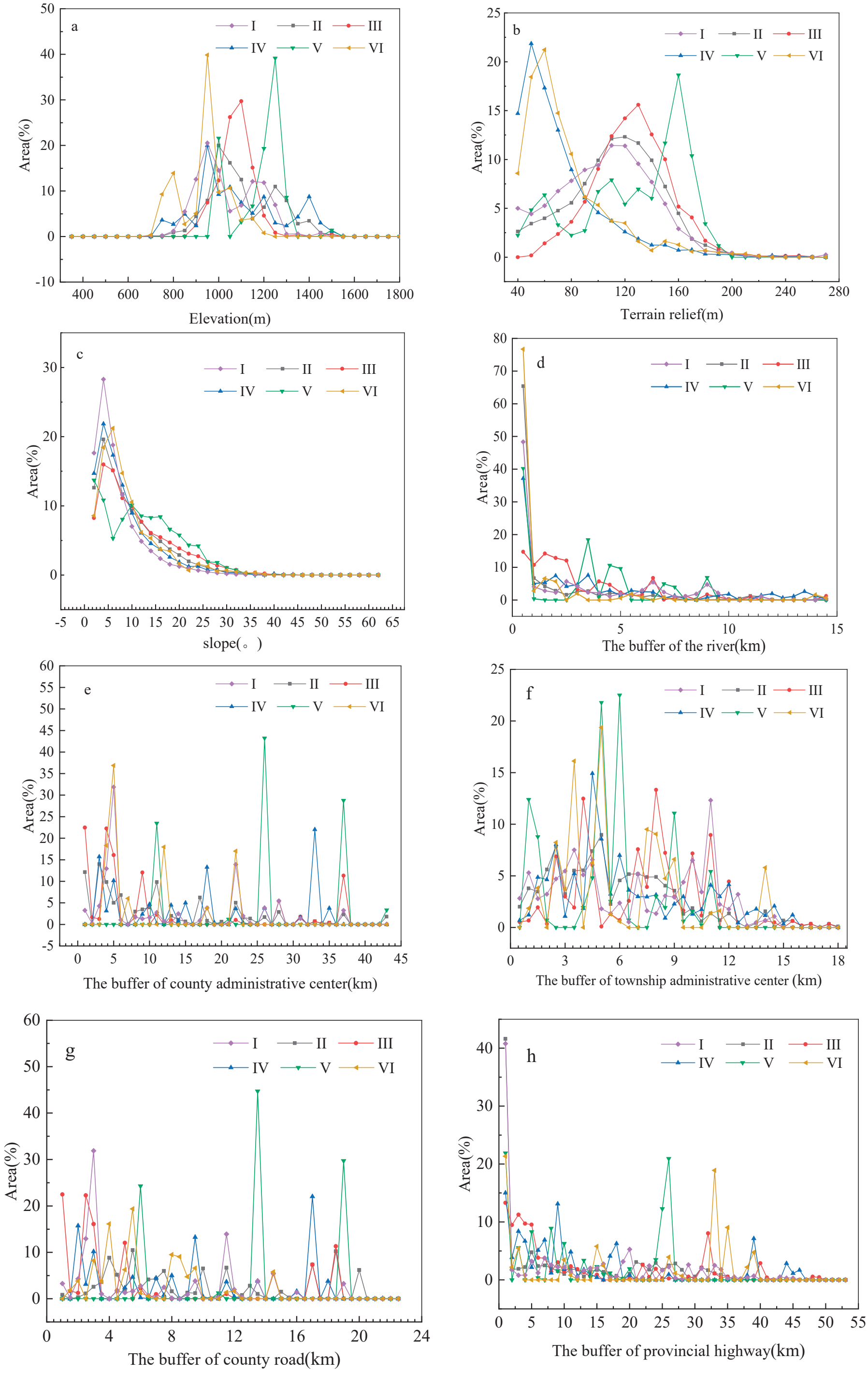


Figure 6. Spatial variation of gully farmland in Yan'an City. Note: Fruit forest zones (I); Greenhouse vegetables (II); Pond farming (III); Grain planting (IV); mulberry leaves (V); tobacco (VI).

4.2. Analysis of the Main Influencing Factors on GAPT

Drawing on the enlightenment of existing research and the relevant methods [37–39], the gully farmland expansion region (1), contraction region (−1), and no obvious change region with a total of 4861 in the four periods of the study area were analyzed in ArcGIS 10.4. The numbers of the three types of regions are roughly equal to ensure the stability of the coefficients of the explanatory variables in the model. During the study period, the sample data were processed by GTWR, and all passed the significance test ($p < 0.05$) (Table 3). Moreover, a linear regression OLS model was used to verify the applicability of GTWR. It could be seen that the R^2 value of the GTWR model was higher than that of the OLS model, and the Akachi information criterion (AIC) index was lower than that of the OLS model (Table 4). AIC was an important indicator of good model fitting, and the smaller the value, the higher the accuracy [35]. The AIC value (11.38/11.54 = 98.61%) and R^2 value (0.22/0.14 = 157.14%) of the GTWR model were significantly higher than OLS. Since the GTWR model added a time dimension, it was higher than that of the traditional model in dealing with spatio-temporal non-stationary data.

Table 3. GTWR parameter estimate summaries.

Indicators	Minimum Value	1/4 Quantile Value	Median Value	3/4 Quantile Value	Maximum Value
Intercept C	−0.3919	−0.0565	0.0257	0.1320	0.6239
T6	−1.3399	0.0229	0.1001	0.2295	0.5488
T11	−2.2942	−0.4253	−0.1709	0.0469	0.8249
T15	−3.8430	−0.1501	0.1863	0.4926	1.7699
T14	−6.6169	−0.6932	−0.2322	0.4463	1.5808
T15	−5.1133	−0.4521	−0.0995	0.2985	1.5287
T19	−8.7846	−0.3760	−0.1529	0.0356	0.8274
T20	−1.0248	−0.2259	0.0695	0.3779	3.8356
T18	−1.7000	−0.4558	0.3068	0.9633	1.0030
T9	−2.6693	−2.3905	−1.0851	−0.2395	1.2369
T16	−6.1140	−2.3399	−0.3992	0.5243	0.7178
T17	−4.1616	−0.3849	0.2826	0.9404	2.8666
T10	−1.4554	2.7472	4.6608	8.6157	5.8123

Table 4. Comparison of model diagnostic results.

Models	Correlation	AIC	R^2	F (r^2)	p (r^2)
GTWR	0.525	11.3803	0.226	5.546	<0.001
OLS	0.377	11.5464	0.140	56.311	<0.001

Comprehensively considering the spatial representation and driving factors difference and combining with the actual situation in gully areas [40,41], 21 indicators of four driving factors were selected, including nature, economy, population, transportation, location, and policy. To eliminate the influence of multi-factor collinearity, this paper firstly analyzed the correlation of the driving factor set, and the result showed that the correlation of selected factors was significant. Then, principal component analysis was performed on the driving factor set, and the load matrix and coefficient matrix of each component were obtained. Moreover, regression analysis was used to obtain the comprehensive score value of each sample. The dominant factors of driving variables are shown in Table 5.

Table 5. Dominant factors of principal component driving variables.

Classification	Principal Component	Composition	Dominant Direction	Driving Type
Continuity	F_1	T_2, T_3, T_4	Social and economic development	Multivariate
Periodicity	F_2	T_6, T_2	Investment and development dominance	Dual factor
	F_3	T_{20}, T_{17}, T_1	Location dominance	Multivariate
	F_4	T_{14}, T_{16}	Traffic dominance	Dual factor
	F_5	T_2, T_4, T_{19}	Economic dominance	Multivariate
	F_6	T_{11}, T_{13}	Terrain slope dominance	Dual factor
	F_7	T_{14}, T_{17}	Traffic dominance	Dual factor
	F_8	T_{13}	Topographic relief dominance	Single factor
	F_9	T_1	Population density dominance	Single factor
	F_{10}	T_{21}	Water factor dominance	Single factor

4.3. Spatio-Temporal Differentiation of Influencing Factors of GAPT

According to Figure 7, it can be seen that the high value of F_1 in the study area during the 20 years has shifted from west to east first, and then expanded from south to north. The driving difference is reduced and gradually tends to be balanced, eventually forming a clustering and distribution situation around the Baota district. The positive high value from 1995 to 2000 was concentrated in Yanchang-Ansai-Wuqi, while Zichang, Yanchuan, and the central area of Baota were relatively low value. From 2000 to 2005, the negative high value shifted to Zhidan, and the positive and negative effect intensity was significantly different between northwest and southeast. The positive high values from 2005 to 2010 were mainly distributed in Ganquan and Ansai, and the difference in the driving factor value range narrowed and tended to be balanced. The pattern evolution from 2010 to 2018 gradually formed a circle with the Baota as the core, the positive high value of Ganquan, and the negative low value of Yichuan. From the perspective of the evolution of economic factors, the economic development of the Baota has a higher spillover effect on the expansion of gully farmland. The location dominant factors (F_3) were quite different, and the positive effect of the township was stronger than that of county administrative centers in which population and economy were the two most significant factors. The population was also the direct driving force for the conversion of gully farmland, and economic development was the core driving force. The location characteristics directly affected the population flow and capital flow and promoted the transformation of gully farmland. In addition, some related policies (Grain for Green project) and engineering measures (Gully Land Consolidation) had accelerated the conversion of gully farmland, thereby promoting the spatial transformation of gully farmland.

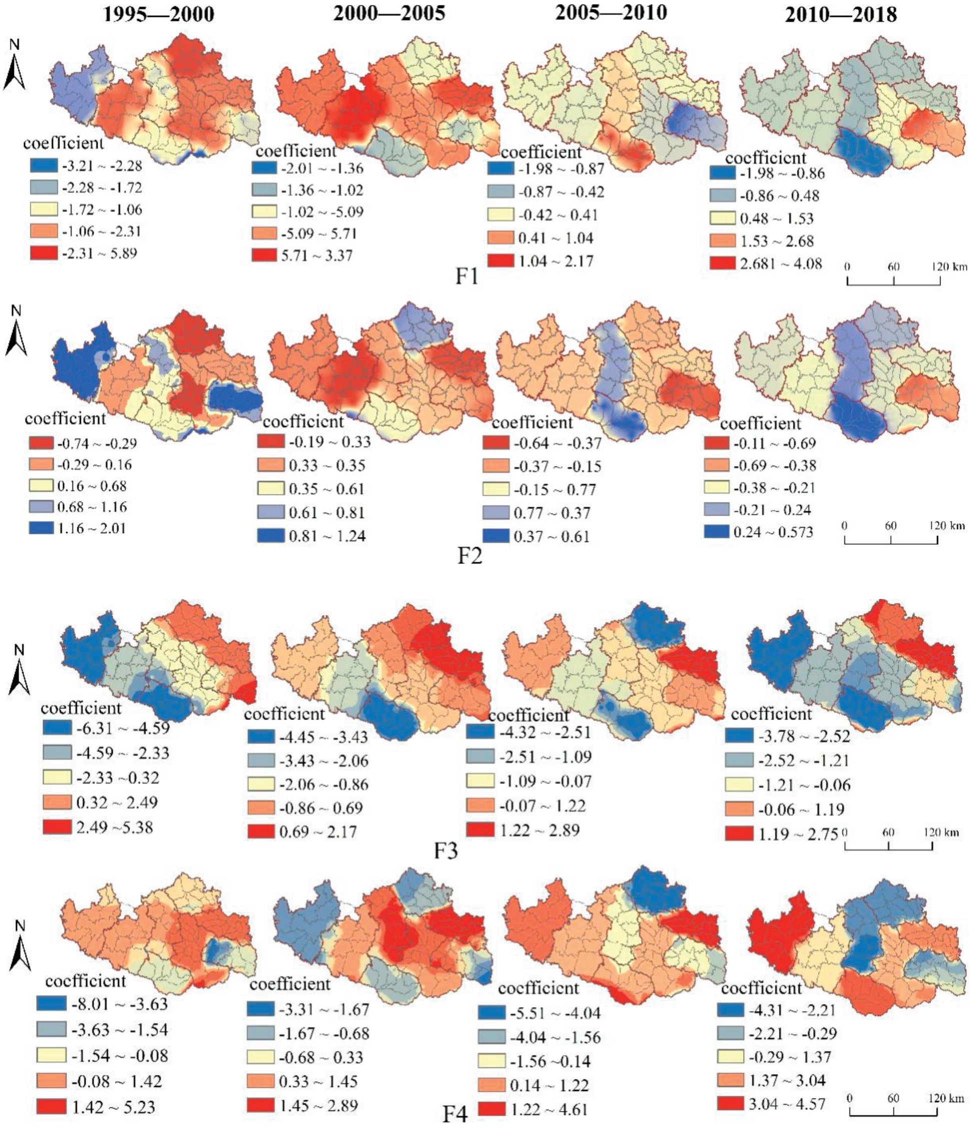


Figure 7. *Cont.*

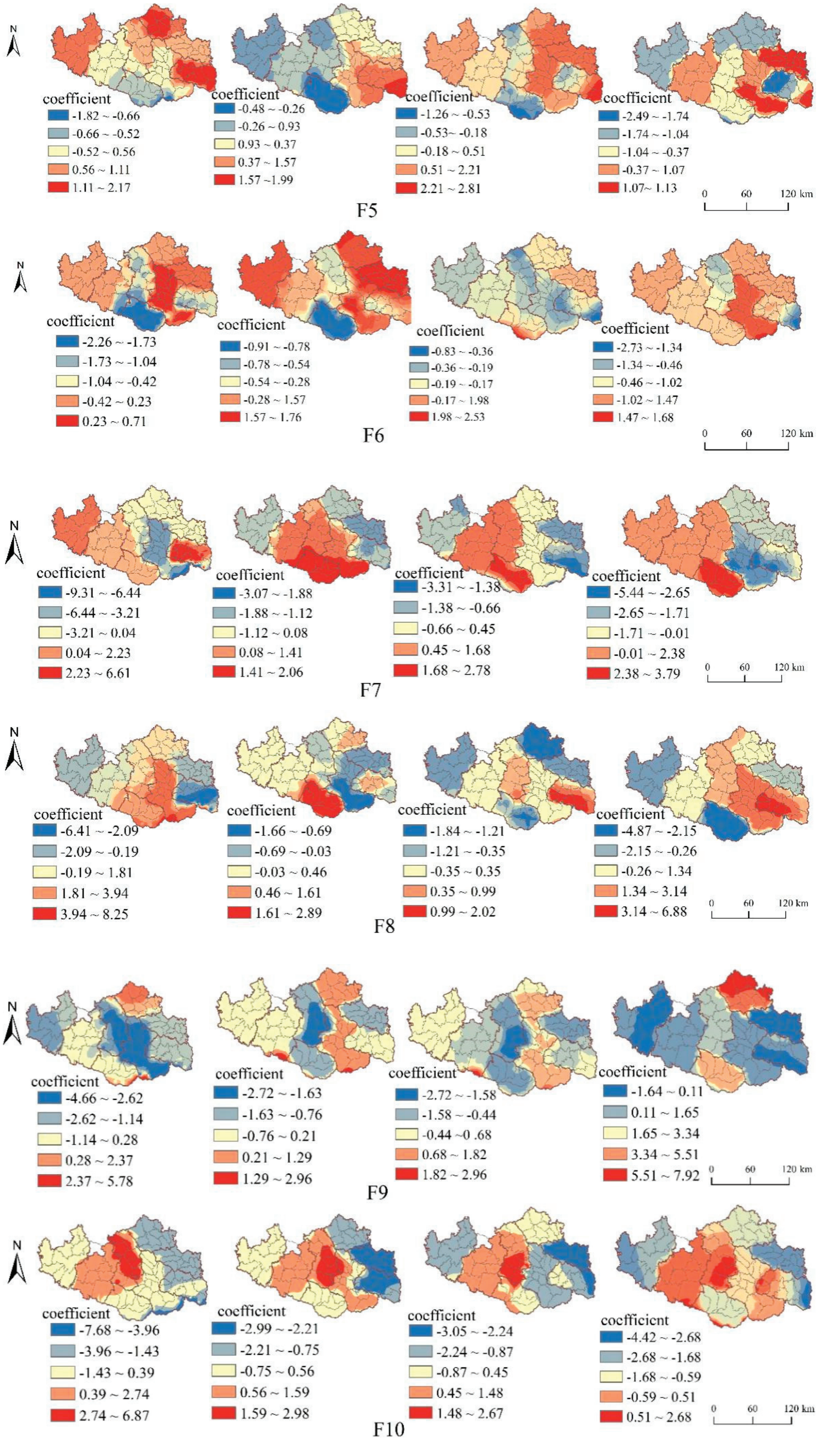


Figure 7. Spatio-temporal variation pattern of dominant factor coefficient of gully farmland expansion.

According to Figure 7, the changes of F_3 and F_5 were relatively similar. Normally, natural factors had no significant effect on gully farmland conversion from 1995 to 2018, and the overall north-south changes in space were obvious, mainly due to the difference in topography and geomorphology in the north and south of the study area. According to F_4 (traffic location dominant), the influence intensity distribution of distance to national road and distance to main highways presents two significant characteristics: First, it formed a distribution pattern of high in the south and low in the north at the regional level, and the high-value region gradually shifted from the southwest to the east of Yan'an City over time. Second, some high-value regions were scattered in some county boundaries, such as the southwest of Yanchang near the border of Baota District, the northwest border of Yanchuan, the southwest part of Baota, and the border area of Ansai and Zhidan.

The distance to the provincial road (F_4) had an overall evolutionary trend toward being high in the central area and low in the surrounding area. From 2000 to 2005, the vertical expansion to Baota district was a "W"-shaped high-value area layout. From 2005 to 2018, it further expanded to the north to Ansai County, and the positive effect on the expansion of gully farmland in the Baota area was further enhanced. Water dominated factor (F_{10}) was mainly distributed in Wuqi County and Yanchang County along Luo River and Yanhe River from 1995 to 2000. The high-value area gradually moved down from 2000 to 2005. Since 2005, the scope of high-value areas was further expanded, showing a distributed pattern of dots in the area.

From the perspective of the driving force change range of gully farmland conversion, the largest growth of driving factor was the economic factor of per land GDP. From the perspective of the regional change pattern of the driving force, various geomorphic factors have different effects on the expansion of gully farmland, which was closely related to the geomorphological differentiation characteristics of the gully area. The impact of economic development on gully farmland presents a "core edge" funnel-shaped distribution, and its changes tended to "flow" to the core. The influence of the neighboring factors on the roads in Yan'an had its own characteristics, which was closely related to the spatial distribution of the road network. Areas with significant changes were concentrated in the central area of Yan'an City and focused on the Baota area, roughly forming a "T"-shaped distribution pattern.

4.4. Analysis of GAPT Response Mechanism

The factor coefficients of the four stages in the study area from 1995–2000, 2000–2005, 2005–2010, and 2010–2018 were statistically separated, and the average factor coefficients of each stage were obtained as shown in Figure 8.

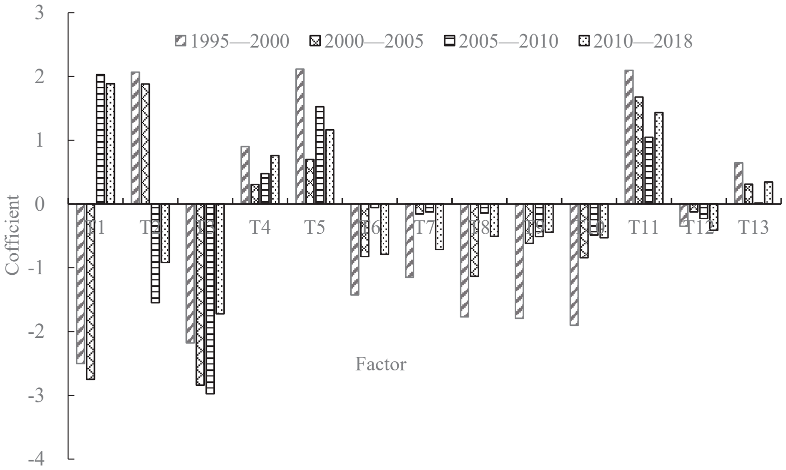


Figure 8. Time series distribution of factor average coefficient change in each period.

(1) Judgment of the whole area core factors: From 1995 to 2018, the conversion of gully farmland of the study area was mainly based on the population and GDP per land area of socio-economic factors. The slope of natural factors and the distance from the water area of neighboring factors were the core influencing factors. Among them, the population factor and slope factor had always been in a dominant position, and they were the main driving factors for the conversion of gully farmland. The intensity of population was higher than that of the slope during 1995–2000 and 2010–2018. The driving effect of the slope on gully farmland conversion during 2000–2005 and 2005–2010 was obvious.

(2) Temporal evolution of the whole area core factors: Slope was the most influential factor in the conversion of gully farmland. The intensity of its effect was a fluctuating and rising trend from the beginning of 1995 to 2010, and the intensity was the greatest in 2010. The relationship between population and the transformation of gully farmland was negatively correlated in the first 10 years. The overall effect of the population on the expansion and transformation of gully farmland showed a downward trend. Slope aspect and topographic relief factors were positively correlated with gully farmland shrinkage. From the whole study period, the intensity of aspect effect intensity first decreased and then increased, and remained flat. The influence of traffic neighborhood factors generally showed a slight decrease. The gully was negatively correlated with the transformation of farmland shrinkage. The distance from the center of the county was negatively correlated with the shrinkage of gully farmland. The intensity of the impact first decreased and then increased, showing an overall increasing trend. There was a positive correlation between the distance from the water area and the center of town and the change of gully farmland shrinkage in Yan’an City, and the intensity of these factors was gradually declining.

At the county level, it was the basis of regional differentiation governance to identify the driving force of gully farmland contraction. In order to identify the difference in the conversion drive of the gully farmland between the counties and determine the time series change of the drive strength, the incidence of factors driving the transformation of gully farmland contraction was compared among the counties as follows (Figure 9). Among these, the positively related variables were directly taken as logarithm exp (g), and negatively related variables were converted into positive cumulative values through the factor of 1/exp (g).

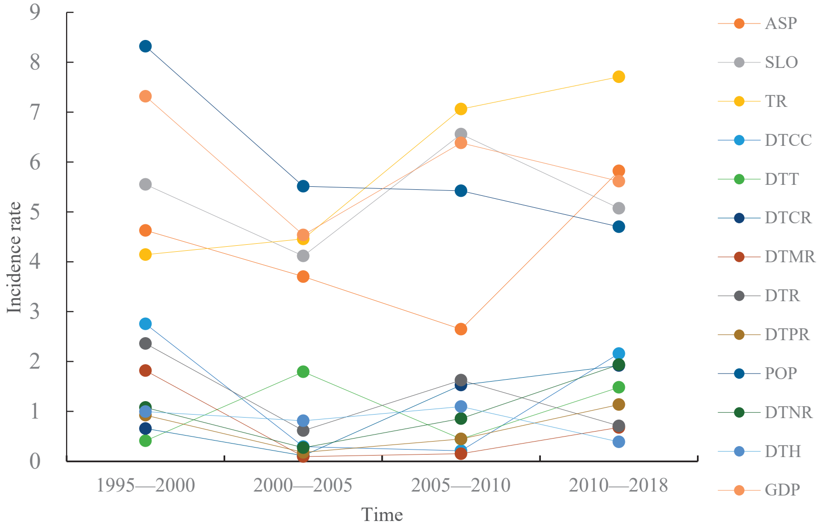


Figure 9. The positive incidence rate of GAPT.

The core driving factors for the conversion of gully agricultural land in the past 20 years were population, topographic relief, slope, aspect, and GDP per land. The first driving factor of Yanchang and Zhidan was population. The per land GDP in Baota was the primary driving factor before 2000, and then population became the primary driving factor after 2000. Moreover, Ganquan, Ansai, and other counties showed obvious phased characteristics. In regional spatial distribution, the counties with strong population and economic driving force were concentrated in the east and middle of Yan'an. Most of the counties with strong driving forces such as slope, aspect, and topographic relief were in the west. There were significant differences between the eastern and western regions at the county level. From the perspective of the time sequence of the slope of the dominant factor affecting the conversion of gully farmland. Except for Ganquan, the driving force for the conversion of gully farmland by the slope of the counties had not declined. It showed that the restriction of natural background conditions was still strong.

5. Summary and Implications

5.1. General Law of Rural Land Use Evolution in Gully Areas

Rural development gets a lot of attention around the world. However, compared with cities, rural areas are backward for reasons that include migrant mobility, poverty, labor quality, biased policy, and week rural land management [42]. Generally, the cultivated farmland within the rural man-land system in plain areas is evenly distributed [43], and the effect of intensive cultivation and utilization is significant, which is easier to integrate the land resources than that in hilly areas.

Hilly rural settlements and agricultural land distribute scattered, and the tillage radius is wider than that in the plain. The unique geographical characteristics shape the unique rural man land system to a certain extent. In addition, environmental elements are the essential factors influencing spatial distribution [44]. The natural environment, including temperature, precipitation, terrain, and rivers, is the basis for the formation and development of agriculture and the countryside [45]. The farming environment created by conscious social labor in the process of agricultural production has a significant impact on its development and distribution [46]. In the socioeconomic environment, dynamic changes in the spatial pattern of GAPT are determined by factors of urbanization rate, main highway density, per land GDP, the proportion of primary industry employment and land consolidation planning, etc.

Moreover, the influence of the commodity economic location environment on rural land use and development continues to increasing [47]. Gully agriculture tends to develop in the win-win situation of ecology and economy. GAPT is comprehensively affected by a variety of internal and external factors, which not only depend on the external resource and environmental status of the gully, but also have a comprehensive effect on the gully's rural internal economy, society, ecology, and culture. On the micro-valley level, GAPT is related to the benefits and efficiency of exchanging energy. On the macro-regional level, GAPT is a summary and generalization of the spatial differentiation of gully regional production-living-ecology.

This paper represents the general law of gully rural land use in LHGR, and the process of GAPT can reveal the LUT mode in China's loess plateau and modern gully man-land system development in LHGR (Figure 10). With rural population outflow, GAPT will promote the gully living space reconstruction and intensive use of production, and the man-land system development tends to be coordinated and efficient. Specifically, GAPT reflects the characteristic of gully agriculture crops, ecological maintenance, and rural living environment construction in LHGR. The combination accelerates rural transformation in LHGR, which has an indicative implication for the high-quality development of agriculture and rural in China's Yellow River Basin.

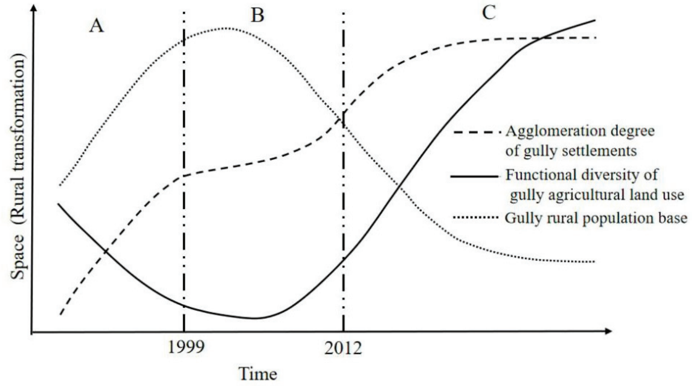


Figure 10. The transformation model of gully rural.

5.2. Policy and Practical Implications of Gully Agriculture Development

According to the characteristics of GAPT types, rational rural land use and agricultural planning can improve the gully agricultural production environment by enhancing the conversion rate of GAPT and improving regional infrastructure supporting engineering. Policymakers should establish adaptive measures for gully land consolidation and formulate structural readjustment measures for different gully agricultural planting types to promote intensive land use.

The phenomenon of GAPT in the LHGR reveals the general law of the evolution of the river basin and rural man-land system driven by ecological construction and gully land consolidation engineering, that is, ecological security and food security. In the new era, the gully agriculture of the Loess Plateau should be based on the economic-ecological "win-win" benefits, focusing on ecological civilization and green sustainable development, and using the two major projects—the Grain for Green project and Gully Land Consolidation—as important platforms for transformation and development, and coordinating watersheds up-and-down collaboration, gully and slope collaboration, multi-scale classification and coordination, giving full play to the technical support role of geographic engineering, and in-depth exploration of new ways to optimize gully agricultural production methods and innovate business management models. As the goal, the ecological economy is "win-win" as the direction, and modern geographic engineering is the technical means to finally achieve high-quality development of quality benefits and development efficiency [48]. GAPT in the LHGR has promoted the integration of policies such as the Grain for Green project and Gully Land Consolidation. On the premise of protecting and improving farmers' livelihoods, it is important to promote the integration of the three beings (production, living, ecological) in the gully region and bring to light the significance of promoting the integration of the three industries and high-quality development of the Loess Plateau.

5.3. Limitations and Prospects

There are still some shortcomings. For data and technical methods, this paper uses remote sensing image data from April to October to interpret the types of gully agriculture, and the crop and grassland are easy to distinguish. There may be some misclassification conditions. In addition, the spatial-temporal geographic weighted regression model realizes a comprehensive measurement in the spatial-temporal perspective and more precisely describes the temporal and spatial evolution characteristics of the driving factors and the dominant driving mechanism. However, how to improve the accuracy of image classification based on the spatial location information of ground objects and further optimize the "circle-belt-region" multi-level spatial structure system of human land system in rural areas of loess hilly and gully region [5,49], still need to be further explored.

It is undeniable that GAPT has significant positive economic benefits to gully rural areas, but whether it can bring ecological benefits is still unknown. In addition, policy as a non-quantitative factor is essential and crucial in GAPT. With the development of gully land consolidation engineering, the amount of gully farmland is also changing. At the same time, the willingness of farmers and the reform of property rights are also factors to be considered. Furthermore, by selecting typical types of areas, the process and mechanism of the changes of different types of regions are explored from the micro-scale, and then the scientific principles of the rural man land system based on gully farmland and the mechanism of rural "human-geosphere" are revealed should also be the focus of future work.

6. Conclusions

Under the background of "Grain for Green" (GFG) land management policies and the rural population transfer, the focus of gully farmland distribution gradually migrates down to low-altitude flat dam areas. Spatio-temporal distribution of different driving factor coefficients of GAPT has different effects. The intensity of the population and slope is always in the dominant position. The high-value area of GDP per land forms a funnel-shaped pattern of "core edge" in the northern and central-western regions, and its changes tend to be the core "flow". In the Loess Plateau, GAPT is driven by many factors, and the regional background differences and different actors will promote the development and contraction of gully farmland in different directions, but in principle, they are driven by the major national and regional development policies. In the development process, we should pay attention to the dual orientation of ecology and economy, maximize the sustainable use of gully farmland, explore the coordination and optimization of gully farmland and human settlements, and realize housing and industry synergy.

Current studies on gully agricultural production on the Loess Plateau based on gully land consolidation have good theoretical and practical significance. Taking a typical loess hilly and gully region of Yan'an City located in the center of the Loess Plateau as the case study area, this paper revealed the intensive land use under the background of population contraction in the Chinese Loess Plateau and its transformation trend by defining the gully agricultural production transformation (GAPT). To some extent, the multiple elements of the agricultural production system in gully areas from the perspective of farmer subject and regional production space and type change has been deconstructed towards the gully agricultural production development. However, more empirical studies in the gully region are still urgently needed to verify this key topic. In addition, we proposed a theoretical model for gully agricultural evolution in gully areas, this theoretical model needs further verification. It is worth mentioning that, we have evaluated the interaction mechanism that drives changes in the human–land relationship in the LHGR. We will further observe, monitor, and reevaluate the GAPT and report new progress in the near future.

Overall, the study area's typicality reflects the general law of rural land use evolution in gully areas. Policymakers can implement the adaptive measures for modern gully land consolidation measures and formulate structural readjustment measures for different gully agricultural planting types to promote intensive land use, ultimately achieving a balance of the regional modern rural man-land relationship.

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Land Abandonment in Mountain Areas of the EU: An Inevitable Side Effect of Farming Modernization and Neglected Threat to Sustainable Land Use

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Abstract: In a period of rising concern for sustainable land management systems to achieve food security at a global scale, land-use changes demand increased attention. This study assesses the past observations and future risk calculations for land abandonment across European regions, highlighting the particular risk for mountain areas. It draws from a study commissioned by the European Parliament to investigate the situation and probability for high and very high risk of land abandonment until 2030. Revealing that land abandonment is at three times higher risk in mountain areas than in non-mountain areas, the need for action to cope with this pressure is the core result. We reveal that the high disparity in agricultural competitiveness between regions (at fine geographical scale) is the main driving force leading to the spatially uneven performance of land management. Viewing this wide set of drivers and mitigation options, land abandonment is understood as the outcome of a multitude of factors of socio-ecological systems and a combination of farm-specific, internal regional and trans-regional factors. The present dominance of narratives of effectiveness leaves little scope for mountain regions under threat of abandonment and marginalization. In this situation, policy reform would address the issue but this might turn out to be influential only if the complex nature and trade-off of the comprehensive policy framework are prioritized.

Keywords: land-use change; land management; spatial effects; small-scale context; socio-economic drivers; policy assessment; CAP; policy trade-offs; mitigation policies

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1. Introduction

In a period of rising concern for sustainable land management systems to achieve food security at a global scale, land-use changes demand increased attention. However, these are not merely linked to quantitative aspects of food provision, but inherently refer to the beneficial effects linked to socio-ecological systems of primary production. The threat of neglecting such crucial issues of food and forestry production is at the core of current discussions about how to realign dominating features of sector activities and respective policies [1] with sustainable development goals. Over past decades, with the emergence of agricultural surplus and due to the high divergence of farming conditions, productivity and viability, more and more agricultural land have become fallow land and are regarded as "abundant" for market production. This process has led to land abandonment processes in almost all European countries [2]. Due to the wide scope of drivers, it occurred gradually at the plot level and was felt particularly at local scales, thus hampering general recognition and awareness of the phenomenon.

Following deep concern over the concentration of agricultural production [3,4], the impacts of modern agribusiness on the cultural basis of farming and its close relationship with place-specific land-use systems [5], land abandonment was an early issue of farm modernization prospects. As early as in the 1970s, agricultural policies in the European Economic Community (EEC), but also in several European countries (Switzerland, Austria, Norway), recognized the limited farmland viability in certain regions and created policy instruments for "less-favored areas" to cope with these challenges [6]. In the initial concept of that policy, it was understood as a farming system under threat, being particularly "marginalized" and prone to lose, with the ongoing land abandonment, its viability and functions for the society [7]. The ongoing technological developments and market changes further increased apprehension about the continuation of land management, and through it, the preservation of positive environmental and socio-economic benefits of agricultural activities [8] in these "disadvantaged" areas.

Pressure for giving up land further increased due to continuous productivity increases and the intensification of agriculture. However, propensity for land abandonment is not equally distributed across the regions, land types and management systems of the EU [9]. While these processes of land use are not exclusive to European regions, the legacy of place-specific land-use patterns marked by significant diversity in land cover and land management is particularly strong here. Moreover, it is historically linked to rural livelihood features that translate to both high attachment to the specific regions and attractive assets seen in those "rural amenities" by non-rural populations and visitors from other areas. Rural amenities are thus seen as strongly enhancing tourism development (of different forms) in close relationship to specific land-management systems [10].

Studies on transitions of land management regimes over long time periods recognize the ongoing but uneven intensification process of agricultural land use and urban growth. Jepsen et al. [11] observe that science has traditionally addressed mainly the spatial determinants of land-use change, neglecting, to some extent, the array of other aspects influencing land-use decisions. Moreover, as historical data are often unavailable, the periods of land-use change observation tend to be short and might overlook the influences of contrasting and interrelated drivers of land-use change. Despite large-scale processes of industrialization across European regions, high path dependency preserved a "marked spatial heterogeneity in land-management regimes" until around 1950 [11] (p. 63). Since then, periods of collectivization, intensification, de-intensification and commercialization and rising environmental awareness have led to divergent and spatially very different developments. A recent study of land-use change across Europe depicts the substantial loss of utilized agricultural area (UAA) over recent periods [12]. This overall trend is linked to three main components:

- Gaps in land rent between settlement areas and agricultural areas are so high that economic valorization stimulates the conversion of agricultural land into artificial land use. Urbanization and urban sprawl are not restricted to agglomeration areas but reduce UAA, also within rural regions.
- On the other hand, UAA is converted into forests. Such land-change processes are observed primarily for areas where agriculture is economically challenged, and afforestation may be part of an agricultural extensification strategy.
- Beyond those two, clear-cut trends of general land-use change, productivity increases and changes in regional competitiveness of agricultural production might lead to gradual adaptation in the production structure, and spatial concentration of production. As a result, agricultural land use of some farmland might be ceased, depending on a series of local and individual factors.

While the general land-use changes toward urbanization or afforestation are obvious trends, the critical phenomenon of land abandonment may be mostly linked to the third aspect. It is captured by the formulation in the recent Joint Research Centre's (JRC) study, providing the following most commonly used definition of land abandonment: According to the authors it "refers to land that was previously used for crop or pasture/livestock grazing production, but does not have farming functions anymore (i.e., a total cessation of agricultural activities) and has not been converted into forest or artificial areas either" [12] (p. 1).

Analyzing the causes and main influences on land abandonment processes requires facing contrasting land-change tendencies across spatial units. What is more, trends might be divergent for small, medium and large scales, pointing to a diverse relevance of drivers for different areas and levels. Thus, understanding land abandonment as "a complex multi-dimensional process with interlinked economic, environmental and social aspects" [13] (p. 2) implies its heavy impact on regional sustainability pathways [14]. While its occurrence and relevance are particularly linked to specific and changing space-time contexts [15], many studies acknowledge a wide range of influencing drivers and a high degree of interrelated factors impacting land managers' decisions [13,16–18]. With the rising concern for food security at a global scale [19] and the rising focus on food sovereignty [20,21], the loss of agricultural land has become a crucial issue in many regions. The increased attention is palpable through a number of case-specific and comparative studies at the European scale [22], highlighting the great diversity of drivers and trajectories in various spatial contexts (for example, explored in another Special Issue of this journal, *Land* [23]). They reveal that a complex interplay of a wide set of "sociodemographic, economic, technological, policy and institutional factors but also cultural factors may drive (land) abandonment" [23] (p. 4).

Even if these studies regularly underpin that landscape changes are highly dependent on specific political, institutional, economic, cultural, technological, natural and spatial factors as drivers [24], there is a conspicuous spatial pattern for land-abandonment processes. Comparative monitoring of the extent of past changes and model calculations of impending land abandonment risk [12] point to mountain areas as specific, remote locations that are particularly affected. They underline that land abandonment has to be seen as "a complex multi-dimensional process with interlinked economic, environmental and social aspects" [13] (p. 2) that plays out in areas of natural constraints much more than in other small areas limited in their production capacity by local biophysical or other development conditions.

It is a main research hypothesis that a spatially differentiated view to focus on land use and landscape development is required, and analyses on the implications for mountain areas are a priority concern where land management challenges cumulate.

With a focus on the complex set of socio-economic pressures on mountain economic activities and living conditions in those regions, the particularly high-risk level is no surprise. Klein et al. [25] provide survey data from 57 mountain 'socio-ecological systems' from all parts of the world and reveal similar and diverse problem patterns and opportunities across these mountain locations. In terms of land change, there is a high degree of stressors and challenges for ecosystem services provision observed in many respects [26]. Highlighting the particular, large array of pressures but also a simultaneous, large scale of mountain-specific opportunities, these tensions are framed as 'paradoxes' that create substantial challenges for sustainable development options. As a specific concern, land abandonment may be more pronounced in areas with limited production capacity and productivity, e.g., in areas facing natural constraints (ANC). In particular, agriculturally less-favored areas, such as mountain areas, islands and other remote parts of Europe, are reported to face significant challenges in retaining vital farming structures and have long been confronted with a steady decrease in agricultural land use [27]. Location in socio-economically disadvantaged areas add to these "handicaps", impeding swift market integration, access to value chains or networks. Instead, the focus is on niche development and innovative, quality schemes of mountain products [28,29] and the elaboration of specific mountain value chains [30] to bypass unfavorable challenges of mass production and remoteness. However, land abandonment is not only a sector issue, but has wider implications for societal development, ecological performance, and the rural fabric [31]. As farm holdings with reduced viability prospects are often regarded as particularly prone to abandonment processes, particularly wide-spread, small-scale structures (e.g., in Southern or Eastern Europe) could aggravate negative regional performance of the whole economy and contribute to demographic decline, often referred to as 'shrinking rural regions' due to the long-time persistence of downward trends [32].

In many remote and mountain contexts, the progressive reduction in farm numbers and agricultural land use has implied a loss of important landscape features and ecological performance [7]. This structural change has been accompanied by agricultural land abandonment in substantial parts of the EU's rural regions. Particularly, the focus on intensive land management systems has propagated these adverse effects and is adding to the pressures experienced in low-productivity areas such as the mountains. Any strategy to cope with abandonment aspects need to address the balance of intensive and extensive areas, and the capacity to achieve a shift toward sustainable production management systems, including the spatially uneven potentials and capacity to shift toward sustainable pathways.

Scale and location are thus crucial considerations when assessing the drivers, as well as the effects (both negative and positive) of land abandonment. In this paper, we focus on the large-scale observations of land abandonment for mountainous areas, as these are primarily affected by the ongoing tensions and for decades have been threatened by these processes. We begin by synthesizing quantitative model results on risk assessment across the EU and revealing the particularly high threat for mountain regions. The strong pressure on land-use change is linked to a wide set of drivers, implying the effects of natural constraints for land uses and harmful effects to other sectors. In the discussion, emphasis is put on highlighting the dichotomous trends in land management, favoring a continuous orientation toward competitiveness without responding adequately to rising social and ecological challenges. This will be taken up in the conclusion to underpin the necessity to review existing policy frameworks and the implications of ongoing land-use trends of mountain regions, expressed, in particular, through exacerbated levels of land abandonment, on ecological performance, landscape development and the specific amenities of those areas.

2. Materials and Methods

The paper builds on a study that was commissioned by the European Parliament to provide a deeper and up-to-date understanding of land abandonment in the EU based on available data and information, including its development, drivers, mitigating measures across EU policies, not limited to the EU's Common Agricultural Policy (CAP) and respective scenarios [22]. The resulting report was provided to assist the members of the Committee on Agriculture and Rural Development (AGRI Committee) of the European Parliament in discussing the legislative proposals regarding CAP post 2020, including the Commission Communication and Action plan on "A long-term vision for Rural Areas", expected in 2021. Its scientific assignment was to complement existing evidence with specific research on land abandonment to differentiate trends of diverse land management systems and types of regions, and to draw conclusions relevant to policymaking regarding the post-2020 CAP policy [33]. This paper retrieves spatial information relevant for mountain area trends and highlights the particular affectedness of this type of region for land-abandonment risk.

With a view on assessing the pace and occurrence of land abandonment across mountain regions in Europe, the paper benefits from an intensive literature review on studies exploring both general trends and the differentiation of land-use change at a fine geographical scale within mountain areas. It is particularly necessary to include the fine-grained internal divergence of mountain contexts where abandonment and intensification of various uses might take place in closely adjacent areas. Moreover, trends are quite different from mountain range to mountain range, and thus any large-scale appraisal should point to these internal divergent and context-specific developments [34]. The analysis is based on quantitative data used by the Joint Research Centre (JRC) of the European Commission [12] as well as other data sources, such as Corine Land Cover data for land use change. These data are the basis for further quantitative and qualitative analyses. In particular, GIS analyses and quantitative analyses, such as Naïve Bayes classifier [35], were applied to provide different geographical resolutions of land abandonment and define groups of regions with specific regional characteristics. This also resulted in probability checks for increased risk level of mountainous areas due to these data sources. Qualitative data collection and analysis via desk research, four case studies in diverse European regional contexts, and expert interviews complemented the statistical database, particularly to take account of the multiple set of drivers impacting land use and change in management decisions. This also provided input to scenario building on future development perspectives with regard to land abandonment outcomes. The results from specific case study exploration and scenario building are presented here only in relation to mountain development aspects, as contextual aspects are highly uneven between specific geographical places.

Quantitative and qualitative assessments of land abandonment trends and influencing aspects were also analyzed against a review of CAP instruments and their implications, both favoring and disfavoring aspects of abandonment and future scope to address challenges of sustainable land-use pathways. This appraisal mainly reflects the large-scale European perspective and would need place-sensitive investigations for differentiating implications on individual regions. Methodological issues have strong implications for the resulting effects in CAP reform discourse and policy framework outcomes. Many analysts underpin the need for more place-specific commitment in policy reform, a stronger need for shifts in policy objectives toward integrating climate-change needs and ecological challenges [36] and addressing more actively agroecological approaches in the future policy [37].

3. Elevated Risk of Land Abandonment in Mountain Regions

The description of observed trends of land abandonment supports the assumptions for the stronger relevance of the issue within mountain areas. In the first part of this section, the respective quantitative assessment of risk calculation (at different levels) is presented in a comparative manner between mountain and non-mountain areas of the EU-28, and for different mountain ranges within the EU. This analysis is then supplemented by a discussion of the driving forces for this spatial feature of land-use change and an assessment of policy framework addressing this challenge.

3.1. Risk Assessment in Mountain Regions of the EU

The analysis focuses on the survey presentation of the status and trends of quantitative development of land abandonment for all countries of the EU and differentiation by regions and geographical types. Building on the long-term concern of land-use changes across European regions [38], the cumulative effects of concentration and abandonment trends are analyzed. With regard to mountain areas, a comparative view against the situation in non-mountain areas reveals significant differences in threats experienced in mountain contexts. Analyses at the NUTS-3 regional level (nomenclature of territorial units for statistics) show that the higher the share of mountainous areas, the higher the risk of land abandonment (and vice versa—the higher the share of non-mountainous areas, the smaller the risk of land abandonment as shown in Figure 1).

The relationship is presented against five classes of regions, ranging from very low characteristics of mountain areas (less than 20% of total area to be classified as mountainous) to very high area shares (of more than 80% of mountainous areas). These classes are matched with the probability of regions belonging to different risk levels of land abandonment. Similar to geographical classes, the risk level is also grouped into five classes (labeled as "very high, high, moderate, low, very low" probability of risk). From the model output (Table 1) the probability of regions belonging to either a high or even a very high risk of land abandonment attains more than 50% for regions with a very high share (more than 80%) of mountainous areas. The strong correspondence of a high share of mountain areas and a high share of risk is underpinned by the respective results for other classes. In mixed regional contexts, moderate risk levels prevail but these might also appear for regions with low mountain profiles where aspects other than geographical specificity (e.g., structural features) might prevail as influencing aspects.

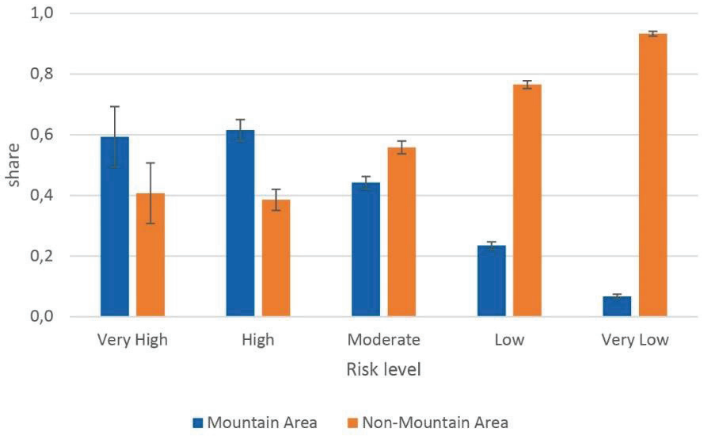

Figure 1. Average share of five risk levels for mountain and non-mountain areas in EU.

Table 1. Conditional probability [1] of mountainous areas in EU per risk level.

Share of Mountain Areas	Very High (>80%)	High (60–80%)	Moderate (40–60%)	Low (20–40%)	Very Low (<20%)
Risk level (%)					
Very high	0.545	0.0455	0.0455	0	0.364
High	0.511	0.145	0.046	0.015	0.282
Moderate	0.169	0.266	0.162	0.052	0.351
Low	0.012	0.055	0.210	0.232	0.491
Very Low	0.017	0.005	0.019	0.061	0.898

[1] Based on DEGURBA data from EUROSTAT (2019), calculation based on model output by Naïve Bayes classifier. Source: [22] (p. 33).

The model results for the various classes of mountain regions so far presented focus on the European assessment, on average. To understand and grasp the actual local situation, geographical differentiation and fine-grained spatial attribution are required. In the first instance, data for the main mountain ranges in Europe are reported in Table 2, highlighting the great variance of risk levels between these contexts. From this overview, the high incidence for risk in mountain ranges, in general, can be deducted (20.5% of high or very high risk in mountain areas vs. 7.7% in non-mountainous areas) and at the same time, the specific relevance for several mountain ranges particularly affected can be observed. In particular, the Eastern Mediterranean Islands and the Alps are affected by a specifically high degree of risk level. Such diverse contexts, such as the Balkan mountain regions and those of the British Isles, show substantial shares of high or very high risk levels. In interpreting these results for mountain ranges, we have to acknowledge that these comprise large areas and thus might include quite different internal divergences. To some extent, we might delineate the very wide-spread relevance of medium risk for almost all mountain ranges across Europe, thus indicating that geographical features of mountains might induce factors for increasing risk levels. In most mountain ranges, this class is relevant for more or less than half of the respective space (at EU-28, average 42.9%, and for non-mountain areas, just 21.8%).

Table 2. Risk for land abandonment in European mountain ranges (in %).

Mountain Range	Medium Risk	High/Very High Risk
Alps	42.7	46.6
Apennines	56.7	13.0
Balkans/Southeast Europe	34.0	29.3
British Isles	27.0	29.6
Carpathians	58.7	21.7
Central European middle mountains 1 (BE + GE)	35.9	3.0 [1]
Central European middle mountains 2 (CZ; AT; GE)	28.2	9.3 [1]
Eastern Mediterranean islands	41.8	58.2 [1]
French/Swiss middle mountains	26.7	17.9
Iberian mountains	46.4	16.1
Nordic mountains	49.6	5.7 [1]
Pyrenees	39.2	14.8 [1]
Western Mediterranean islands	67.5	13.5 [1]
Mountain areas (EU-28)	42.9	20.5
Non-mountain areas (EU-28)	21.8	7.7

[1] Only high risk observed in this mountain range. Source: [22].

The results correspond to the findings of many case-specific studies on selected regions that observe the high incidence of land abandonment in mountain areas [7,9,27,39–43] and underscore the particular risk for future developments [9,44,45].

As risk of land abandonment is variable at low geographical detail, presentation in an overview map for the European situation requires applying a more large-scale unit level. The respective map (Figure 2) summarizes findings from a model calculation by the JRC study [12] and depicts the average risk level at the NUTS-3 average, ranging from very low (green color) to very high (dark red color). It reveals the particular relevance of land-abandonment risk for mountain regions of Europe in comparison to lowland areas, which are, to a large extent, characterized by very low or low risk levels. Exceptions from this general picture are visible for remote regions in Scandinavia, Baltic countries and Eastern border regions of EU New Member States. On the other hand, most large-scale mountain ranges dispose at least moderate, if not high or very high, risk levels. This very crude visualization of spatial distribution of the land abandonment challenge underpins the general appearance of land-use changes at a high level. It should be emphasized that place-specific, local influences might lead to locally very different effects and internal divergent trends within small distances. Community development analyses, such as those for a Tyrolean municipality [43], might be accessed as instructing examples for this phenomenon. These fine-grained territorial differences link to the need to understand the driving processes of land abandonment more comprehensively, an aspect which is explored in detail in the following section.

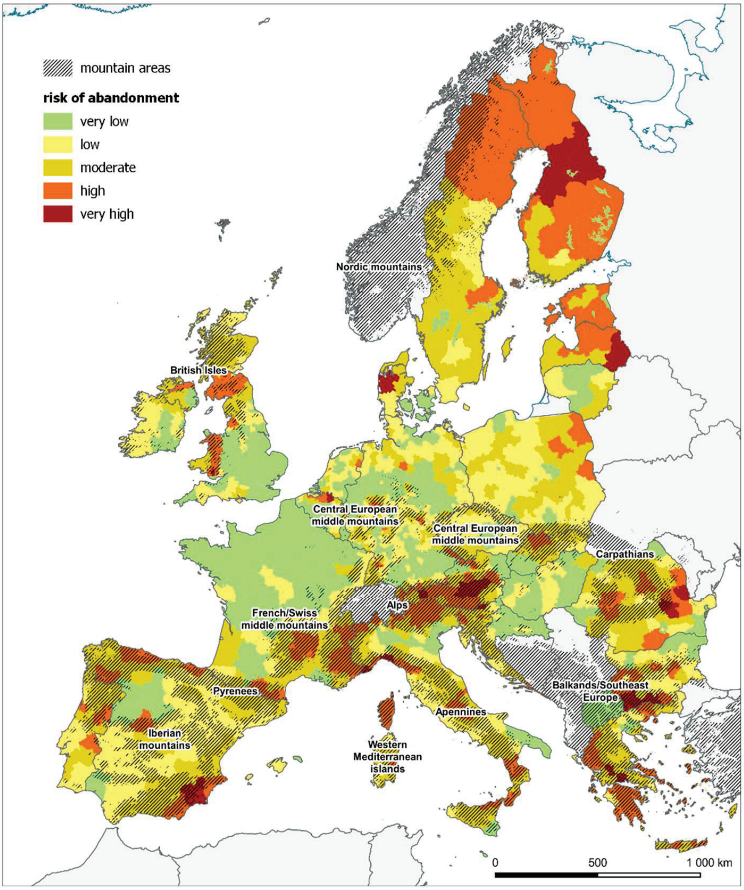

Figure 2. Risk of land abandonment at the NUTS 3 level and mountain areas.

3.2. Drivers and Policy Framework to Respond to Land Abandonment Challenges in Mountain Areas

The significant changes for land use and risk for land abandonment addressed for mountain areas across Europe are the result of a highly diverse set of influential forces impacting land use in these areas and the relative developments of land management with regard to other, more favored agricultural areas. In assessing the main drivers for the regional development of land use, it seems crucial to frame the analysis in such a comparative view. Without taking into account developments in other regions, any analysis would fail to incorporate the full set of contributing forces for land abandonment.

These large-scale, systemic aspects are at the core of many previous studies, which underscored both the scope of different factors impacting the amount and specific areas used for agricultural purposes within a particular area, and the diverse orientation of effects. It seems important to underscore that for some bundles of indicators, reinforcing effects (for others, contradictory effects) and various types of mixed effects might occur. Perceiving pressures on land use and the resulting changes in landscapes in specific geographical areas such as mountain regions, particular concern for shifts in spatial features and functions has been raised over past decades [7]. Accompanying the policy commitment to address the foundations for land management decisions, a wide array of influencing aspects have been discerned. Even if the complexity of drivers is widely acknowledged the details of cause-effect relationships, triggering events and action, the scale of implications and interrelations, and the relative dependencies between different spaces and land use and land management systems remain largely unclear at a general level. Beilin et al. [46] reveal in their analysis of agricultural land abandonment across diverse bio-physical regions (Sweden, Portugal and Australia) that historical trajectories of land cover change and the relative importance of each driver and its scale of action might have a different impact for future trends. “Pressures and attractors encouraging agricultural abandonment” would, thus, depend significantly on that study on place-specific features of the interplay of land management and social and institutional aspects.

Investigating the main drivers of land abandonment at the EU level relies, therefore, on a good understanding of the variability of influential factors, their relative weight, complementary or reverse effects and the complexity of cause-effect chains. This seems particularly pertinent in spaces that are experiencing challenges for competitiveness and productivity of land management systems, such as mountain regions. As the specific problem patterns of these areas are key for future land-use decisions, it is crucial to include an analysis of the interplay of non-land management based regional activities, economic uses and service provision with the organization and trends of land-use persistence. This view extends also to consider widespread environmental degradation trends, increasing land-use conflicts, and actors and triggers in complex socio-ecological systems [47]. Such a comprehensive perspective on ecological and regional contexts implies an in-depth account of rural areas’ perspectives and the role of strategies to enhance the viability of rural regions. The preparation of the Communication on the Long-Term Vision of Rural Areas (LTVRA) by the European Commission [48], to be approved in mid-2021, sets out an appropriate action plan and demands commitment for inspiring local and regional activities with significant knock-on effects for land abandonment implications.

A number of studies assessing the features and causes of land abandonment [7,11,14–16,49,50] have contributed to elaborating a wide set of drivers. which are presented in groups in Figure 3. As the interrelations in the presentation underpin, there are complex interactions between these groups of drivers and between every single impacting factor as well.

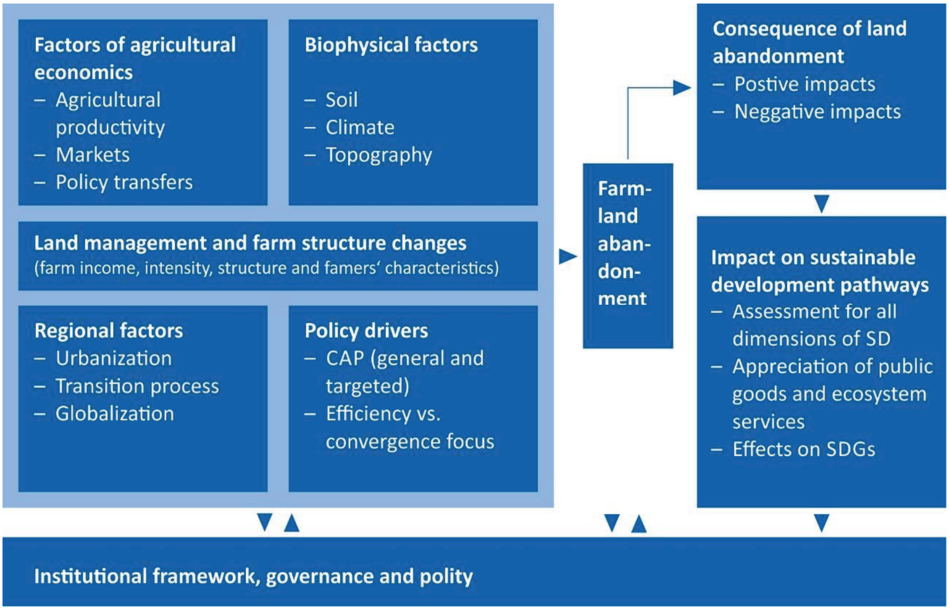

Figure 3. Drivers of land abandonment and integration into sustainable development pathways. Source: Modified from [14] in [22].

The interactions addressed emphasize how land abandonment is dependent not just on biophysical aspects, management strategies and agricultural market conditions, but also on economic development, socio-cultural drivers, and regional and institutional aspects. Despite the wide array of factors influencing land abandonment, management issues and structural adaptation remain key driving forces. The complex nature of linkages between these primary, internal drivers and the aforementioned large-scale, mainly external triggers contributes to the difficulty of observing land-abandonment processes [15]. Moreover, assessment is exacerbated when geographical specificities add restricting requirements through limited access and institutional weaknesses. Sectoral approaches might limit a reflected position on the core role of governance frameworks to address the facilitating role of local and regional actors in coping with marginalization and abandonment issues [51,52].

Deficiencies of mountain areas to address and mitigate these effects in the short-term underpin the long-term nature of land-use adaptation processes. In particular, this is related to the under-provision of highly demanded public goods that are linked to specific land management types, related to region-specific land use systems, such as low-intensity grassland, pastures and mountain meadows. 'Paradox' captures are increasingly experienced in these contexts [25]. The need for including local actors in "planning to envision mountain socio-ecological systems" [53] to realize place-sensitive management schemes is often hampered by failures in institutional settings and inadequate policy frameworks. In 'marginal' areas, land-use systems tend to be limited [54]; hence, the pressure on policy regulations to secure public goods provision is pervasive. As these values are not adequately recognized in current support mechanisms, there is a need for a 'step change' in CAP policy [55] to 'correct' policy failure.

This need to revise the agricultural policy framework touches a crucial issue of reorienting the CAP policy outline and the implementation to address, from top-down, the risk of falling short of providing an effective and sufficient scope for instruments addressing ecological needs and, particularly, mitigating the detrimental effects on land management, implicating higher levels of abandonment [56] (p. 20). It seems particularly crucial to address ecological needs and the diversity of place-sensitive agricultural systems through shaping land management adaptation in different spatial contexts [36]. In this vein, it is, moreover, argued that failure to "remunerate(e) farmers for all the services they provide could lead to land abandonment and closed landscapes" [56] (p. 26). These gaps in the policy setting are particularly distinct in relation to policies for ANCs, permanent grassland or support for organic farming systems, as well as with regard to the biodiversity strategy and nature protection approaches [56] (pp. 38 and 61).

In assessing the policy framework addressing the wide range of drivers, it appears decisive that general European policy instruments might provide an important, basic framework, which is, however, not sufficient for addressing the multiple threats to which mountain areas are exposed when aiming at mitigating land abandonment trends. Even if implementation details address local specificity and relate to particular development options or obstacles, the orientation and effectiveness of policy instruments should be differentiated by their scale of impact. Figure 4 matches the scale of policy application with the diverse intervention programs. It indicates the crucial farm level (farm unit and even parcel unit) which many instruments of CAP Pillar 1 address by shaping fundamental aspects for market integration and individual management decisions [18]. Space specificity is core here, and has long been a building block of CAP. In particular, the less favored area (LFA) scheme, which aimed at (partly) 'compensating' relatively low competitiveness chances [57] and simultaneously addressing demographic and ecological problems and opportunities of rural areas [6], is the long-term leading instrument in this respect. The evolving policy discourse revised its orientation and refocused its remit much stronger toward its core function to cope with its characteristics of ANCs as it has been termed for several years [58]. However, these instruments, targeted at land managers themselves, need to be complemented by interlinked action at local and regional levels, as well. As the discussion on the interrelated system of drivers suggests, rural economic development, environmental performance, human-nature relationships, skills development, educational attainment, enterprise involvement, market chain development and many more aspects, impact on the outcome in land use change and require adapted policy considerations. Beyond that, national and global influences are experienced as a decisive backdrop to many local and regional actions. This underscores the view that land abandonment is embedded in these larger frameworks, which are hardly affected by local management decisions and related policies.

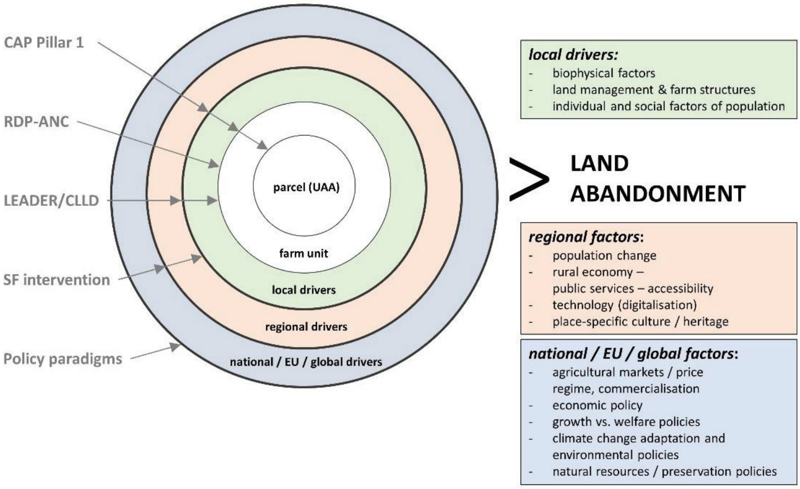

Figure 4. Relevant policies for land abandonment and scales of intervention. Source: [22] (p. 48).

The conceptual framework analyzed for mountain regions is, thus, largely dominated by strong external pressures [25] but also a need for an approach going beyond a simplified, linear, cause-effect relationship as often expressed in monitoring and evaluation practices and concepts of theory of change. As they convey just one plausible development pathway and unique outcomes for specific policy instruments, such views neglect alternative opportunities. We have to conceive the policy arena much more as complex settings of contradictory policy objectives with manifold, unexpected outcomes. Complex evaluation thinking is increasingly addressing these limitations of previous assessment practice, advocating a systemic evaluation design that supports sustainable development pathways [59]. In essence, these approaches are particularly centered on the aspect of how to realign "human and natural system interests (that) too often stand opposed to each other (or outright ignore each other)" [60] (p. 46). Emerging evaluation concepts encompass such an interrelated view of human action effects on natural systems, emphasizing an increasingly intensive array of "contextual conditions and drivers", "baseline assumptions" and scope for intervention design within the socio-political "landscape" [61].

4. Discussion

As Lambin et al. [62] explored long ago (2001), viewpoints on causes for explaining land use and land-cover change are often superseded by generalized myths and a simplified perception of cause-effect relationships, as well as potential policy interventions. This also applies to land abandonment analysis in mountain regions. In our analysis of the current challenge of land abandonment in European mountain regions, we aimed to capture the trend that "various human-environment conditions react to and reshape the impacts of drivers differently, leading to specific pathways of land-use change" [62] (p. 266). As abandonment is a highly complex and gradual process, the observation and differentiation for types of areas at the European level are methodologically difficult. Capturing the various steps of initial reduction in agricultural and forestry intensity, and gradual transition toward temporary, transitional and permanent abandonment requires fine, geographical detail, and the process steps usually can only be delineated along specific cases. Past and recent studies have underscored the great variety of processes and diverse sets of influencing drivers, and sector and institutional responses.

As the background study [22] underscores, the pertinence of the problem to secure land management in mountain areas is at the origin of the evolution of important policy instruments [63] and is impacting current discourses of policy reform [33,36,64]. The limited effectiveness of related policies points to inherent obstacles and an assessment bias toward the prioritization of farm competitiveness versus other, interrelated policy goals. While respective studies are largely aware of this trade-off, the adaptation of policy and national implementation are adopting such perspectives only by and by. This expert-policy-practice tension with regard to face land abandonment pressures in mountain regions as a persistent and trans-boundary problem involves a series of inter-related aspects:

- The large variety of causes for land abandonment across European regions and the methodological complexity in assessing land\-use changes and status blur the common and large-scale triggers for long-term underlying trends. Scale aspects and the multitude of drivers contribute to a simplified understanding of areas taken out of management [9,65].
- Although an increased attention to local assets and opportunities of remote and mountain regions is visible, myths about causes are still predominant [62]. These relate particularly to overly generalized views on focusing on the present land use (path-dependency), role of forest areas, urbanization processes and globalization as a unifying, but undervalued aspect.
- Processes of land abandonment, natural successional transition and marginalization in remote regions of Europe lead to a decline in pastures, grassland, and arable habitats as well as an increase in scrub and forests. This implies pressures on high nature value (HNV) farmlands, loss of biodiversity and viability of farm units in these areas [66].
- On the other hand, these re-vegetation trends might improve soil organic matter content, enhance carbon sequestration and contribute to regulating water flow to prevent flooding, particularly in mountain areas [2,65,67].
- Land management in mountain areas is key for providing important ecosystem services for local and trans-regional demand [26]. These functions are represented in public discourse often as public goods [68,69], the specific shaping of features of landscapes and landscape development [47,70–72], securing heritage features of cultural landscapes [73] and the diversity of habitats and biodiversity, thus ensuring place-specific nature contributions to society [74,75].
- While there might also be some benefits from land abandonment due to species re-establishment and the development of new habitat mosaics in mountain regions [16,67], several studies assess that a decline in habitat heterogeneity and species diversity across mountain landscapes is predominant [9,65,67]. This is due to the fact that species that benefit from land abandonment are often generalist species of low biodiversity value [76].
- Beyond human-nature relationships, land abandonment in mountain areas is contingent on issues of location (accessibility), cultural heritage and social preference. In particular, prospects for regional performance and transnational perspectives on functions of land use are of decisive influence [77,78].

Large-scale influences are increasingly experienced as persisting pressures for mountain regions [25]. The observed land-use changes and impending risk for land abandonment in this study [22] underpin a long-term concern for viable practices of land management in mountain areas. The spatial dimension of agricultural transformation [79] is particularly driven by spatial concentration processes, due to the intensification of a part of the sector [4,62] leading to regional concentration effects [3] with tremendous consequences for mountain areas. Even within these areas, internal shifts in land use and intensification and abandonment processes have to be differentiated [27]. The CAP is shown to pay substantial attention to these challenges in elaborating the dedicated policy instrument of LFA/ANC, which, however, falls short of "compensating" or overcoming the pressures, particularly in remote mountain areas. Much of the remaining policy concern is due to the implicit trade-offs in the overall policy framework and the limitations of policy action to tackle inherent market mechanisms and socio-ecological frameworks [80]. Therefore, "(p)olicy responses to land abandonment in Europe must move beyond agriculture-oriented schemes under the purview of the Common Agricultural Policy to incorporate a range of independent, holistic rural development programs" [65] (p. 1). Such a perspective advocated by various researchers should be adopted by policymakers to overcome overly narrow agricultural-oriented rural policy, including particularly contextual conditions of mountains, long-term trends of 'rural shrinkage' [32] and human-nature relationships at the core of land-use decisions and outcomes. The current pandemic intensifies these pressures and aggravates the need for diverse, context-specific local support in mountain areas. Ongoing discussions of CAP reform might improve the respective responses, but reluctance to open up to such an encompassing policy framework and regional development practice seems widespread. On the other hand, prospects to turn toward a pathway-enhancing action, inspired by the 'Long-Term Vision for Rural Areas', which is now being initiated, still seems limited.

5. Conclusions

Land-use development is not just an issue of adjusting management to local and regional contexts and sector performance, but is dependent on the interplay of all sectors and drivers of respective socio-ecological systems. In providing a comprehensive survey on the experience and future risk for land abandonment, analyzed at various scales and for geographically specific areas, the high incidence for uneven spatial effects becomes clear. Mountains have long been under pressure with regard to maintaining agricultural land management that has increasingly concentrated on extensive grassland systems. This has led to place-specific habitats that dispose of, to a large extent, high nature value farmlands. These consequences present the particular threat arising from the further decrease in managed land within these geographical contexts.

Land abandonment is, however, characterized by a much more complex system of cause–effect relationships and effects. The analysis of a host of diverse studies in the past and our synthesizing study for the European Parliament provide powerful evidence of a combination of many factors for which sometimes, one is predominant over the others. However, in general, mutually reinforcing effects lead to 'spiraling down' processes for land management. These cause-effect chains and threatening outline are particularly valid in mountain regions with high internal differences and specific regional 'hotspots' of abandonment. From current observations and data analyses, there is no ease in this problematic situation in sight for the coming decade.

The main driver for the land-use management and land change prospects are contingent on ongoing intensification processes, due to technological changes and uneven agricultural competitiveness conditions. As long as the approval for a narrative to foster efficiency, technological progress and growth in productivity, i.e., intensity, is the leading paradigm, any strategy to cope with land abandonment and marginalization processes will face almost insurmountable obstacles, as it always would act in a framework of 'compensation'-relative deficiencies in competitiveness.

The deep concern for dealing with the 'failures' or 'restricted impact' of past CAP has spurred concern to reflect the challenge of land abandonment and to revise the agricultural policy framework. It touches on a crucial issue of reorienting CAP policy outline and implementation to address, from top-down, the risk of falling short of providing effective and sufficient scope for instruments addressing ecological needs and mitigating the detrimental effects of land abandonment, particularly in mountain regions. It seems, therefore, necessary to conceive appropriate policy measures beyond CAP, including a comprehensive array of policies with interrelated effects on land management aspects.

Such a wide scope of policy instruments would include regional and social policies (structural funds), environmental regulation, infrastructural organization and public services for remote regions, and should be addressed also by the recent EC policy reorientation in Green Recovery.

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Article

Forests, Farms, and Fallows: The Dynamics of Tree Cover Transition in the Southern Part of the Uluguru Mountains, Tanzania

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Abstract: Forests and woodlands remain under threat in tropical Africa due to excessive exploitation and inadequate management interventions, and the isolated success stories of tree retention and tree cover transition on African agricultural land are less well documented. In this study, we characterize the status of tree cover in a landscape that contains forest patches, fallows, and farms in the southern part of Uluguru Mountains. We aimed to unveil the practices of traditional tree fallow system which is socially acceptable in local settings and how it provides a buffering effects to minimize forest disturbances and thus represents an important step towards tree cover transition. We assessed land cover dynamics for the period of 1995 to 2020 and compared tree stocking for forest patches, fallows, and farms. We found that tree biomass carbon stocks were 56 ± 5 t/ha in forest patches, 33 ± 7 t/ha in fallows, and 9 ± 2 t/ha on farms. In terms of land cover, farms shrank at intensifying rates over time for the entire assessment period of 1995–2020. Forest cover decreased from 1995–2014, with the reduction rate slowing from 2007–2014 and the trend reversing from 2014–2020, such that forest cover showed a net increase across the entire study period. Fallow consistently and progressively increased from 1995–2020. We conclude that traditional tree fallows in the study site remain a significant element of land management practice among communities, and there appears to be a trend towards intensified tree-based farming. The gains in fallowed land represent an embracing of a traditional land management system that supports rotational and alternate uses of cropping space as well as providing a buffering effect to limit over-exploitation of forests. In order to maximize tree cover and carbon stocks in the farm landscape, this well-known traditional tree fallow system can be further optimized through the incorporation of additional innovations.

Keywords: deforestation; shifting cultivation; traditional fallow; swiddens

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1. Introduction

Tropical forests account for 45% of global forest cover, and their deforestation significantly contributes to CO_2 emissions from biogenic sources [1,2]. Broad scientific recognition of the considerable leverage of forest management in the global climate system has catalyzed efforts to better understand trends in deforestation and forest degradation [3,4]. In the tropics, swidden agriculture is strongly associated with deforestation [5]. Farmers practice swiddens by clearing forest vegetation, burning it, and then planting crops. Swiddens are believed to reduce carbon in the landscape via the destruction of relatively large aboveground carbon stocks, including forest resources [6,7]. For example, swidden is estimated to have removed one-third to one-half the aboveground carbon stocks in primary forest across Brazil, Cameroon, and Indonesia [8]. Nevertheless, the exact impact of swiddens and land use change on carbon dynamics differs with vegetation types and management models [9], and the varying types of swidden techniques used to fell forests, ranging from selective to total clearance, add further complexity. Varying swidden techniques create uncertainties and variability in the rates of deforestation and regrowth, as well as in the carbon density of various land uses throughout the landscapes [10,11].

One of the attempts to counter the challenges of swiddens is the use of fallow systems, which fosters alternate cropping-and-cessation cycles in the landscapes. Traditional fallows remain common tropical smallholder agricultural practices even as legal and social contexts shift [12]. Fallow entails a temporal cessation of cultivation after several cropping seasons and can serve various purposes [8,13]. In some areas, the complexities of land tenure, forest tenure, and tree tenure limit and shape how landscape management is conducted and may contribute to the presence or absence of swidden and fallow practices [14]. When it is economically viable, complete forest restoration may be achievable after shifting cultivation. More practically, fallows have remained the optimal trajectory of most tree cover restoration efforts on agricultural lands [15].

In Tanzania, community-held forestlands remain largely without legal protection except for village forest reserves under decentralized forest management regimes and traditionally protected sacred forests used for rituals [16]. Forests and woodlands cover 48.1 million ha, of which almost 50% is under legal protection [5]. The absence of proper incentives to protect forests undermine the sustainable management of forestlands in villages, despite some success stories in parts of Tanzania. Deforestation in the country is estimated to stand at approximately 470,000 ha/year, mostly affecting unprotected forestlands within community-held areas, and agriculture accounts for 80% of the causes [17,18]. Agriculture is the primary force behind this deforestation and is also the main source of food and livelihood for the majority of rural households [17]. Policies on decentralized forest management in the late 1990s led to upscaling of best practices in many parts of Tanzania and strengthened institutional capacities at the local level [19], but deforestation has continued, particularly in unprotected forests [20].

Traditional fallows form an integral part of agricultural landscape mosaics in some parts of Tanzania, with varying degree of composition in terms of crops, other land uses, and their spatial arrangement. In the southern part of Uluguru Mountains of Tanzania, trees and shrubs are prominently featured in the traditional fallow systems, thus contributing to forest cover and aboveground carbon, as well as the availability of woody and non-woody tree products [21]. The practice is highly socially acceptable and widespread among smallholders.

In the current study, we examine the significance of traditional fallows in the Kolero sub-catchment of the southern Uluguru Mountains through tree stocking and land cover analyses in the forest–agriculture interface. Attempts to study forest recovery following agricultural-induced disturbances have been gaining momentum in the recent past [22]. In our current study we focused on understanding how the traditional fallows are important to land use, on-farm natural resource stock, and carbon storage. Therefore, our objectives were to quantify tree cover and above ground carbon stocks in different land use types, quantify trends and patterns of land cover and forest fragmentation changes between 1995 and 2020 in the southern part of Uluguru Mountains of Tanzania.

2. Materials and Methods

2.1. Study Site

The study was conducted in the Kolero sub-catchment in the southern part of the Uluguru Mountains, Tanzania. The Uluguru Mountains are part of the Eastern Afromontane Biodiversity hotspot, known for its biological diversity, species richness, and high degree of species endemism [23]. The richness of strict- and near- endemic species in the Uluguru Mountains is highest for shrubs, herbs, trees, and climbers [24]. Located at 6°50′–7°25′ S and 37°33′–37°52′ E, the Kolero sub-catchment covers 35,405 ha and is comprised of four administrative wards: Kolero, Kasanga, Bungu, and Bwakila Juu (Figure 1). The study area ranges from 260 to 1250 m elevation and has an average annual precipitation of 1800 mm; temperatures range from 22 °C and 33 °C [25]. As of 2012, the sub-catchment had an estimated population of 26,241 people with an annual growth rate of 2.4%, of which 9301 are in Kolero, 6558 in Kasanga, 4406 in Bungu, and 5976 in Bwakila Juu [26].

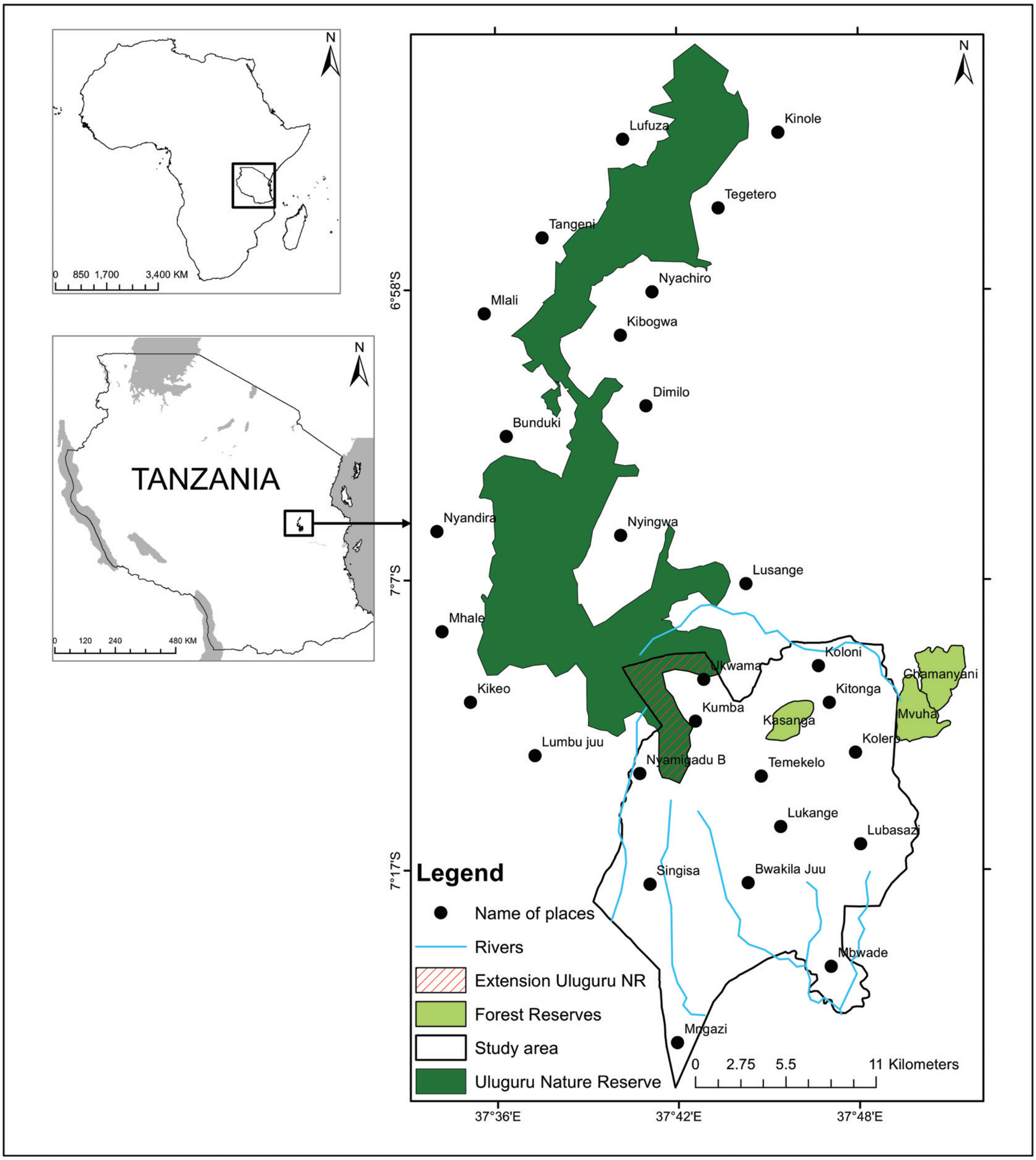

Figure 1. Location of the Kolero sub-catchment, Uluguru Mountains, Tanzania.

The study site is adjacent to three state-owned forest protected areas: Uluguru Nature Reserve (24,115 ha), Mvuha Forest Reserve (758 ha), and Chamanyani Forest Reserve

(806 ha). The Kolero sub-catchment is largely comprised of agricultural land but contains numerous remnants of forests, including sub-montane forests, riverine forests, and dry forests. Most of these remnants are traditionally protected as sacred forests owned by clans, while others are unprotected forests within village lands. Parts of state-owned Kasanga Forest Reserve (429 ha) and an extension of Uluguru Nature Reserve (1707 ha) are also found within the boundaries of the study site.

2.2. Land Tenure and Farming Systems

Land tenure in the Uluguru Mountains is complex due to an amalgamation of traditional practices based on customary law and modern statutory arrangements. According to tradition, land is owned by clan or a family within a clan, and inheritance is matrilineal. In this system a piece of land is held in common by all members of the clan or family, and allocations for use are decided by clan leaders. Despite stable tenure for use after allocation, individuals cannot claim perpetual ownership of the piece of cropping land. Changes and redistribution can happen any time; hence, individuals are hesitant to make long-term investments in their farms, such as tree planting or other costly investments like terraces.

In addition, a considerable proportion of land is owned by individuals, especially in areas near their homesteads where permanent cropping is exercised, and the stability of land tenure is high. However, most individually owned farms are small in size, and so are not involved in the traditional fallow system. Swidden agriculture is the main practice, which entails clearing forests, followed by crop cultivation and then by fallow. Traditional tree fallows are maintained for more than 5 years. The cycle repeats when fallows are cleared for farms. Ownership of cropland is restricted to clan and family members; hence, outsiders must rent the land for use over a short duration that may be as brief as one cropping season. Farms are characterized by sparse tree vegetation and open fields on hilltops, hillsides and in valleys. Common crops include maize, upland and paddy rice, and cassava. Perennial crops such as bananas and fruit trees are common near homesteads and in valleys.

2.3. Tree Inventory on Farms, in Forests, and in Fallows

The landscape of the study area is a mosaics of forest patches, farms, and fallows. Through a combination of remote sensing and ground-based techniques, we stratified the study area into sampling units by dividing the area into forest, farm, and fallow land use categories. We then laid 48 sample plots, sized 50 m × 20 m, at least with 1 km intervals within farmland areas, including forest patches (n = 20), fallow (n = 15), and farms (n = 13). The plot spread was independent of individual management units, and we optimally distributed them to cover the landscape to compensate on low sampling intensity. Next, we identified and recorded the diameter at breast height (dbh in cm) of all trees with a dbh greater than or equal to 10 cm. Heights (m) were not measured. A separate set of 300 trees of various sizes, categorized as large, medium, and small, were randomly selected adjacent to the sampled plots. We measured these trees for height and dbh to develop height-dbh relationship (Equation (1)), which we used to determine the heights (m) of trees that were not directly measured. Due to accessibility challenges and our intention to limit the study to community-managed land, we did not include in the tree inventory parts of state-owned forest reserves that fall in the study site.

$$\mathrm{Ln(Ht)} = 1.1734 + 0.6026 \times \mathrm{Ln(dbh)},\ (R^2 = 0.72,\ \mathrm{SE} = 3.14) \tag{1}$$

where Ln = natural logarithm, Ht = height (m), dbh = diameter at breast height (cm), R^2 = coefficient of determination, and SE = standard error.

We summarized tree stocking parameters by plot and transformed them into per-hectare values for number of stems (N), basal area (G), and volume (V) [27]. We then computed above-ground biomass (ABG) using an allometric equation (Equation (2)) developed for tropical trees [28] and transformed the results on a per-hectare basis:

$$AGB = 0.0673 \times (\rho dbh^2 H)^{0.976} \quad (2)$$

where AGB = above ground biomass, ρ = wood-specific gravity obtained from the literature (g cm^{-3}) [29,30], dbh = diameter at breast height (cm), and H = height (m). Carbon was computed as 0.5 of the biomass.

We used histogram plots, the Shapiro-Wilk test, and the Anderson-Darling test to assess the normality of our sample data. First, we compared a histogram of density, basal area, volume, and carbon data to a normal probability curve. Next, we subjected each histogram to both Shapiro-Wilk and Anderson-Darling tests in R [31]. We found that our data followed a normal or Gaussian distribution. We then used a one-way analysis of variance (ANOVA) for Gaussian distribution sample data to compare differences in stand parameters—density, basal area, volume, and carbon data—between land uses. We further applied the Tukey honestly significant difference (HSD) test for post-hoc multiple comparisons to compare differences in stand parameters within land uses in R [31].

2.4. Land Use Land Cover Assessment and Landscape Fragmentation

To produce land cover maps for the study area, we acquired readily available Landsat Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) datasets from the U.S. Geological Survey Earth Explorer for the dry season. Our choice of satellite imaging was based on absence of cloud cover and availability between 1995 and 2020. We used the fast line-of-sight atmospheric analysis of spectral hypercubes (FLAASH) to correct the TM and OLI images, minimize atmospheric effects, and produce surface reflectance images. We collected 80 training samples through transect walks in additional to 48 training sites collected in the tree inventory to support a supervised classification based on major land uses (Table 1). These transect walks involved a group of ten people comprised of community elders, village leaders, and other people knowledgeable of the area.

Table 1. Land use classes for the assessment of land use, land cover, and forest fragmentation.

Land Use and Land Cover	Description
Forest	Land covered by closed forest, semi-closed forest, and open forest under both protected and unprotected management regimes.
Fallow	Land that has been previously cultivated and left under no prescribed management for at least five years.
Farm	Land under active crop farming of annual and perennial crops. A farm further includes land under settlement and infrastructure.

We chose paths that passed through all the major land uses to ensure good coverage of our training samples. Through a supervised classification approach using a support vector machine algorithm [32], we classified the satellite images into three major land cover classes. Using 128 validation GPS points across the study area, we selected the Kappa coefficient, overall accuracy, user's accuracy, and producer's accuracy to assess the accuracy of classifications. In order to detect land cover changes, we used a cross-tabulation tool to produce a land cover change matrix that provides directions of change, specifying gains or losses.

Fragmentation analysis was conducted in ArcGIS landscape fragmentation tool (LFT v2.0, www.arcgis.com, accessed 7 June 2020). Following a standard procedure, for each year, we reclassified forest and fallow classes as forest, and cropland as non-forest, ergo, fragmenting land cover. Then, we classified forest into 4 major categories: (i) core forest, defined as forest pixels that are not degraded and are more than 100 m from the nearest farms; (ii) patch forest, defined as forest fragments that are degraded and do not contain any core forest pixels; (iii) edge forest, defined as forest along the periphery of a forest patch where it meets non-forest areas; and (iv) perforated forest, defined as areas along the inside edge of small forest gaps [33]. The core category was further divided into the following three classifications: (i) small-core forest, meaning an area of less than 101 ha; (ii) medium-core forest, or an area between 101.17 and 202 ha; and (iii) large-core forest, an area greater than 202 ha.

3. Results

3.1. Tree Cover Stocking

A number of sacred forests owned by clans and families were identified within the study site as part of forested areas scattered among farmlands (Table 2). The small size and large number of the forests signifies that forests are fragmented in the study landscape. On the other hand, the large number of sacred forests afforded protection suggests that traditional beliefs and customary practices offer strong tools for the preservation of forests.

Table 2. Sacred and other general-purpose forests in the Kolero sub-catchment, Uluguru Mountains, Tanzania.

Ward	Village	Forest	Size (ha)	Uses of the Forest
Kasanga	Kitonga	Mongwe	20	Water catchment
		Kivule	0.5	Sacred
		Ng’obambe	0.5	Sacred
		Lubakwe	1.5	Water catchment
	Kasanga	Bomani	32	Water catchment
		Sungwi	5	Sacred
		Lukwangule	>200	Sacred and water catchment
	Kizagila	Mtembe	25	Sacred and water catchment
		Kikwega	8	Sacred and water catchment
		Bagala	9	Water catchment
Kolero	Kolero	Chasamoyo	0.5	Sacred
	Lukange	Mapanga	0.25	Sacred
		Kiduge	0.25	Sacred and water catchment
		Ng’amba	0.5	Water catchment
	Lubasazi	Pango A	4	Sacred
		Pango B	1.25	Sacred
		Uhamvi	38.5	General purposes
		* Chalupia	>50	Sacred and water catchment
		Mapanga	10	Sacred and water catchment
		Dabala	15	General purposes
Bungu	Mihange	Kunguwi	5	Sacred and water catchment
		Mihange	1.5	Sacred and water catchment
	Malowani	Kitala	2	Sacred and water catchment
	Balani	Lutite	35	Sacred and water catchment
		Mingo	>50	Water catchment
Bwakila Juu	Bwakila Juu	Msinule	>30	Sacred and water catchment
		Kigenge	0.5	Water catchment
		Milango Miwili	0.25	Sacred and water catchment

* Also known as *Kwa Bibi*, a Swahili term that means “belongs to Grandmother”, this forest contains graves of prominent traditional ritual leaders.

The stand parameters on a per-hectare basis indicated that forest was more heavily stocked with woody biomass and carbon storage than fallow and farmland, respectively (Table 3). Forests had on average the largest number of stems, basal area, and volume of wood—meaning they had the most, thickest, and largest trees of any land use type. Tree biomass carbon stocks were 56 ± 5 t/ha in forests, 33 ± 7 t/ha in fallows, and 9 ± 2 t/ha on farms. Fallows come in second in all these stocking parameters, featuring the next-best tree cover, woody biomass, and carbon storage. Furthermore, a one-way ANOVA test shows that the mean scores for stand parameters differed significantly between land uses: stocking (F (2, 45) = 53.245, $p < 0.001$); basal area (F (2, 45) = 32.143, $p < 0.001$); volume (F (2, 45) = 17.493, $p < 0.001$); and carbon (F (2, 45) = 18.114, $p < 0.001$). Post-hoc comparisons using the Tukey HSD test indicated that forest, farms, and fallow are all significantly different from each other in terms of stocking, basal area, volume, and carbon data ($p < 0.01$). A further notable result of our stocking analysis is that forest stocking is relatively low, characteristic of the perforated forests that cover much of the study area.

Table 3. Descriptive statistics of stand parameters in the Kolero sub-catchment, Uluguru Mountains, Tanzania.

Stocking Parameters	Land Use	Sample Size (N)	Mean	SE	95% Confidence Interval	Minimum	Maximum
No. of stems (stems ha^{-1})	Forest	20	346.00	23.06	297.73–394.27	170.00	580.00
	Fallow	15	178.00	11.88	152.52–203.48	120.00	290.00
	Farm	13	64.62	17.19	27.15–102.08	10.00	210.00
Basal Area (m^2 h^{-1})	Forest	20	1.10	0.08	0.93–1.26	0.61	1.82
	Fallow	15	0.60	0.10	0.38–0.82	0.17	1.67
	Farm	13	0.18	0.04	0.10–0.26	0.03	0.48
Volume of wood (m^3 ha^{-1})	Forest	20	13.19	1.12	10.84–15.53	5.90	25.29
	Fallow	15	8.01	1.84	4.06–11.96	1.43	25.93
	Farm	13	2.17	0.57	0.94–3.41	0.27	7.48
Carbon (t ha^{-1}C)	Forest	20	56.05	4.98	45.62–66.48	26.25	115.17
	Fallow	15	32.85	7.47	16.83–48.86	6.59	103.55
	Farm	13	8.99	2.29	4.00–13.98	0.91	28.12

3.2. Land Use/Cover Change

For the year 2014, we obtained an overall accuracy of 87% and kappa coefficient of 0.84. We chose the year 2014 because during this period, ground reference data were collected composed of 48 plots used in the forest tree inventory and additional 80 training sites collected during transect walks. About 82% to 100% of reference data representing all land-cover classes in the classified maps were correctly identified. The probability that map users would find all classified land-cover classes on the ground ranges from 86% to 92% (Table 4).

Table 4. Cross-tabulation error matrix of a classified image versus reference data for 2014.

	Reference Data			
Classified Image	**Forest**	**Fallow**	**Farms**	**Total**
Forest	46	4	0	50
Fallow	0	45	5	50
Cropland/Farms	0	4	24	28
Total	46	53	29	128
Producer Accuracy	100%	85%	82%	
User Accuracy	92%	90%	86%	
Overall accuracy		89%		
Kappa		84%		

From 1995–2020, land cover assessments indicate consistent increases in land cover under fallow and decreases in farmland (Figure 2 and Table 5). Forest, meanwhile, initially shrunk from 2007–2014 but expanded from 2014–2020. The annual rate of change in land cover was highest for farmland, followed by fallow and forest, respectively. Overall, the net change in land cover was positive for fallow and forest, but negative for farmland.

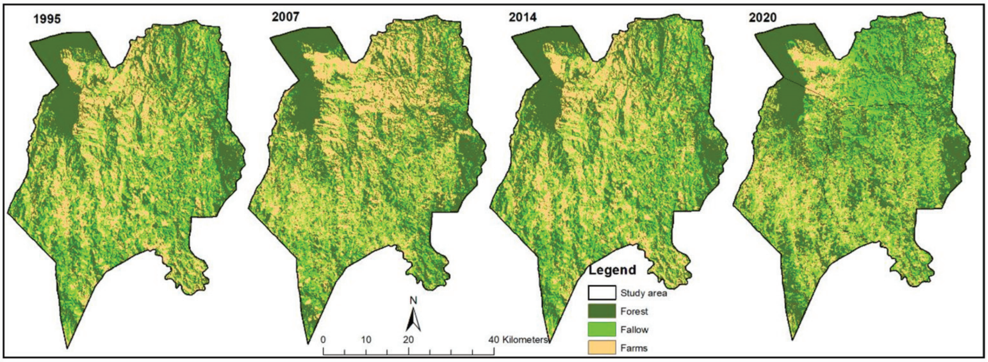

Figure 2. Land cover map for the years 1995, 2007, 2014, and 2020.

Table 5. Land cover area, change, and annual rate of change (ha) for the study landscape, 1995–2020.

Land Cover Type	1995	2007	2014	2020	Change (1995–2007)	Change (2007–2014)	Change (2014–2020)	Total Change (1995–2020)	Annual Change
Forest	14,909.85	14,450.76	14,258.07	15,268.41	−459.09	−192.69	1010.34	358.56	14.34
Fallow	5027.13	5572.89	6987.87	8229.42	545.76	1414.98	1241.55	3202.29	128.09
Farm	12,467.88	12,381.21	11,158.92	8908.38	−86.67	−1222.29	−2250.54	−3559.50	−142.38

The overall land cover size of core areas remained unchanged from 1995–2007, but consistently increased for fallow and decreased for forest and farmland from 2007–2014 and 2014–2020. From 1995–2020, all the three land cover classes experienced losses and gains between 3000–7000 ha, indicating dynamic land use. During this period, fallow was more dynamic than forest and farmland (Table 6).

Table 6. Land use change (ha) between 1995 and 2020. Bold numbers indicate no change in land cover during the assessment period.

Land Cover	Forest	Fallow	Farm	Total (2007)	Losses
Forest	10,933	1964	1554	14,451	−3518
Fallow	1836	1310	2427	5573	−4263
Farms	2141	1753	8487	12,381	−3894
Total (1995)	14,910	5027	12,468	32,405	
Gains	3977	3717	3981		
Land Cover	**Forest**	**Fallow**	**Farm**	**Total (2014)**	**Losses**
Forest	10,359	1611	2289	14,258	−3899
Fallow	2119	2026	2842	6988	−4961
Farms	1972	1936	7250	11,159	−3909
Total (2007)	14,450	55,723	12,381	32,405	
Gains	4092	3546	5131		
Land Cover	**Forest**	**Fallow**	**Farm**	**Total (2020)**	**Losses**
Forest	10,248	2743	2276	15,268	−5020
Fallow	1236	2421	4572	8229	−5808
Farm	2773	1824	4311	8908	−4597
Total (2014)	14,258	6988	11,159	32,405	
Gains	4010	4567	6848		

There is a clear decrease in overall farmland (Table 5) coupled with the shrinkage of core, stable areas devoted to agriculture (Table 6). Additionally, core areas devoted to fallows remain constant (Table 6). Finally, the overall prevalence of fallows within this landscape points toward the importance of traditional fallow practices, which entail rotational and alternate uses of cropping space, for communities in the Kolero sub-catchment.

3.3. Forest Fragmentation

In total, perforated forest grew in area by over 39% from 1995–2020, and significant change occurred in the last assessment period of 2014–2020. Forest fragmentation analysis shows that perforated forest exhibited more changes than other categories (Figure 3, Table 7). Patch, edge, and perforated forests occupy large spaces in the study area, which indicates the scattered nature of these types of forests. They exhibited large changes compared to large, medium, and small core forests. From 1995–2020, the area's perforated forests experienced continuing decline. This data indicates the continuing effect of forest fragmentation—which can give way to deforestation in time—within the study area, especially in its eastern, southern, and western regions.

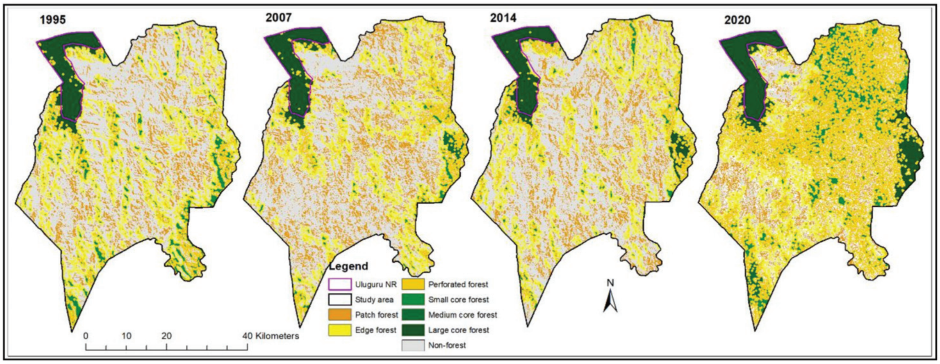

Figure 3. Maps of the forest fragmentation pattern in the study area for the years 1995, 2007, 2014, and 2020.

Table 7. Forest fragmentation and annual change of each class (% area), 1995–2020.

Forest Class	Forest Cover (%)				Forest Cover Change (%)				
	1995	2007	2014	2020	1995–2007	2007–2014	2014–2020	1995–2020	Annual Change
Patch forest	21.62	32.03	28.56	7.89	10.42	−3.48	−21.43	−14.48	−0.58
Edge forest	37.20	31.67	35.48	11.35	−5.54	3.81	−24.12	−25.85	−1.03
Perforated forest	20.60	19.29	18.38	60.14	−1.31	−0.91	41.76	39.54	1.58
Small core forest	7.85	2.87	2.97	8.00	−4.98	0.10	5.03	0.15	0.01
Medium core forest	0.00	1.05	0.00	0.62	1.05	−1.05	0.62	0.62	0.02
Large core forest	12.73	13.09	14.61	12.00	0.35	1.53	−2.62	−0.74	−0.03

4. Discussion

4.1. Stocking Levels and the Potential of Fallows to Support Forest Recovery

Overall, the tree stocking parameters for the forests in the study site demonstrate the typical extent of stock depletion of Tanzanian Miombo woodlands [34]. In general, tree stocking levels decrease from forest patches to fallows to farms, as was expected, but the level of stocking itself, especially for tree fallows, was significant. We found that stocking levels for the forests under study were lower than for the sub-montane forests of the Uluguru Mountains [35]. If woody material in tree fallows is no longer harvested, forest patches may fully recover with time. Other studies have noted a positive relationship between basal area and fallow age in other parts of the Eastern Arc Mountains [13]. We posit that the longevity of fallows determines their tree species composition, tree size, and the colonization of land towards forest transition.

The longevity of tree fallows, in turn, may depend upon factors such as distance from residential areas, type of terrain, and perceived soil fertility. Communities indicated that the cycle of tree fallows lasts between 10 and 15 years. Cycle duration depends on landforms, such as hilltops, hillsides, and valleys, and on proximity to residential areas. Tree fallows on hilltops persist longer than those on hillsides, in valleys, and close to homesteads, perhaps because hilltops are far from most homesteads and feature difficult terrain and apparently low soil fertility.

The presence of leftovers of large trees on fallows and the proximity of forest patches guarantee the availability of seed sources dispersed by wind and animals, but germination and recruitment remain challenging. Tree regeneration in the Kolero sub-catchment fallow occurs mainly through asexual propagation as cut stumps and roots sprout. Farmers do not uproot cut stumps, so most of them survive. Tree seedlings that make it to the sapling stage flourish, but most become suppressed and die during their infant stage, while others fail to germinate in the first place. We observed the presence of long grasses in fallows, which impact the recruitment of tree species. The dominance of long grasses that are persistent and aggressive on the tree fallow floor deprive tree seedlings of the chance to flourish from propagation; a similar phenomenon has been observed in the East Usambara Mountains [27]. What is more, wildfires commonly occur at the study site in the dry season as a result of fire-based swidden methods. Wildfires suppress seed germination, root sprouting, and seedling recruitment, which has also been observed in the tropical woodlands of southeast Angola [36].

Even after trees mature, there are other barriers to forest transition. For instance, extraction of woody material from tree fallows remains a common practice through selective harvesting of sizeable and desirable trees according to their usefulness; people believe forests and fallows in farmland are open access, especially those forests that lack traditional and formal institutional protections, but this practice slows progress in forest transition [37]. Small- to medium-sized trees are extracted for energy, building materials, and various other uses, while large trees are left on-site. We observed more recent tree cuts in fallows than in forests and on farms. In addition, most large trees either are varieties that have no immediate economic value in the area, such as *Sterculia appendiculata* and *Bombax rhodognaphalon*, or have become overgrown and unsuitable for timber due to heart rot.

Yet good land management practices, informed by climate-smart agriculture, may boost the forest transition process. For example, attempts were made between 2011–2014 to improve tree cover on farm in Kinole sub-catchment. A climate-smart agriculture project (www.fao.org/in-action/micca/knowledge/climate-smart-agriculture/en/, accessed 10 December 2020) led to planting of estimated 110,000 trees including species such as *Grevillea robusta*, *Khaya anthotheca*, *Tectona grandis*, *Acacia crassicarpa*, and *Terminalia cattapa*. This project might help explain the unusually sharp surge in tree cover that occurred in the assessment period of 2014–2020.

4.2. Shrinking Farms, Expanding Fallows

Since the 1930s, population growth in the Uluguru Mountains has been linked to agricultural expansion [38]. According to the population census, the number of people has doubled from 1,753,362 in 2002 to 2,218,492 in 2012 in Morogoro Region, and 73% of this population resides in rural areas [26]. Our observation, to the contrary, indicates that overall population growth in the Kolero sub-catchment and the Uluguru Mountains at large does not correspond to expanding farms. From 1995–2000, indeed, the area occupied by farms consistently declined (Table 5), and the stable, unchanged portion of farmland also continuously dwindled (Table 6). The data imply an unexpected trend of halted agricultural expansion and increased dynamism in land use.

This shrinkage of farms might be due to the increasing area under fallow. Projections from 1967 estimated that fallows in the Uluguru Mountains constitute 30% of the farmland area [39]. From 1995–2020, however, fallow area covered more than 40% of farmland, indicating that traditional tree fallows occupy a notable share of land in Kolero sub-catchment. The importance of fallows is further exemplified by the land use change matrix, which shows increments of unchanged fallow land in 2007–2020, a clear indication that the expansion of farms is contained.

In recent years, meanwhile, forest cover loss has also slowed in the study area. From 1995–2007, forest cover loss was higher than in 2007–2014. Most recently, the period of 2014–2020 experienced forest cover gain (Table 5), indicating a reduction in deforestation across the Kolero sub-catchment. Previous studies in the Uluguru Mountains highlighted similar trends of heightened deforestation prior to 2000 [40], and reduced deforestation and/or forest recovery in the early 2000s [41]. We speculate that the declining rate of forest loss in recent years may have arisen from a combination of factors including fewer forest disturbances, the diminishment of swidden, and the growing role of fallow in supplying forest produce.

Accessibility from and proximity to villages may explain differences in forest cover changes because, as other studies have noted, there is often a relationship between accessibility and disturbances to forest vegetation [42]. The two state-owned forests in the study area furnish a good example of this effect. From 1995–2020, an extension of the Uluguru Nature Reserve remained stable, whereas Kasanga Forest Reserve succumbed to degradation from 1995–2007 and later recovered from 2014–2020 (Figure 2). The extension of Uluguru Nature Reserve is inaccessible, encompassing ridges with no roads, rough terrain, and deep valleys. It stands close to 1650 m above sea level, while the nearest villages, such as Mgata, Ukwama, and Longwe on the side of the Kolero sub-catchment, are located at 1250 m above sea level. Such physical barriers reduce and hinder human-induced disturbances. At 850 m above sea level, on the other hand, the Kasanga Forest Reserve is accessible from multiple directions and borders intensively cultivated farms, so it is prone to human-induced disturbances including fires.

Other positive factors may have influenced the expansion of fallow and increased tree cover. For instance, it seems that more farms were left as tree fallow and that the trend towards tree-based farming systems such as agroforestry has increased from 2007–2020. Between 2011 and 2014, conservation agriculture was promoted in the study site, but farmers did not view the returns as profitable [43], which may have dampened adoption rates [44]. However, we suggest that this effort may have increased awareness of agricultural intensification and so contributed to the reduction of swidden practices.

Traditional institutions are one of the key success factors in promoting community-led forest management in Tanzania [10]. Sacred forests under community-based forest management (Table 2) were found to be more protected and stable than forest patches that had no traditional significance. Despite their small size, sacred forests that are protected under traditional norms and customs provide important refugia for plant species, because access is limited to a few non-destructive utilizations. On the other hand, forest patches in farmland without community-based forest management arrangements faced excessive exploitation including conversion to other uses. Similarly, in other parts of Tanzania, traditionally protected forests have withstood exploitation pressure and remained intact [45].

4.3. The Threat of Deforestation

The study area faces a grave trend toward fragmentation that if not checked will result in complete deforestation. Across the whole of the Eastern Arc Mountains, deforestation has caused habitat reduction and forest fragmentation that has impacted more than 77% of the original forest cover in the past 2000 years [46]. At local and regional scales, forest fragmentation has caused a loss of biodiversity, continues to undermine forest transition in the Uluguru Mountains, and accelerates the extinction of important species such as birds [47,48].

The trend toward increasing forest fragmentation in the Kolero sub-catchment landscape is notable, defined by the increasing isolation of continuous forests into smaller patches (Figure 3, Table 7). Forest fragmentation is exhibited both in spatial and temporal patterns. Temporal fragmentation can lead either to perforation (subdivision) or attrition (shrinkage) of the forest. Our observations on fragmentation (Table 7) conform with the tree inventory results (Table 3), indicating low stocking levels typical of perforated forests. In other parts of the Eastern Arc Mountains, forest fragmentation has involved encroachment affecting both protected and non-protected forests [49].

Forest fragmentation in the Kolero sub-catchment results from deforestation and forest degradation mainly due to anthropogenic factors such as expanding agricultural frontiers, excessive extraction of woody products, and fires. The scale and trends of forest fragmentation (Figure 3, Table 7) suggests the continuous decline of perforated forests throughout the assessment period of 1995–2020, especially in the eastern, western, and southern parts of the study site. Edge and small-core forests scattered across the study landscape also experienced shrinkage. Our field observations indicate that forests are not opened up in large-scale clearing but rather in small, incremental areas adjacent to existing farms. Similar observations were made previously of significant forest fragmentation in less dense forest classes in the Uluguru Mountains [50].

5. Conclusions

Our results indicate that whereas forests offer the best stocking of woody biomass and carbon storage, fallows also offer advantages in this regard. We found that, contrary to long-held assumptions, active farms in the study area are shrinking and fallows are expanding despite population growth, these fallows could help address the urgent risks posed by deforestation. These findings demonstrate the importance of traditional fallows in terms of tree stocking at the forest-agriculture interface, and points toward options for how fallow practices can be optimized to improve natural resource stocks in the community. This represents an underreported success story for traditional practices from rural Africa in terms of tree cover transition and landscape improvement.

Deforestation is an urgent concern in the study area. While the spatial and temporal arrangement of forests, farms, and fallows in the Kolero sub-catchment may not be optimal for maximizing carbon inputs, the current practices of tree fallows in the southern Uluguru Mountains offer significant opportunities for improvement toward becoming exemplary dry mountainous land management system. Given time, tree fallows promise to boost tree cover and support forest transition, offsetting the effects of deforestation. Although forests offer superior carbon storage, nonetheless tree fallows also represent an important carbon sink in a previously deforested landscape [22].

Any improvement of the traditional fallow should adhere to existing practices. The current land management arrangement is effective and socially acceptable and incorporates community expectations. It evolved through lengthy traditional experience from one generation to another, not through a top-down approach imposed by outsiders such as the government, non-governmental organizations, and researchers; hence, it is more likely to prevail in the long run. Attempts to impose best-bet technologies that are not compatible with traditional and well-accepted local practices often do not lead to proper adoption [51] or fall short of long-term sustainability [52].

Certain policy interventions that build on traditional fallow could continue to improve the landscape and reduce deforestation. For instance, wildfires endanger tree recruitment and retention. In response, we recommend local by-law guidance on prescribed fire for farm preparations and stronger enforcement of community-led wildfire management. In addition, farms in the Kolero sub-catchment are typically characterized by reduced tree cover because of continuous clearing and prioritization of shade-intolerant crop varieties such as upland rice, paddy rice, cassava, pineapples, and sesame. (The major exception to this is the middle and low altitudes, where tree planting and retention are commonplace around homesteads and in valleys, with strong preferences for fruit trees such as *Artocarpus heterophyllus*, *Artocarpus altilis*, and *Cocos nucifera*.) Farm preparation during the onset of cropping seasons is normally accompanied by swidden practices, which diminish long-term tree and shrub recruitment [51]. Adequate agricultural extension services and continuous public awareness campaigns targeting smallholders could effectively contribute to the tree cover transition.

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Population Trends and Urbanisation in Mountain Ranges of the World

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Abstract: This study assesses the global mountain population, population change over the 1975–2015 time-range, and urbanisation for 2015. The work uses the World Conservation Monitoring Centre (WCMC) definition of mountain areas combined with that of mountain range outlines generated by the Global Mountain Biodiversity Assessment (GMBA). We estimated population change from the Global Human Settlement Layer Population spatial grids, a set of population density layers used to measure human presence and urbanisation on planet Earth. We show that the global mountain population has increased from over 550 million in 1975 to over 1050 million in 2015. The population is concentrated in mountain ranges at low latitudes. The most populated mountain ranges are also the most urbanised and those that grow most. Urbanisation in mountains (66%) is lower than that of lowlands (78%). However, 34% of the population in mountains live in cities, 31% in towns and semi-dense areas, and 35% in rural areas. The urbanisation rate varies considerably across ranges. The assessments of population total, population trends, and urbanisation may be used to address the issue "not to leave mountain people behind" in the sustainable development process and to understand trajectories of change.

Keywords: population; population trends; urbanisation; sustainable development

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1. Introduction

The challenges of making a living in mountains have been extensively described in informative reports [1–3], book chapters [4], and scientific papers [5]. Livelihood hardships in mountains are related to the limited land suitable for human habitation, which is often concentrated in valley floors where settlements, main transport routes, critical economic and social infrastructure (schools, hospitals, and energy and industrial facilities), and productive agriculture compete for the limited land resources [6]. Quantitative data on mountain population are generated using global datasets [7]. However, it is also reported that sustainable development in mountains is hindered by the "lack of targets, appropriate indicators, measurements, reliable data and applicable systems for monitoring and steering sustainable mountain development at all levels" (as reported by [1] page 17).

Mountain population estimations rely on a definition of mountains first made available by the World Conservation Monitoring Centre (WCMC) [8]. The first global assessment of mountain population used Landscan gridded population density [9] for the year 2000 [10]. More comprehensive population estimates in mountainous areas were generated to address food insecurity [11]. Recent studies include the analysis of population in the Global Mountain Biodiversity Assessment (GMBA) [12] based on a new definition of mountains [13], which provided population estimates for each range for the years 2000 and 2012 using FAO statistics and Landscan gridded population [11]. The GMBA mountain outline study [12] addresses issues related to the definition difference and surface estimation difference with WCMC mountain areas. The study also estimates the surface area of the GMBA mountain ranges per climatic belt and provides area and population estimation at the continental level.

We propose an approach that combines biophysical traits of WCMC definition, and geomorphological, biodiversity, and socio-ecological traits of GMBA Mountain Ranges. We use the WCMC definition to delimit the outer mountain boundaries as used in the 2030 Sustainable Development Agenda reporting [14]. We could not incorporate in this analysis the third mountain definition [15] as that would add complexity, and the comparative assessment between mountain definitions is beyond the scope of this paper. We understand that the mountain research community is addressing the definition of mountains as a key research priority [16] for future analysis on mountain areas. The GMBA mountain range breakdown was developed for addressing biodiversity and this research argues that it is also useful to address the human impact on the environment and that of a warming climate on mountain societies [17].

We considered using the Global Human Settlement population (GHS-POP) spatial grid of 1×1 km^2 [18] over other gridded population datasets used in previous studies [4], as the data are open source, are consistent and comparable in time and space [18–20], and most importantly are used in implementing the Degree of Urbanisation (DoU) [21]. The DoU is a method that outlines dense urban areas, semi-dense areas, and rural areas and is used to generate standardised urbanisation statistics globally [22]. The DoU was developed to generate comparable urbanisation statistics across the world, as countries define urbanisation in different ways. The GHS-POP datasets are used in a number of applications including disaster alerts and assessment of exposure to hazards, an essential societal variable [23] that cuts across all Sustainable Development Goals [14].

This study has two aims: first to provide the mountain research community with data on urbanisation and population change in the mountain ranges of the world; second, to inform policymakers of potential indicators of use in adaptation to a changing climate, development assistance, disaster risk, and humanitarian aid for mountain ranges of the world. The novelty over previous work lies in using open-source population density datasets that are consistent over a time span of 40 years, and in estimating urbanisation within each mountain range perimeter using an internationally endorsed standardised methodology. Urbanisation is typically associated with lowlands, but this research argues that urbanisation is also an important societal process in mountains. Urbanisation in mountain areas generates high pressure on natural resources and that is a concern for sustainability [3,24,25]. The study focuses on the value of mountain range scale analysis over that conducted at national or regional levels. By providing a global overview, the study strives to detect unreported trends and possibly identify needs to support decision-makers at both local and global levels in prioritizing interventions, which is part of the second aim of this study.

This study has four objectives for use by the mountain research community and to inform policy decisions: (1) To provide new finer scale estimates of population dynamics (changes between 1975–2015) and urbanisation rate in 2015 for global mountain areas following the WMCM definition. (2) To comparatively analyse those dynamics in GMBA defined mountain ranges and other ranges not identified by the GMBA inventory. (3) To compare urbanisation rates amongst GMBA ranges. (4) To identify trends in population dynamics across ranges. We then discuss these findings in relation to the mountain development and protection international policy agendas and future pathways.

2. Methods

The overall analysis relies on open-source spatial datasets and spatial grids, pre-processing steps, and workflow to produce output statistics at three-level spatial aggregation units (Figure 1). The information for accessing the open-source datasets is provided in the references listed in the datasets section. We used datasets with different thematic content and resolutions originating from different disciplines. We pre-processed the datasets to make them suitable for analysis. We intersected the spatial grids with the spatial aggregation units in a stepwise approach. We used three exclusive spatial extents (Figure 1). The global land masses global spatial extent (Level 1) partitions WCMC mountain areas from lowlands. The WCMC spatial extent (Level 2) partitions GMBA ranges from other WCMC ranges referred to hereafter as "Other Ranges".

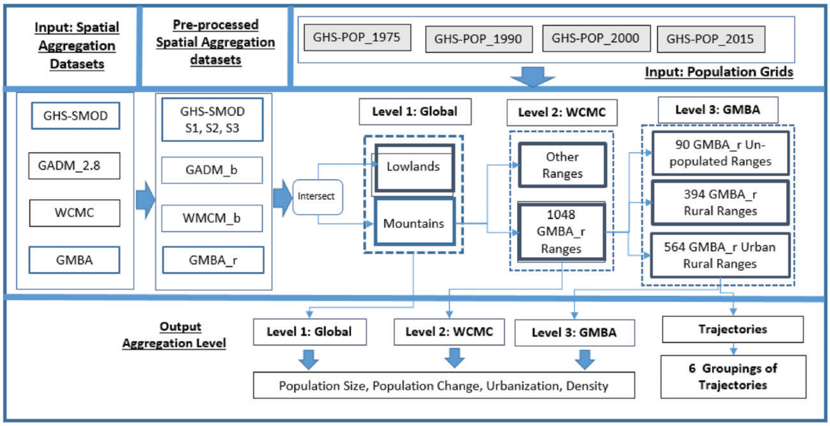

Figure 1. The workflow shows the input Spatial Aggregation Datasets and Population and the output Spatial Aggregation levels. Level 1: Global terrestrial land masses partitions Mountains and Lowlands. Level 2: WCMC partitions GMBA from Other ranges; Level 3: GMBA groups ranges based on population presence, urbanisation rates, population change, and density and then re-groups them into trajectories—ranges with similar characteristics.

The GMBA spatial extent (Level 3) analyses GMBA_r ranges based on the presence of population, based on the presence of urban and rural population in 2015; and based on population change in the 1975–2015 timeframe. Urbanisation is analysed based on three settlement classes available from the GHS Settlement grid: the rural areas (S1), the towns and semi-dense areas (S2), and the cities (S3). We define urbanisation as recommended in the DoU: that is the percentage of towns and cities (S2 and S3) over the total population in 2015.

For the GMBA spatial extent (Level 3) we grouped GMBA_r ranges into seven classes of population size to facilitate the discussion. We used thresholds used in urbanisation and population studies as follows: the 5 thousand and 50 thousand population threshold is used in the DoU, while the 500 thousand and 5 million is used in World Urbanisation Prospects [26]. Class 1 groups range with populations above 5 million. Class 2 groups range with populations between 500 thousand and 5 million. Class 3 groups range with populations between 50 thousand and 500 thousand. Class 4 groups range with populations between 5 thousand and 50 thousand. Class 5 groups range with populations between 5 hundred and 5 thousand. Class 6 groups range with populations under 500. Class 7 groups range with no populations (Figure 2).

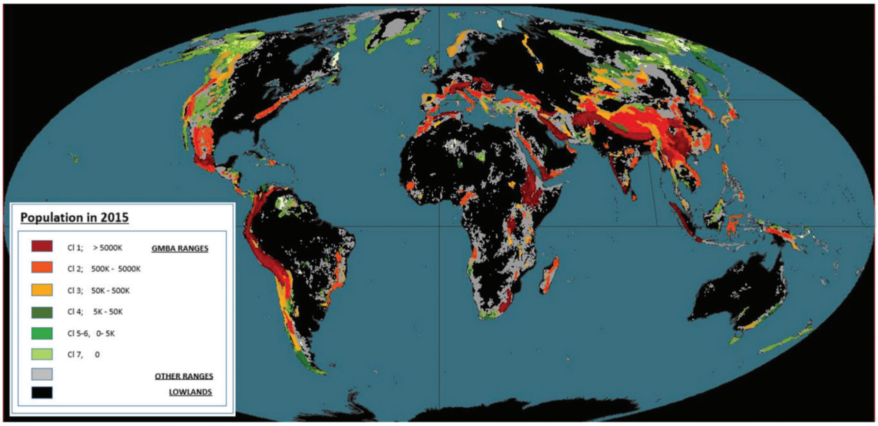

Figure 2. Overview of WCMC mountain extent with GMBA mountain ranges grouped in classes of population size. Ranges above 5 million (Cl_1), between 500 thousand and 5 million (Cl_2), between 50 thousand and 500 thousand (Cl_3), between 5 thousand and 50 thousand (Cl_4), between 5 hundred and 5 thousand (Cl_5), below 500 (Cl_6), and not populated ranges (Cl_7).

The subset of GMBA ranges that include both urban and rural populations is analysed based on urbanisation rates, population change, and overall density. For each variable of that subset, we generate groupings of GMBA ranges: six groupings for urbanisation, five groupings for population change, and four groupings for density. The three sets of variables are then combined into a composite indicator that we refer to as "trajectory". Finally, we group the most populated trajectories into six groupings.

2.1. Datasets

We used two open global mountain datasets (the WCMC and GMBA) to outline mountain areas and the GHS-SMOD for the spatial delineation of settlements (Figure 1). The WMCC mountain dataset [8] is the set of reference mountain data layers used in reporting for the 2030 Sustainable Development Agenda. It was generated by processing the GTOPO-30, a 30 × 30 arc seconds elevation datasets [8]. WCMC consists of seven mountain classes based on a hard threshold on elevation or a combination of elevation and ruggedness. Ruggedness is defined by elevation changes within a spatial 7 km radius circular area, combined with that of elevation. The inclusion of a rather flat terrain surrounded by mountain areas is also included in WCMC definition and retained in this study.

The GMBA range is a unique dataset of 1048 mountain range perimeter outlines [12]. The mountain range boundaries originate from digitally encoding mountain range perimeters from atlases and cartographic documents at different scales, often at 1: 10 × 10^6 km^2 [12]. The 1048 GMBA Mountain range outlines, encoded in a shape file in the Geographic Coordination System are associated with the corresponding mountain range name. The GMBA is the most detailed partition of mountain areas available as open-source data and is generated for global comparison, thus independent from national criteria.

The GHS-POP is the main input population dataset. The GHS-POP is a spatial grid of population density for the epoch 1975, 1990, 2000, and 2015. The GHS-POP is generated by disaggregating census data available at administrative spatial units into 1 × 1 km^2 grid cells of built-up density from the GHS-BUILT [18]. The four epoch GHS-POP spatial grids are the input variables used to generate the population statistics for the mountain ranges of this research, and are accessible from [27].

The settlement model spatial grid (GHS-SMOD) is a gridded information layer that partitions the terrestrial landmasses into settlement classes [27], based on the DoU [21]. In this study we use three classes from the first hierarchical level of the DoU [22]: the cities (S1)—technically referred to as "Urban centres", towns and semi-dense areas (S2)—

technically referred to as "Urban Clusters", and rural areas (S1) technically referred to as "Rural grid" cells (S1). Cities (S3) are defined by having adjacent grid cells with at least 1500 people/km^2 whose population totals 50 thousand people. Towns and semi-dense areas (S2) are settlements with adjacent grid cells of at least 300 people/km^2 that total 5 thousand people. Rural areas (S1) are settlements with fewer than 300 people per km^2. Following the guidelines of the DoU, we use the combination of cities (S3) and towns and semi-dense areas (S2) to generate the "urban" settlements, and the rural areas (S1) the "rural" settlements.

2.2. Workflow

The datasets used in this research have different granularity (spatial resolutions), different cartographic projections, and hold different information content. We used a number of pre-processing steps to make the data suitable for analysis. First, all datasets were re-projected into the World Mollewide equal area cartographic projection suited to produce spatial grids with cells of equal size that can also be used to estimate area and population density. Second, the seven WCMC classes were merged into one single mountain class, which we refer to as WCMC binary (WCMC_b). We excluded Antarctica from WCMC_b. We intersected WCMC_b with the continental landmasses—excluding Antarctica—derived from GADM 2.8 to generate the two mutually exclusive classes of mountain areas and lowlands of the world (Figure 1).

The spatial outline of GBMA ranges was combined with that of WCMC_b. We retained the GMBA areas intersecting that of WCMC_b and we refer to it as GMBA reprocessed (GMBA_r). GMBA_r is a subset of the WCMC_b. This spatial analysis resolves two spatial inconsistencies between the two datasets. The first inconsistency is related to scale. The GMBA is generated by encoding input data of a relatively coarse geographical scale. The encoding has generated a spatial "overflow" of some GMBA range perimeters into some water bodies or into the lowlands. The GMBA and WMC inconsistency is also due to the relatively rigid elevation threshold imposed by WCMC that does not consider as "mountainous" terrain the surfaces that lay in the proximity of shorelines. That spatial inconsistency between the GMBA ranges with that of the WCMC mountain outline was analysed in [11]. Our pre-processing shows that 15% of the total GMBA area has been clipped at the margins of the mountain range perimeters to comply with the definition of mountains set forward by WCMC_b. For the aims and scope of this analysis, we consider omitting 15% of the GMBA ranges an acceptable compromise.

For each of the three nested hierarchical spatial aggregation units—Level 1, 2, and 3—we compute the population total, population change, urbanisation based on population living in cities (S3) and towns and semi-dense areas (S2), and density. Level 1 is between mountains and lowlands; Level 2 partitions the WCMC defined mountains into the GMBA_r ranges and the WCMC surface area outside the GMBA_r ranges that we refer to as Other Ranges. Level 3 analyses the GMBA ranges by grouping the ranges further into non-populated ranges, ranges with only rural populations, and ranges with both urban and rural populations (GMBA_r urban rural). This last set of ranges are analysed based on similar urbanisation rates, population change, and density, and are grouped into trajectories of ranges with similar characteristics.

3. Results

The results are summarised in four subchapters that include an overview of population and urbanisation in world mountains (Figure 2), an overview on all the GMBA ranges, an overview of the GMBA ranges that include both rural and urban populations, and a discussion of the GMBA population trajectories.

3.1. Population and Urbanisation in World Mountains

Mountain areas included in the WCMC definition account for 1050 million people in 2015 (Table 1). The population has nearly doubled from just over 500 million in 1975. The share of mountain population over the total world population accounts for 14% and has remained constant across the 1975–2015 timespan. The GMBA mountain ranges combined account for over 703 million people in 2015, which is 67% of the total WCMC mountain population of 1050 million. The GMBA accounts for 73% of the WCMC surface. The population of the GMBA ranges increased by 78%, from 380 million in 1975 to 703 million in 2015. The Other Ranges with over 165 million people account for 27% of the WCMC population and 27% of its surface area. The Other Ranges population increased from 185 in 1975 to 350 million people in 2015, which is 33% of the WCMC population.

Table 1. Population in four epochs, population trends, urbanisation in 2015 including a breakdown for Rural areas (S1), Towns (S2) and Cities (S3), and Surface and density for the two Earth land masses subsets: the lowlands and the WCMC (Level 1); and for the two WCMC subsets, GMBA_r and Other Ranges (Level 2).

	1975 ($\times 10^3$)	**1990 ($\times 10^3$)**	**2000 ($\times 10^3$)**	**2015 ($\times 10^3$)**	**P. Change 1975–2015 ($\times 10^3$)**	**P. Change (%)**	**Urbanisation % in 2015 (S1, S2, S3)**	**Surface (km^2)**	**Density (2015) P/km^2**
Level 1 WCMC_b	578,868	761,338	879,979	105,339	474,520	82	66 (34, 31, 35)	33,284,509	32
Level 1 Lowlands	3,500,612	4,476,103	5,263,515	6,246,611	2,745,999	78	78 (25, 28, 50)	134,717,800	62
Level 2 GMBA_r	394,762	515,715	594,019	703,424	308,662	78	65 (35, 31, 34)	22,369,962	31
Level 2 Other Ranges	184,105	245,623	285,959	350,009	165,919	90	67 (33, 31, 36)	1,0914,547	32

The average urbanisation in lowlands for the Earth landmasses accounted for 78% and 66% for WCMC. In lowlands, 50% of people live in cities and 28% in towns and semi-dense areas, while in mountains 35% live in cities and 31% in towns and semi-dense areas. The percentage of the rural population in mountains is 34% while in lowlands it is 25%.

In GMBA_r ranges, urbanisation is slightly lower (65%) than that of Other Ranges (67%). In the GMBA ranges, 35% of its population lives in rural settlements, 31% lives in towns and semi-dense areas, and 34% in cities. In Other Ranges it is slightly different; 33% live in rural areas, 31% in towns and semi-dense areas, and 36% in cities. The remaining part of this analysis generates mountain range population and urbanisation statistics only for the surface area corresponding to the 1048 GMBA ranges.

3.2. Population and Urbanisation in GMBA Ranges

Population density varies across GMBA ranges. Figure 3 plots the total population (y-axis, logarithmic scale) for each range against its surface area (x-axis, logarithmic scale). The figure shows that the highly populated ranges are also large in extent. However, a number of large ranges in surface area have very little population. Only seven ranges out of the 30 largest in surface area are also among the 15 most populated. The largest mountain range—referred to in the GMBA as the "Tibetan plateau"—had less than 1 million people. Five of the 30 largest ranges in surface area have populations under 10 thousand and another 5 between 10 thousand and 100 thousand.

Figure 3 also shows the ranges populated by both urban and rural populations (GMBA urban rural) and those that host only rural populations (GMBA rural). Figure 3 shows that highly populated GMBA ranges are those with urban rural population, and make up 99.7% of the total GMBA population, while those with only rural population are smaller in size and host only 0.3% of the total GMBA population (Table 2).

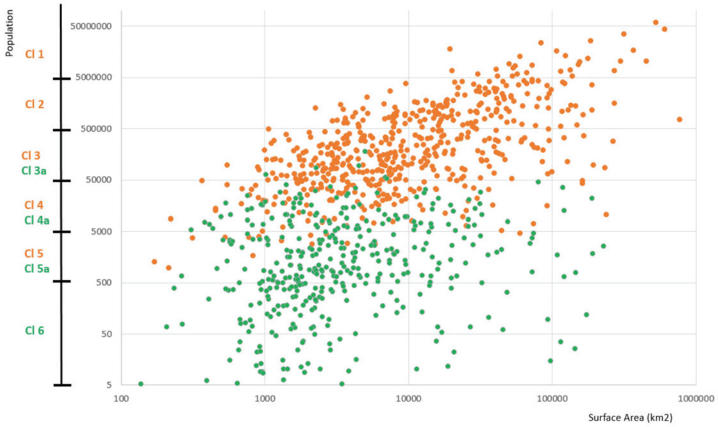

Figure 3. Population in 2015 (y-axis) and surface area (x-axis) both in logarithmic scale, for GMBA ranges with urban and rural population (red) and those with only rural population (green). The figure also shows the groupings of GMBA ranges in classes of population size. Ranges with above 5 million (Cl 1), between 500 thousand and 5 million (Cl 2), between 50 thousand and 500 thousand (Cl 3), between 5 thousand and 50 thousand (Cl 4), between 500 and 5 thousand (Cl 5), and that with fewer than 500 people (Cl 6).

Table 2. Overview of the population in the 958 populated GMBA ranges grouped in classes of size.

Cl	Class Threshold	N. GMBA	Area km^2	Area%	Population 2015 ($\times10^3$)	P_2015%	Density Inhabitants/km^2	PCh-2015-75 ($\times10^3$)	Urban Population 2015 ($\times10^3$)	Urban Population % 2015%
GMBA Mountain Ranges with urban and rural population										
1	5×10^6	30	4,834,567	21.6	412,520	58.6	85	191,667	289,252	70
2	5×10^5	154	6,586,304	29.4	240,196	34.1	36	96,640	143,633	60
3	5×10^4	248	4,443,133	19.9	45,325	6.4	10	19,653	23,156	51
4	5×10^3	118	1,524,641	6.8	3112	0.4	2	1157	1331	43
5	5×10^2	14	81,260	0.4	44	0.0	1	19	15	33
	Sub-Tot	564	17,469,906	78.1	701,197	99.7		309,137	457,386	
GMBA Mountain Ranges with only rural population										
3a	5×10^4	6	26,863	0.1	528	0.1	20	318	0	0
4a	5×10^3	101	1,235,865	5.5	1407	0.2	1	−827	0	0
5a	5×10^2	151	1,933,952	8.6	269	0.0	0	85	0	0
6	5×10^2	136	12,07,106	5.4	24	0.0	0	1.4	0	0
7	EQ 0	90	496,270	2.2	0	0.0	0	0	0	0
	Sub-Tot	484	4,900,056	21.9	2228	0.3	0	−422	0	0
	Total	1048	22,369,962	100	703,425	100		308,715	457,386	

Class 1 and 2 combined (Cl 1 and Cl 2), that of ranges respectively above 5 million and above 500 thousand people, host 93% of the total GMBA population. Ranges between 50 thousand and 500 thousand account for 6.5% of the total GMBA ranges. Only six ranges are rural, representing 0.1% (Class 3a), while all other ranges are Urban and Rural, accounting for 6.4 of the GMBA population (Cl 3). Class 4—ranges between 5 thousand and 50 thousand—accounts for just 0.6%, of which 0.4 is in urban rural ranges (Cl 4) and 0.2% in rural ranges only (Cl 4a).

Over 300 GMBA_r ranges have populations between 500 and 5000 people, 44 ranges have an urban population (Cl 5) and the other 269 ranges (Cl 5a) are all rural. There are 136 ranges with fewer than 500 people (Cl6) for a total population of 24,000, that make up 5.5% of the GMBA surface. In fact, the rural ranges cover nearly 20% of GMBA surface area and only 0.3% of its population. The class ranges are also geographically located in Figure 2.

The 394 GMBA rural ranges (Class 3a, 4a, 5a, and 6) account for just over 2 million (that is 0.31% of the total GMBA population) and cover a surface of 18% of the total GMBA mountain ranges (Table 2). 90 ranges were not inhabited in 2015 and those ranges cover 2.2% of the GMBA surface area (Cl 7). The 151 least populated rural ranges, those with populations below 5000 people, account for 23 thousand people. The ranges between 5 thousand and 50 thousand (Cl 4a) account for just over 1.5 million and decreasing population. Six ranges account for more than 50 thousand people (Cl 5a) with the most representative being the San Sao Range in Laos with over 178 thousand out of a total of over 250 thousand in the grouping.

The 564 ranges with both urban and rural population account for 99.7% of the population while occupying 78% of the total surface area (Table 2). For these 564 ranges, we carry the analysis further and analyse urbanisation rates, population changes from 1975 to 2015, and density for 2015.

3.3. GMBA Urban Rural Ranges

The 564 GMBA urban rural ranges were analysed based on three criteria: urbanisation rate in 2015, population change between 1975 and 2015, and population density in 2015. To facilitate the discussion, we created classes of GMBA ranges based on hard thresholds for the three variables. For urbanisation, we used two thresholds of 40% and 60%. Finally, we generated common trajectories of GMBA ranges based on the three variables combined.

3.3.1. Urbanisation in GMBA Urban Rural Ranges

We grouped GMBA classes based on two criteria, the presence of cities (S3) and the overall percentage of urban population (S2 and S3) (Table 3). Of the ranges that include cities (Cl_3) we grouped those with more than 60% urban (UR_C1), those between 40–60% urban (UR_C2) and those with less than 40% urban (UR_C3). Of the ranges that do not include cities, we grouped those with more than 50% urban population (UR_C4), those with urban populations between 40% and 60% (UR_C5) and those with less than 40% (UR_C6). Table 3 also shows the number of ranges per class, the total and percentage of Rural population (S1), of the population in Towns (S2), and the population in Cities (S3).

Table 3. Grouping of GMBA ranges based on the presence of cities and urbanisation rates. Ranges that host cities and urbanisation respectively more than 60% (UR_C1), between 40% and 60% (UR_Cl2) and less than 40% (UR-C3). Ranges that do not host cities but only Towns and Semi-dense areas with urbanisation more than 60% (UR-C4), with urbanisation between 40% and 60% (UR_C5) and urbanisation lower than 40% (UR_C6).

Criteria						Rural (S1)	Urban (S2 and S3)		% Rural	% Urban (S2 and S3)	
Urbanisation Class	**Cities(S3)**	**% Urban**	**Ranges**	**P_2015 ($\times 10^3$)**	**P_2015%**	**S1 ($\times 10^3$)**	**S2 ($\times 10^3$)**	**S3 ($\times 10^3$)**	**S1 (%)**	**S2 (%)**	**S3 (%)**
UR_C1	Yes	>60	163	402,305	57.4	89,134	119,861	193,310	22.2	29.8	48.1
UR_C2	Yes	40–60	92	219,851	31.4	103,121	77,204	39,525	46.9	35.1	18.0
UR_C3	Yes	<40	47	46,004	6.6	31,063	10,290	4649	67.5	22.4	10.1
UR_C4	No	>60	52	4090	0.6	1241	2849	0	30.3	69.7	0.0
UR_C5	No	40–60	71	9635	1.4	4973	4662	0	51.6	48.4	0.0
UR_C6	No	<40	139	19,309	2.8	14,277	5032	0	73.9	26.1	0.0
Total			564	701,197		243,810	219,900	237,485	35	31	34

In total, 95% of the population lives in the 312 mountain ranges that include cities (UR_C1, UR_C2, UR_C3). Less than 5% are in the 262 ranges with low-density urban population (Towns) and rural population (UR_C4, UR_C5, UR_C6). 400 million people (57%) live in the 163 ranges with more than 60% urban population (UR_C1), and 220 million in those with urbanisation between 40% and 60% (UR_C2). Only 46 million (6.6%) in ranges with urbanisation less than 40%.

3.3.2. Population Change in GMBA Urban Rural Ranges

Population in GMBA urban rural ranges increased from 392 million to 701 million. The 78.8% increase is two percentage points less than the population growth computed for the WCMC mountain surface area for the same 1975–2015 timeframe. In order to facilitate the discussion, we grouped the ranges based on the percentage of growth of the 1975–2015 timespan into 5 classes of population change (Table 4). 126 ranges (Ch_C1) show very high population growth, more than 200% from the 1975 reference. 123 ranges (Ch_C2) have more than doubled their population growth between 100–200% and we refer to them as high growth. The 127 ranges that grew between 50% and 100% are referred to as moderate growth (Ch_C3); 137 ranges that grew between 0–50% are referred to as low growth (Ch_C4); and 51 ranges reported a decrease in population (Ch_C5) as shown in Table 4. Populations that showed negative growth for all ranges combined account for just over 6 million people, a small fraction of the total change in a mountain population of 300 million.

Table 4. GMBA ranges grouped in classes of percent population growth between 1975 and 2015 (Pch_2015-75).

Change Class	Population Change %	GMBA Ranges	P_2015 ($\times 10^3$)	P_2015 (%)	PCh_2015-75 ($\times 10^3$)	Pch_2015-75 (%)
Ch_C1	>200	126	93,651	13	73,734	24
Ch_C2	100–200	123	202,460	29	119,679	39
Ch_C3	50–100	127	215,297	31	92,116	30
Ch_C4	0–50	137	156,325	22	29,706	10
Ch_C5	<0	51	33,465	5	−6098	−2
Total		564	701,197	0	309,137	100

The overall population increase occurs as expected in the most populated ranges (Figure 4). The relative increase mapped in Figure 4 shows that increase rates vary across the spectrum of GMBA size ranges and are related to the fertility rate of the region or continent. Half of the mountain population lives in ranges with relative growth ranging between 50% and 200%.

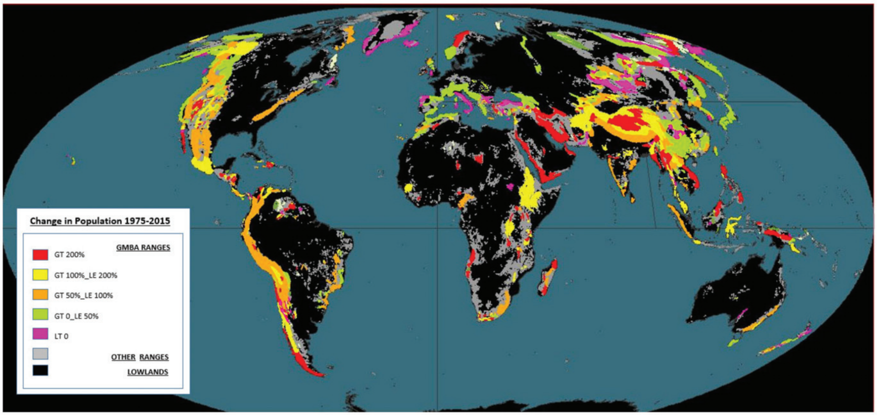

Figure 4. GMBA ranges grouped based on percent population change over 1975–2015 timeframe. The population growth rate uses 1975 as a reference year. Class 1 (Ch_C1) groups ranges growing in population more than 200%; Class 2 (Ch_C2) groups ranges growing between 100% and 200%, Class 3 (Ch_C3) ranges with growing between 50 and 100%; Class 4 (Ch_C4) ranges growing between 0 and 50%, and Class 5 (Ch_C5) ranges that decrease in population.

3.4. GMBA Ranges Trajectories

The final classification of GMBA ranges is based on a combination of urbanisation, population change over time, and density, and we refer to these as societal trajectories for the mountain ranges. We use the six urbanisation rate classes of Section 3.3.1; the five population change classes of Section 3.3.2 as well as four density classes as summarised in Table 5. Density refers to overall population density within the overall surface area of the range. We use four thresholds for density, and group ranges as follows. Densities with more than 200 people/km^2 (De_C1) are very high-density ranges; densities between 100 and 200 people/km^2 (De_Cl2) are the high-density ranges; ranges between 30 and 100 people/km^2 (De_C3) are the medium-density ranges; and ranges with fewer than 30 people/km^2 (De_C4) are the low-density ranges (Table 5).

Table 5. Codes and relative groupings of ranges used to generate trajectories.

Urbanisation			Population Change			Population Density		
Code	Label	Criteria Urbanisation (Urban Population %)	Code	Label	Criteria Population Change (%)	Code	Label	Population Density (People/km^2)
1	UR_C1	≥60	1	Ch_C1	≥200	1	De_C1	≥200
2	UR_C2	40–60	2	Ch_C2	≥100–200	2	De_C2	100–200
3	UR_C3	<40	3	Ch_C3	≥50–100	3	De_C3	30–100
4	UR_C4	≥60	4	Ch_C4	≥0–50	4	De_C4	<30
5	UR_C5	40–60	5	Ch_C5	<0			
6	UR_C6	<40						

From the 120 possible combinations of 6 urbanisation classes, 5 population change classes, and 4 density classes, we obtain 82 outcomes that we refer to as trajectories (Table S1). The 20 most populated trajectories that include 232 GMBA urban rural ranges are listed in Table 6. The trajectories are labelled based on a sequence of three digits. The first digit corresponds to the urbanisation classes, the second digit to the population change class, and the third digit the density class. Table 6 also lists the total population, the percentage population out of the total, its ranking, and the number of GMBA ranges included in these 20 trajectories.

Table 6. Trajectories combine urbanisation rate, population change rate, and overall density. The table lists the population for each trajectory, its relative population referred to the total GMBA population, the number of ranges, and the representative ranges for each trajectory.

Trajectories Grouping	Trajectories	P_2015	P_2015%	Ranking (P_2015%)	Ranges Number	Representative Range in the Trajectory
1 High urbanisation, very high growth	112	29,008,594	4.1	10	9	Malakand Range, Yemeni Mountains
	113	30,022,766	4.3	9	23	Alborz, Zagros Mountains
	114	8,720,727	1.2	19	16	Yemeni Highlands
2 High urbanisation, high growth	121	46,248,614	6.6	4	6	Abertine Riff, Parahyangan Highlands
	122	91,020,395	13.0	1	8	Ethiopian Highlands, Eje Volcanico Transversal
	123	32,407,108	4.6	7	17	Hindu Kush
	124	8,868,388	1.3	18	15	Cordillera principal

Table 6. *Cont.*

Trajectories Grouping	Trajectories	P_2015	P_2015%	Ranking (P_2015%)	Ranges Number	Representative Range in the Trajectory
3 High urbanisation, medium growth	131	9,790,163	1.4	17	5	Venezuelan Coastal Range
	132	39,371,683	5.6	6	8	Cordillera Oriental Colombia Venezuela, Western Ghat
	133	32,245,817	4.6	8	15	Cordillera Central Ecuador
	134	19,803,621	2.8	11	8	Cordillera Occidental Peru Bolivia Cile
4 High urbanisation, medium and low growth	142	11,113,490	1.6	16	6	Tell Atlas
	143	17,271,796	2.5	12	9	Qin Ling, Japanese Alps
	152	15,979,233	2.3	13	3	Chinese Ranges (Dalou, Micang Shan)
5 Medium urbanisation, medium to low growth	233	75,719,141	10.8	2	19	Himalaya
	241	12,743,486	1.8	14	1	Wumeng Shan
	242	47,654,775	6.8	3	6	Yunnan Guizhou, Daxiang Ling
	243	45,491,303	6.5	5	16	European Alps, Carpathian, Daba Shan
6 Low urbanisation, medium to low growth	333	11,846,375	1.7	15	4	Drakensberg
	343	7,596,752	1.1	20	6	Appalachian Mountains

The 20 trajectories account for 620 million people: that is 84% of the GMBA population. All 20 trajectories include GMBA ranges with cities and with urbanisation above 40% with two exceptions: trajectory 333 (Drakensberg) and 343 (Appalachian) both have urbanisation less than 40%. Each of the 20 trajectories accounts for at least 1% of the GMBA total population.

We group trajectories into six sets (Table 6). The first set of three trajectories (112, 113, 114) include high urbanised ranges that are also growing in population very quickly (above 200%). These trajectories are typical of the West Asian mountain ranges and differ in their density from high 112 to low 114. The trajectory 112 (4.1% of the GMBA population) is represented by the Makaland and Yemeni mountains that show a high overall density, trajectory 113 represented by Alborz and Zagros mountains with high density accounting for 4.3% of the GMBA population; and trajectory 114 Yemeni Highlands with medium density accounting for 1.2% of the GMBA population.

The second set of four trajectories (121, 122, 123, 124) is made of highly urbanised ranges that doubled their population in the time frame analysed. The representative ranges with the highest density (121) are Albertine Riff in Africa and Parahyangan in Indonesia; those with high density are the Ethiopian Highland (Africa) and the Eye Volcano range in Central America. Trajectory 123 includes medium-density ranges like the Hindu Kush in Asia, and trajectory 124 with low density is represented by the Cordillera Principal in Latin America.

The third set of four trajectories (131, 132, 133, 134) includes highly urbanised ranges with populations that grow slowly (between 50% and 100%). These are trajectories represented by the ranges of Latin America. Trajectory 131 is represented by the Venezuelan ranges at low latitudes that show the highest density, trajectory 132 is represented by the Cordillera of Ecuador with medium density, and trajectory 134 is represented by the Cordillera of Peru and Bolivia showing the low densities.

The fourth set of three trajectories (142, 143, 152) includes highly urbanised ranges with cities but with very slow or even negative growth. The representative ranges are the Tell Atlas with high overall population density, the Qing ling, and the Japanese Alps with low density. This grouping also includes the ranges with decreasing populations that are represented by the Dalou and Micang Shan ranges of China.

The fifth set of four trajectories 233, 241, 242, 243 includes medium urbanised ranges. The medium growth and medium density, such as the Himalayas (233). The medium urbanised trajectories with low growth include the high-density Wumeng Shang (241), medium-density Yunan and Daxiang Ling (242), and the low-density European ranges, for example, the European Alps and Carpathian Mountains (243).

The sixth set of trajectories includes ranges with no cities and low urbanisation. Drakesberg (333) shows slow growth and low density while the Appalachians have very slow growth (343) and low density. There are also relevant trajectories outside those that capture most of the population. For example, trajectory 111 identifies very high urbanisation, very high growth, and very high density. These ranges include Mt. Elgon with over two million people and the Virunga mountains with over 1 million that both are adjacent to protected areas, and the ranges with that trajectory are likely to exert pressure on the adjacent natural resources.

The representative ranges for the trajectories of Table 6 are also part of the 30 most populated mountain ranges, those with populations above 5 million people. The population, growth, and the percentage of population in cities, towns, and rural areas of these ranges is shown in Figure 5.

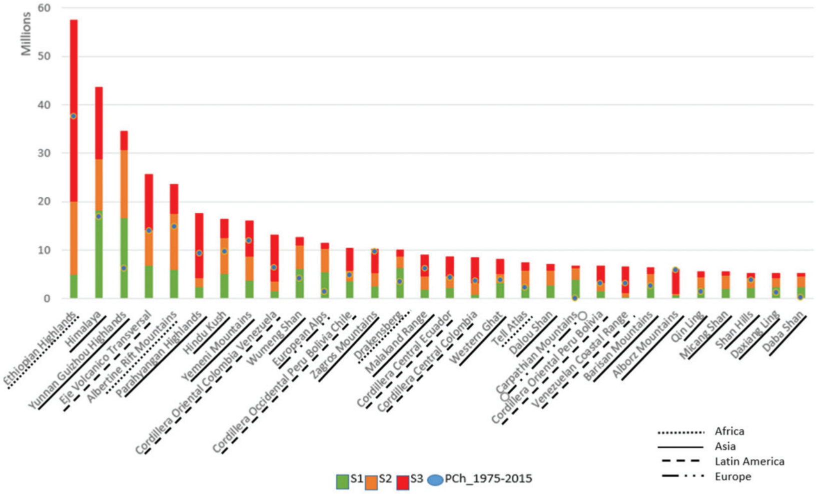

Figure 5. Population total for 30 most populated GMBA ranges with shares of Rural population (S1), Towns (S2), Cities (S3) for 2015, and Population changes over the 1975–2015 timeframe (Pch_1975-2015).

These top 30 ranges account for 412 million people in 2015, that is, 58.6% of all people in GMBA ranges. The top five ranges, The Ethiopian Highlands, the Himalayas, the Yunnan Guizhou highlands, and the Eye Volcanic and Albertine Rift Highlands, all exceed 20 million inhabitants in 2015, making up 10% of the total population living in mountains. Four of the five ranges (with the exception of the Yunnan Guizhou) also show the highest absolute population growth over the 1975–2015 periods. The combined population increase in the top five ranges amounts to 192 million people. That implies that 18% of the total mountain population since 1975 was added to just the five top populated ranges. The top 15 most populated and largest ranges are located largely in Asia and in Africa. The

European Alps and the Carpathian Mountains are the only two ranges of the European continent, with the Alps also being the largest in area at over 170 thousand km^2.

4. Discussion

In this study, we propose the combination of three demographic parameters—urbanisation, population change, and density—as an indicator of the demographic trajectories of mountain ranges. The three variables are amongst the fundamental traits of mountain socio-ecological systems. These may be interpreted as indicators of human pressure, for example, on biodiversity and ecosystem functions, as well as indicators of societal development, for example, in- or out-migration, livelihood type either for individual mountain ranges or for larger clusters of ranges with similar traits.

We show that mountain areas have a high urban population and that is relevant for sustainable development. Development investment schemas will be different if people are concentrated in cities and towns or if it is rural and towns only. Likewise, the spatial pattern of population density and demographic trends are fundamental traits for planning tailored conservation strategies for individual ranges or across those sharing similar trajectories. On the other hand, with this study, we also identify and bring to attention the mountain people inhabiting very low-density rural settings, in line with the SDG principle of "leave no-one behind".

The findings support trends identified by previous authors [12]. Our research shows that the population in mountains accounts for 14% of the total world population and that percentage varies by 1% over the 4 epochs considered. Other authors reported 12% [12,28] population living in mountains using datasets that differ in the following ways. Our work uses a reduced spatial extent of GMBA mountains as we have clipped the margin of the ranges to match the WCMC definition. However, in the overall mountain areas, we also include WCMC class 7—that of the 25 km^2 flat areas surrounding mountains. Finally, our GHS-POP is based on criteria of "residential population" while other studies [7,11,12] use the concept of "ambient population", where the population is also found along transport networks in between cities and towns and as well as on other landcover types [9]. Some authors also indicate 10% [24] population living in mountains without providing criteria on how that figure was produced.

Our global assessment excludes Antarctica as that continent is not inhabited while other recent reports include also this region in their assessment [7]. Our analysis uses open-source datasets to assure transparency and repeatability of our estimations over time. We implement and advocate for a GIS-based geographical analysis. We used open-source global datasets as the only datasets that allowed us to generate these statistics. This research should therefore be considered a preliminary assessment on mountain areas as there are no authoritative datasets that define land area, nor any dataset that defines mountain areas, or one that defines population spatial grids that is endorsed by the community.

We measured trends over time and recorded a population change of less than a decimal point within the four epochs 1975, 1990, 2000, 2015 analysed. Overall population increase in mountains is consistent with global growth rates [29] and 475 million people have been added to the mountain areas of the world from 1975 to 2015 based on our assessment. We find that the GMBA ranges in low latitudes are more populated than those of high latitudes and are also those that grow most. We have identified population trends of mountains that reflect regional fertility with high growth in Africa and South Asia, population stagnation or decline in China reported also in [30]. Population stagnation is also measured in East Asia and Europe, and moderate growth is reported for Latin America. The urbanisation figures in mountains in this research are based on the DoU and we compared it to that of the lowlands, and this constitutes a novelty and brings new findings. The DoU is often used to generate urbanisation figures using the country border as the spatial unit of reference [31]. The OECD report shows that global urbanisation rates are higher than those of mountain areas reported in this study. However, urbanisation rates in some mountain ranges are higher than global averages and urbanisation impacts environmental sustainability by generating increasing demands on environmental resources even when at lower rates [24].

This study quantifies mountain people living in dense urban areas (35%) and in towns and semi-dense areas (31%) and that the urbanisation fraction is available for all GMBA ranges. Overall, global urbanisation rates are higher than in mountain areas, and urbanisation rates for each country assessed with the same datasets and same methodology are available for reference in [32]. Regional studies do address urbanization using regional assessments [28] based on different methodologies. High latitude GMBA ranges are large and sparsely populated. No cities are included in 40% of the GMBA surface area, 20% of the total GMBA surface area accounts for only 0.3% of the total GMBA population all in rural settlements. Another 20% of the GMBA surface area hosts 5% of the population located in towns and rural settlements but not in cities.

The GMBA analysis over the 564 urban rural ranges allows us to identify patterns important for sustainable development that may not be detected in estimates from aggregated mountain populations at the country level. For example, the very high urbanisation density and population change in ranges that host natural protected areas (Virunga and Elegon Mountains), and the remarkable population decline in the Nuba mountains as highlighted in the report from the Department of International Development of the United Kingdom [33]. The Nuba population decline is striking as it comes in a continent with very fast population growth. Relevant to mention is also the high density of people in some areas of the world including the Lebanon ranges and the Parahyangan range in Indonesia. Countrywide urbanisation assessments [32] overshadow urbanisation in the diversity of trajectories for the high densely populated, urbanised, and fire-prone mountains around the metropolitan areas of the Western United States as opposed to the larger but less sparsely populated ranges of the Appalachians. The analysis also identifies and locates the stagnation and often decline of population in European ranges. The European Alps are reported to show an increase in total population, and this is probably due to the GMBA European Alps outline that captures in its perimeter larger cities, an issue already discussed in the literature [12].

Most of the GMBA ranges show an increase in population between 1975 and 2015, but 100 ranges show a decrease of at least 100 people. That overall decrease in population is relatively small. The cumulative decrease of the 100 ranges accounts for just over 6 million, 0.7% of the total mountain population. Ranges with declining populations are located in Europe (Apennines, Sardinia, Sicily, Cantabrian Mountains), in Eastern Asia with the Chinese ranges, and ranges in Turkey.

This mountain range based analysis also helped us to locate the very fast-growing population in Western Asia mountain ranges and can be compared to some adjacent countries such as Turkey, where the population in mountain areas is moderate or negative. We detected also what we feel are anomalies, possibly from the Census data. For example, the Vilikonda ranges (Eastern Ghats, India) show no population in 2015 while reporting a significant population for all previous epochs. That trend may need to be verified, as a population decline of that magnitude has not previously been reported in the literature. The mountain range based analysis may also be of use to address pressure on mountain ranges with protected areas that include more countries (i.e., Virunga mountains).

Mountain ranges continue to include a good part of the global population that continues to increase. This is important to consider in relation to the potential future development of mountain areas and the opportunities for sustainable pathways [25]. The increase in mountain population occurs mostly following the fertility trends of host nations, typically those in developing countries. Population increase in Ethiopian highlands and Himalayan foothills are to be evaluated against sustainable development targets, as development trajectories may not be sustainable under the current livelihood regime.

There are methodological challenges for work beyond this preliminary analysis of 1048 ranges. Future analysis may need to evaluate other ways to break down or compare sizes. We analyse the populations in four epochs to understand the trends in population overall. The total amount of mountain population is 14% and remains constant throughout the epochs. Additionally, 27% of mountain areas were analysed as the Other Ranges and could not be split into more meaningful units. We could however assess that the Other Ranges grow slightly faster (2%). We do not discuss in this paper the results per continent or per country even if the statistics were available based on GADM datasets. We feel country-based analysis should rely on country border datasets endorsed by United Nations agencies that can take into account the many border disputes that are often occurring along mountain ranges. An updated assessment of this work should also use new population census figures from the 2020 census.

The GMBA partitioning of mountain ranges allows a finer scale insight into single mountain ranges while maintaining the global overview for comparison. Further partitioning the WCMC areas not included in the GMBA—that we refer to as Other Ranges—would allow a better understanding of the distribution of people in that 27% of mountainous land. A systematic overview of mountains of the world would eventually require a complete outline based on topographic criteria and features based on high-resolution DEM, such as that made available by [24]. The partitioning could be based on catchments analysis or geomorphological criteria similar to that available for the European Alps. The spatial precision in outlining mountain ranges does affect urbanisation statistics, as cities and towns often occur at the interface between mountain and lowlands, and improved spatial detail may provide more precise and consistent population estimates. Beyond biophysical traits, other traits such as administrative, governance, and management units could also be considered for in-depth analyses of demographic trajectories in mountain ranges, for example, country or protected area boundaries.

Future updates of population spatial grids may provide more spatially consistent population density estimates. The procedure to generate population densities uses satellite-derived built-up layers as the spatial proxy for disaggregating population figures. The global built layers are generated from highly automatised information extraction algorithms developed to allow the processing of entire satellite archives spanning four decades for the entire globe [34]. However, the settlement detection is not error-free as shadows and rock outcrops may be confused with built-up structures. The future updates of settlement information are based on improved spatial resolution satellite sensors including that of the Sentinel sensor and have been shown to improve the detectability of settlements in mountainous areas [34]. In addition, finer reporting units recommended in the census will also increase the precision of population grids [35].

The settlement model spatial grid partitions all the built-up of the world in settlement types based on population size and density. In this research, we group the settlements into two classes, the “urban” and the “rural” classes. This provides a general assessment of urbanisation patterns in mountain ranges. Future analysis may consider additional settlement classes that may provide a more nuanced understanding of population distribution in mountains.

5. Conclusions

This study supports previous findings on mountain populations, provides more updated population trend assessments, and generates new urbanisation statistics. It confirms that mountain areas host an important share of the world population that increases in line with global population growth rates. Our analysis shows the latitudinal trends of the population in mountains, with high densities at low latitudes and very low densities at higher latitudes. Using a newly endorsed methodology that allows us to compare statistics globally, we quantify the degree of urbanisation and we show that it is also an important megatrend in mountains. One-third of the mountain population lives in cities with more than 50 thousand inhabitants, one-third in towns and semi-dense areas, and one-third in rural areas. The findings vary across mountain ranges. There are clear regional trends in urbanisation and population growth. The most relevant are the very high population growth of West Asia (with the exception of those in Anatolia) and South Asia ranges, the very low or declining population growth in East Asia and Europe; the high urbanisation and moderate population growth of the Latin America ranges.

By generating an assessment of mountain ranges, we were also able to provide insights that would be overshadowed by country-wide or regional analysis. For example, the population decline for the Nuba Mountains, the high-density fast-growing population of the Virunga Mountains, the high percentage of the rural population in some Southern Asia ranges. Mountain range based analysis also allows the assessment of differences between ranges within a country. For example, mountain ranges surrounding the Southern California metropolitan areas—the Santa Monica Mountains, San Gabriel Mountains, Santa Ynez Mountain—are highly urbanised and different from the low urbanised Appalachian ranges.

If proven useful, this approach of quantifying population urbanisation should be continued, as population change and urbanisation are key societal processes. The approach will need to be refined based on improved population and urbanisation datasets—considered essential societal variables—that could be combined with other variables for use in addressing the sustainability of mountain communities and of use to policymakers and scientists. The precondition would be to have a commonly accepted definition of mountain areas and subdivision of mountain areas into ranges or other spatial units agreed upon within the mountain research community.

Some of the improvements are already underway as the WCMC may be revisited with improved criteria and new calculations based on finer resolution DEM ranges. All mountain areas of the world should be partitioned into mountain ranges. The ranges could be classified based on climatic/topographic gradients and zones that would allow a comparison of mountain ranges in similar climate and ecological regions in order to understand the impact of possible future climate warming and develop the needed adaptation strategies.

Mountain populations change in numbers and demographic composition. People living in mountain ranges also change their livelihoods as economic and societal systems change. Some societal systems—those more related to subsistence agriculture and on livelihoods that rely only on the resource of the ranges—are more vulnerable and more susceptible to the impact of climate change, since that will change the services provided by the ecosystems as well as change the impact of disasters. This study shows that quantitative assessments of societal processes can provide useful insights into these most vulnerable mountain communities of the world and those that will be most affected by changes in the global environment. That work should be continued and integrated with quantitative ecological and biodiversity assessments on mountains.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-445X/10/3/255/s1, Table S1: List of 564 GMBA Urban Rural ranges classified based on urbanisation, population change, population density and societal trajectories.

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Water-Facing Distribution and Suitability Space for Rural Mountain Settlements Based on Fractal Theory, South-Western China

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Abstract: The establishment of rural settlements in the topographically complex mountainous area of South-Western China is restricted by various geographical features. The fractal characteristics and water-facing distribution of rural mountain settlements and the suitability of spaces for rural mountain settlements were analyzed for a greater scientific understanding of what factors would facilitate a more appropriate selection of residential sites. The results showed that: (1) Rural mountain settlements have significant fractal characteristics—the fractal dimension values of rural mountain settlements in terms of elevation, slope, disaster risk, and water-facing level ranged from 0.853 to 1.071, 0.716 to 0.997, 0.134 to 0.243, and 0.940 to 1.110, respectively. (2) The fractal dimension value of rural mountain settlements initially increased and subsequently decreased with increasing elevation, and gradually decreased with increases in slope and disaster risk, but with wave-curve increases in water-facing levels. (3) The suitable spaces for rural mountain settlements were those with a low disaster risk and with slopes less of than 5° under a water-facing level of 0 ~ 500 m in the elevation range of 1500–2000 m. Currently, 8.77% of rural mountain settlements are situated in high-risk and sub-high-risk areas. The spatial planning of national land in China may enhance the land consolidation of rural mountain settlements and plan for the placement of settlements in suitable spaces while avoiding high-risk areas and sub-high-risk areas to ensure the safety of lives and property. The results from this study could be used as a reference for future revitalization activities and the site selection of rural mountain settlements.

Keywords: fractal characteristics; natural geographical features; water-facing distribution; suitable space; rural mountain settlements

1. Introduction

Fractal theory was put forward by MANDEL-BROTBB, an American mathematician in 1975. It is used to refer to a kind of body composed of parts which are similar to the whole in some way, and then to analyze the self-organization evolution law of fractal form from the perspective of form, structure, and order [1]. The spatial characteristics of rural residential areas are irregular, unstable, and highly complex and are therefore difficult to study using traditional geometric theory [2]. However, fractal theory can provide a framework for understanding the spatial characteristics of irregular, unstable, and highly complex structures [3], and fractal characteristics are therefore very important for studying the spatial characteristics of rural settlements, especially in rural mountain settlements.

Fractal theory has been developed from the concept of "fractals", the invariant laws, levels, and scales hidden within complex natural and social phenomena [4]. Fractal models are used to study urban growth [5], urban boundaries [6], urban road networks [7,8], and have achieved reliable results. Cheng (2016) [9] analyzed the urban primacy index, the scale-grade fractal characteristics and the equilibrium and relevance of the urban systems in the mountainous Qinba area of Sichuan province. Based on the geographical features of rural settlements, Che (2010) [10] and Song et al. (2013) [11] concluded that the spatial distribution of rural settlements was self-similar, and the fractal dimension reflected the spatial occupying ability and clustering ability of rural settlements. However, most of these studies focused on urban areas, with less attention given to rural mountain settlements with a complex and varied topography.

Whether urban or rural, the development of the distribution of a settlement depends on a reliable water source. The influence of a river on settlement distributions in urban areas has been thoroughly studied. Cronon (1991) [12] and Berziant (2000) [13] purported that riverine and estuarine areas were the first and naturally advantageous areas to be considered for urban settlements. Che (2010) [10] found that the fractal dimension of the residential area was higher than that of the traffic and water system. Liu (2012) [14] studied the relationship between the distribution of 655 organized cities and the natural environment and found that a city's dependence on water is high, and the higher the city grade, the stronger the dependence. However, the effects and spatial correlation of natural geographical factors, especially the water-facing level (also known as distance to water), on the characteristics of rural mountain settlements are poorly known.

Mountainous areas are constrained by landform and physiognomy and characterized by closure. Rural mountain settlements are more constrained by geographical environments. A significant problem for rural mountain settlements is the lack of understanding on the selection of appropriate building sites. The fractal theory could help us judge the space occupying capacity of mountain rural settlements, and then identify the suitability space for mountain rural settlements. The fractal characteristics of rural settlements take on distinct spatial characteristics, with, for example, changes in the elevation, slope, and distribution of geological hazards [15]. Therefore, natural geographical factors, such as elevation, slope, water-facing level, and disaster risk, are used to analyze the fractal characteristics and distribution of rural mountain settlements. Studies of factors that influence the characteristics of residential areas have mostly examined factors separately [16]. In our study, we addressed the effect of interactions between the water-facing level and other natural geographical factors on the distribution of rural mountain settlements. The specific aims of this study were to: (1) Analyze whether the rural settlements and natural geographical factors have fractal characteristics, (2) determine the water-facing distribution of rural mountain settlements, and (3) identify the suitability of space for rural mountain settlements. We believe that the research results would provide reliable suggestions for policy-making in spatial planning for the future revitalization and site selection of rural mountain settlements in the mountainous area of South-Western China.

2. Study Region and Data Sources

The Panxi area, located in the south-western area of Sichuan province in China, is the transition zone between the Qinghai–Tibet Plateau and the Yunnan–Guizhou Plateau to the Sichuan Basin and mainly includes Panzhihua City and the Liangshan Yi autonomous prefecture [17]. The terrain of this area inclines from the northwest to the southeast with a large height difference [18]. The mountainous characteristics of the river are distinctive, with most being deep canyons. The proportion of the passing run-off water is relatively high, accounting for 73.5% of water resources in the region [19]. Four river basins (Figure 1), including the Anning, Yalong, Yantang, and Jinsha River Basins, containing more than 90% of rural settlements in Panxi area, were selected as the research areas. Data include a Landsat Thematic Mapper remote sensing image of the Panxi area (2010) using a 1:50,000 digital elevation model (DEM) of Panxi.

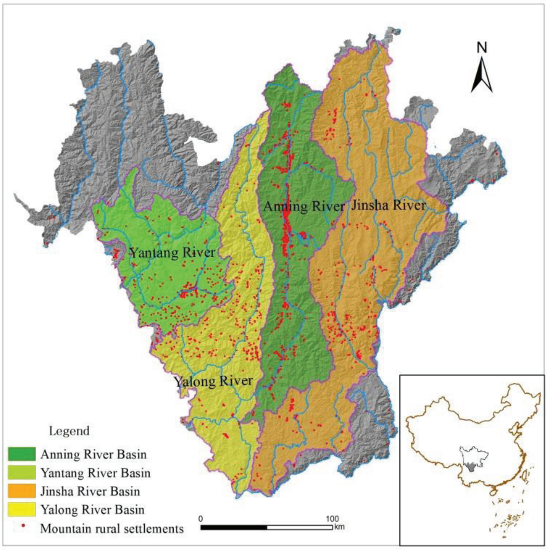


Figure 1. Sketch map of the study area.

3. Methods

In order to identify the suitability space of rural mountain settlements and judge the impact of the water systems on rural mountain settlements distribution, the rural settlements' spatial distribution characteristics on different natural geographical factors and the water-facing distribution of rural mountain settlements should be determined firstly. Then, the fractal dimension values of rural mountain settlements were analyzed to identify the most important factors affecting the fractal characteristics of settlements in the mountainous region and therefore identify the importance of suitable space for rural mountain settlements. The main applied methodology methods and research process (Figure 2) are as follows:

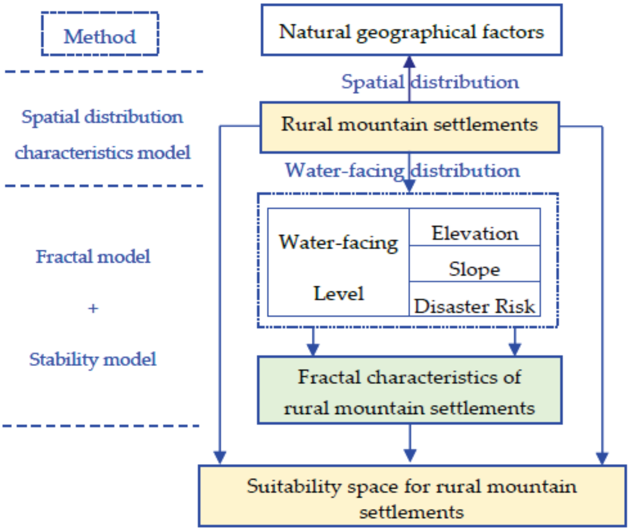


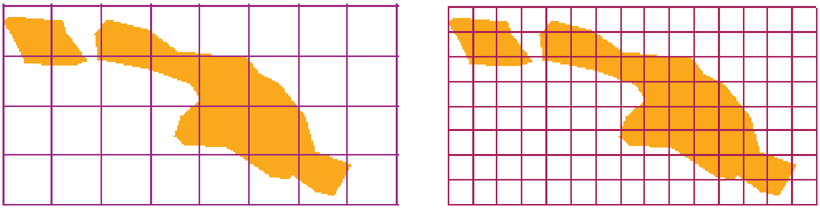
Figure 2. The process diagram.

3.1. Fractal Model

The fractal body of rural residential settlements in the south-western mountainous area is imbalanced. Therefore, we used the information-counting method [4] to calculate the information dimension of rural settlements in mountainous areas to identify the development of an orderly state, identify the spatial distribution's equilibrium degree of rural settlements, and characterize the ability of rural residential settlements to occupy space. The information dimension of the fractal model is a generalization of the box dimension (Figure 3); that is, this covers the fractal body with a small box with a side length *r or r*/2, numbers each small box, and records the probability that the part of the fractal falls into the *i* small box as P_i. The average amount of information measured using the small box of scale *r* is:

$$I = -\sum_{i=1}^{N(r)} P_i \ln P_i, \tag{1}$$

$$D = -\lim_{r \to 0} \frac{\ln(-\sum_{i=1}^{N(r)} P_i \ln P_i)}{\ln(r)}. \tag{2}$$



(**a**). Box with side length *r* (**b**). Box with side length *r*/2

Figure 3. Diagram of the information dimension.

If *I* is substituted for small box number *N*(*r*) in Equation (1), the information dimension D_i can be obtained [4].

3.2. Spatial Distribution Characteristics Model

Using ArcGIS 10.3, the spatially aggregated curves of the rural mountain settlements were established with the Variable Clumping Method (VCM) [20,21]. A GIS spatial analysis was undertaken to quantitatively analyze the spatial clustering characteristics of the rural settlements in the study area based on elevation, slope, water-facing level, and disaster risk. The clustering of rural settlements in mountainous areas was quantified by the buffer analysis, and statistical analyses of the related attributes data were carried out by SPSS:

$$VCM_i = N_i / S_i \ (i = 1,2,3, \ldots, n), \tag{3}$$

where VCM_i is the degree of spatial aggregation, N_i is the number of rural settlements in buffer *i*, and S_i is the area of buffer *i*.

3.3. Stability Model

Mandelbrot held that the fractal dimension (*D*) of the Brownian motion was 1.50, and the *D* value drew closer to 1.50 the more unstable this was. According to this principle, Xu et al. (2001) [22] defined the patch morphology stability index, S_i, as the following:

$$S_i = |D - 1.5|. \tag{4}$$

S_i is the stability index that characterizes the difference between the fractal dimension of rural residential areas and that of the Brownian motion, and is an indicator of the stability of rural residential areas. The higher the S_i value, the more stable the plaque pattern in rural settlements and vice versa.

3.4. Grading Standards

The natural geographical factors affecting the spatial distribution of rural mountain settlements mainly include elevation, slope, river, and disaster in South-Western China. Therefore, the fractal dimensions of residential points at the natural geological factors were analyzed. The grading standards for the natural geological factors are listed in Table 1—e.g., the distance grades of elevation (≤500 m, 500–1000 m, 1000–1500 m, 1500–2000 m, 2000–2500 m, and 2500–3000 m) were respectively labelled as elevation zone 1, elevation zone 2, . . . , elevation zone 6.

Table 1. Grade standards for the natural geographical factors.

Influencing Factors	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Elevation (m)	≤500	500–1000	1000–1500	1500–2000	2000–2500	2500–3000
Slope (°)	≤5°	5–10°	10–15°	15–20°	20–25°	25–30°
Disaster Risk	Low risk	Medium risk	Sub-high risk	High risk	/	/
Water-facing Level (m)	≤500	500–1000	1000–1500	1500–2000	2000–2500	2500–3000

4. Results

4.1. Spatial Distribution Characteristics of Rural Settlements on Natural Geographical Factors

Rural settlements in the Anning, Yalong, Yantang, and Jinsha River Basins account for 41.63%, 16.37%, 22.58%, and 19.42% of the total rural settlements (Figure 1).

The spatial distribution characteristics of rural settlements in terms of elevation, slope, disaster risk, and water-facing level were analyzed. A total of 81.45% of the rural mountain settlements were distributed at 1500–2500 m. As the elevation increases, the numbers of rural settlements initially increase and subsequently decrease. The number of rural settlements is the maximum at the slope of 0–5°, which accounts for 41.38% of the total rural settlements. When the buffer radius of the slope exceeds 15°, the overlapping areas between the rural settlements and the buffers decrease sharply. A total of 88.03% of the rural mountain settlements are distributed within 1 km of the river. When the water-facing level exceeds 1 km, the overlapping areas between the rural settlements and the buffers decrease. A total of 91.23% of the rural settlements are distributed in low- and medium-risk areas. As the disaster risk increases, the numbers of rural settlements decrease significantly.

4.2. Water-Facing Distribution of Rural Mountain Settlements

4.2.1. Water-Facing Distribution of Rural Mountain Settlements in Terms of Elevation

The VCM curve reflects the spatial correlation and distribution characteristics of rural mountain settlements in terms of the water-facing level and terrain (Figure 4). The overall change trend of rural settlements is the same in water-facing levels 1–6. As the elevation increases, the number of rural settlements initially increases and subsequently decreases. However, local variations in the water-facing levels are significantly different, with two major trends. At water-facing levels 1–3, the number of rural settlements is the highest at 2000 m, while at water-facing levels 4–6 the number of rural settlements is highest at 3000 m.

4.2.2. Water-Facing Distribution of Rural Mountain Settlements in Terms of Slope

According to the VCM curve of rural settlements and slopes in terms of water-facing levels (Figure 5), the spatial correlation characteristics of rural settlements and slopes undergo similar changes. There are two major trends. At water-facing levels 1–3, the number of rural settlements decreases with increasing slope, with the highest number at the slope of 5°. At water-facing levels 4–6, the number of rural settlements initially increases and subsequently decreases with increasing slope, and with the highest number at a slope of 15°.

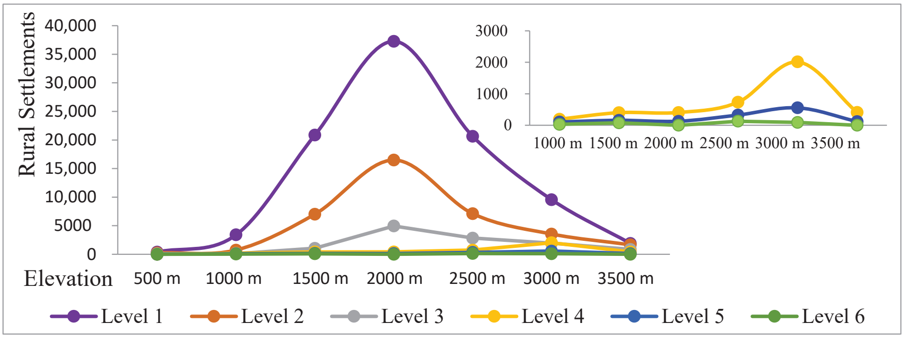


Figure 4. Variable Clumping Method (VCM) curves of rural settlements and elevation in terms of water-facing level.

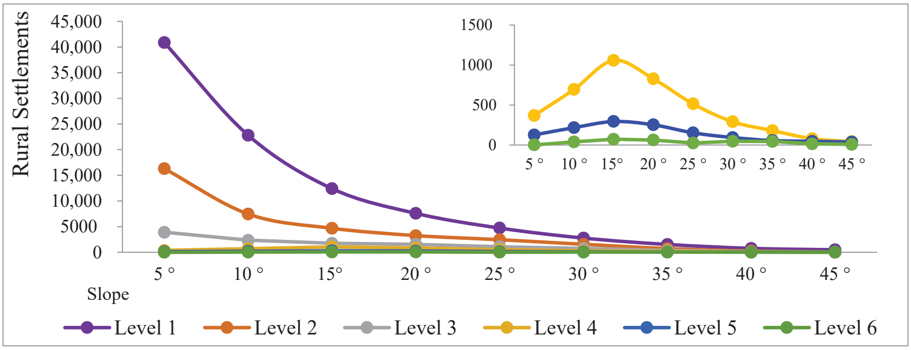


Figure 5. VCM curves of rural settlements and slopes in terms of water-facing levels.

4.2.3. Water-Facing Distribution of Rural Mountain Settlements in Terms of Disaster Risk

According to the VCM curve of the rural mountain settlements and disaster risk in terms of water-facing levels (Figure 6), the spatial distribution characteristics of rural settlements and disaster risk undergo similar changes. The number of rural settlements decreases with increasing disaster risk, with the highest number in the area at a low disaster risk.

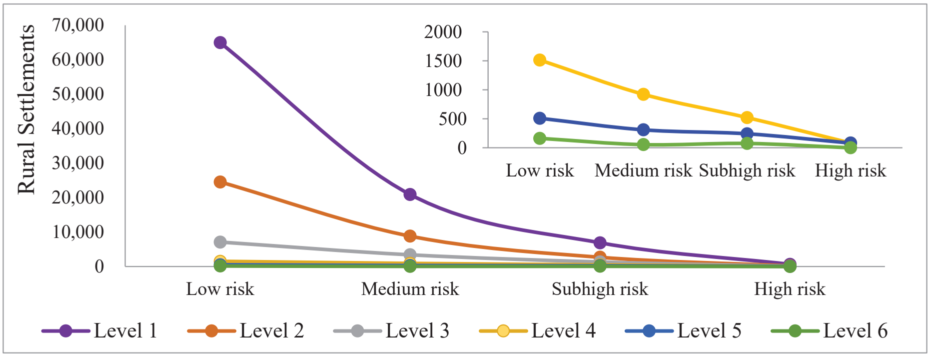


Figure 6. VCM curves of rural settlements and disaster risk in terms of water-facing levels.

4.3. Fractal Dimension Value of Rural Mountain Settlements

By creating a fishnet grid in ArcGIS 10.3 with side lengths of 100, 500, and 1000, the *ln r* and *ln I* values corresponding to different sizes of rural mountain settlements were obtained. The fractal dimension of rural settlements was subsequently obtained in the natural geographical factor zones. A double logarithmic regression analysis established that R^2 was greater than 0.99, and the rural mountain settlements' fractal dimension value was 1.17. The fractal dimension curve of rural mountain settlements showed that the effect of fractal dimension values separately on elevation (Figure 7), slope (Figure 8), disaster risk (Figure 9), and water-facing level (Figure 10) ranged from 0.853 to 1.071, 0.716 to 0.997, 0.134 to 0.243, and 0.940 to 1.110, respectively. Through comparison, the fractal dimension value of water-facing level is the highest. The fractal dimension value of disaster risk is the lowest.

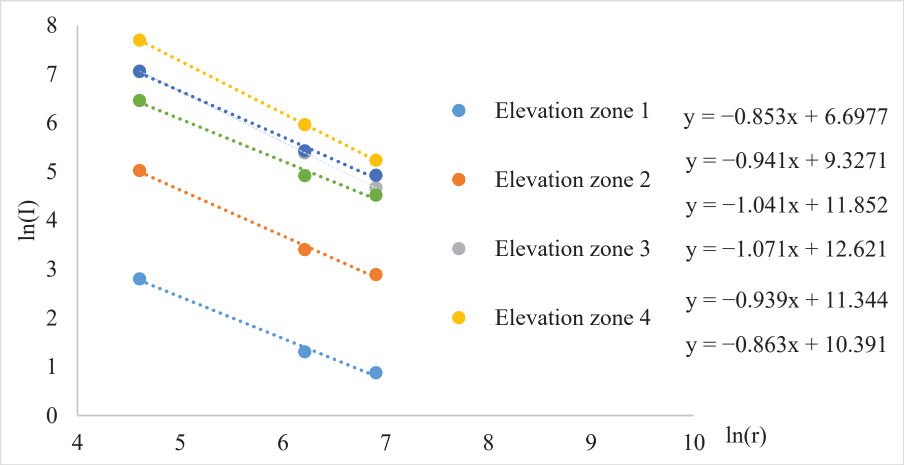


Figure 7. Fractal dimension curve of rural mountain settlements in terms of elevation.

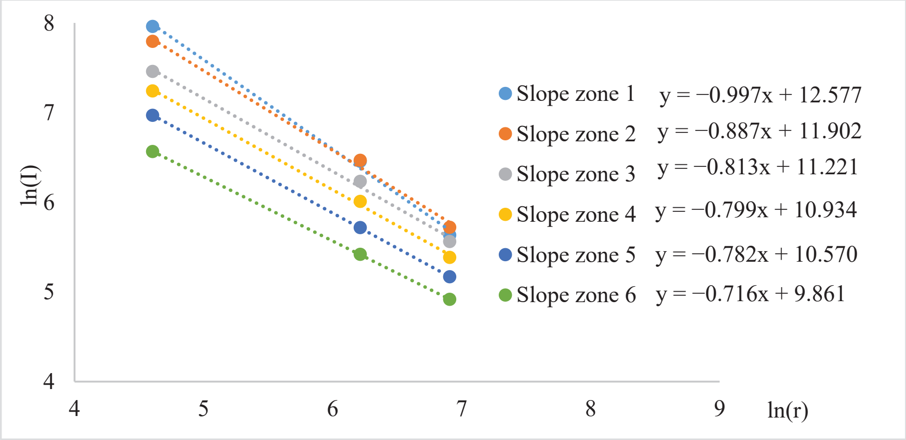


Figure 8. Fractal dimension curve of rural mountain settlements in terms of slope.

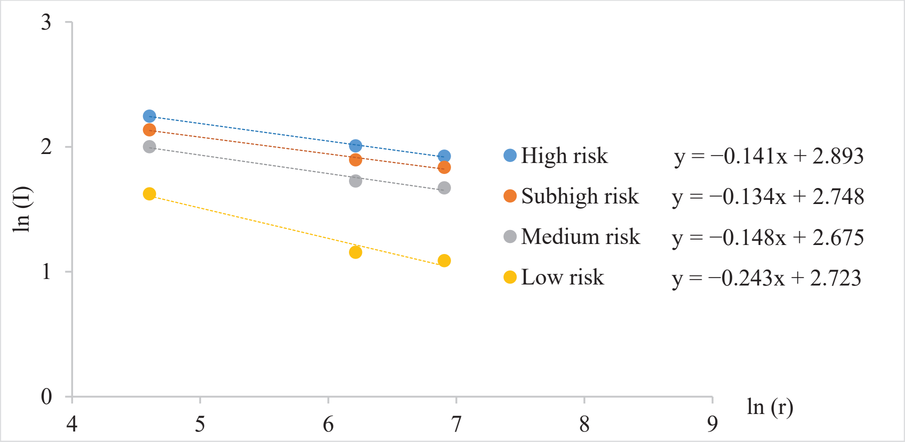


Figure 9. Fractal dimension curve of rural mountain settlements in terms of disaster risk.

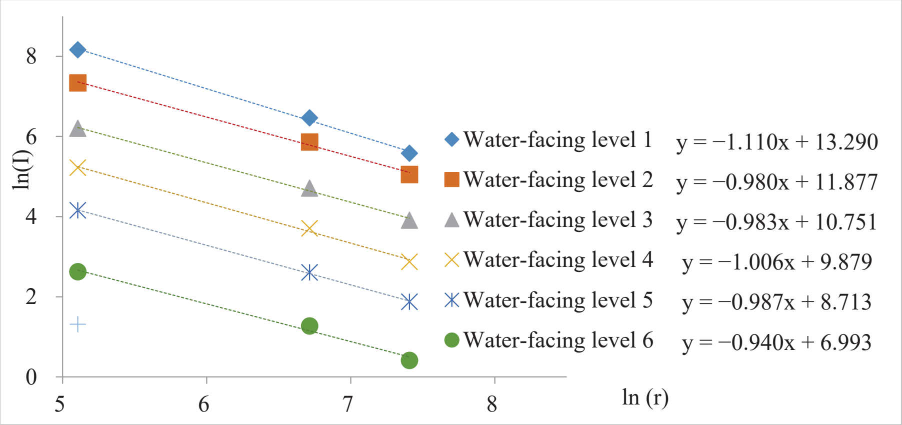


Figure 10. Fractal dimension curve of rural mountain settlements in terms of water-facing level.

4.3.1. Fractal Characteristics of Rural Mountain Settlements in Terms of Elevation

The fractal dimension of residential points at elevation zones (Figure 11) showed that with increasing elevation, the fractal dimension value of residential areas initially increased and subsequently decreased, with the highest value at elevation zone 4. The fractal dimension values of distinct zones were lower than those of the whole area by 1.17. To a certain extent, the higher the number of settlements, the higher the fractal dimension. This finding indicates that elevation is an important factor that affects the fractal characteristics of settlements.

4.3.2. Fractal Characteristics of Rural Mountain Settlements on Slope

The fractal dimension value gradually decreases with increasing slope (Figure 12). In the range of slope zone 1, the spatial structure of residential areas is the most complex and the space occupation capacity is the strongest. In addition, the variation in fractal dimension at zones 1–3 is higher than at zones 4–6, indicating that the space occupation capacity at zones 1–3 is higher than at zones 4–6, with different fractal characteristics.

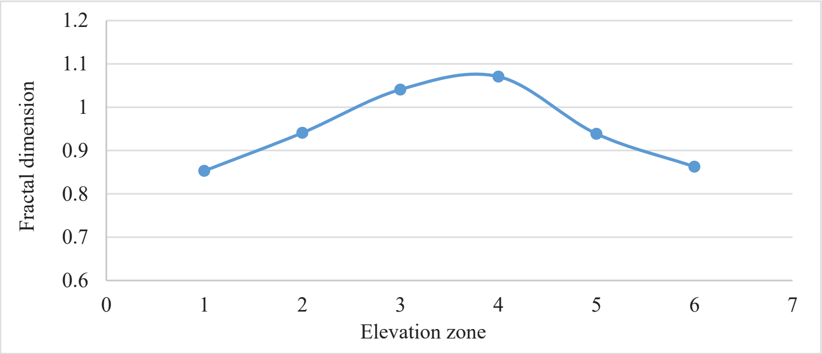


Figure 11. Fractal dimension of rural settlements in terms of elevation zones.

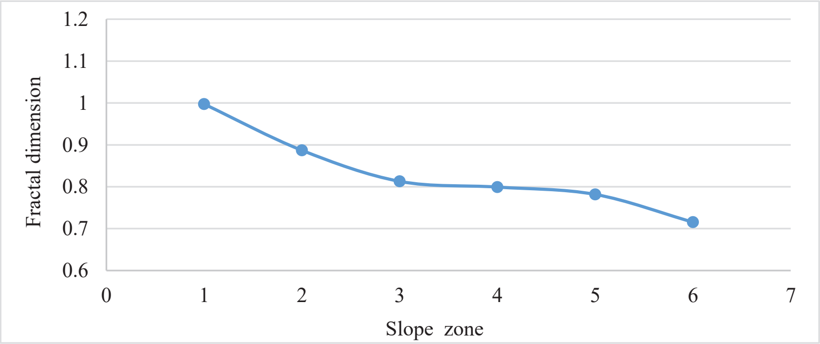


Figure 12. Fractal dimension of rural settlements in terms of slope zones.

4.3.3. Fractal Characteristics of Rural Mountain Settlements on Disaster Risk Zone

As the risk level of disasters increases, the fractal dimension value of the settlements decreases (Figure 13) in disaster risk zones. The highest fractal dimension is in disaster risk zone 1, and the distribution of settlements becomes complicated.

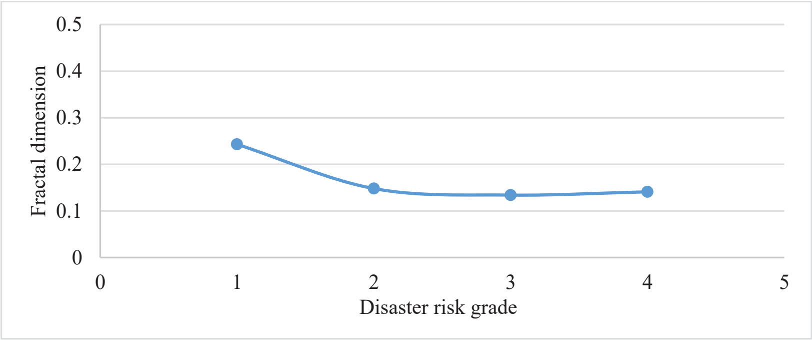


Figure 13. Dimension value of rural settlements in terms of disaster risk zone.

4.3.4. Fractal Characteristics of Rural Mountain Settlements in Terms of Water-Facing Level

The maximum fractal dimension value of rural mountain settlements in the Panxi area appeared at the first water-facing level (Figure 14), indicating that rural settlements have the strongest space occupation capacity in those areas. The fractal dimension value decreases with wave curves in water-facing levels. During spatial change in rural settlements, attention should be paid to coordinated development to avoid damage to the rivers' natural environment. Rivers play a direct or indirect role in the course of the evolution of these settlements.

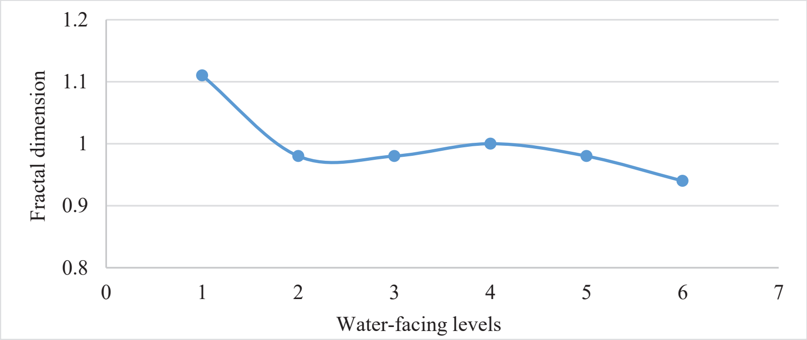


Figure 14. Fractal dimension of rural settlements in terms of water-facing levels.

5. Discussion

5.1. Water Systems Affect the Distribution of Rural Mountain Settlements

In mountainous areas, water systems play a significant role in controlling settlement distribution [17]. Restricted by the topography of mountainous areas, rural mountain settlements are situated along riversides to facilitate production and life. There is significant negative correlation (k = −1.00 ***) between water-facing level and rural mountain settlements, which means that water systems are the key factor affecting the distribution of rural settlements in mountainous areas. By comparison, most rural mountain settlements are established on the first water-facing level (Figure 15) at every elevation, slope, and disaster risk level. The first water-facing level is better than other water-facing levels for settlements, with approximately 88.03% of rural settlements being established within 1 km from the river. Therefore, we consider that the area within 1 km from the river is ideal for the site selection of rural mountain settlements because this is close to the water source and the terrain is relatively gentle, which makes it convenient for farmers to take water for irrigation. However, the mouth of the mountain gully is usually a flood passage or debris flow alluvial fan, where geological disasters are easily induced during rainstorms or extreme weather events. Therefore, to ensure the safety of life and property, areas at high risk of geological disasters within the range of 1 km from the river need to be avoided.

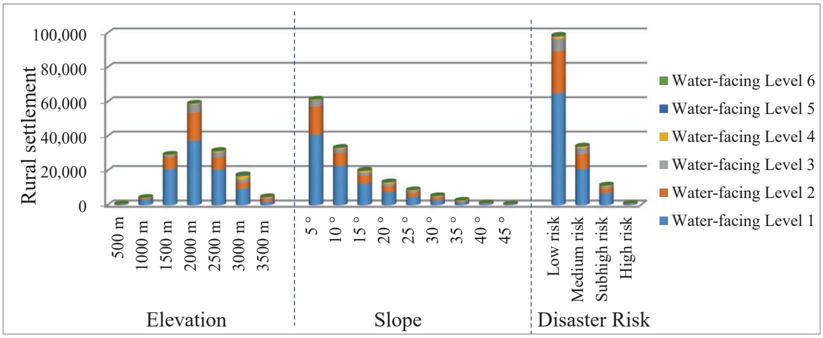


Figure 15. Water-facing distribution of rural mountain settlements in terms of natural geographical factors.

5.2. Suitability Space for Rural Mountain Settlements

There is a significant negative correlation (k = −1.00 *) between disaster risk and rural mountain settlements. The S_i of disaster risk is higher than that of elevation, slope, and water-facing level (Figure 16). To a certain extent, this indicates that disasters are one of the most important factors affecting the fractal characteristics of settlements in mountainous regions. Rural mountain settlements are most numerous in the low-risk zone with a higher S_i, indicating a more stable plaque pattern in the low-risk zone. Li (2014b) [23] identified a lack of understanding relating to the appropriate selection of establishing residential areas and therefore identified the importance of locating suitable spaces for rural mountain settlements.

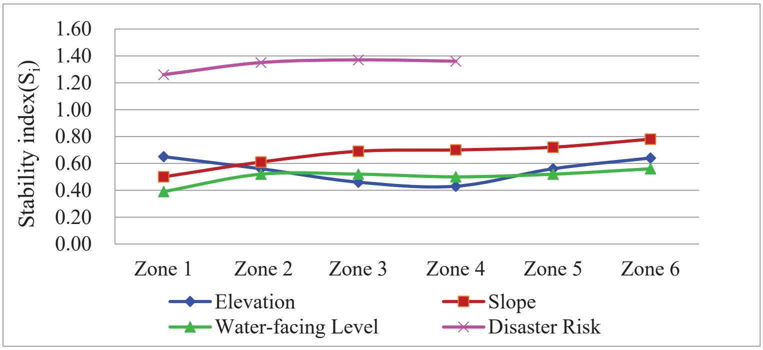


Figure 16. The stability of rural mountain settlements in terms of natural geographical factors.

According to fractal theory, the larger the fractal dimension value, the stronger the space occupying capacity and the more complex the settlement pattern [17]. On the contrary, the settlement pattern becomes simple and tends to shrink in space [2]. The results showed that the largest fractal dimension values of rural mountain settlements in terms of elevation, slope, disaster risk, and water-facing level were 0.85, 1.00, 0.24, and 1.11, respectively (Figure 17). Rural mountain settlements therefore have the strongest space-occupying capacity in disaster risk zone 1, slope zone 1, elevation zone 4, and water-facing level 1, meaning that the ideal suitability space for rural mountain settlements development (Figure 18) occurred where there was a low disaster risk and a slope of less than 5° in the elevation of 1500 m–2000 m under the water-facing level of 0–500 m.

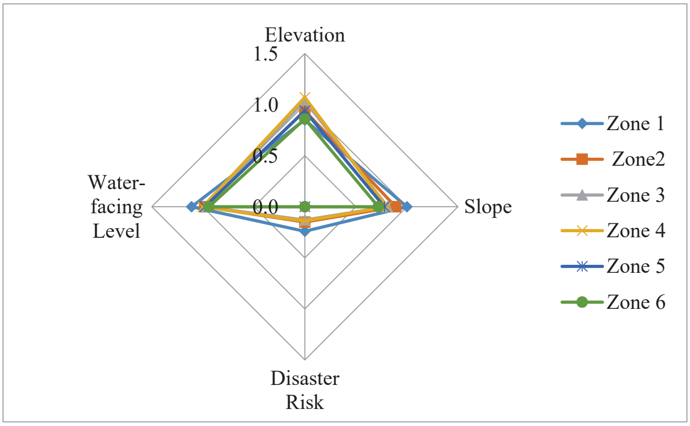


Figure 17. Fractal dimension value of rural mountain settlements in terms of natural geographical factors.

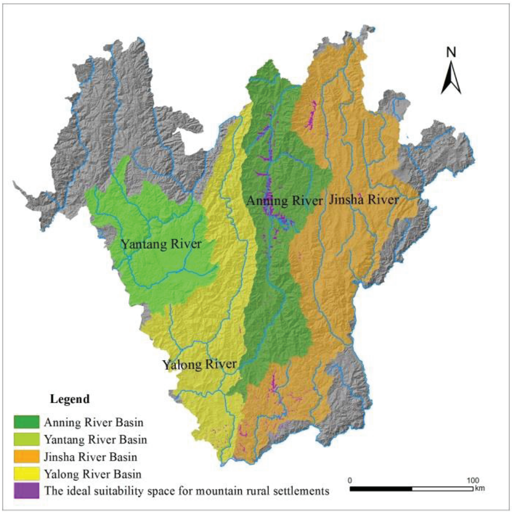


Figure 18. The ideal suitability space for rural mountain settlements.

Currently, 8.77% of rural mountain settlements occur within high-risk and sub-high-risk areas (Figures 13 and 15). These settlements have poor production and living conditions, and are in the high-risk and sub-high-risk areas (Figure 19) which are not suitable for settlement development, and need to be relocated to safer places. There is a need to formulate scientific and reasonable resettlement plans that will gradually guide population transfer to a central village that has a relatively complete infrastructure. The 3D maps (Figures 18 and 19) showing the suitable areas for the settlement development and the settlements which are in the unsuitable areas, would help us make the decision about the relocation planning where the settlement should be stopped or cleared if required.

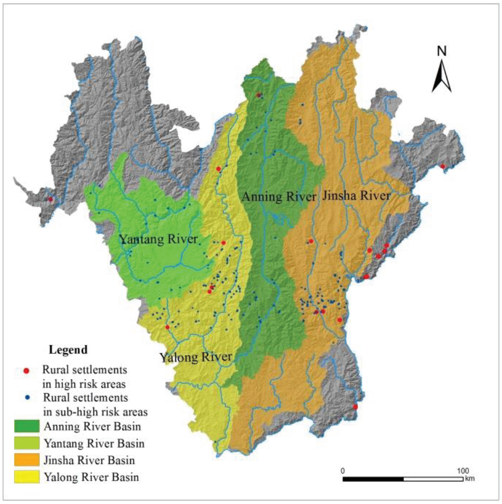


Figure 19. The rural mountain settlements in high risk and sub-high risk areas need to be relocated to safer places.

6. Conclusions

Rural mountain settlements are constrained by the geographical environment. The fractal dimension value of rural mountain settlements showed that the fitted double logarithmic coordinates were in the scale-free area. Therefore, the rural settlements and natural geographical factors all had fractal features. Through a series of analyses from the perspective of elevation, slope, water-facing level, and disaster risk, we identified the suitability of spaces for rural mountain settlements.

Water systems and disasters are the key factors affecting the distribution of rural settlements in mountainous areas. In the mountainous areas of southwest China, construction land is scarce. Rural mountain settlements are scattered and their positioning lacks systematic planning. To carry out rural construction in China, the land consolidation of rural mountain settlements should be facilitated using the spatial planning of national land. For the scattered rural settlements, the relocation planning should be undertaken to avoid settling people in high-risk areas and sub-high-risk areas, and the settlements should be arranged in a suitable space to ensure the safety of people's lives and property. It is very important to improve the life safety index and happiness index of mountain residents. The fractal characteristics and water-facing distribution of rural mountain settlements in the study area can be used as a reference for the future revitalization and site selection of rural settlements. Suitability spaces for settlement should be found to avoid high-risk areas and to ensure the safety of lives and property. The results of the study could be used as a reference for future settlement planning and development.

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Conflicts of Interest: The authors declare no conflict of interest.

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Article

VegeT: An Easy Tool to Classify and Facilitate the Management of Seminatural Grasslands and Dynamically Connected Vegetation of the Alps

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Abstract: Alpine pastures and meadows are agroecosystems of biological, cultural-historical, and economic importance that are undergoing profound imbalances and which are in a rapid decline due to changes in management and/or abandonment. The European Union is making efforts to protect this heritage and resource. However, the dialog among the different professionals in charge of studying and managing these agroecosystems needs to be as easy and comprehensible as possible for grasslands conservation/restoration actions to be successful. This research introduces VegeT, an easy-to-use tool to facilitate information transfer between botanists and practitioners responsible for providing guidelines for the correct management of mountain grasslands. VegeT is a Microsoft Excel® worksheet that allows the classification of seminatural grasslands and dynamically connected vegetation (shrublands and forests) of the Alps employing two ecological indexes: the index of nutrients (N) and the index of mowing tolerance (MV). VegeT was elaborated upon the floristic-ecological analysis of the vegetation of Taleggio Valley (Italian Alps) performed applying multivariate analysis techniques. From the analyses, it emerged that N and MV are the main variables on which to base a classification system of alpine mountain grasslands and dynamically connected vegetation able to facilitate the interpretation of floristic-vegetation data and to return useful information for management decisions.

Keywords: ecological indices; land abandonment; land management; meadows; mountain agroecosystems; mowing tolerance; mountain vegetation; pastures; spreadsheet

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1. Introduction

Mountain meadows and pastures represent agroecosystems that are, other than an important economic and historical-cultural heritage, biodiversity hotspots and elements that contribute to landscape enrichment [1–3]. The diversification of management guarantees maximum biodiversity [2]. Meadows and pastures have connoted alpine landscapes for centuries, and the uniqueness of the alpine landscape is one of the keys to the success of its touristic appreciation [3]. These ecosystems, today, are nevertheless undergoing profound imbalances in the most industrialized areas of the planet and are in rapid decline [4] mainly due to the abandonment of mountain areas by man [5,6]. It is frequent to find the bottom of alpine valleys affected by severe urbanization rates due to the conversion of grasslands in other cropping systems or human settlements. This occurrence is accompanied by the total land abandonment in the upper fascia. This is a common circumstance that has been deeply investigated and highlighted by many authors [3].

Pastures and meadows are, in fact, seminatural systems whose origin goes back to Neolithic [7,8], and they require regular and periodical management by humans: grass-mowing, manuring, sometimes irrigation, domestic animal grazing and bush removal [9]. These management interventions induce a distinct floristic composition in the different typologies of mountain grasslands that is then strictly linked to the management practices [10,11] besides the bio-geographic area.

In the last decades, and even today, the European Alps have been subject to abandonment by population [12]. This anthropic process caused the progressive neglection of agricultural practices [13–15], and then the forest expansion in areas once occupied by mountain grasslands (meadows, pastures, and meadows-pastures) [16–18]. Forest expansion is a phenomenon following the timeline and the modalities of secondary plant succession: once the grasslands start to be unkempt, their plant communities are generally replaced by herbaceous plant communities (fringes) that afterward, passing the time, give way to shrublands (mantles) and, finally, to forest communities [19,20]. This phenomenon could have an impact on the qualitative and quantitative availability of forage for domestic animals [18] from a productive point of view. In addition, the forest expansion threatens the landscape richness [21] and the conservation of some species and habitats [22] from a naturalistic and landscape management point of view. Therefore, the neglect of mountain grasslands could also trigger socioeconomic effects as the reduction of high-quality agri-food from the dairy production chain [3] or beekeeping [23].

Due to their biological and landscaping importance, European Union included meadows and pastures among the ecosystems to safeguard under Habitats Directive (92/43/EEC) [24], which is the most important European legislation for nature conservation. Further, in the last years, many projects (at a local, national, or international level) focusing on safeguarding or restoring some alpine agroecosystems (among which mountain pastures and meadows) were launched. Some examples are the projects promoted by Rural Development Programs financed by the European Union (UE Regulation 1305/2013) [25]. In order to be successful, safeguarding and restoring projects need actions that require the involvement of actors with different roles and expertise who can be able to dialog in an agile and comprehensible way. Very often. The bodies managing the alpine resources (municipalities, parks, regions, etc.) do not have technically qualified staff able to analyze complex agroecosystems as mountain grasslands, so they turn towards experts/professionals as environmental scientists or botanists.

One of the most used and effective approaches to understanding grasslands characteristics is a floristic-vegetation analysis [26]. It is mainly operated by phytosociological, who collect data on the floristic composition of plant communities (performing phytosociological relevés) with the principal goal of defining "plant associations" and frame them in a hierarchical classification system (syntaxonomic scheme) by statistical analysis techniques as cluster analysis. The plant association is the base unit of phytosociology defined as: "a system of vegetal organisms with a floristic composition that is statistically repetitive; it is a range of different features such as the structure, the ecological value (significant for different environmental parameters) and the quality of the dynamic and catenal relationship that it has with other communities [27]. Especially pertinent for this definition and identification is the characteristic specific complex, consisting of the preferring plants which are particularly linked to it in statistical terms and that are biogeographically and ecologically differential compared to similar synvicariant or geosynvicariant associations" [27].

Technical-scientific reports produced by phytosociologists have a high technical level of information (floristic composition and species abundance of each plant community allocated in *syntaxa*: phytosociological classes, orders, alliances and associations). However, they are regrettably difficult to understand by a non-specialist in the field, such as land managers. In fact, they are widely descriptive and/or constructed on long tables (phytosociological tables) containing the abundance/dominance indices of each species of every phytosociological relevé divided in *syntaxa* [28]. This results in criticalities concerning their usage outside the circle of phytosociologists, among which the difficulty for land managers to interpret and use them for designing and realizing the appropriate practices for meadows management/protection. This could be overcome by building tools to simplify the information exchange among botanists and practitioners who, in the different alpine Macro-region countries [29], manage the agricultural and natural resources of the Alps. The land managers are often agronomists, foresters, geologists, architects or engineers and not botanists.

This research, supported by the Department for Regional Affairs and Autonomies (DARA) of the Italian Presidency of the Council of Ministers, has the goal to develop an easy-to-use tool able to translate the floristic-vegetation data collected by botanists into useful and comprehensible information for technicians in charge of providing guidelines for the preferred management/conservation/restoration of mountain grasslands of the Alps. The aim was to elaborate this tool by analyzing ecological and floristic characteristics of grasslands and other vegetation linked to them by dynamic-catenal relationships (shrublands and forests) [19], using a case study in Taleggio Valley (Southern Alps, Italy). Shrublands and forest species may be considered indicators of lack of management of the mountain grasslands since some young individuals of shrubs and trees may inhabit grasslands modifying the floristic composition (and then the vegetation typology) even before the physiognomy (aspect) changes.

2. Materials and Methods

2.1. Study Area

Taleggio Valley is an area of about 66 km^2 situated in Northern Italy (Lombardy region, Bergamo province; latitude: 45°53′40″ N; longitude: 9°34′20″ E) in the Orobic pre-Alps (Figure 1). It is enclosed in Taleggio and Vedeseta municipalities, and it is partially enclosed in the Orobie Bergamasche Regional Park [30,31] and in "Valle Asinina" site of community importance (SCI IT2060007 managed by the Orobie Bergamasche Regional Park). The park was established in 1989 and protects endangered species (plants and animals) and habitats of community interest. Some human activities are allowed in the park, including grazing of cows/sheep/goats.

Taleggio Valley is a typical alpine valley characterized by a mainly mountainous territory (elevation range: 700–2050 m a.s.l.) and a low population density (11 inhabitants per km^2) [32,33]. It develops mainly on calcareous-dolomitic rocks but also on terrestrial rocks of the Mesozoic Era (252–65 million years ago) [34]. From a climatic point of view, it is enclosed in the temperate oceanic bioclimate zone [35]. The annual rainfall of the Taleggio Valley is 1998 mm (with a winter minimum), while the average annual temperature is 10 °C (data source: Regazzoni R. climatic station, 1977–2011).

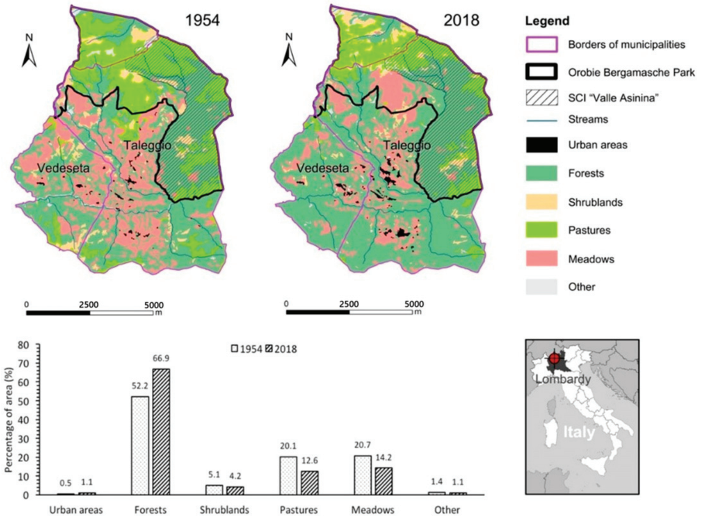


Figure 1. Geographic location of the study area (Taleggio Valley) and land-use changes from 1954 to 2018 (data source: [33]). Orobie Bergamasche Regional Park was created in 1989.

Taleggio Valley belongs to the Insubric district [36] of Central and Eastern Alps ecoregional section (alpine Province) [37]. The Central and Eastern Alps ecoregional section is 126,000 km^2 wide, and it is constituted by alpine territories with similar climatic features, physiography (litho-structural regions and morpho-tectonic sectors), biogeography and vegetation (potential vegetation complex and flora). It includes a considerable amount of the alpine Province, and it is constituted by an oceanic temperate climate at the uppermost elevation and temperate continental in interior valleys: precipitations range from 570 mm up to 2600 mm (with winter or early spring minimum) while the mean annual temperature ranges between 2 °C and 14 °C [37].

The potential vegetation of the study area is composed by the forest of *Tilio platyphylli–Acerion pseudoplatani* phytosociological alliance in the valley bottom and by the forest of *Aremonio agrimonioidis–Fagion sylvaticae* alliance in the mountain belt [38,39], the latter being the dominant forest typology of the whole study area. Today, the Taleggio Valley forests cover 67% of the area, and the anthropogenic grasslands (meadows, meadows-pastures, and pastures) cover just 27% [33] (Figure 1). In the last decades and even today, due to the loss of population and consequently the reduction of agricultural activities (both inside and outside the Orobie Bergamasche Park), forests gradually expanded to the detriment of grasslands (Figure 1), which were replaced by shrublands and then forests, following the secondary plant successions processes [20,39]. This phenomenon is not exclusive to the studied area but is common to many marginal areas of the Alps [12,18].

2.2. Vegetation Sampling

The following vegetation types of the mountain belt (720–1710 m a.s.l.) of Taleggio Valley were considered in this research:

- A—meadows: grasslands regularly mowed (from one to three times a year) and manured once a year for the past 10 years or more;
- B—meadows-pastures: grasslands that have been managed as meadows (mowed and manured) or pastures (grazed by cattle) alternatively for at least five years or that are regularly mowed once a year (on May–June) and then grazed (August–September);
- C—pastures: grasslands, with the occasional presence of small shrubs that have been grazed by cattle for more than ten years;
- D—shrublands: areas dominated by shrubs grown where grasslands have not been managed for at least five years;
- E—forests: vegetation dominated by woody species (trees cover over 60%), *Fagus sylvatica* (beech) in particular, managed to produce firewood or unmanaged (current potential vegetation [27]).

The information about the territory management was gathered by interviewing 27 local farmers and extrapolated from maps on land use supplied by management bodies (municipality of Taleggio and Vedeseta). This preliminary work out allowed the individuation of 7 meadows, 6 meadows–pastures, 5 pastures, 7 shrublands and 7 forests included in the five types described (A, B, C, D and E).

Further, the local farmers provided the following guidelines concerning the meadows and pastures of Taleggio Valley management: meadows located under 1200 m a.s.l. are mowed at least twice a year while the ones at higher altitude are mowed just once a year; meadows are manured with ripe manure (by manure spreader and distributing an average 2 kg of ripe manure per square meter) once a year before winter; pastures are grazed by adult cattle or heifers of Italian Friesian and/or Brown Swiss, in a range from five to ten units per hectare; the most neglected pastures and meadows are those characterized by lack of accessibility or excessive slope (over 30%) making mechanized operations impossible.

Floristic data of these vegetation types were collected performing 48 phytosociological relevés in accordance with the method of Braun-Blanquet [40]: species of the plant communities were identified using the dichotomous keys of [41], and their coverage was estimated using the conventional abundance/dominance scale of Braun-Blanquet (Table 1). The relevés were performed in June–July

2018 and 2019 on a surface of 25 m^2 (5 × 5 m) for meadows, meadows-pastures and pastures, and on a surface of 100 m^2 (10 × 10 m) for shrublands, and 400 m^2 (20 × 20 m) for forests. For each meadow (n = 13 relevés), meadows-pasture (n = 6 relevés), pasture (n = 7 relevés), shrubland (n = 14 relevés) and forest (n = 8 relevés), from 1 to 3 relevés were performed based on the dimension and heterogeneity of plant community.

Table 1. Meaning of the abundance/dominance indexes of Braun-Blanquet [40] and transformation values proposed by [42].

Abundance/Dominance Indexes of Braun-Blanquet	Plant Coverage	Transformation Values of Abundance/Dominance Indexes
r	rare species in the relevés	0.01%
+	<1%	0.50%
1	1%–5%	3.00%
2	6%–25%	15.00%
3	26%–50%	37.50%
4	51%–75%	62.50%
5	76%–100%	87.50%

The data of the relevés were arranged in a matrix (relevés x species) where abundance/dominance indexes of every species were converted into the percentage of coverage as proposed by [42] (Table 1) to perform numerical and statistical analysis.

The scientific names of the species and the name of the syntaxa are in accordance with [41,43], respectively.

2.3. Ecological Indices and Data Analysis

The conventional ecological indexes of Landolt [44,45] (T, temperature; K, continentality; L, light intensity; F, soil moisture; R, substrate reaction; N, nutrients; H, humus; D, aeration) and mowing tolerance index (MV), reported in tables published in [45] or in the software "Flora Indicativa" [45], were used to analyze the ecological characteristics of the different vegetation typologies. For every relevé, the average value of each index (weighted by the percentage of coverage of every single species) was calculated. To do this, "0" value was used instead of the symbol "-" (species not tolerating annual cut or grazing) of MV index and records identified with "x" symbol (species with a wide range of variation) were excluded. Average values of Landolt indexes of each relevé were calculated.

Detrended correspondence analysis (DCA) was performed on the matrix of the relevés to assess plot grouping in each vegetation type and to detect similarities in species composition. Further, a DCA considering floristic data and average values of ecological indexes of each relevés was performed in order to seek the relationships between vegetation types and environmental variables (Landolt indexes). These variables values were then analyzed by ANOVA test (once the assumptions of normality of group data and homogeneity of variances were verified using the Shapiro–Wilk test and Levene's test, respectively) in order to validate significant differences ($p < 0.01$) among the five different vegetation typologies. When significant ecological differences were found among vegetation types, the Tukey post hoc test [46] was carried out to detect the difference between each pair of vegetation types. These statistical analyses were performed using R 3.5.2 [47] and considering first all vegetation types and then grassland types alone. To develop a classification system of grasslands and create a tool (VegeT) able to return useful information for management purposes, particular attention was devoted to the analyses of those indices able to give information regarding grasslands management. These indices were: N, which relates to the level of manuring of grasslands, and MV, which relates to the use intensity of the pasture or the frequency of mowing of the meadows [44,45]. The differences concerning the range of N and MV relating to the different grassland types were analyzed and used to calibrate the grasslands of Alps classification tool VegeT, elaborated using Microsoft Excel® software. Considering that few highly intensive grasslands can be found in Taleggio Valley, some relevés drawn from the scientific literature were used to improve the calibration of VegeT. In particular, six relevés of *Rumex alpinus* communities (*Rumicetum alpini*) [48] and one relevé performed in an overgrazed pasture [18] were used (Table S1).

3. Results and Discussion

3.1. Floristic and Ecological Features

Two hundred sixty-one species were identified (Table S2) to be the most widespread in the alpine region [49,50] in management systems like the ones of Taleggio Valley. We found 98 species in meadows, 87 in meadow-pastures, 89 in pastures, 173 in shrublands and 84 in forests. DCA biplot (Figure 2) showed the floristic differences among the diverse vegetation typologies. Along the first axis (DCA1), forests were distinct from the other vegetation types thanks to the presence of some tree and herbaceous species of *Fagetalia sylvaticae* order [43,51] such as *Fagus sylvatica*, *Helleborus niger*, *Hepatica nobilis*, *Cyclamen purpurascens* and *Euphorbia amygdaloides*.

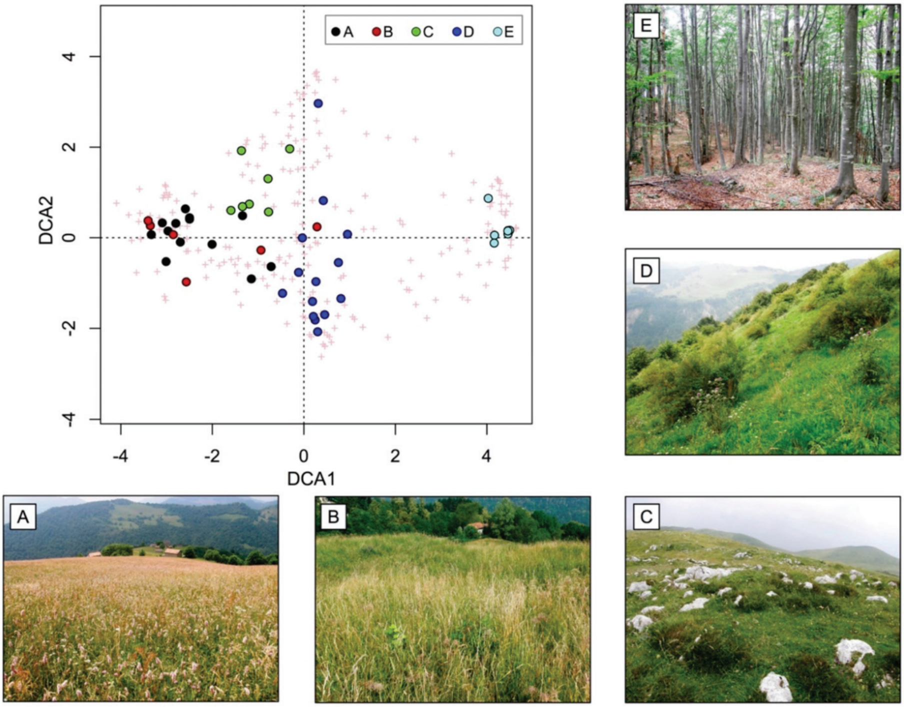


Figure 2. Detrended correspondence analysis (DCA) biplot of relevés. Capital letters indicate the five types of vegetation: (**A**) meadows (number of species: 98); (**B**) meadows-pastures (number of species: 87); (**C**) pastures (number of species: 89); (**D**) shrublands (number of species: 173); (**E**) forests (number of species: 84). Eigenvalues for the first four axes of DCA are reported in Table S3.

Along the first axis of the DCA biplot (Figure 2), grasslands (meadows, meadows-pastures and pastures) separated from shrublands which, although having some ecosystem-specific woody species (such as *Rubus idaeus*, *Rosa canina*, *Salix caprea*, *Betula pendula* and *Laburnum alpinum*) share some other species with grasslands (such as *Achillea millefolium*, *Dactylis glomerata*, *Hypericum maculatum* and *Centaurea nigrescens*). Meadows, meadows-pastures, and pastures have several species in common, but also some specific ones. In particular, meadows and meadows-pasture are characterized by the presence of species of *Molinio–Arrhenatheretea* class (such as *Trisetum flavescens*, *Polygonum bistorta*, *Trifolium pratense*, *Rumex acetosa*, *Poa pratensis*, *P. alpina* and *Arrhenatherum elatius*) while pastures are rich in species of *Festuco–Seslerietea* class (such as *Sesleria varia*, *Horminum pyrenaicum*, *Primula glaucescens*, *Carex sempervirens* and *Anthyllis vulneraria*), vegetation typologies common in all the alpine region [43,51–53].

One-way ANOVA test results (Table 2) showed that no significant differences were found among the different vegetation typologies regarding indexes F and R, while there were significant differences ($p < 0.01$) for MV, N, D, L, K and T.

Table 2. One-way ANOVA results of the effect of the vegetation type on ecological indices of Landolt [45]: T, index of temperature; K, index of continentality; L, index of light intensity; F, soil moisture index; R, index of substrate reaction; N, index of nutrients; H, index of humus; D, aeration index; MV, mowing tolerance. Key: *, significant ($p < 0.01$); ns, not significant.

Source of Variance	Mean Square	$F_{4,43}$	p	
T	0.55	14.99	<0.01	*
K	0.71	7.91	<0.01	*
L	7.71	54.56	<0.01	*
F	0.11	1.73	0.16	ns
R	0.03	0.23	0.91	ns
N	1.06	4.67	<0.01	*
H	0.16	1.14	0.35	ns
D	1.21	8.39	<0.01	*
MV	14.63	54.01	<0.01	*

From the floristic analysis of the mountain grasslands of the Taleggio Valley, it emerged that meadows, pastures and meadows-pasture are mainly constituted by species widespread in all the Alps, while from the ecological analysis, it emerged that the different vegetation types are significantly different in N and MV indices, those returning the most of the information regarding the management of the grassland. T, K, L and D highlighted instead of the differences among the grasslands and the other typologies considered. All the indices were useful for the vegetational framework of the area, but N and MV returned specific information for the management of grasslands. In fact, the L index made it possible to distinguish grasslands (composed mainly of heliophilous species) from forests (constituted by many sciaphilous species). At the same, T, D and K resulted significantly different for the various vegetation typologies (Table 2) due to the characteristics of climate (mainly dependent on elevation) and soils of the areas where the plant communities are localized, but they do not provide information on their management.

Figure 3 shows the two DCA biplots that display the relevés ordered according to their floristic composition and their values of ecological indexes, the trends of MV and N are also shown. Grasslands had high MV values while shrublands had values inferior to 2.5 and forests to 0.5. Concerning grasslands, the MV trend generally showed values higher for meadows and lower for pastures, although some overlapping was also observed. Value 3.2 of the N index returned a more noticeable distinction among meadows and pastures. From the graph of Figure 3b, in fact, it is possible to see that most of the meadows have N higher than 3.2, while most of the pasture has an N index lower than 3.3. Meadow-pastures had very variable values that follow both the trends of meadows and pastures. These results are also confirmed by the DCA performed, considering only the grasslands relevés (Figure A1).

Figure 4 boxplots confirmed what was mentioned above and show Tukey's test results evidencing the significant difference for MV ($p < 0.01$) among grasslands, shrublands and forests and showing that meadows and meadow-pastures are significantly different from pastures thanks to N values (lower in pastures).

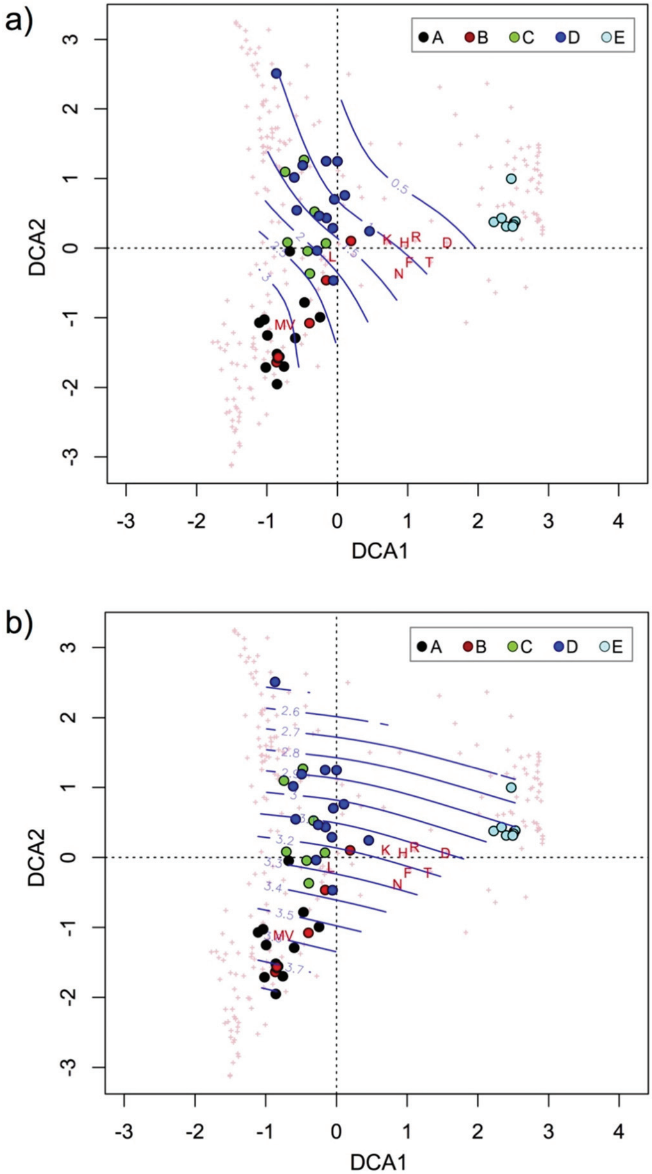


Figure 3. DCA ordination of relevés overlapped with the MV (mowing tolerance, (**a**) and N (index of nutrients, (**b**) contour lines. The points indicate the relevés: A, meadows (number of species: 98); B, meadows-pastures (number of species: 87); C, pastures (number of species: 89); D, shrublands (number of species: 173); E, forests (number of species: 84). Landolt values (T, index of temperature; K, index of continentality; L, index of light intensity; F, soil moisture index; R, index of substrate reaction; N, index of nutrients; H, index of humus; D, aeration index; MV, mowing tolerance) and species (crosses) are plotted. Eigenvalues for the first four axes of DCA are reported in Table S3.

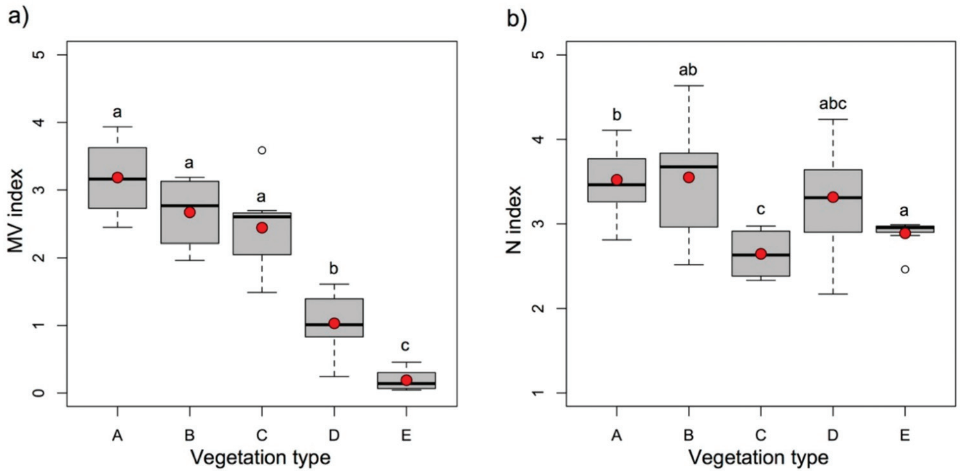


Figure 4. Boxplots of the distribution of mowing tolerance index (MV) (**a**) and index of nutrients (N) (**b**) for each vegetation type (A, meadows; B, meadows-pastures; C, pastures; D, shrublands; E, forests). For each boxplot, mean (red dot) and median (black line) are highlighted. Different letters above the boxes indicate significant differences ($p < 0.01$) among vegetation types: A, meadows; B, meadows-pastures; C, pastures; D, shrublands; E, forests.

Our results indicate that N and MV indexes are useful for creating a classification system of grasslands (and connected vegetation) based on their management. N index indicates whether the soil of the grassland considered is rich or poor in nutrients. This index is expected to be higher in meadows than in pastures as meadows are manured every year while pastures are not. In fact, meadows are generally colonized by less nitrophilous species [1,9]. This aspect also emerged in our study area, where pastures are inhabited by more oligotrophic species than meadows (Figure 4). Only in some cases, pastures or meadow-pastures can be characterized by a high presence of nitrophilous species (hyper-eutrophic pastures or meadows-pastures). This can happen in the plains where cattle were/are kept for milking and/or night rest (resting and milking areas). These areas are dominated by tall nitrophilous grass not palatable for cattle as *Rumex alpinus* and other of *Rumicion alpini* alliance [43], which grows abundantly where the animal excretions enrich excessively in nitrogen and other nutrients the soil [9,53]. This vegetation type, widespread on the entire alpine region, [18,43,48,51], is not widespread in the Taleggio Valley, where we only had one relevé (Table S2, relevé 9). N index values help define guidelines on the necessity of increasing or reducing the manure quantity distribution on a meadow or on diminishing the cattle stationing in a pasture or a meadow-pasture. For example, in oligotrophic or mesotrophic grasslands, manuring should be encouraged to preserve the presence of species requiring soils rich in nutrients, while fertilization should be reduced for nitrophilous grasslands such as those found in some alpine areas intensively managed [54]. For nitrophilous pastures or meadow-pastures, actions to reduce the nutrients input in the soil as refraining from manuring and/or not letting the cattle stationing too much should be considered. Although index N can return information on the nutrient quantity in the soil, manuring some particular kinds of oligotrophic pastures must be evaluated with attention. In fact, some oligotrophic pastures of *Festuco–Seslerietea* class (alpine and subalpine calcareous grasslands) are included in the Habitat Directive (92/43/EEC), and to preserve them in their original conditions, the enrichment of the soil with nutrients must be avoided [53].

While the N index helped distinguish meadows from pastures and also helped suggest management guidelines (increase/reduce nutrients), MV allowed for a clear separation between grasslands and other vegetation typologies (shrublands and forests). MV, compared to N, was elaborated only in 2010 [45]; it has not yet been widely used in plant ecology. It is based on [55,56] research and synthesizes the grass tolerance to three disturbance factors: mowing, trampling and grazing [45]. Briefly, this index allows distinguishing vegetation were shrubs or tree and/or grass not tolerating mowing/trampling are dominant from vegetation composed mainly of herbaceous species resilient to mowing, trampling and grazing. In our research, MV values decreased from meadows to pastures (Figure 4), and this was mainly due to the presence of small individuals of shrub species also in actively managed pastures (for example, *Calluna vulgaris*, *Erica carnea*, *Vaccinium myrtillus*, *Thymus* spp.) while such shrubs were never found in regularly mowed grasslands (meadows). This index also shows information about land abandonment or management changes requiring guidelines for the conservation/restoration of grasslands. In fact, grasslands without a high MV index are probably composed of plant communities with the presence of shrubs and/or grass not tolerant mowing, and this means that mowing is not correctly or regularly performed, and then the land is no longer managed as meadows. The same happens for pastures: those with a low MV value are not actively managed, and shrubs and/or trees are becoming increasingly abundant at the expense of herbaceous species characteristic of pastures. The information returned by the MV index seems very useful for territorial stakeholders, as it could help them identify which grasslands are undergoing (or underwent) management changes or abandonment and to help them in starting targeted actions to preserve/restore them. These actions are mowing/removing trees and/or shrubs to restore the pastures and regularly mowing to restore meadows.

3.2. VegeT

A classification system was elaborated and calibrated based on MV and N indexes (Figure 5). This activity was based on the results obtained from the ecological analysis and on the considerations concerning the information content (linked to the management of seminatural grasslands) of MV and N indexes. This system is constituted by 25 vegetation categories resulted from the combination of the five MV classes (forest, shrubland, pasture, meadow-pasture and meadow) and 5 N classes (hyper-eutrophic, eutrophic, mesotrophic, oligotrophic, hyper-oligotrophic). Figure 6 shows the 25 vegetational categories (and corresponding threshold value) and the location of the relevés. A large part of Taleggio Valley grasslands is eutrophic meadows and eutrophic/mesotrophic meadow-pastures, while pastures fall mainly in the categories: oligotrophic pastures and oligotrophic/mesotrophic meadows-pastures. The only relevé performed with high coverage of *Rumex alpinus* along with the relevés of *Rumicetum alpinum* and of the overgrazed pastures were used to define the hyper-eutrophic grasslands category.

"Hyper-oligotrophic" pastures were not found in Taleggio Valley. This result is explicable with the fact that value 1 of N index is ascribed only to those species growing on "very infertile" substrates [45] such as dolomitic-calcareous rocks that, even if present in alpine pastures, are rarely with a high cover percentage. The category "hyper-oligotrophic" was, however, preserved because some peculiar plant communities of the Alps could be included in this category, such as some grasslands of low fertile soils present where dry prairies are common as in the Dolomites massifs [57].

The classification system of Figure 5 was used to create VegeT ("Vege" = vegetation, "T" = type) (Spreadsheet S1), a classification tool of grasslands of the Alps and other vegetation types (forests and shrublands) with which very often grasslands are in a dynamic-catenal relationship [58]. VegeT is a Microsoft Excel® file constituted by spreadsheets: the first reports data-entry and data-exit forms (Figure 6), the two other sheets contain the numerical calculation and the vegetation classification formulas (Spreadsheet S1).

The data as input in VegeT to determine the vegetational categories are abundance, MV and N of each species of the plant community. While MV and N values are readily available in [45] or in the software "Flora Indicativa" ("Indicative Flora") elaborated by the same authors [45], abundance values depend on the operator's evaluation during the field observations. Generally, the abundance of a given species in a plant community can be evaluated with the application of abundance/dominance indices, which may be numeric or not. Numeric data are needed for VegeT; if this is not available, abundance/dominance scales must be converted to ordinal scales using the methods proposed by, e.g., [42,59,60]. VegeT also allows for optional data inclusion (not essential for calculation): species and family names and other notes, for example (Figure 6). The data output screenshot returns the vegetation category (one of the 25 defined previously), a graph similar to Figure 5, the mean values of MV and N and some parameters widely used in plant ecology useful for the description of the vegetation characteristics: the number of species composing the plant community (species richness), Shannon index (biodiversity) [61] and evenness (equitability) [62].

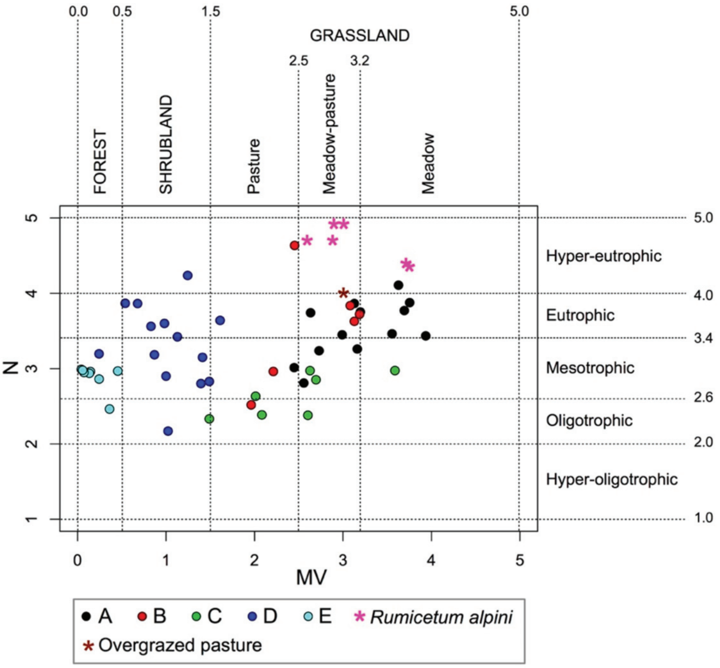
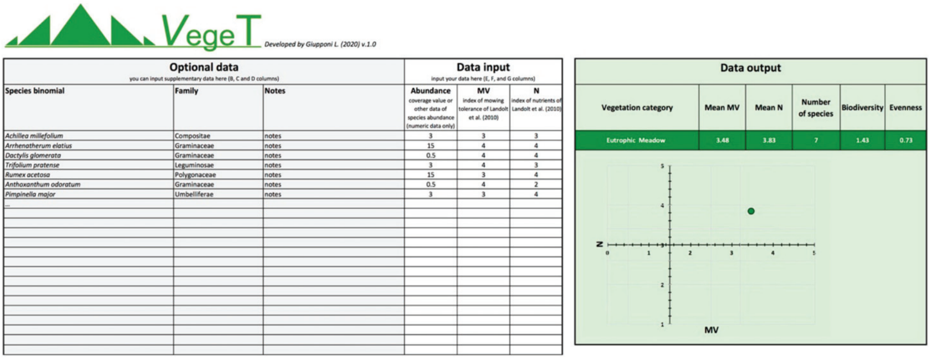


Figure 5. Scatter plot of MV (mowing tolerance) and N (index of nutrients). The graph shows the relevés performed in Taleggio Valley (dots: A, meadows; B, meadows-pastures; C, pastures; D, shrublands; E, forests), the relevés of *Rumicetum alpini* [48] and the relevé of overgrazed pasture [18] (Table S1). The grid with the 25 vegetation categories and the respective threshold values are shown.



Optional data you can input supplementary data here (B, C and D columns)			Data input input your data here (E, F, and G columns)		
Species binomial	**Family**	**Notes**	**Abundance** coverage value or other data of species abundance (numeric data only)	**MV** index of mowing tolerance of Landolt et al. (2010)	**N** index of nutrients of Landolt et al. (2010)
Achillea millefolium	Compositae	notes	3	3	3
Arrhenatherum elatius	Graminaceae	notes	15	4	4
Dactylis glomerata	Graminaceae	notes	0.5	4	4
Trifolium pratense	Leguminosae	notes	3	4	3
Rumex acetosa	Polygonaceae	notes	15	3	4
Anthoxanthum odoratum	Graminaceae	notes	0.5	4	2
Pimpinella major	Umbelliferae	notes	3	3	4
...					

Data output

Vegetation category	Mean MV	Mean N	Number of species	Biodiversity	Evenness
Eutrophic Meadow	3.48	3.83	7	1.43	0.73

Figure 6. Input–output interface data of VegeT spreadsheet.

The uniqueness of VegeT, other than being based upon only two indexes able to provide information for management purposes, is being a user-friendly tool. The working software is, in fact, a spreadsheet Microsoft Excel®, a software widely used. In addition, the input–output interface is easy and comprehensible (Figure 6). It was considered appropriate to include other variables enabling better characterization of the plant communities in addition to the information concerning the vegetation category and the scatterplot showing MV and N values: the number of species, Shannon index and evenness. The first two can return information on the plant community richness and biodiversity, parameters widely used in ecological and nature conservation, which can help identify grasslands intensively managed [54]. Evenness (equitability) indicates if there are one or few dominant species in a plant community (in which case evenness values will be close to 0) or if species are equally represented (in which case evenness values will be close to 1) [62]. Some plant communities are dominated by few species (for example, *Rumex alpinus* or *Nardus stricta* in degraded pastures).

To elaborate on the classification, VegeT requires floristic composition and species abundance of plants constituting the plant communities. The greater the detail of the data input, the more reliable information VegeT can return.

Although the grassland classification on which VegeT is based has the benefit to go beyond the syntaxonomy [63] (commonly to other modern systems of classification of habitats [64,65]), this instrument has the limitation of being only operational in the Alps (and nearby areas) because N and MV indexes used were built on about 6500 species of Alps [45]. This limitation can be overcome with future studies that analyze the nutrients requirements in the soil and the mowing tolerance of species inhabiting other geographical areas so that N and MV indexes value can be determined. However, VegeT could potentially be used in areas with floristic biodiversity similar to the Alps (as Apennine, Pyrenees, Dinaric Alps and Carpathians) or rather where plant communities are mostly constituted by species with N and MV known values [45]. In this study, for example, the data of the relevés of *Rumicion alpini* (Figure 5) performed in Western Carpathians [48] were used, and just one species (*Aconitum firmum*) did not have known values of N and MV as reported in [45].

For Taleggio Valley, as for other mountain areas in the Alps, VegeT could be a useful instrument to improve the agro-food products from grasslands (for example, honey and cheese). In Taleggio Valley, in fact, cheeses of high quality and of protected origin are produced. The production regulations of these cheeses stipulate that the alimentation of cattle must rely on local forage for the most part of their diet, although this forage is becoming less available due to grassland abandonment (Figure 1). VegeT cannot substitute other tools/procedures to evaluate the forage quantity and quantity neither the biological values of grasslands [3,9,18,65–68]. However, it can be combined with other tools to facilitate the definition and planning of the best management practices for maintaining grasslands that, other than being a biodiversity heritage, could be excellent resources for agro-food production chains [69]. In addition, when using VegeT, it should be considered that this is a useful tool for the overall classification of grasslands, but specific cases must be considered for a correct interpretation when we want to preserve, for example, a condition of low fertility necessary to the survival of some specific protected species. Some plant communities, such as alpine and subalpine calcareous grasslands included in the Habitat Directive, must be identified as special cases and be managed carefully for their conservation values. In these occurrences, botanists' competencies are needed because other than guaranteeing their recognition; they can direct land managers towards the best actions to manage/preserve these special habitats.

Finally, it must be highlighted that VegeT is the first edition of an instrument that can be improved and/or integrated (if needed) thanks to user (researchers, technicians and land managers) feedback. Greater usage in the next few years, including its application in different alpine areas and the consideration of different grasslands typologies [57], will contribute to the improvement of the tool.

4. Conclusions

This research enabled the development of a tool (VegeT) based on the floristic and ecological study of the vegetation of Taleggio Valley. The aim of this tool was to assist in the interpretation of the floristic-vegetation datasets (created by botanists) for practitioners in charge of providing guidelines for the appropriate management of mountain grasslands of the Alps. In fact, it returns outputs straightforwardly understandable and needs easy to use, simple, affordable and easy to find materials and methods: floristic-vegetation data provided by botanists, N and MV indexes of Landolt [45] and Microsoft Excel®. For these reasons, VegeT can become useful not only to facilitate and improve grasslands conservation/restoration projects but also to improve their management for productive purposes to promote the sustainable development of alpine areas as Taleggio Valley, that was in the past an important center of low input and sustainable agricultural activities as pastoralism.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/9/12/473/s1, Spreadsheet S1: VegeT spreadsheet. Table S1: Table of relevés of *Rumicetum alpini* and overgrazed pasture. Table S2: Table of relevés performed in Taleggio Valley. Key: A, meadows; B, meadows-pastures; C, pastures; D, shrublands; E, forests. Cover indices refer to the Braun-Blanquet abundance/dominance scale. Table S3: Eigenvalues for the first four axes of DCAs.

Author Contributions: Conceptualization, L.G. and V.L.; methodology, L.G.; software, L.G.; validation, L.G. and V.L.; formal analysis, L.G.; investigation, L.G.; plant identification, L.G.; data curation, L.G. and V.L.; writing—original draft preparation, L.G. and V.L.; writing—review and editing, L.G. and V.L.; visualization, L.G. and V.L.; project administration, L.G.; funding acquisition, L.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

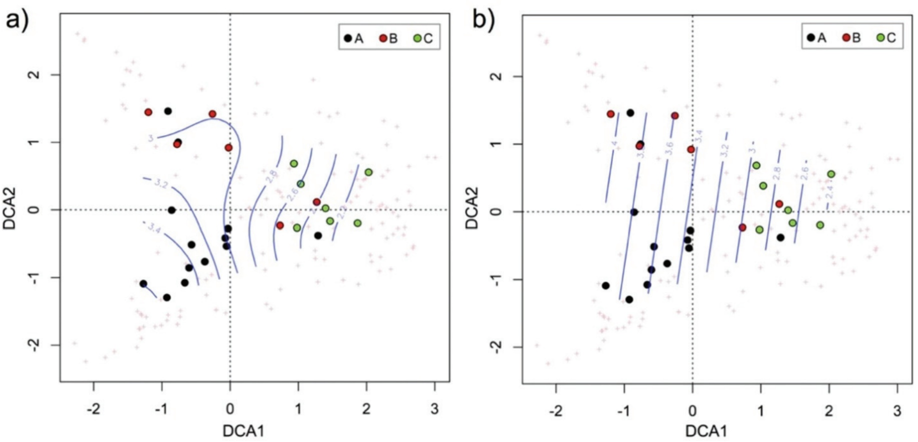

Figure A1. DCA ordination of grasslands relevés overlapped with the MV (mowing tolerance, (**a**) and N (index of nutrients, (**b**) contour lines. The points indicate the relevés: A, meadows; B, meadows-pastures; C, pastures. Eigenvalues for DCA axes are reported in Table S3.

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Endangered Mediterranean Mountain Heritage—Case Study of *katuns* at the Kuči Mountain in Montenegro

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Abstract: The study gives an insight into the domain of seasonal mountain settlements for summer cattle grazing (*katuns*), characteristic for the mountainous areas in the Mediterranean basin. The area of the Kuči Mountain in Montenegro was chosen for the case study. The area contains numerous characteristics exemplary for the topic—193 katuns with more than 2900 belonging housing and subsidiary objects. The presented results originate from the 3-year-long investigations, where the data obtained from archival documents were combined with those acquired through intensive field work and visits to each and every katun determined and documented within the area. The density of these settlements, as well as their architectural and constructional characteristics, show the high level of importance they had for the local population up until the last third of 20th century. Currently, changed sociodemographic trends rendered their intensive traditional use obsolete, but used building techniques, their internal organization and organic connection to the surrounding mountain landscape, have nominated them for important part of region's historical heritage.

Keywords: Mediterranean; Montenegro; mountain; katun; traditional architecture; vernacular heritage; transhumance; extensive cattle rearing

1. Introduction

Traditional seasonal settlements, intended for summer cattle grazing on mountain pastures, are widespread in the Mediterranean basin. In Western Balkans, they are called *katuns* (hereinafter: katun(s)) and, especially in Montenegro, have played an important role in its social and economic history. Due to the lack of arable land, the vast majority of Montenegrin population pursued the cattle rearing as the main agricultural and economic activity. On the other side, climate conditions, characterized by hot summers and droughts, determined that the food for cattle existed only on the abundant pastures on the slopes of numerous Montenegrin mountains. Having a possibility to establish katuns there, was the only way to create food supplies for winter and product surpluses for market, often meaning the sheer difference between survival and starvation.

This practice created a social and economic base for further growth and extension of Montenegrin villages—summer pastoralism in the mountains enabled the increase in cattle herds and sheep flocks, which prompted the search for larger pastures for winter and thus the movement towards the plains in the southern parts of the country. Rich and big villages in these areas have rarely been the primary source of creating katuns in the mountains, and since this process developed in an absolutely opposite direction, their establishment came out mostly as the result of the previous conquest of the vast pastures higher in the mountains. Such a development pattern lasted from early 15th to the middle of 20th century, becoming the most characteristic and widespread economic activity among the local population.

With social, economic and demographic changes in the Montenegrin society emerging after World War II—characterized by massive urbanization and industrialization—rural areas and katuns have lost their importance, with later almost fully disappearing as a prominent agricultural category. The most of them were abandoned, while remaining households predominantly consisted of elderly people, without visible intention of their heirs to continue such a lifestyle. Economic crisis—present in the region from the late eighties of 20th century—which forced into shutdown big industrial enterprises and caused a massive unemployment, forced some families to reconsider their decisions to abandon the traditional cattle rearing. There is a slow and scattered, but still visible return of some population in their late thirties and early forties to katuns for summer grazing, either with own or rented cattle and sheep. At the same time, more people are building their weekend cottages in the areas of traditional katuns. While it preserves the connection between people and mountain, it more than often devastates the traditional landscape through constructing objects using inappropriate materials, at inappropriate places and in traditionally inappropriate sizes and styles.

Accordingly, the current domain of topics related to Montenegrin katuns includes their historical background, economic trends and perspectives, environmental and landscape qualities and characteristics—as well as the sphere of cultural heritage and its protection and valorization. Here, these categories interact, creating a whole where the dimensions and construction of mountain cottages fully represent economic and social status and perspective of the dwellers, fitting into the natural landscape as an almost organic part. These constructions—as the incarnations of the same driving forces all over the Mediterranean basin—display the universality of human responses to the natural and social challenges, showing a high degree of matching among the areas in the Adriatic background and, let's say, the Western Alps [1]

Unfortunately, the katuns in the region of Montenegro—including ones at the Kuči Mountain as well—have not yet been sufficiently researched and valued from the aspect of the protection of cultural heritage, although as seasonal mountain settlements, they represent a significant segment. Cultural heritage 'includes all aspects of the environment resulting from the interaction between people and places through time' [2], the cultural landscape is the widest and most comprehensive category of cultural heritage—the common work of nature and mankind. Such permeation is clearly visible in traditional katuns of the area, where every anthropogenic organizational, architectural and constructional action follows the postulates of understanding the surrounding nature, being it protection of wolves, preservation of pastures and use of water sources or utilization of terrain geomorphology.

It is assumed that the term 'katun' has been used for shepherds' village since the 13th century [3] (p. 113). In different researchers' works, katuns are defined as 'summer villages in the mountains' [4] (p. 366), 'summer abodes' [5] (p. 4), 'summer flats' [4] (p. 78), 'temporary summer flats' [6] (p. 8), 'an entire temporary summer livestock farmers' settlement' [7] (p. 235) or 'groups of cabins of wood on summer pastures' [3] (p. 113). In any case, these terms define the seasonal mountain settlements that are regularly visited by the same occupants every summer, rearing their sheep, cattle and horses to grazing at surrounding pastures.

The existing scientific and scholarly works have treated the thematic of katuns only through its place in a broader context of the life and history of Kuči, Montenegro and northern Albania. Among the authors, one should mention Marko Miljanov, Jovan Erdeljanović, Stevan Dučić, Marko Rašović, Vaso Čubrilović, Ivan Božić, Đurica Krstić, Ljubinka Bogetić-Ćirić et al. [7–15]. An exception is the book of Novo Vujošević *Kučki katuni* (*The Kuči Katuns*) [16], as the first of only few dedicated attempts of a thematic research on this issue [16–18]. However, neither of them provided a full and precise inventory of katuns at the Kuči Mountain, their exact locations and number, condition, type and description of belonging structures, approach roads, availability and type of water supply infrastructure and many other things. While the seasonal mountain settlements in Alps were the topic of many interesting investigations [19], katuns in the background of the Adriatic remained out of social and scientific focus.

For all this, our research was aimed to contribute to more precise describing heritage values of the katuns in case study area, trying to list and quantify all the important categories of the visible objects. Their sheer number testifies on their importance in social life until the late 20th century, so the lack of basic data on their organization, disposition, structures and subsidiary objects, greatly impedes the growth of knowledge on this topic. We expected that—according to obtained figures on katuns and subsidiary objects—we will be able to determine more precisely the intensity of this social and economic way of life at the Kuči Mountain, as well as to establish similar correlation for the other Montenegrin and Balkan's mountain regions. Existing data—acquired through archival investigations, consulting literature and interviewing locals—implied that there may be found up to 120 katuns on a mountain. The fact that the final number reached almost twice figure, also meant that the general importance of katuns in the life of the local population was greatly underestimated.

Knowing that this area was just the one among many similar in the Dinaric mountain chain, one of the research goals was to promote and encourage further similar scientific endeavors. This research, with all its limits and deficiencies, was the first of the kind in decades in Montenegro. One of its purposes was to bring katuns back on the map of scientific topics, as well as to push relevant stakeholders at governmental and non-governmental levels to take necessary steps for putting katuns and transhumance on the national list of protected intangible cultural heritage. It is also worth noting that the transhumance in matching pastoral areas of the Alps, the Apennines and Greece, have already been inscribed in 2019 on the Representative list of the intangible cultural heritage of humanity [20], along with traditional techniques of drystone walling inscribed a year before [21].

2. Materials and Methods

The Kuči Mountain territory belongs to the chain of the Southeastern Dinarides. The region has a surface area of about 220 km^2, northeast of Podgorica, comprising of the mountain range of Žijevo, the southern part of Komovi and the western part of the Prokletije massif (Figure 1). The local climate is characterized as a humid, warm temperate climate type (moderately Cf), represented by subtypes Cfb and Cfws"bx" in the southwestern part of the region, and cold and humid climate (Df), represented by subtype Dfbx", in the northeastern parts [22]. The southwestern region is built of solid chalk limestone and of the Triassic limestone, mixed with dolomites and dolomitic limestone. In the northeastern sector, the limestone is often interrupted with silicate rocks—the Upper Cretaceous flish—better known in literature as the *Durmitor flish* [23].

In this respect, a tradition of seminomadic (katun) livestock farming developed, which for a long time was the basic economic activity of the local population at the Kuči. The richness of mountain pastures enabled summer grazing of livestock, providing both reserves of food for winter and surpluses for sale on the market.

Believing that determining basic quantitative characteristics of the region is one of the prerequisites for its development, through the project *Valorization of Montenegrin katuns and sustainable development of agriculture and tourism—KATUN* [24], an attempt was made for the first inventory of the architectural heritage of the Kuči Mountain, to determine as accurately as possible the number of katuns and their locations, as well as types and conditions of structures within them. Desk and field investigations on this topic were conducted in the period of July 2015–November 2017. The methodology of the research itself started from collecting information available in the existing literature, through the conversation with the inhabitants of the Kuči and a study of printed and electronic cartographic material. The Google Earth online service was of particular importance, enabling us to determine the exact locations of katun settlements—even in the areas for which neither written data existed, nor their existence remained in the knowledge or memory of the people interviewed for the needs of this research.

It should be noted that this research covered only the katuns built of solid material, and whose remnants are still visible. We are aware of the fact that methods of cattle-rearing originates from the distant past in this area, but the non-existence of relevant archaeological surveys forces us to limit our research focus only to locations where the objects were built in stonemasonry techniques, allowing them to fully or partially survive to this day. Since the use of stone for wall construction in this area started only in the second half of 19th century, the chronological frame of research covers the period of the last ca. 150 years.

Figure 1. Map of the case study location.

Considering the number of katuns in the researched region—and lack of relevant data in the available printed and electronic literature—the determination of the factual state required a large number of field trips to previously known localities, as well as to those found after a thorough study of the terrain image on Google Earth. This is especially important to emphasize for those katuns on which there is no other information, and which would certainly remain unnoticed without the use of this contemporary navigational aid. The approach to the localities varied from a simple approach along an asphalt road, to the use of a 4WD vehicle along the tough mountain roads, to several-hour walks up mountain trails and paths. Every katun, however, was personally approached and all data with following photo documentation, referring either to the katun itself or to individual traditional dwellings—*gladas* (huts, hereinafter glada(s)), were taken on site.

The subject of the research was all parts of the Kuči Mountain where katuns was established. Considering that the construction of structures of hard material in this region spread only in the mid-19th century, the research was also limited only to those areas where it was possible to find visible material remains of katun structures. In the katuns that entirely or predominantly kept their traditional character, the inventory of all the existing structures—regardless of their origin, age or the context of construction—was conducted.

Google Earth satellite imagery and topographical maps were used as an essential data entry base. The above-mentioned maps were used first for fieldwork and the identification of all locations, and then for data entry as well. Very important information was recorded during the conversations with people, who still move up to the katuns with their family members, livestock and movable property. During the research, project team members took a host of photographs, architectural sketches and videos of the existing structures and visible remnants. Tables with additional information were filled for every katun on site and then moved into the working version of the database. This first database of Montenegrin katuns was created in QGIS 2.8.3. The aforementioned register is still not available online, but it is planned to post at least some of its parts as an open information source. The mentioned database maps not only settlements, but also any built structures, i.e., different kinds of wooden or stone architectural structures (Figures 2 and 3).

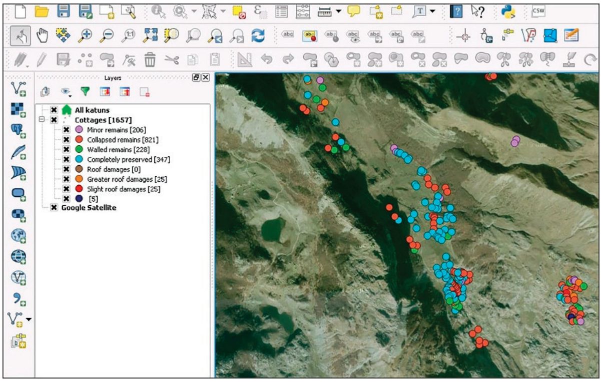


Figure 2. Overview of katun in database—Širokar, Google satellite imagery, entry by O. Pelcer-Vujačić.

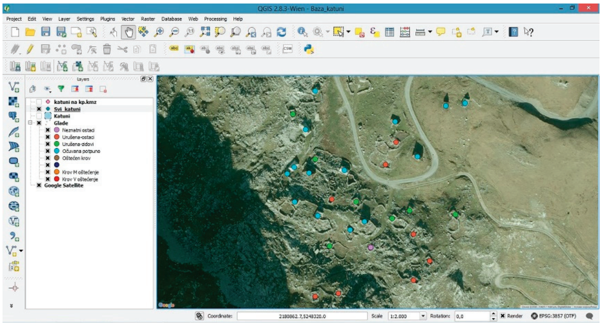
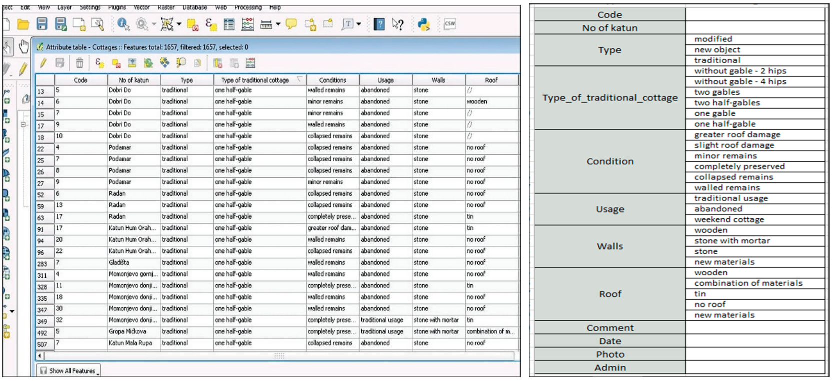


Figure 3. Snapshot from database - katun Ljakovića, entry by O. Pelcer-Vujačić.

Files of katuns and gladas—containing characteristic descriptive categories—were composed for the need of the research. The condition of each glada was additionally described through an auxiliary information sheet (attribute table) referring to the state of preservation of structure, types of material for walls construction, roof styles and front wall forms, as well as additional information on structure purpose (Figure 4).



Attribute table - Cottages :: Features total: 1657, filtered: 1657, selected: 0

	Code	No of katun	Type	Type of traditional cottage	Conditions	Usage	Walls	Roof
13	5	Dobri Do	traditional	one half-gable	walled remains	abandoned	stone	()
14	6	Dobri Do	traditional	one half-gable	minor remains	abandoned	stone	wooden
15	7	Dobri Do	traditional	one half-gable	minor remains	abandoned	stone	()
17	9	Dobri Do	traditional	one half-gable	walled remains	abandoned	stone	()
18	10	Dobri Do	traditional	one half-gable	collapsed remains	abandoned	stone	()
22	4	Podamar	traditional	one half-gable	collapsed remains	abandoned	stone	no roof
25	7	Podamar	traditional	one half-gable	collapsed remains	abandoned	stone	no roof
26	8	Podamar	traditional	one half-gable	collapsed remains	abandoned	stone	no roof
27	9	Podamar	traditional	one half-gable	minor remains	abandoned	stone	no roof
52	6	Radan	traditional	one half-gable	collapsed remains	abandoned	stone	no roof
59	13	Radan	traditional	one half-gable	collapsed remains	abandoned	stone	no roof
63	17	Radan	traditional	one half-gable	completely prese...	abandoned	stone	tin
91	17	Katun Hum Orah...	traditional	one half-gable	greater roof dam...	abandoned	stone	tin
94	20	Katun Hum Orah...	traditional	one half-gable	walled remains	abandoned	stone	no roof
96	22	Katun Hum Orah...	traditional	one half-gable	collapsed remains	abandoned	stone	no roof
283	7	Gladišta	traditional	one half-gable	walled remains	abandoned	stone	no roof
311	4	Momonjevo gornj...	traditional	one half-gable	walled remains	abandoned	stone	no roof
328	11	Momonjevo donj...	traditional	one half-gable	completely prese...	abandoned	stone	tin
335	18	Momonjevo donj...	traditional	one half-gable	walled remains	abandoned	stone	no roof
347	30	Momonjevo donj...	traditional	one half-gable	walled remains	abandoned	stone	no roof
349	32	Momonjevo donj...	traditional	one half-gable	completely prese...	traditional usage	stone with mortar	tin
492	5	Gropa Mićkova	traditional	one half-gable	completely prese...	traditional usage	stone with mortar	combination of m...
507	7	Katun Mala Rupa	traditional	one half-gable	collapsed remains	abandoned	stone	no roof

Code	
No of katun	
Type	modified new object traditional
Type_of_traditional_cottage	without gable - 2 hips without gable - 4 hips two gables two half-gables one gable one half-gable
Condition	greater roof damage slight roof damage minor remains completely preserved collapsed remains walled remains
Usage	traditional usage abandoned weekend cottage
Walls	wooden stone with mortar stone new materials
Roof	wooden combination of materials tin no roof new materials
Comment	
Date	
Photo	
Admin	

Figure 4. Overview of katun's attribute table in database and parameters for glada file, entry by O. Pelcer-Vujačić.

The data on katuns were arranged in a simple and comprehensible form. It contained an identical type of information for all katuns, such as name, geographic coordinates, elevation, belonging, state of population, number, type and current state of structures, as well as descriptions of transport, water supplies and electrical infrastructure belonging to them. Geographic coordinates were given according to a particular point within the katun itself and they match the format used by Google Earth, while the elevation was given singly, according to an average (if it was a katun on flat terrain or in the cirque) or in a range, when a katun on the slope was in consideration. The data on 193 katuns and over 2900 gladas were collected and entered into a database in one vector layer [25].

3. Results

The research determined that on the mountain there were 193 katuns, 59 of which were permanently inhabited, and around twenty more were occasionally inhabited. According to their position, katuns at the Kuči Mountain can be divided into katuns on the slope, in the cirque and in the forest (Figures 5–8). The largest number of katuns is situated on the mountain slopes. They are located in pastures zone, above the forest zone and below the zone of rocky mountain peaks. Besides the katuns on the slopes, one often comes across the katuns in cirques, particularly in the southern, karstic part of the Kuči Mountain. Katuns in the forests are rather rare. In most cases, they were built at forests edges or clearings within the forests. In some cases, due to a neglect and disuse of the mountain, forest expanded and comprised katuns as well. Since the position of katuns also depends very much on the availability of water, in regions in which there is water, they are located next to springs, brooks, puddles or lakes, while in arid regions, katuns are situated in the vicinity of snow sinkholes.

Figure 5. Katun on the slope—Širokar Ljakovića, photo: I. Laković.

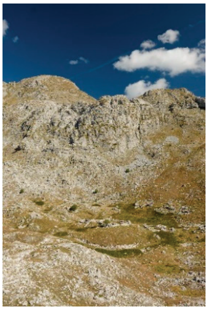


Figure 6. Katun in the cirque—Gropa Beljeva, photo: I. Laković.

Figure 7. Katun in the forest—Crna Rupa, photo: I. Laković.

Figure 8. Katun next to the lake—Rikavac, photo: I. Laković

On the katuns situated on the slope, gladas with corrals were most commonly built longitudinally, parallel to the contours of the terrain, immediately below the lower or above the upper forest edge. The katuns in the cirques are organized similarly as villages in such cases, in a way that the natural advantages of the terrain were used to the maximum. Gladas with pens are most commonly positioned along the edge of the cirque or on smaller hillocks if there were some in the cirque, while flat surfaces covered with pastures were left free. When in a particular location, in hollows, cirques or around lakes there were minor hillocks, gladas and pens grouped around them. In the katuns lower down the mountain, next to gladas and pens, arable surfaces appear as well [4] (p. 79).

Altitudinal distribution of the katuns ranges within ca. 700 m of altitude, from 1154 to 1879 m. This pattern depends on the projected use of katun, where the ones at lower altitudes were used mostly earlier in the summer (until late July). After the pastures in the area were exhausted by grazing and summer drought, the shepherds would have moved up to the higher katuns with enough grass for their cattle. This two-staged transhumance was the privilege of wealthier and stronger clans and communities, who could afford possession of two katuns. Most the others had to establish their katuns somewhere in the middle, at altitudes ranging from 1300 to 1600 m and to spend all the summer there.

The other decisive factor was the water supply. The area of the Kuči Mountain consists of two different types of bedrock that determine the appearance of water springs. The limestone in southwestern region is very water porous, hence there are only few springs in the whole area. The main sources of water here are the caves where snow remained until summer. In the northeastern sector, the bedrock is made of flish with many water springs. Here, the katuns were mostly located above the upper forest line (above ca. 1700 m). The middle part of the mountain—characterized by mixture of these two zones—has the moderate amount of water springs, but two glacier lakes enabled formation of many katuns in their vicinity [26].

3.1. Cabins/Gladas

The traditional mountain cabin—the shepherd's dwelling called glada in the Kuči area—is the most important segment of architectural heritage of katuns of the Kuči Mountain. Although representing the simplest form of dwellings, their types developed and changed over the time. The oldest and the simplest ones had only a roof starting straight from the ground. It may have been made above a circular or rectangular plan, with a simple construction of logs and different kinds of cover—*krovina* (roofing) from available materials. The most widespread forms among those simplest forms of cabins—particularly in forested regions—were cabins of a circular plan, with the hearth in the middle, covered with the roof in the shape of a cone. In Montenegro, including the region of the Kuči Mountain, this type of cabin is most frequently called *dubirog* (hereinafter dubirog(s)), while in the northern part of the country, the name *savardak*—a Turkish name derived from the word denoting a roll or a (firearm) cartridge [6] (p. 12), is also used for the same object. For the Kuči region, there are data that the original cabins were covered with cloth/canvas from goat's hair, and then with straw as well.

It looked like a big nomadic tent, having a ridge fixed on the poles, over which, on both sides, a large and wide piece of *pustina* (cloth) was tightened around all its four sides and fastened to the ground. It could have also been broken down, loaded onto the horse and that way moved from place-to-place.

Later, more complex types developed, in which in the base received a wall of stone made in the drystone wall technique, onto which a roof construction and a roof were laid. Over time, they also changed and developed, resulting in several different kinds—depending on the size and form of the plan, the wall height, materials and building techniques (Figure 9).

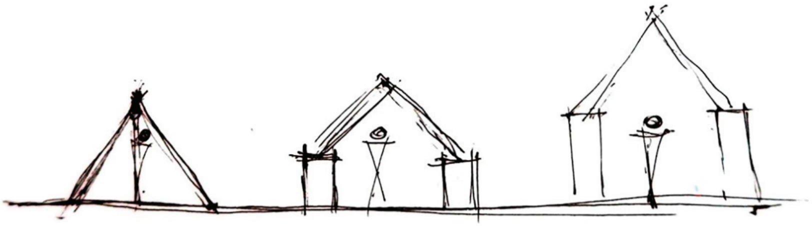


Figure 9. Development of cabin, sketch: A. Kapetanović.

At Kuči Mountain, remains of older, simpler types of cabins that did not have any walls of stone, but only a roof with a wooden roof construction, were not preserved. We know about them only from literature. Only the remains of more complex, newer types of cabins—with stone walls, roof constructions above them and circular and rectangular plan—have survived to these days.

3.1.1. Types of Cabins

The gladas with a rectangular plan are the most prevalent types of traditional cabins at the Kuči Mountain, while dubirogs—the cabins of a circular plan—occur in a considerably smaller number. During the field research, ca. 2600 traditional and modified gladas in total were identified, almost all of which were of a rectangular plan and only some twenty dubirogs. In comparison to the simplest type of dubirog, which consists of a roof in the shape of a cone only, the more developed form features a small circular wall, made of crushed stone, without a bonding agent, 'in dry', on which a wooden construction for the roof in the shape of a cone was laid (Figure 10).

At the beginning of the 20th century, Jovan Erdeljanović described the dubirogs at the Kuči Mountain in the area of Komovi, while Antonio Baldacci, an Italian biologist, did the same in the region of the Mokra in 1902. They both assumed that the Kuči modeled them according to pattern that existed in the neighboring Montenegrin tribes [27] (p. 788). In this period, some dubirogs in the region of Korita were covered with turfs and were known as '*busare* (turf huts)' [5] (p. 79).

Similar to the gladas of the rectangular form, the dubirogs were most commonly built on gently sloped terrain, on the rear side partially dug into the terrain. The opening for the door was situated on the lower side, down the slope. In most preserved ones, the interior diameter ranges from 4.50 to 5.60 m, and a smaller number of them has a diameter of about 3.60 m. The walls of dubirog—similar to the walls of rectangular gladas—were built of stone in the drystone wall technique, with two faces of larger blocks and smaller rubbles. The thickness of such walls varies, ranging from the 60 cm (although rather rarely) to a maximal 140 cm. Often, the width of walls within the same dubirog varied in different segments. The height of its walls was approximately around 120 cm, while the highest wall measured was 155 cm high.

Figure 10. Dubirog at Korita, photo: I. Laković.

The opening for the door in the stone walls of dubirog is most commonly about 100 cm wide. It is often narrower towards the interior, from 70 to 80 cm, and it widens in a trapezium shape towards outside, up to 100–110 cm. In the semicircular walls of dubirog, as well as in the walls of rectangular gladas, on the interior side, the niches serving as shelves can be found (Figures 11 and 12).

Figure 11. An entrance into dubirog—katun Crna rupa, photo: I. Laković.

In several locations (Javorci, Stružica, Velji do) within the complex, next to gladas, there are smaller dubirogs as well, with an interior diameter of 2.5–3 m, which are assumed to have served as subsidiary objects. Although dubirogs were simpler for construction, it is supposed that due to the circular plan, they were less suitable to the needs of the interior organization of space, and therefore they were superseded by gladas with rectangular plan, which become the dominant type of structure at the mountains.

Traditional gladas—as the most common type of cabins on the Kuči Mountain—are the structures of an elongated rectangular plan, built of stone in the drystone wall technique, with the wooden roof construction and the gable roof or the hipped roof, originally covered with straw or wood. These gladas are very similar to the simplest forms of houses which the Kuči built in the villages, '*suhozadice* (drystone wall houses)' or '*slamnjače* (thatched houses)' [5] (p. 81), which were without windows and covered most commonly with straw.

Figure 12. Niches in the wall of the dubirog—katun Crna rupa, photo: I. Laković

Houses in the Kuči villages were, like gladas, also of an elongated, rectangular plan. In houses, the longer walls are called *rebra* (literally translated 'ribs') and the shorter, side ones, *listras*. One of the long walls, on which there was the entrance, is called 'face', and the other long wall is called rear face'. Often on drystone wall houses, gables were not erected, but the side walls remain level with the long walls, so the 'hipped roof' is made. The wall of this kind of house is a drystone wall, so, basically, gladas in katuns follow this constructional pattern. The gladas on the Kuči Mountain were first described in this manner at the beginning of the 20th century by Jovan Erdeljanović [7] (p. 236), [27] (p. 697).

Gladas can be divided into different types according to the shape of sidewalls, which determined the roof shapes as well. The classic sidewall was higher than the face of the structure, and in the upper section, it finished with a stonework triangular ending in the form of a gable. The sidewalls of gladas can also be completely leveled, i.e., at the same height as the long walls of the front and rear face of the house. In that case, by means of a wooden construction, the hipped roof or more commonly the gable roof can be formed, and in some cases even the one with three slopes. We often come across the examples of gladas on which one of the sidewalls is with a stonework triangular ending—the gable, while the other is at the same level with the long walls. In these cases, the roof can be called "gable roof" or "three-pitched roof" (Figure 13).

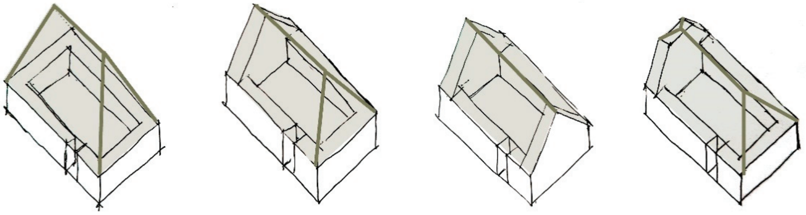


Figure 13. Variants of gladas' walls: a leveled sidewall, one gable wall, two gable walls and a half-gable wall drawing: A. Kapetanović.

There are some gladas with sidewalls representing a transitional form between gable walls and leveled sidewalls, so-called 'half-gable walls'. On them, the triangular ending of the gable was cut out, therefore that upper section of the side wall is in the shape of a trapezium. In this case, the roof above the 'half-gable wall' was cut out and it represents a transitional shape between gable roof and three-pitched roof. 'Half-gable walls' are mainly found on one side only (there are only several cases of gladas with two half-gable walls), and that is the one which is oriented towards the hill, in the case when a glada is partially dug into the terrain.

Based on data from the terrain—as well as notes of explorers of the area of Kuči at the beginning of the 20th century—it may be concluded that in the katuns of the Kuči Mountain, there were two kinds of gladas, with lower and higher roofs. In the area of the Upper Mountain, gladas with shorter roofs prevail, having either stonework gable walls or leveled sidewalls. The height of the sidewall, i.e., the height of the roof was determined by the availability of timber for roof construction and the roof cover. In the Lower Mountain, gladas with long walls and sidewalls at the same height and with much higher hipped or gable roofs with wooden constructions and the cover of straw or wood were common. With the passing of time, the type with higher roof became the standard all over the area.

3.1.2. Basic Characteristics of Gladas, Position in Relation to the Terrain

Gladas were built in a way that they were maximally adapted to the advantages of the terrain. Often, especially earlier, the existing stone formations, rocks and larger blocks of stone were used for foundations or parts of gladas' walls. That way the work was reduced, materials were saved and gladas obtained additional stability (Figures 14 and 15).

Figure 14. Existing rocks and larger blocks of stones were used for parts of gladas' walls. Studenica, photo: I. Laković.

Figure 15. Existing boulder as the part of sidewall—Carine, katun of Popovići, photo: I. Laković.

Gladas can be oriented with their longer side—the long wall/face vertically or parallel to the terrain line. Depending on the configuration of terrain and the position of the glada within the katun, we find both examples (Figures 16 and 17). However, gladas vertically oriented to the terrain prevail, as it was the practice with houses in the villages [5] (p. 80).

When gladas were built on slopped terrain, they were most commonly partially dug into the terrain with its rear part next to the slope, regardless of whether they were oriented parallel or vertically to it. It was practiced in order to get a flat base for a glada on slopped terrain, faster and easier construction, greater stability and durability, as well as thermal insulation. In the part that was dug into the ground, only one face of the stone wall was built, whereas the rest of it continued with two faces. The digging into the ground may have been partial, up to a certain height of the wall, but often the entire back wall was also dug into the ground (if it was flat). When the back wall of the glada was the classic gable wall (the stonework triangular ending), the lower section of the wall was dug into the ground, while the triangular section remained above.

Figure 16. Glada with its face oriented parallel to the terrain, partially dug into the ground—Građen, Podgradski katun, photo: I. Laković.

Figure 17. Gladas with its faces oriented perpendicularly to the terrain, partially dug into the ground—Koštica, Kutski katun, photo: I. Laković.

3.1.3. The Size, Dimensions and Proportions of Gladas

The interior dimensions of the narrower side—sidewalls most commonly range from 3.00 to 3.50 m, maximally up to 4.30 m. The interior dimensions of the longer side—long walls or face walls vary from 4.20 m up to 7.80 m. The exterior dimensions of sidewalls of gladas are most commonly range from 4.80 to 6.00 m, and of the face from 7.20 m up to 9.70 m. Only around ten gladas in the entire region of the Kuči Mountain have a face longer than 10 m. It is assumed that such gladas were used in the institution of *supona*, when two or more families shared the same glada during their stay in the katun. The proportions of gladas' plans, the ratio of the narrower to the wider side of the rectangle, i.e., the sidewall to the long wall/face, range from 1.25 up to 2.0 m. It can be noticed that this proportion is often approximately around 1.6—which matches the golden section (Figure 18).

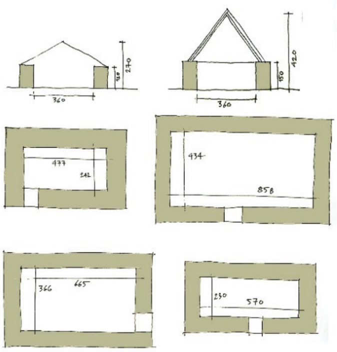


Figure 18. Cross-sections through two types of gladas and examples of plans of gladas of different dimensions, drawing: A. Kapetanović.

The thickness of gladas' walls is determined by the drystone wall technique applied, with two faces and the filling of smaller stone. The thicknesses of the wall most commonly range from 80 to 90/100 cm, although there are also walls up to 120 cm—and even to 130 cm—thick. In rare cases, there are thinner walls as well, up to 70 cm. Often, in the same glada, there is a difference in walls thickness. The sidewalls, especially in the upper parts, can be more delicately built and thinner than other walls.

Unlike the houses in villages, the walls of the cabins/gladas were relatively short and always shorter than the height of a man. The height of face walls of the preserved gladas most commonly ranges from 120 to 130 cm. However, there are also walls, which are around 150 cm high—and some even up to 170 cm.

In gladas with stonework sidewalls, for which it is possible that they represent an older type, the height of the sidewall, which also determines the height of the roof, ranged from 2.70 to 3.00 m. In gladas, which have leveled sidewalls, with a gable or a hipped roof, the height of the roof may were from 3.70 to 4.20 m. The height of the roof construction itself, from the top of the wall, in such cases was in the range from 2.00 to 2.70 m. When a glada had a stonework half-gable wall, its height most commonly ranged from 2.20 to 2.50 m.

3.1.4. Materials, Construction and Building Techniques

Along with climatic characteristics of the region and the way of life and economy of people, available building material to the greatest extent influenced the construction and the manner of construction of structures [6] (p. 4). Stones and wood, quality sufficiently presented nearby, were used for the construction of gladas and the other structures and constructions at the Kuči Mountain.

All constructions of stone at the Kuči Mountain were originally made in the drystone wall technique [9] (p. 81), from blocks of crushed or dressed stone arranged 'in dry', without any bonding agent—mortar, i.e., quicklime [9] (p. 26, 63). Until the second half of the 18th century (until about 1760), houses in the Kuči villages were also made only of stone in the drystone wall technique, and lime mortar started being used only later [9] (p. 80). The walls of gladas made in the drystone wall technique were built with two faces, the interior and the exterior, of larger blocks, between which the filling of rubbles was put. It was the simplest and most common stonework building technique, applied to gladas, dubirogs and subsidiary objects. Considering the geological composition of rocks in the area and the dominance of limestone, the walls of gladas were mostly built from irregular stone blocks of very hard, gray limestone (Figures 19 and 20).

Figure 19. Construction of limestone, photo: I. Laković.

Gladas were built from stones, which were presented in the very place or in the immediate proximity. The blocks of stone were picked or taken out of the ground, and in such a shape or with a little bit of dressing, they were built into the wall [9] (p. 80) (Figure 21). In some zones, we come across the gladas made of more delicately dressed stones and with a better arrangement (Figure 22). The type and quality of the stone which was found in the area of katuns affected building technique, arrangement types, as well as the look of the walls and their durability. In the zones with slate, gladas were built of more regular blocks of slate or sandstone in different colors.

Figure 20. Construction of slate, photo: I. Laković

Figure 21. Glada built of the stones from the immediate vicinity—Momonjevo, the lower katun, photo: I. Laković.

Figure 22. Glada with larger and better-dressed blocks—Upper Rikavac, the katun of Dučići, photo: I. Laković.

There is a very small number of structures built in stone brought from remote mines and quarries, and they are all of a more recent date. The quality of stone located in the area of the katuns directly determined building techniques and the durability of structures built that way, and there are several katuns where, due to the lack of suitable stone, wood was used as the material for building all or individual walls of glada (Figure 23). It is interesting to note that the practice of building such structures existed only in the katuns in the border regions of the mountain (locations Ćićerača, Velja and Mala Ćura), where the influence of building traditions of neighboring tribes should not be excluded either. In the areas where there were not enough available quality stone for building, such as Lještanski katun on Sumor, wooden, Bosnian pine (*Pinus heldreichii*, locally named *munika*) beams were used as a skeleton around which stone was arranged, providing it with stability and toughness.

Figure 23. Glada with wooden walls, the katun of Ćićerača, photo: I. Laković.

3.1.5. The Roof Construction and Cover

The roof construction of all types of gladas at the Kuči Mountain is wooden. Those are very simple constructions, possible to be made with the material and tools available at the mountain. Depending on the type of glada, the roofs can be simple gable roofs on gladas with stonework gable wall; gable roofs with the roof construction on the sidewalls; hipped roofs and, in some cases, three-pitched roofs. The simplest gable roofs are basic roofs with rafters (Figure 24), which are called *nožice* at Kuči, which lean onto the wall of the glada, sometimes directly—and sometimes over a horizontal beam—*vjenčanica* (the wall plate) [7] (p. 236).

The simplest wall plates can be made of round logs, with a circular diameter of 12 cm and more. In older katuns, we find wall plates of a triangular shape, especially when they were made of the Bosnian pine or fir. They are of greater dimensions, with sides from 15 up to 30 cm—and sometimes even more. In addition, wall plates of a rectangular or square cross-section, ranging from 12 up to 16 cm, occur. In the construction of roof of greater dimensions, between the rafters, collar beams are often set at 1/3 or 2/3 of the height of the roof. In some cases, double collar beams are set as well, on both sides of the rafter (Figures 25–27).

Figure 24. Roof construction of the glada with rafters, Momonjevo, photo: I. Laković.

Figure 25. Roof construction with collar beams, photo: I. Laković.

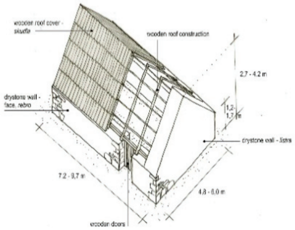


Figure 26. Basic aspects of glada, sketch: A. Kapetanović.

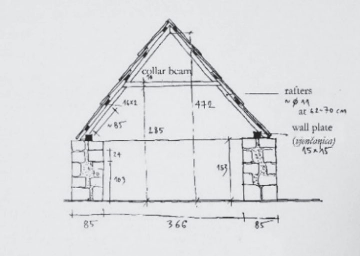


Figure 27. Cross-section through the glada's construction, sketch: A. Kapetanović.

Most commonly, the wood of fir, beech and Bosnian pine was used for building. Due to its mechanical characteristics, the fir (*Abies alba*) was most commonly used for roof building of gladas, either for the construction itself or for the board the roof which it was covered with. The Bosnian pine was used in the same way, but considerably more rarely. It is interesting to note that its extraordinary toughness and resilience often enabled the roof construction to outlive the very stone walls, in particular if these were built or the stone of a poorer quality [28]. The beech (*Fagus moesiaca*) was used, particularly more recently, for both the construction and the roof cover. In zones where quality timber was available and quality stone lacked, wood was used for building entire cabins, their walls, construction and roof. Wooden constructions on gladas, including their walls, were commonly made and built by katun people themselves through *moba* (the voluntary common work of all) [15] (p. 45).

Roof covers of gladas at the Kuči Mountain changed over the time. The oldest types of gladas were originally covered with *pustina*—the cloth of goat's hair, then with straw, afterwards with wood, and lately they were covered with tin or other contemporary materials. Gladas with the cover made of *pustina* have not been preserved, while the roof of straw, widespread at the eve of 20th century, survived on only several gladas at the Kuči Mountain nowadays [7] (p. 26) (Figure 28).

Figure 28. Roof cover of straw—Radan, photo: I. Laković.

Until the sixties of 20th century, wooden boards in different variants were most frequently used for the roof cover. Earlier, particularly in higher katuns, gladas were covered with cut planks called *skudla* [9] (p. 26) (Figure 29). The planks were cut from fir or pine in forests in the immediate proximity of a katun and on horses brought there. Based on the photographs and notes from the beginning of the 20th century, it can be concluded that the planks may have been around 1.2 to 1.8 m long [9] (p. 60) and 20–30 cm wide. These boards were not originally fixed with nails, but at the end of the season, they were removed and piled inside the walls of the glada. In that way the roof construction was protected from exposure to the pressure of snow cover [9] (p. 25, 36). Only later, with more modern tools for wood processing, a period of the permanent covering of roofs started.

Figure 29. Roof cover of *skudla*—Bankanjski katun, photo: I. Laković.

Such roofs evolved into ones made of *skudla* boards, mostly made of beech wood and of one ell in length (around 71 cm). Throughout the middle of 20th century, this was the most widespread type of traditional wooden roof cover of gladas with higher gable or hipped roofs. As gladas did not have chimneys, the smoke from the hearth escaped through openings and cracks in roof constructions [15] (pp. 46–47). The smoke itself served as a sort of preservative for wooden roof constructions and the roof cover of straw or wood, preventing the development of microorganisms causing decay.

At the beginning of the 60 s of the 20th century, the thick tin, obtained by flatting metal barrels, became very popular as material for covering the roofs. Cheap, available in the region and durable, it has been in a mass used throughout, especially in katuns accessible by roads so the building material could have been brought in by lorries. Over time, tin totally pushed out wood as material for covering gladas' roofs (Figures 30 and 31). Today, except in older gladas, wooden roofs are presented only on weekend structures and in the cases when the owners, for esthetic reasons, want to imitate as much as possible the traditional look of the cabins.

Figure 30. Metal covered roof—Mokra, photo: I. Laković.

Regular maintenance, repair of damaged parts of the drystone wall or roof constructions every spring were crucial for the preservation of gladas [7] (p. 235). At the Kuči, tribal contract on katuns of 1904, stated "That no one is to touch building material from someone else's pen or a plank from the cabin. Who do that without permission of the owner, such shall be at once delivered to the court of law for a trial in the sense of the law; he shall be treated harshly as a thief" [9] (p. 24).

Figure 31. Glada's roof made of the tin barrels—Koštica, Kotski katun, photo: I. Laković.

The use of new materials such as bricks and concrete blocks for the construction of walls or different kinds of covering materials for roofs is more than common nowadays, but such structures are rarely considered to be gladas. The local population connects this term to just one specific type of structure, which is deeply rooted in its tradition.

3.1.6. The Interior of Gladas, Their Elements and Subsidiary Objects

Gladas in katuns of the Kuči Mountain feature a simple interior organization, usually a one-unit space without partitions and with one door [27] (p. 121). "In the middle of the glada, there is the hearth and, close to it, a bed space for sleeping made of stone and beams" [7] (p. 236). In most cases, the door was located on the longer wall, most frequently at 1/3 of it. In that way the position of the door functionally divides the interior space of the glada in two parts. The zone around the hearth was mainly related to regular activities around preparation of dairy products: sitting benches, niches in the walls, shelves. The beds were located on the other side, but often raised off the ground, so that the space beneath them can be used as well.

The floor in the glada is of beaten earth. The hearth is located on the floor, on the same level as the floor and is ringed by stone blocks. It can be of a square or circular plan, with a diameter of about 70 cm. Table was most commonly located in the middle of the glada, longitudinally right next to hearth. In order to have a space on the floor free, the wooden shelves were attached to rafters of the roof construction [7] (pp. 236–237) (Figure 32).

Figure 32. Interior of the glada, Carine, katun of Popovići, photo: I. Laković.

In the sleeping part, probably it was originally slept on the floor or on the benches next to the wall. Wooden beds or galleries for sleeping appeared later. One type of these constructions is beds in the corners of a glada, set on small wooden pillars. In the examples of such beds which have been preserved, they are at a height of 80 and 120 cm off the floor, 1.3–2.1 m in width and about 2 m in length [27] (pp. 735, 782). There are also examples of forming wooden platforms for sleeping between two long walls of a glada, when a wooden beam is stretched between two walls and boarding is set on it towards a sidewall. In preserved examples, such constructions were raised at around 95 or 130 cm above the floor. In more numerous families, this kind of construction often grew into a wooden attic (gallery), placed on the glada walls, where several more people could have slept.

In gladas, there are no windows, but sometimes, at the front of the gable or hipped roof, there was one minor opening near the top. There was no chimney, so the smoke escaped through the above-mentioned openings and cracks in the roof. With the introduction of the wood-burning stove instead of the hearth, in the interior of the glada, a metal drainpipe was also added, which usually led to the opening in the upper part of the sidewall. In gladas where the hearth originally was placed in the exact center, with table closer to the sidewall, stove and table would have exchanged their places. Such a solution contributed to a better warming, with minimal interventions on the entire construction of the structure.

Apart from gladas, there are many other katuns' subsidiary objects, which were of great importance for life and everyday livestock farming activities. They were made in the similar masonry manner as gladas, but smaller in dimensions and with less material, being mostly used for making and preserving dairy products.

Torine—the sheep corrals are mainly located beside gladas, for facilitating work concerning livestock and protection from wolves. They were built predominantly in the drystone wall technique [29] (Figure 33). Although sporadically, in katuns of the Kuči Mountain, there were also pens weaved with switches, pens of nailed branches, pens of sticks and combined pens.

Figure 33. Sheep corral (*torina)* built in drystone—Bušat, photo: I. Laković.

The sizes and shapes of corrals vary according to the configuration and morphology of the terrain, sizes of the flock and financial capacities of the household, and the largest ones are getting a new purpose today. Considering that there is the best manured soil in katuns, they provide favorable conditions for growing potatoes in the areas where livestock grazing—especially sheep grazing—was reduced or abandoned (Figure 34).

Figure 34. Torina turned into a potato crop–Kastrat, photo: I. Laković.

4. Discussion

In the last ice age, the mountainous area of the southern Dinarides—including the Kuči Mountain—was exposed to the impact of glaciers. Their activity formed characteristic forms of glacial relief, including glacial lakes and glacial valleys with moraines. Villages and katuns in the mountainous zones "...are mainly located around stadial moraines and in the cirques which are sheltered from winds, as well as on cirque terraces..." [4] (p. 243).

The mentioned natural forces that shaped and designed the forms and outlooks of katuns at the mountain, also provided the framework for organization of specific lifestyle within and around them. That lifestyle—lasting for generations and surviving numerous social and political changes intact until the second half of 20th century—created a complex heritage that decisively shaped the sense of population's identity. It means that in such defined context, both individuals and community were functioning according to social rules established through adjusting to natural ones. In small and economically poor societies—as those in the Southern Balkans mostly were—this led to societal grouping thoroughly determined and defined by the landscape.

Starting there, the heritage stories spread out in different directions, creating different subcontexts and subcategories, and resulting in contemporary mountain heritage diversity. At the Kuči Mountain, that flow was shaped by the nature of different landscape characteristics and the community response to it. Every katun's community had to adjust to them, largely adopting their impact as the part of local self-definition. Even though their villages looked similar, the differences among their katuns greatly influenced their self-recognition. The elements of tangible and intangible heritage from these areas almost always bear the marks of this sensibility.

Regardless of category or kind, the katun heritage is the widest context encompassing complete lifestyle circle, from legal documents, through solid objects and economic practices, to the realm of customs, beliefs and behaviors of the people living at the Montenegrin mountains. Although this research primarily dealt with its architectural and construction sphere, gladas' roofs and corrals' walls refer to a much wider heritage domain.

The tribal contract [10] (pp. 343–345), which regulated a seasonal stay of inhabitants of the local community in the mountains, entailed, apart from rules on the use of pasturages, the right of felling trees, heating and other needs of the household, including making objects for the household and building katuns and dwelling cabins. "...At Kuči, the layout of katuns as complexes and buildings within them has also been dictated by the need for protection from enemies and other mountain nuisances such as beasts and not only by economic moments, which in normal circumstances should be of primary significance. Therefore, the Kuči katuns and cabins—gladas are more of a nucleated type...." [13] (p. 130).

Traditional mountain cabins—gladas are the most important category of architectural heritage of the Kuči Mountain. Their appearance evolved with the development of available tools and with the improvement in the material and financial state of the population itself. The original type of dwelling was a mobile construction of wooden beams set in a circle and connected in one point by tying. It was originally covered with the cloth of goat's hair, and then with beech branches, leaves or straw. This kind of structure was intended to last only one season. The first stonework structures, so-called dubirogs, were also of a circular form, made in the drystone wall technique and partially dug into the slope. The roof construction entirely resembled the original temporary structures, with the difference that the roof beams did not start from the ground, but from the wall of the structure [15] (pp. 44–46). Although simpler for building, this type of structure was less suited to the needs of the interior organization of space, therefore it was superseded by stonework structures with a rectangular plan.

In the mid-19th century, the construction of squarish gladas with stone walls started, where, most commonly, the sidewalls were made in stonework up to the top. As building material, stone was both more available and it required fewer tools for processing, so the aim was to reduce the use of timber to the smallest possible extent. The tops of the sidewalls were connected with the ridge board, from the timber of the fir or the Bosnian pine, and less often of the beech and covered with cut boards.

These boards were not originally fixed with nails, but they were removed and piled inside gladas' walls at the end of the season. That way the roof construction was protected from exposure to the snow cover pressure, and later, with more available tools for wood processing, the period of permanent roof covering started, as well as the construction of structures with one stonework sidewall or without them. Where it was available, roofs were covered with straw for isolation [15] (p. 46).

It is important to notice that even simplest and smallest improvements in common wealth led to significant leaps forward in specific spheres of katun's life. For example, the use of metal nails became common practice in construction only at the beginning of 20th century. This enabled construction of more sophisticated and solid roofs, providing a significant increase in quality of life and work in katuns. Along with making the dwellers' lives cozier, it consequently benefited to improving conditions for producing and preserving dairy products, as it was the main goals of the whole activity. In such objects, more comfortable for life and work and with higher hygienic level, it was easier to produce traditional cheese and other products in larger quantities and of better quality. This seemingly insignificant change, at the time taken for granted in many other parts of the Mediterranean, had an enormously positive influence to the whole system of mountain pastoral economy.

Techniques of the masonry construction of gladas range from the original drystone wall technique, over the technique of drystone wall filled with mortar after building, to the technique involving use of mortar as a bonding agent during the building itself. The drystone wall technique was the sole method of construction of structures until the beginning of the 20th century. Filling, originally with lime mortar, and later with cement mortar, was used only for consolidation and reconstruction of built structures in the drystone wall technique. The use of mortar, as a basic bonding agent, today is the most common form of construction, considering that roads enabling transport of the appropriate quantities of cement and sand, nowadays reach most katuns.

The katuns are now facing with three different trends—traditional use for summer grazing, transformation into recreational and leisure settlements and abandonment. The number of families who still bring up their cattle and sheep to the mountain pastures is rather small, but still visible and relevant. The second trend is mostly related to people who inherited the right to build the cottages in the katuns' areas, but don't have the intention to practice agriculture activities. There are different examples of how this trend influences the katun's life and general landscape. Such practice preserved some connection between people and the mountain, but, more often than not, new constructions disturb the outlook of the traditional landscape with use of inappropriate materials, construction techniques and designs. We find the results of our research important for dealing with this category, since the presented data can provide the base for national stakeholders to determine the relevant legislation that could both promote the maintaining contact with mountain areas and protect the traditional landscape as the value per se.

The abandonment of katuns is the most visible trend, induced mostly by the changed economic constellation within the society. What also contributes to it is a general silence on the matter, where this topic is rarely covered in the media or draws1 public's attention. Investigations of this kind cannot bring people back to the mountain pastures but can help in creating the atmosphere where the katuns' lifestyle is treated as socially important, pushing the stakeholders to provide more favorable administrative and economic preconditions for continuing that activity.

The comprehensive social and economic changes in the Montenegrin population lifestyle, having emerged from rapid industrialization and depopulation of rural communities in the second half of 20th century, led to the drastic abandonment of katuns. That process not only affected the katuns themselves, but also triggered the scientific demotivation to research this topic. Taking their existence for granted, researchers from this part of Europe have missed the opportunity to tackle the topic in times when a greater number of katuns functioned, and when more data on abandoned ones could have been obtained via oral interviews with locals remembering their previous condition. Nowadays, facing with present danger of losing the whole concept of katun's lifestyle, we assume as our scientific obligation to preserve and analyze still available data on the subject. As mentioned before, one of the first implications we expect that our research will have is acquiring a degree of legal protection for the transhumance, as well as raising the public and scientific awareness on the importance of the topic.

However, the main focus of this research was data gathering for the first complete inventory of katuns in one of the Dinaric mountains range regions. It may sound unbelievable nowadays, but this category has been almost totally neglected and put aside, so it was impossible to find any reliable quantitative information on both katuns and subsidiary objects. Prior to this research, one could find only some scattered data from the beginning of 20th century about katun's life, without figures describing number, disposition, organization, contents and architectural and construction characteristics of katuns and adjacent housing and subsidiary objects. For the first time, we compiled a more complete inventory of katun's material cultural heritage, with reliable and in-situ-checked data related to mentioned categories.

Altogether, the goals of our research were:

- To bring the attention of different scholars (historians, ethnologists, archaeologists, anthropologists, architects, environmentalists, etc.) to this subject;
- To draw public's attention through acquiring specific and previously unknown data on the one of characteristic of katun areas;
- Establish a role model and field work methodology, appropriate for further investigations in similar areas and
- Motivate the local stakeholders to consider enlisting katuns and transhumance in the national list of protected intangible cultural heritage, as it was done in Greece, the Apennines and the Alps [19].

We believe that the obtained results—especially since there were no other currently existing data on this topic regarding Montenegro—can be of great help to the researcher venturing into domain of seasonal mountain settlements in this part of Europe. The research outcomes contain data on different aspects of local architectural heritage, which are relevant to many other Montenegrin mountain areas, as well as the other Balkan regions where the transhumance existed. Precise determination of traditional building techniques and used material, as well as characteristics of thus constructed objects are already recognized by EU member countries as the base for legalization of building activities within protected mountain areas (example of *Velika planina*, a traditional katun area in the Slovenian Alps) [30]. We expect that data emerging after our research will help arranging similar status for the traditional katuns' regions in Montenegro. Moreover, scholars and researchers from the fields of vernacular architecture, ethnology and social history will benefit from data obtained from this research.

5. Conclusions

Nowadays, katuns in Montenegro have lost their traditional economic importance. The contemporary lifestyles, needs, and habits of the population do not include agriculture and livestock-rearing and traditional practices as dominant activities. This leaves the whole infrastructure of rural settlements and katuns—established throughout centuries—in a difficult position where their abandonment and desertion become regular. Deep and thorough social-demographic changes in the Montenegrin society after the World War II rendered realms of existing life practices obsolete, including the seasonal transhumance with livestock to katuns in mountains. The impacts of this phenomenon on the sense of society identification as a whole notwithstanding, this caused a gradual abandonment of hundreds of katuns on the slopes of the Montenegrin mountains—along with tens of thousands traditional housing and subsidiary objects. Their number and contents testify to the way of life. They enabled survival to generations of people, who used to lean on them during their whole life. Overall, they present a valuable cultural and historical heritage that should be treated with due scientific interest, in the very least.

In general, today's condition of the remaining traditional housing objects, even in the still 'living' katuns, is far from good. Dwellings, as their name itself implies, are places to dwell in. Without people, they find it hard to resist entropy and rapidly turn into ruins. The abandoned katuns at the end of the 70 s of the 20th century today resemble archaeological sites from antiquity. Without smoke, wooden roofs rapidly decay and decompose, opening the way for water, which enters the interior of the stone walls. Melting and freezing processes in turns in the period from October to May result in walls unavoidable cracking and collapsing. Better constructed structures, particularly those partially dug into the ground, can last somewhat longer, but there is a very small number of gladas, made in the drystone wall technique, the walls of which remained completely preserved 50 to 60 years after having been abandoned [31] (pp. 14–15).

Besides katuns' individual characteristics, role in economic concepts and value as cultural heritage's treasure, they must be observed as the authentic category of the traditional landscape. Correlations and interactions among natural and artificial structures, people, domestic and wild animals, herbs and forests created a complex picture with clearly defined roles and places of the protagonists. The human interventions in the natural landscape here used to adjust to, rather than to confront mountain rules, where their understanding led to precipitating of generational wisdom enabling constitution and development of the katuns as a viable and resilient system. The relation to terrain geomorphology not only determined the size and shape of katuns, but also distinguished successfully from the failed katun stories. Hence the outlook of traditional katuns does not reflect only the needs, knowledge and may of their direct builders, but the long-time experience of what, where and how to construct in order to last and function. Keeping in mind poverty and the lack of everything, but the basic tools, the quality and the functionality could have been achieved only through maximal adjusting to natural conditions.

On the other hand, traditional relations to pastures, water and forests that have dominantly determined katun positioning, shows a clear intention not to intrude into these domains as much as possible. Most katuns are built at the borderlines of rocky terrain and pasturelands, in order to preserve as much of pastures for grazing. From a purely esthetic point of view, such tendencies allowed an easier blending of shapes of artificial structures with contours of terrain. Made of in situ available materials and in sizes corresponding to the surroundings, the katuns more often melt into surrounding landscape than stand out of it. Unfortunately, without stronger social intervention such as more precise legal determination of preferable, acceptable and unwanted praxis, it seems that not only traditional katuns, but also the traditional katun landscapes as we know them, may be a thing of the past.

While this research covered only one of the traditional katuns' areas in Montenegro, the main postulates can be applied to all the rest. While particular construction methods, shapes of the objects and used materials slightly differ from each other, the context of their use—as well as their present and perspectives—look the same. Since the application of new technologies enables contemporary researchers to acquire, analyze and store the obtained data more easily, the importance of the knowledge on their various domains rises.

In this sense, currently obtained results enable making exemplificative maps, valuable for describing the territory, with selection of the most stimulating points of interest. The results of the geo-database in QGIS contains a corresponding location for each building, their relation with infrastructure, land cover, morphology, vegetation, etc. Eventually, this will provide a centralized source of all relevant data from different locations, in a unified environment and the visualization of data on maps. We expect that in time more layers will be added and all layers can be interconnected and integrated with non-geographic information such as: opening hours of museums and other tourist attractions; hotels and restaurants rates and costs; events calendar; historical data, intangible heritage, flora and fauna, as well as other information regarding local society and economy.

To summarize, this research was the first of this kind in Montenegro, and among the first in region to have the main topic focused on katuns. Its practical results and contributions are presented through obtained detailed data on existing seasonal settlements and belonging objects within the case study area. While this may seem modest, it should be kept in mind that similar data on this topic had not previously existed either in historical documents or in other sources or relevant scientific literature.

The concentration of katuns in observed region proved to be denser and more numerous than expected. When the acquired information is applied to the other mountain areas in the region, it will significantly affect the common knowledge on transhumance, its quantitative framework and architectural and construction heritage it had created. Combined with visible landscape changes caused through blending of creative human energies and the natural characteristics of the environment, such data become a part of not only description of the anthropogenic activity in the mountains, but also the measure of its correlation with them. The number of determined katuns—together with number of belonging housing objects—testifies that only a negligible percentage of the population of the case study area did not participate in this social and economic context, which also means that the situation can hardly differ in other Montenegrin mountain areas. This could mean that the katun heritage presents one of the most important heritage domains in the Montenegrin history, which should attract more of public and scientific attention.

This immense, but neglected category of cultural heritage of the Adriatic region can still provide an unexpectedly fruitful ground for future researchers [32].

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Article

Land Functions, Rural Space Governance, and Farmers' Environmental Perceptions: A Case Study from the Huanjiang Karst Mountain Area, China

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Abstract: Residents of rural areas live and depend on the land; hence, rural land plays a central role in the human–land relationship. The environment has the greatest direct impact on farmers' lives and productivity. In recent years, the Chinese government carried out vigorous rural construction under a socialist framework and implemented a rural revitalization strategy. This study was performed in a rural area of Huanjiang County, Guangxi Province, China. We designed a survey to measure rural households' perceptions of three types of rural spaces: ecological, living, and production spaces. The survey was administered to 379 farmers, and their perceptions and satisfaction with Ecological–Living–Productive spaces were evaluated with the use of structural equation modeling. Analysis of latent and observed variables indicates that: (1) Farmers' overall satisfaction with Ecological–Living–Productive spaces was moderate. The average satisfaction score for production spaces was lowest (2.881) while that for living spaces was highest (3.468) and that for ecological spaces was in between (3.351). (2) The three most important exogenous observed variables associated with living space satisfaction were house comfort > domestic water supply > domestic sewage treatment. The three most important exogenous observed variables associated with production space satisfaction were irrigation water > cultivated land quantity > cultivated land fertility. The three most important exogenous observed variables associated with ecological space satisfaction were garbage disposal > vegetation cover > flood and waterlogging. Based on the requirements of the rural revitalization strategy and the results of our analyses of rural households' spatial perceptions, we propose corresponding countermeasures and suggestions.

Keywords: environmental perceptions; land function; rural space; karst mountain area

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1. Introduction

Rural space is defined as an area of land that rural residents live in and depend on. It plays a central role in the relationship between humans and the land. Rural land has direct impacts on the lives and production capacity of rural farmers [1] and, as such, has long been the focus of research on the relationship between humans and the land. Studies have proven that rural land, transportation, infrastructure construction, and public services all positively affect farmers' satisfaction and quality of life; however, land factors have more significant impacts [2]. When farmers have higher quality land resources, their happiness is generally higher and they receive greater benefits [3]. Land has diverse functions, and effective functioning increases farmers' welfare and happiness [4]. Research on multifunctional land around the globe has evolved rapidly from the early studies of multifunctionality in agriculture [5]. In 2001, international organizations formally proposed the concept of agricultural multifunctionality and, with increased research attention, studies of multifunctional land use have gradually spread from the field of agriculture to various other fields [6,7]. Multifunctionality of land use considers that all types of land use interact. Overall, it relates to the products and services that the land can provide for residents of a certain area [8]. The multifunctionality of land use emphasizes land use versatility; as such, research on it is comprehensive and covers a wide range of topics.

In 2004, the EU Integrated Project SENSOR (Sustainability Impact Assessment: Tools for Environmental, Social and Economic Effects of Multifunctional Land Use in European Regions), first proposed the concept of multifunctional land use [9]. Specifically, it refers to the private and public products and services provided by different land use methods [10] in terms of society, economy, and the environment [11]. Following this, extensive research on land use versatility was performed. It should be noted that there are differing views within the academic community regarding the classification of land use functions. From the perspective of functional subjectivity, land use functions can be divided into three primary categories: economic, social, and ecological [12,13]. Economic functions include material production and economic development, social functions include transportation and residential functions, and ecological functions include environmental regulation and ecological maintenance capabilities [14]. More recently, a new method of categorizing land use was proposed as an increasing number of scholars have begun to study land use from the perspective of production, living, and ecological functions [15–17]. Here, living functions refer to the space's capacity for human production and life [18], production functions refer to the various products and items of value produced by the land [19], and ecological functions refer to the ability of the land to adjust ecologically and maintain human survival [20]. With the increased interest in the theory of sustainable development over recent years, the Ecological–Living–Productive land use model has become a focus of research within the field of multifunctional land use.

Perception is the act of recognizing certain facts [21]. It is the first step in understanding the surrounding environment and the beginning of all behavior [22–24]. Environmental perceptions are the perceptions that people form regarding their natural surroundings and social environment [25–27]. Current studies on the environmental perceptions of farmers focus on their risk perceptions [28], how their perceptions impact behavioral decision-making [29], their perceptions of and adaptation to climate and environmental change [30], and their perceptions of land degradation [31]. In terms of the risk perceptions of farmers, there are many studies of their effects on livelihood [32], environmental risk in the breeding industry [33], agricultural production and operation [34], and the risk perception of farmers in response to climate change [35]. Research on farmers' perceptions primarily examines their influences on behavioral decision-making, analyses perceptions, and adaptive behaviors, and investigates consistency in perceptions and behavior [36]. In particular, there is a relatively large body of literature on farmers' perceptions of climate change and their adaptive behaviors in poor and arid areas [37], and the effects of perceived value on farmers' input behaviors [38], planting decisions, and satisfaction with new residential areas [39,40]. Further, analysis of farmers' perceptions was also applied in the context of the evaluation and analysis of policies such as the rural revitalization policy and the countryside home appliance policy in China [41], the latter of which provides subsidies for farmers to purchase home appliances. Farmers' perceptions of climatic and environmental changes are affected by factors such as soil fertility, land tenure, age, years of education, time spent in agriculture, and use of social networks [42]. Further, many farmers report perceived changes in local temperature and precipitation [43]. Farmers' perceptions of land degradation mainly relate to land erosion, soil erosion, fertility loss, and land fragmentation [44]. Research shows that farmers' understanding of land degradation is a key social factor in controlling land erosion and soil erosion [45].

In summary, current research on land space functions is relatively mature. The focus in this field has changed from early studies of multifunctional agriculture to contemporary studies of multifunctional land use, primarily discussions of land space Ecological–Living–Productive functions. Farmers' perceptions have also led to discussions in several related fields, such as natural disaster risk, climate change, adaptability of farmers' livelihoods, and land degradation; and an increasing number of comprehensive multidisciplinary studies have been conducted. However, studies that have evaluated perceptions of rural spaces have not combined perspectives of production, living, and ecological land use functions. The current study addresses this gap by analyzing farmers' perceptions of, and satisfaction with, rural production spaces, living spaces, and ecological spaces. More importantly, our research is novel as it focuses on farmers' socioeconomic identity to explore its impact on their perceptions of different land spaces. We consider farmers' direct perceptions or evaluations of the internal components of different land spaces and analyze their impacts on their overall evaluation of space, which is a very different approach to that used in previous studies. The main factors affecting perception and satisfaction, as related to production, living, and ecological functions, are analyzed using structural equation modeling (SEM). Finally, based on our results, we propose measures to improve land use quality and suggestions for rural space management.

2. Study Area and Data Sources

2.1. Study Area

Huanjiang County, Guangxi Province, China, is located between 24°44′–25°33′ N and 107°51′–108°43′ E (Figure 1). It covers a total area of 4553 km^2 and is the third largest county in Guangxi. Huanjiang County has 12 townships under its jurisdiction (Table 1) and 149 administrative villages, of which Chuanshan town has the largest area and contains 20 administrative villages with a total area of 66,440.32 ha. The smallest town is Dachai township, which has eight administrative villages under its jurisdiction covering 12,838.92 ha. According to the Statistical Yearbook, the total permanent population in 2016 was 374,312, of which the rural population was 324,101 (86.6%). Huanjiang County is one of 28 poverty-stricken counties in Guangxi and has very poor economic development. As an example, in 2016, the GDP of Huanjiang County was only 4.53 billion yuan, ranking last economically among Guangxi's counties. Huanjiang County is in the low-latitude region near the Tropic of Cancer. The climate reflects a transition from the southern subtropical climate to the mid-lying subtropical monsoon climate, with abundant light, heat, and humidity. As the main landform types in this area are karst landforms, the hydrological features mainly include surface water and groundwater.

2.2. Data Sources

The sampling locations were chosen with consideration of two factors: the distance from each sample village to the administrative center of the county, and the level of economic development. In choosing the sampling locations, we also considered Tobler's first law: the closer the object, the higher the similarity. We tried our best to avoid selecting sample points that were spatially homogeneous. A stratified sampling method was adopted to select 16 sample villages from the 141 villages in Huanjiang County. This study was carried out in two stages using the Participatory Rural Assessment (PRA) method [46]. The first stage was completed between 16–26 May 2016. The first stage involved a survey of the actual situation in Huanjiang County; it involved surveying farmers and holding interviews with key personnel. In the second stage, from 4–14 June 2017, an 11-day in-depth field survey was conducted in Huanjiang County. Data were collected through written questionnaires and face-to-face interviews. We recognized that we may not fully understand the situations of the local villages, especially in those where labor is exported. To select representative villages and avoid ones with no farmers, we consulted local guides and village officials. Questionnaires were completed by interviewers and a total of 363 valid questionnaires were obtained. The questionnaire comprised questions on household characteristics and the basic conditions of farmers, land characteristics, farming conditions, and satisfaction with the Ecological–Living–Productive spaces, among others. The average time taken for the semistructured interviews was 1.5 h. Prior to the survey, the project leader conducted centralized training and field drills with 12 research staff to ensure they had the necessary field survey skills and understood the ethical requirements. In addition, to avoid farmers' misunderstanding the questions due to low education (most were educated to middle high or senior middle school levels, 47.3% and 31.5%, respectively) or differences in local dialect, we selected interviewers able to use the local dialect. During the survey period, one person was responsible for reviewing each questionnaire to ensure that high-quality data were obtained.

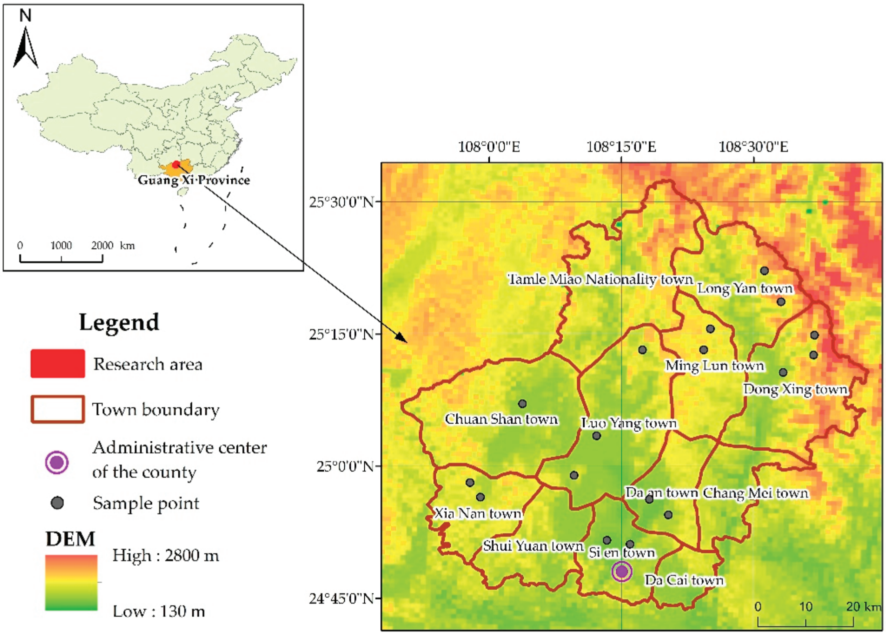

Figure 1. Map of Huanjiang County and its townships.

Table 1. Area and number of administrative villages in Huanjiang County townships in 2018.

Town Name	**Sien Town**	**Dacai Xiang**	**Shuiyuan Town**	**Luoyang Town**	**Chuanshan Town**	**Xia'nan Xiang**	**Da'an Xiang**	**Changmei Xiang**	**Minglun Town**	**Dongxing Town**	**Longyan Xiang**	**Xunle Xiang**
Number of administrative villages	14	8	13	16	20	11	7	6	16	11	13	14
Area (km^2)	27,799.1	12,838.9	35,498.2	46,759.2	66,440.3	25,386.5	22,087.0	23,816.8	45,774.6	49,513.6	40,998.5	58,359.4

3. Research Design and Research Methods

3.1. Data Sources and Scale Design

Based on previous research results, we designed a series of Likert scales to investigate farmers' satisfaction with their local living space [47,48]. Question responses were rated on a 5-point Likert scale as "strongly disagree" (1), "disagree" (2), "general or inaccurate" (3), "agree" (4), and "strongly agree" (5). We put forward a basic hypothesis that the total rural space satisfaction level of rural households was based on satisfaction with three aspects: living, production, and ecology. Rural households wholly depend on their living spaces. A review of the literature suggested that in addition to rural households' perceptions of their own housing conditions, other factors within the living space should be considered [49]. Therefore, to fully assess perceptions of living spaces, we measured perceptions related to road traffic, house comfort, neighborhood relations, domestic water conditions, domestic sewage treatment, local medical treatment, and convenience of shopping at the local market, and used them as observed variables. In terms of perceptions of production spaces, the observed variables included cultivated land quantity, cultivated land fertility, cultivated land access, agricultural facilities, job opportunities in the village, and sufficient irrigation water. The observed variables for ecological space perception included characteristics of rocky desertification in karst areas, the evaluation of local rocky desertification, river water quality, flood and waterlogging, garbage disposal, and vegetation coverage. Among them, the amount of cultivated land, the severity of rocky desertification, and increases in floods and waterlogging were negative evaluation indicators.

3.2. Research Methods

This study used SEM, which is a useful multivariate analysis method primarily used to estimate and test causal relationships between variables [50]. SEM has the advantages of combining factor analysis and path analysis, and processing multiple dependent variables at the same time to give simultaneous estimates of the structure of factors and the relationships between them. It allows for measurement of error in independent and dependent variables and it has been widely used in various disciplines. The analysis process was based on a covariance matrix analysis that included both observed variables and indirectly observable latent variables [51]. An SEM consists of two parts: a measurement model and a structural model [52]. In this study, the satisfaction evaluation of ecological, living, and productive spaces formed the observed variables, and the remaining 18 evaluation factors were used as latent variables. Therefore, an SEM model is appropriate. The expressions of the equations follow:

$$X = \wedge_X \Psi + \upsilon \tag{1}$$

$$Y = \wedge_Y \vartheta + \varsigma \tag{2}$$

$$\vartheta = Q\vartheta + \mathcal{T}\psi + \sigma \tag{3}$$

In the three equations, Models 1 and 2 are measurement models representing measurement levels, and Model 3 is the SEM. X is an exogenous observed variable vector that can be directly measured and Ψ is an exogenous latent variable vector; Y is an endogenous measurable variable vector and ϑ is an endogenous latent variable vector. $\wedge_X$ and $\wedge_Y$ refer to factor loading matrices, which are expressed as the correlation between exogenous observed variables and corresponding exogenous latent variables, and between endogenous observed variables and corresponding endogenous latent variables, respectively. Q is the unique matrix of endogenous latent variables. $\mathcal{T}$ refers to the effect of exogenous latent variables on the corresponding endogenous latent variables. υ, ς, and σ are error terms used in the measurement model and structural equation. SEM data analysis was primarily performed using AMOS (Analysis of Moment Structure) software and basic data processing and inspection were conducted in SPSS (Statistical Product and Service Solutions) 17.0 software.

Based on the principles of SEM and the Likert scale measurement system, this paper established a structural equation as follows (Figure 2).

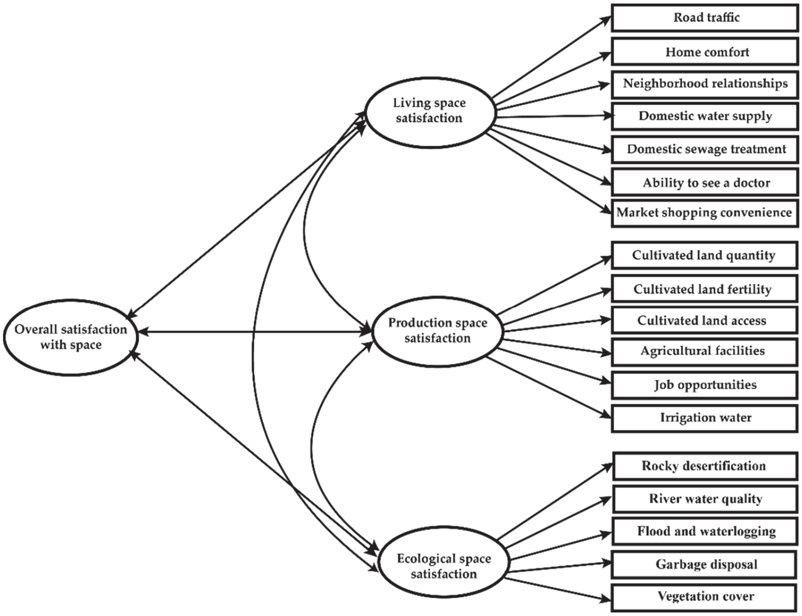

Figure 2. Model of the relationships between farmers' satisfaction and their Ecological–Living–Productive spaces.

4. Results and Discussion

4.1. Reliability and Validity of Measures

Prior to data analysis, the classic alpha (Cronbach) coefficient was used to analyze the credibility and validity of the survey data at different levels. Cronbach's alpha is a measure of internal consistency, that is, how closely related a set of items are as a group. A high alpha value is often used (along with substantive arguments and possibly other statistical measures) as evidence that the items measure an underlying (or latent) construct [53]. Some classic studies have demonstrated that the coefficient has a strong effect on the reliability index of the measured data; the higher the coefficient, the higher the reliability [54]. The test results are shown in Table 2. It can be seen that the α coefficient (CA) value (0.762) exceeds the required value of ≥0.7. Thus, the scale is reliable. Further, the three latent variables were tested separately and returned CA values of 0.724, 0.821, and 0.773, respectively, all of which were >0.7, indicating consistency in the data. Factor analysis was then performed to analyze the validity of the data. The overall KMO (Kaiser–Meyer–Olkin) value was 0.844, and those of the three latent variables were all >0.7 and highly significant. Bartlett's test of sphericity was applied to the KMO values, which showed that the data collected in this study were suitable for factor analysis.

Table 2. Reliability and validity analysis.

Latent Variable	Observation Variable	α Coefficient	KMO Value	Bartlett		
				Approximate X^2	*df*	Significance (p)
Living space satisfaction	X1–X7	0.724	0.769	363.258	163	0.000
Production space satisfaction	X8–X13	0.821	0.742	763.498	174	0.000
Ecological space satisfaction	X14–X18	0.773	0.809	641.347	236	0.000
Overall	X1–X14	0.762	0.844	1498.245	561	0.000

KMO: Kaiser–Meyer–Olkin; df: degree of freedom.

4.2. Overall Evaluation of Satisfaction with the Ecological–Living–Productive Spaces

This study measured satisfaction with the Ecological–Living–Productive spaces overall, as well as with each type of space separately (Figure 3). The overall satisfaction of farmers in Huanjiang County was moderate, with a score of 3.233 out of a possible total of 5. This indicates that farmers were neither satisfied nor dissatisfied with the local living space. Analysis of satisfaction with different types of space revealed that farmers had the lowest satisfaction with production spaces (2.881) and the highest with living spaces (3.468), with ecological space satisfaction falling between these values (3.351). This indicates that new rural construction, rural environmental quality, and infrastructure construction carried out in Huanjiang County in recent years were relatively effective, as farmers perceive that the quality of the living environment has significantly improved. However, the production space satisfaction scores were relatively low, which reflects, to some extent, farmers' dissatisfaction with the local agricultural production environment.

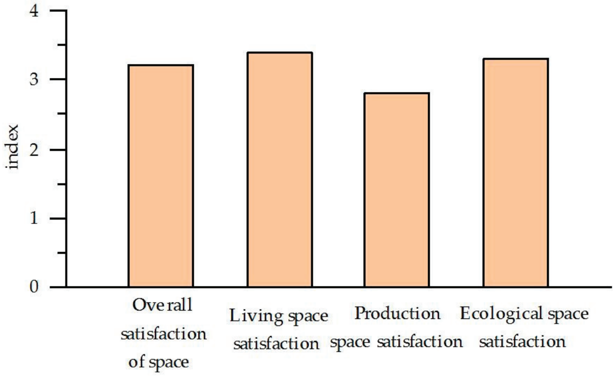

Figure 3. Overall evaluation of satisfaction with Ecological–Living–Productive spaces.

4.3. Satisfaction with Land Space Characteristics Based on Farmers' Attributes

We found that the satisfaction of farmers varied according to the attributes of household income level, gender, education level, age, household size, and household location, especially household income level, education level, and household location (Table 3). Among them, farmers with higher incomes tended to be more satisfied with the overall space. It should be noted that farmers with an annual income of <20,000 CNY had very low satisfaction with production spaces. Farmers with higher education levels were more satisfied with the overall and individual spaces. In terms of the geographic position, farmers in the Valley region had significantly higher satisfaction with the overall space than those living in the Middle Mountain and low-lying regions, who also had the lowest satisfaction score for production spaces.

Table 3. Satisfaction scores for land spaces based on farmers' attributes.

Items	Farmer Household Attributes	Percentage (%)	Overall Satisfaction	Living Space Satisfaction	Ecological Space Satisfaction	Production Space Satisfaction
Household income level (CNY/Year)	20,000 and less	23.3	2.902	3.046	3.229	2.431
	20,000–50,000	40.3	3.294	3.573	3.197	3.112
	50,000–100,000	28.9	3.264	3.468	3.351	2.973
	100,000 and more	7.5	3.471	3.663	3.681	3.069
Gender	Male	59.4	3.268	3.503	3.214	3.087
	Female	40.6	3.198	3.496	3.091	3.007
Education level	Elementary school and below	14.9	3.102	3.482	3.233	2.591
	Junior high school	47.3	2.976	3.143	2.891	2.894
	Senior middle school	31.5	3.475	3.673	3.691	3.061
	University and above	6.3	3.379	3.564	3.495	3.078
Age	25 and below	8.6	3.281	3.485	3.561	2.797
	26–40	25.3	3.161	3.507	3.475	2.501
	41–60	36.8	3.287	3.695	3.177	2.989
	60 and above	29.3	3.203	3.415	3.169	3.025
Household size(person)	3 and below	21.4	3.196	3.219	3.335	3.034
	4–5	57.9	3.273	3.557	3.491	2.771
	6–8	13.1	3.187	3.269	3.227	2.765
	9 and more	7.6	3.276	3.305	3.272	3.251
Household location	Middle Mountain	19.4	3.076	3.383	3.566	2.279
	Low-lying land	37.9	3.091	3.678	3.598	2.297
	Valley	42.7	3.532	3.706	3.439	3.453

4.4. Exploratory Factor Analysis

Principal component analysis is commonly used for exploring the influences of observed variables. Orthogonal rotation was applied to the data to explore the correlations between factors and extract common factors (Table 4). The results show that three variables (Ecological–Living–Productive space satisfaction) explain 62.17% of overall satisfaction with spaces in Huanjiang County. However, within some of the common factors, there were differences in the interpretation of the survey ratings. In order to further explore and test the reliability of the variables and measure the degree to which the observed variables explain the latent variables, we analyzed the combined validity of the survey. The test results are shown in Table 5. The combined reliability of the three-dimensional variables was greater than the reference standard of 0.50, which shows that the scale designed in this paper has relatively high convergent validity and discriminant validity.

4.5. Modification of the Rural Households' Ecological–Living–Productive Space Satisfaction Model

An initial model of Ecological–Living–Productive space satisfaction was established through analysis of the data. Then, the maximum likelihood estimation algorithm was used to estimate and modify it. The parameters of the Ecological–Living–Productive space equation were obtained through repeated experimentation and verification. The SEM of overall satisfaction, the detailed parameter estimates, and the standardized path coefficients are shown in Figure 4. The χ^2 test value of the rural households' Ecological–Living–Productive space satisfaction model was 211.634. Combined with the degrees of freedom, the absolute fit index (137.354/69) was 1.991, which is within the specified range (1–3). The reduced index IFI (increasing fit index), relative fit index NFI (canonical fit index) and TLI (Tucker–Lewis index) were 0.976, 0.915, and 0.943, respectively, which are all greater than the reference standard of 0.9. The RMSEA (root-mean-square error of approximation) value was 0.074, which is less than the standard of 0.1. These findings indicate that the model generally fit the data well, indicating that it is reasonable to model the three latent variables in the household Ecological–Living–Productive space satisfaction model.

Table 4. Exploratory factor analysis of Ecological–Living–Productive spaces.

Latent Variable	Observation Variable	Standardized Coefficient Load	Error Variation	Composite Reliability	Average Variance Decimation (AVE)
Living space satisfaction	Road traffic	0.589	0.438	0.727	0.307
	Home comfort	0.358	0.361		
	Neighborhood relationships	0.750	0.476		
	Domestic water supply	0.502	0.298		
	Domestic sewage treatment	0.523	0.705		
	Ability to see a doctor	0.613	0.813		
	Market shopping convenience	0.702	0.472		
Production space satisfaction	Cultivated land quantity	0.654	0.317	0.699	0.287
	Cultivated land fertility	0.476	0.461		
	Cultivated land access	0.442	0.607		
	Agricultural facilities	0.532	0.578		
	Job opportunities	0.471	0.441		
	Irrigation water	0.564	0.392		
Ecological space satisfaction	Rocky desertification	0.711	0.439	0.621	0.364
	River water quality	0.433	0.573		
	Flood and waterlogging	0.391	0.641		
	Garbage disposal	0.535	0.324		
	Vegetation cover	0.626	0.517		

Table 5. Combined test of survey validity.

Observed Variables	Factor Loadings		
	Component 1	Component 2	Component 3
Road traffic	0.736	0.013	0.160
Home comfort	0.815	0.149	0.043
Neighborhood relationships	0.512	0.214	0.081
Domestic water supply	0.807	0.121	0.112
Domestic sewage treatment	0.778	0.235	0.217
Ability to see a doctor	0.449	0.042	0.141
Market shopping convenience	0.722	0.193	0.217
Cultivated land quantity	0.235	0.757	0.037
Cultivated land fertility	0.188	0.532	0.128
Cultivated land access	0.181	0.761	0.052
Agricultural facilities	0.073	0.811	0.034
Job opportunities	0.214	0.423	0.120
Irrigation water	0.369	0.797	0.201
Rocky desertification	0.216	0.078	0.765
River water quality	0.124	0.023	0.496
Flood and waterlogging	0.103	0.072	0.658
Garbage disposal	0.241	0.165	0.798
Vegetation cover	0.207	0.253	0.590
Eigenvalue	17.268	5.697	4.021
Variance (%)	39.452	13.761	8.957
Cumulative variance(%)	39.452	53.213	62.170
Extraction method: principal component analysis			

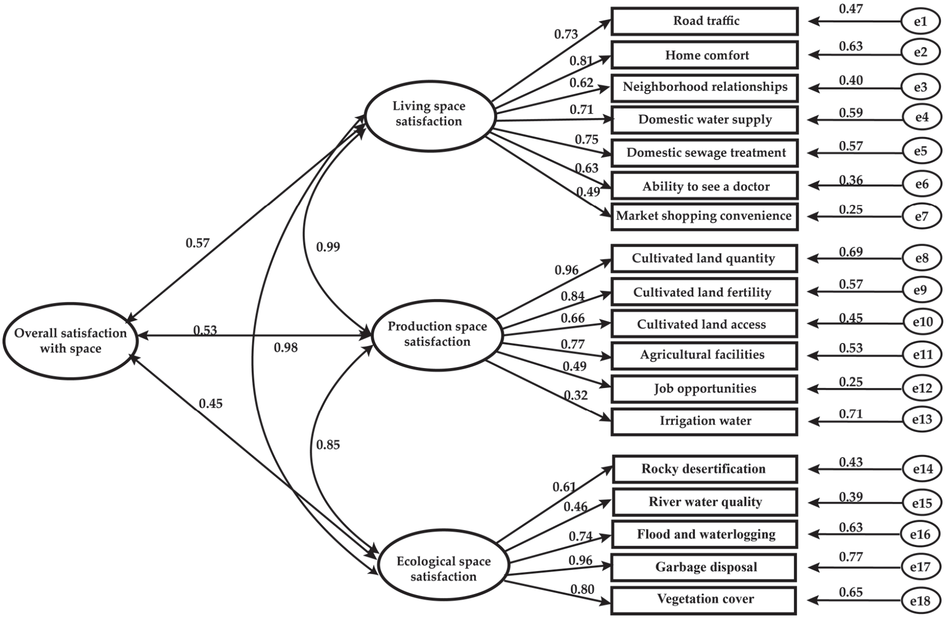

Figure 4. Estimated standardized path parameters of the Ecological–Living–Productive space satisfaction model.

5. Discussion

According to the overall modeling results (Figure 4), the basic hypothesis—that the three latent variables underlie household Ecological–Living–Productive space satisfaction—is upheld. The three latent variables can be ranked according to the values of their coefficients as follows: living space satisfaction > production space satisfaction > ecological space satisfaction. This shows that most people in the rural areas of Huanjiang County are gradually becoming wealthier. Incomes have increased and living standards have gradually improved. While residents in these areas previously focused on production issues, they are now becoming increasingly concerned with improving their quality of life. This is also consistent with Maslow's demand-level theory. The findings as they relate to the observed variables and their three corresponding exogenous latent variables are described below.

5.1. House Comfort, Domestic Water Supply, and Domestic Sewage Treatment Significantly Affect Farmers' Perceived Satisfaction with Their Living Space

The standardized path map of exogenous observed variables that affect living space satisfaction indicates that there are clear differences in their strength of effect. These can be ordered according to their coefficient values as house comfort > domestic water supply > domestic sewage treatment > road traffic > neighborhood relationships > ability to see a doctor > market shopping convenience, with corresponding values of 0.63, 0.59, 0.57, 0.47, 0.40, 0.36, and 0.25, respectively.

Among them, the exogenous observed variable with the highest coefficient value was comfort of the house, which relates to the residential area and housing conditions. This finding indicates that rural housing areas and housing conditions are the primary factors influencing farmers' satisfaction with their living spaces. This is consistent with studies that have reported that the condition of the house has a significant impact on farmers' rural housing satisfaction [55]. Huanjiang County has a large variation in per capita housing area ownership, and there is an uneven spatial distribution in housing space areas. In our survey, the largest households were 150 m^2 per capita, while the smallest households were only 37 m^2 per capita. Therefore, vast differences in housing conditions likely led to significant differences in farmers' satisfaction with their living spaces.

The second strongest exogenous observed variable was domestic water supply. Similar to the results of Yang (2016), we found that reduced water resources in this karst area have had adverse effects on the lives of farmers [56]. Due to the influence of eroded landforms, surface precipitation in this area rapidly moves deep underground [57], which makes it difficult for farmers in the area to access water. The third strongest observed variable was domestic sewage treatment. Consistent with the results of Zhong (2009) [58], we found that the treatment of rural garbage and sewage is an important influence on farmers' evaluations of their living spaces. In recent years, local townships and villages have developed extensively; however, sewerage treatment in this area has not kept up. For example, a survey of farmers from a village in Luoyang Township indicated that the entire river became fouled after the construction of a breeding farm in the upper reaches of the village. As a result, the whole village smelled bad in the summer. Although some rural areas have begun to set up centralized garbage collection and treatment stations, there are generally few installations and the rural population is generally less conscious of environmental protection, which makes it difficult for rural wastewater to be effectively treated. The results of this study indicate that the above three factors have a significant influence on the degree of perceived satisfaction that farmers have in relation to their living spaces.

5.2. Irrigation Water Conditions and the Quantity and Quality of Cultivated Land Significantly Affects Farmers' Satisfaction with Production Spaces

The standardized path map of exogenous observed variables that affect farmers' satisfaction with production spaces indicates that the observed variables can be ranked as follows: irrigation water > cultivated land quantity > agricultural land fertility > agricultural facilities > cultivated land access > job opportunities; the corresponding coefficient values are 0.71, 0.69, 0.57, 0.53, 0.45, and 0.25, respectively.

The strongest exogenous observed variable was irrigation water. Our results are similar to those of Wu (2009), indicating that the limited irrigation water in karst rural areas is a primary factor affecting farmers' agricultural production [59]. Our investigation also found that although precipitation in Huanjiang County was sufficient, it primarily occurred from May to September, which is also the season with the most severe waterlogging. The uneven seasonal distribution of precipitation, combined with the shortcomings of the karst geological environment discussed above, cause seasonal water shortages in rural areas that impact farmers' agricultural production. The second strongest observed variable that affected satisfaction with production spaces was cultivated land quantity. A previous survey found spatial imbalance and substantial variation in per capita cultivated land in Huanjiang County. The lack of cultivated land resulted in a shortage of basic resources required for farmers' livelihoods, leading to dissatisfaction with their own agricultural production spaces. The third strongest observed variable affecting farmers' satisfaction with their production spaces was cultivated land fertility. Due to variation in the geographical location of farmers, the conditions on the land they own also vary [60]. The long-standing local system of land distribution has divided the land that is within the jurisdiction of the village to village farmers, with little cross-regional land distribution between villages. The village location, therefore, determines the quality of land resources available to farmers to a large extent. Compared with farmers living in low-lying land or the Middle Mountain region, farmers in valleys have more paddy fields and less dry land. Generally speaking, paddy fields are dominated by partial loam soil, while dry land is mainly dominated by clay and sandy soils. Loamy soil is highly fertile, followed by clay, with sandy soil exhibiting the poorest fertility [61]. Thus, paddy field farmers tend to exhibit the highest levels of satisfaction. It is clear that differences in cultivated land fertility have an important impact on farmers' perceptions of production spaces.

5.3. Garbage Disposal, Vegetation Cover, and Flood and Waterlogging Significantly Affect Farmers' Satisfaction with Ecological Spaces

The standardized path coefficients for the exogenous observed variables affecting satisfaction with ecological spaces can be ranked as follows: garbage disposal > vegetation cover > flood and waterlogging > rocky desertification > river water quality, with corresponding coefficients of 0.77, 0.65, 0.63, 0.43, and 0.39, respectively. The strongest path coefficient was for garbage disposal. The status of garbage disposal around farmers has become an important factor impacting their local ecological spaces. China is currently implementing a policy of habitat management in rural areas throughout the country, and the government of the study area has allocated funds to construct several centralized garbage collection points. However, some farmers do not have a strong awareness of environmental protection which, coupled with a lack of publicity of centralized waste disposal sites by some village leaders, sometimes results in garbage being dumped elsewhere. In rural areas where garbage disposal systems are better, the satisfaction of farmers is very high. The second strongest path coefficient was for vegetation coverage. Farmers with better vegetation coverage had a higher degree of satisfaction with it. Generally speaking, most farmers were positive about recent improvements in vegetation coverage in their region. The third strongest influential factor was rocky desertification, which can cause serious damage to the ecological functioning of the land [62]. Rocky desertification in karst areas slows the recovery rate of soil formation, seriously affecting farmers' satisfaction with ecological spaces [63].

5.4. Household Education, Income, and Location Significantly Affect Farmers' Satisfaction with Ecological–Living–Productive Spaces

In the results presented in Section 4.3, it was shown that farmers with higher levels of education had higher satisfaction with land spaces. This is in contrast to previous studies, where residents with higher education also had higher expectations of their living spaces, resulting in generally low satisfaction [64]. In our work, the more educated farmers in the areas we studied typically had more opportunities and resources (e.g., money) to choose a superior space to live in, and so were typically more satisfied with their land spaces. This also corroborates the conclusion that farmers with higher income levels have higher satisfaction with the overall local spatial environment. Our field research found that farming households with higher income levels also, typically, had more abundant farmland resources or more nonfarm income channels and, therefore, had higher overall satisfaction with the local subsistence environment. Geographical location is a cause of farmer inequity. Our study area was in a karst mountain area and farmer locations were of three broad categories: middle mountains, low-lying land, and valleys. Farmers in the valley area had more high-quality land resources such as water fields than farmers in other locations. They also had better access to transportation, so they had more opportunity to access a better life, and their overall satisfaction with local land spaces was higher. Therefore, differences and imbalances in resource endowments are important factors contributing to differences in farmers' ratings of spatial satisfaction.

6. Conclusions and Implications

In this study, SEM was used to simulate and analyze data on the perceptions of farmers with respect to Ecological–Living–Productive spaces. The findings indicate that karst landforms, lack of irrigation water, and land quality and quantity issues are key factors affecting perceptions of production spaces. These problems may become more influential at certain times, especially during the dry season (from December to March). The current findings, together with the available literature, clearly indicate that rural production spaces have become a highly significant problem for farmers. This finding is supported by their low satisfaction with production spaces, which included the lowest scores in the study. Domestic water was one of the most significant factors affecting living space satisfaction. Farmers' living space and ecological space satisfaction were relatively high, which can be closely linked to the Chinese government's recent implementation of a rural construction and revitalization strategy. This also suggests that, in terms of the governance of rural space in karst areas, issues related to living spaces and ecological spaces are no longer the primary issues. An important question for the future is: How can we increase the quality of karst rural production spaces? Based on our results, we propose that spatial governance of rural karst areas be strengthened in relation to the following aspects.

(1) Strengthening of water management. Underground water leakage has always been a key factor causing water shortages in karst areas. Therefore, increasing water use and storage infrastructure would help deal with rural irrigation and domestic water use problems.

(2) Improvements in land quality and redistribution of cultivated land resources should become a focus of governance in karst areas. Land management in the karst mountains, especially in relation to the prevention of soil erosion, remains a difficult problem. Due to China's traditional land distribution system, the reallocation and balancing of land resources among farmers will become an important future direction for land consolidation in the karst mountains.

(3) Continuous improvement in garbage treatment in rural areas is important for increasing rural space quality in karst mountains. With the current promotion of China's garbage classification system, the treatment of rural garbage and sewage will become a new priority for rural space management.

(4) Finally, ways of relocating farmers, especially those living in the middle mountains and low-lying land to valleys, should be the focus of government policy so that poorly-endowed farmers get access to better resources. Actively improving farmers' skillsets so they can obtain nonagricultural income could also be an important policy direction.

This study had some shortcomings that affected the results. We did not incorporate the socioeconomic characteristics of farmers into our econometric analysis. Instead, we only used descriptive statistical analyses to illustrate the possible causes of different land space satisfaction evaluations among farmers with different socioeconomic attributes. Therefore, in future research, we will focus on the impacts of farmers' socioeconomic characteristics on land space satisfaction and their implications for land consolidation. We also need to further investigate the role of rural governance.

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Review

A Framework for Reviewing Silvopastoralism: A New Zealand Hill Country Case Study

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Abstract: Silvopastoral systems can be innovative solutions to agricultural environmental degradation, especially in hilly and mountainous regions. A framework that expresses the holistic nature of silvopastoral systems is required so research directions can be unbiased and informed. This paper presents a novel framework that relates the full range of known silvopastoral outcomes to bio-physical tree attributes, and uses it to generate research priorities for a New Zealand hill country case study. Current research is reviewed and compared for poplar (*Populus* spp.), the most commonly planted silvopastoral tree in New Zealand hill country, and kānuka (*Kunzea* spp.), a novel and potentially promising native alternative. The framework highlights the many potential benefits of kānuka, many of which are underappreciated hill country silvopastoral outcomes, and draws attention to the specific outcome research gaps for poplar, despite their widespread use. The framework provides a formalised tool for reviewing and generating research priorities for silvopastoral trees, and provides a clear example of how it can be used to inform research directions in silvopastoral systems, globally.

Keywords: New Zealand; hill country; poplar; kānuka; agroforestry; silvopasture; soil conservation; erosion; ecosystem services

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1. Introduction

Agroforestry is a land use where at least two plant species interact biologically, at least one of the plant species is a woody perennial (typically trees), and at least one of the plant species is managed for forage, annual or perennial crop production [1]. Silvopastoral systems are a type of agroforestry system where trees are integrated into a pastoral system. Silvopastoral systems are commonly adopted in environmentally sensitive areas to mitigate landscape degradation [2–4]. Many of these are hilly or mountainous, and include for example the poplar (*Populus* spp.) and willow (*Salix* spp.) silvopastoral systems of New Zealand hill country [2], the ñire (*Nothofagus antarctica* (G. Forst.) Oerst.) system of Patagonia [3], and the oak (*Quercus* spp.) silvopastures of California [5], the Indian Himalayas [6], and Spain (the *dehesa* system) [7].

Silvopastoral systems are inherently complex and result in many ecological, economic, and cultural outcomes within the agricultural system. To fully understand and appreciate silvopastoral systems, it is important that research spans as many of these outcomes as possible. If only specific outcomes are studied, research or tree planting choices may be biased towards these narrowly selected outcomes, and other potential benefits may be overlooked or underappreciated. Moreover, if the maximum benefits of silvopastoral tree plantings are to be realised and plantings are to be justified, their full range of known benefits and costs must be compared.

As an example of this, in the hill country of New Zealand (an area characterised by hilly or steep land (> 15°), being below 1000 m asl, and pastoral farming as its main land use) [8], there is a narrow research focus on the principal silvopastoral tree genera that are planted (poplar and willow). The focus is on pasture production, soil conservation, and establishment ease [2,9,10], with soil conservation value and establishment ease primarily informing planting decisions.

These genera have been shown to be highly effective as soil conservation trees [11–13], and can be planted easily as 2–3 m unrooted coppiced poles with sheep and small cattle grazed immediately after establishment [2,14]. Nevertheless, in hill country, as far as we are aware, there has been no research on other silvopastoral outcomes such as biodiversity conservation value, wind run reductions, shelter value comparison between species or genera, and impacts on catchment discharge rates (in typical planting densities of 20–200 tree ha^{-1}), among others that will be highlighted in this paper. Historically, other genera have been overlooked because only a few factors have been considered in planting decisions, even though many alternative species may be more suitable in certain situations, or their overall benefits greater than those of poplar or willow.

Wood [15] presented a framework, which itself was adapted from Von Carlowitz [16], that provides a useful way of looking at the range of outcomes within agroforestry systems. The authors split trees into their bio-physical attributes and related these to 'performance' in an agroforestry system (Table 1). Dividing trees into their bio-physical attributes is useful because it helps show why a tree may be contributing to a positive or negative silvopastoral outcome. This means that alternative trees can be selected based upon their attributes, and silvopastoral species or genera research or tree planting choice can then be optimised for specific silvopastoral systems, based upon a system's outcome needs.

However, the framework presented by Wood [15] is focused on agroforestry rather than silvopastoral systems, and takes a narrow tree performance view on silvopastoral system outcomes, therefore missing their holistic nature. Because of this primary reason, and others that will be explored in the next section, this paper presents a new framework that identifies and links bio-physical attributes to system outcomes like Wood [15], but does so for a silvopastoral system. It also expands the outcomes to account holistically for the full range of known silvopastoral outcomes. Section 2 will present this framework and explain in more detail how it differs from Wood [15], and why these changes are necessary.

We believe that our new framework will appeal to multiple groups. Firstly, it provides a standardised methodology for the research community to review silvopastoral research, and to identify research priorities that will improve the understanding of specific silvopastoral systems. Additionally, it will enable researchers to review trees in relation to all their known potential outcomes, and reduce research biases on specific outcomes, as has been the case in New Zealand hill country to date. The second half of this paper will illustrate the framework being used in this way, and will compile current knowledge for poplar, the most commonly planted and researched silvopastoral tree genus in New Zealand, and kānuka (*Kunzea* spp.), a genus that has received little attention in a hill country silvopastoral context. Based on the framework, the genera will be assessed, reviewed and compared across their full range of known benefits and costs.

Secondly, the framework will provide an opportunity for practitioners and land managers to see the full range of known interactions within a silvopastoral system. It will also clearly highlight the holistic nature of silvopastoral systems, and reduce the focus on only specific outcomes, as has been the case in New Zealand hill country. When trees have been reviewed and compared, this comparison can then be used by land managers to decide which tree may be best for their specific situation, depending on their requirements. Finally, in time, a unit of value could be added to the different outcomes in the framework. This would allow researchers, land managers, and land owners to quantifiably discriminate which tree may be best for a specific situation. This however, is beyond the scope of this paper.

Silvopastoral systems are complex, comprising multiple inter-related components. A framework that captures this complexity is fundamental to ensure that the full potential of silvopastoral trees are researched, realised, and appreciated. The framework will be a valuable tool for those selecting and researching silvopastoral trees, especially in hilly or mountainous regions.

Table 1. An agroforestry framework relating tree attributes to 'performance' in an agroforestry system reproduced from Wood [15], which was adapted from Von Carlowitz [16]. Copyright © 1990 John Wiley & Sons, Inc.

Tree Attributes	Relationship to Performance in Agroforestry Systems
Height	Ease of harvesting leaf, fruit, seed, and branchwood; shading or wind effects
Stem form	Suitability for timber, posts, and poles; shading effects
Crown size, shape, and density	Quantity of leaf, mulch, and fruit production; shading or wind effects
Multistemmed habit	Fuelwood and pole production; shading or wind effects
Rooting pattern (deep or shallow, spreading or geotrophic)	Competitiveness with other components, particularly resource sharing with crops; suitability for soil conservation
Physical and chemical composition of leaves and pods	Fodder and mulch quality; soil nutritional aspects
Thorniness	Suitability for barriers or alley planting
Wood quality	Acceptability for fuel and various wood products
Phenology (leaf flush, flowering, and fruiting) and cycle (seasonality)	Timing and labor demand for fruit, fodder, and seed harvest; season of fodder availability; barrier function and windbreak effects
Di = or monoeciousness	Sexual composition of individual species in community (important for seed production and pollen flow)
Pest and disease resistance	Important regardless of function
Vigor	Biomass productivity, early establishment
Site adaptability and ecological range	Suitability for extreme sites or reclamation uses
Phenotypic or ecomorphological variability	Potential for genetic improvement, need for culling unwanted phenotypes
Response to pruning and cutting management practices	Use in alley farming, or for lopping or coppicing
Possibility of nitrogen fixation	Use in alley farming, planted fallows, or rotational systems

2. A Framework for Assessing Silvopastoralism

Figure 1 shows the new framework for silvopastoralism, which outlines all the known interactions within a silvopastoral system between a tree's bio-physical attributes and system outcomes. The following section explains in more detail how this new framework improves on the original framework by Wood [15].

As Wood [15]'s framework was designed for agroforestry systems in general and not silvopastoral systems, it places little emphasis on the interactions fundamental to a silvopastoral system. These include interactions between trees and livestock, and between the grazing livestock, soil, and pasture.

Many environmental, management, and cultural outcomes associated with silvopastoral systems are also lacking in the original framework. In the new framework, outcomes are expanded to include the following environmental outcomes: 'water and nutrient gains or losses', 'biodiversity interactions (excluding livestock and the forage crop)', 'greenhouse gas implications', and 'longevity of the tree'; management outcomes: 'costs and ease of establishment', 'special qualities reducing animal interactions with the tree', 'longevity of the tree', and 'ability to refine the tree form for improved silvopastoral outcomes'; and cultural outcomes: 'livestock shelter' ('livestock shelter' is a cultural outcome in terms of animal health reasons and a production outcome in terms of live weight increase reasons), 'cultural values', and 'aesthetics'.

In addition to outcomes, the new framework also includes additional attributes of specific relevance to hill country silvopastoral systems, including 'growth rate', 'establishment method (seedling, cutting, pole)', and 'water use'. In hill country, silvopastoral systems commonly need to be established, as trees are generally lacking, so a tree's growth rate and establishment form is a key consideration in planting decisions. Moreover, the interaction between the tree and pasture in terms of water is also important, an attribute lacking in Wood [15]'s framework.

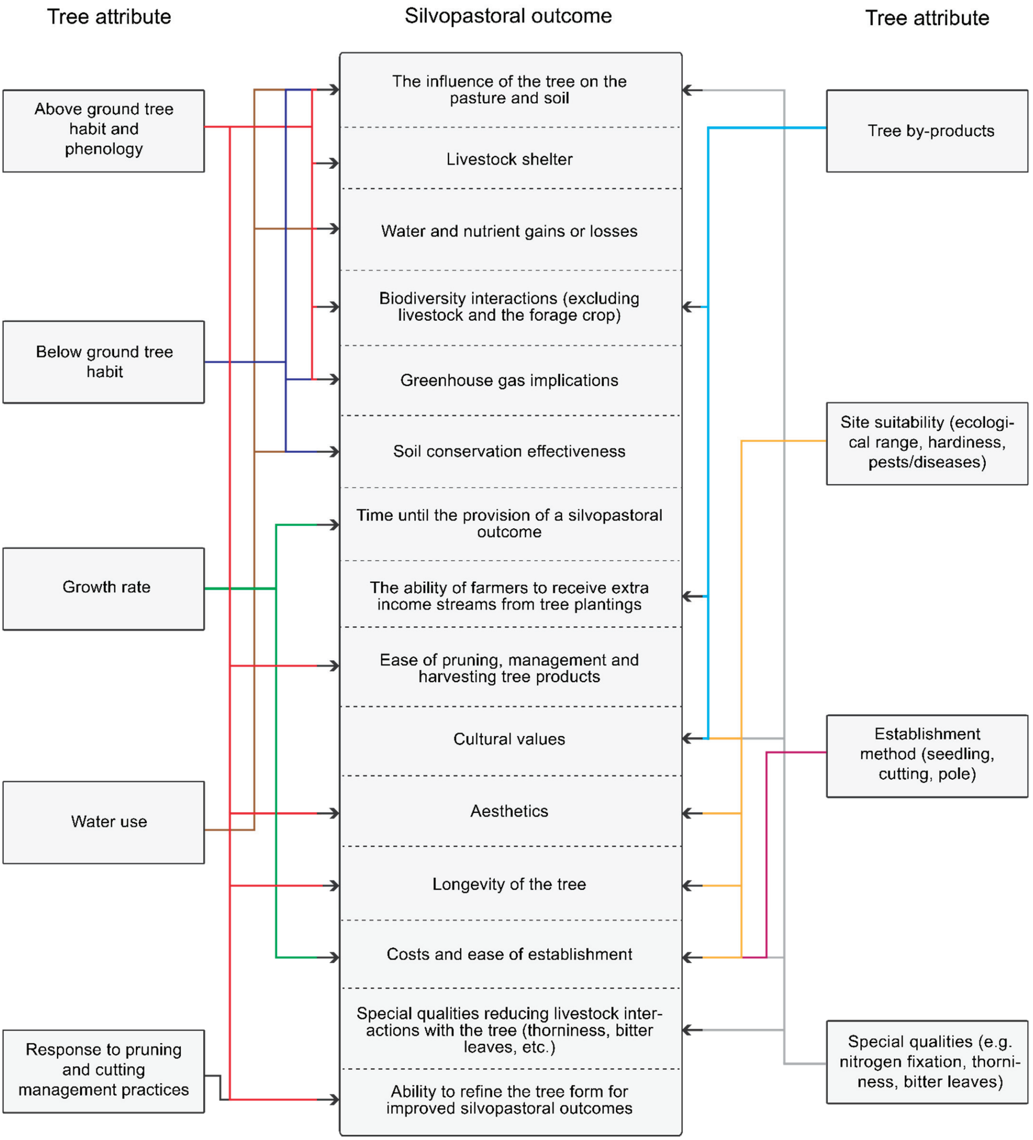


Figure 1. A framework of the interactions within a silvopastoral system between tree attributes and silvopastoral outcomes.

To improve the simplicity of Wood [15]'s framework, multiple attributes have been grouped into one attribute in the new framework. For example, the attributes 'height', 'stem form', 'crown size, shape and density', 'multistemmed habit', 'phenology (leaf flush, flowering and fruiting) and cycle (seasonality)', and 'Di = or monoeciousness' are encompassed into the broader attribute: 'above ground tree habit and phenology'. Moreover, 'pest and disease resistance', 'vigor', 'site adaptability and ecological range', and 'phenotypic or ecomorphological variability' are grouped to form one attribute: 'site suitability (ecological range, hardiness, pests/diseases)'.

A 'special qualities' attribute was also added to the framework so any unique tree qualities in other silvopastoral systems can be incorporated into the framework.

Wood [15]'s framework was primarily developed to inform the selection of trees for agroforestry systems. The new framework can also be used in this way, but we extend the use of our framework and use it to comprehensively collate research and knowledge on particular trees. In doing so, this paper clearly highlights the practical use of the framework to researchers for assessing and comparing silvopastoral trees.

3. Using the Framework: A New Zealand Hill Country Case Study

The following section will illustrate how the framework can be used to review two silvopastoral systems and generate research priorities in a degraded, but economically important, hilly and mountainous region.

As definitions of New Zealand hill country vary [8], so do area estimations, but one estimate of the pastoral farming land area in hill country is 5.2 million ha (19.4% of New Zealand's land mass) [17]. Much of this hill country is marginal agricultural land, associated with reduced organic matter, nutrient levels and water holding capacities, resulting in many areas having a low productive potential [18]. Due to the highly topographic and treeless nature of hill country, soil erosion and surface runoff discharge rates are high [8,19].

These poor conditions have multiple ramifications for New Zealand. High sediment loads alter local floral and faunal streambed habitats [8], reduce river clarity, and reduce the soil base of hill country farms. Nitrogen (N) and phosphorus (P) losses with sediment encourage algal growth [20,21], further degrading river habitats and the quality of water supplies [22]. Furthermore, elevated surface water discharge results in elevated flood severity and risk [23].

3.1. Poplar and Willow

The principal soil conservation intervention in New Zealand is tree planting, specifically aimed at the mitigation of shallow mass movement events (shallow soil slips), earthflows and gully erosion [12,24]. Space-planted poplar and willow are the main genera grown, planted at densities that generally range from 20 to 200 trees ha^{-1} [2,9] (Figure 2). Afforestation is additionally used for soil conservation, in the form of exotic forestry plantations (principally radiata pine (*Pinus radiata* D. Don) at densities ~1200 trees ha^{-1}) [2], native mānuka (*Leptospermum scoparium* J.R. Forst and G. Forst) plantations for honey production [2], or native forest via unmanaged regeneration or native seedling establishment.

Poplar and willow have been extensively researched, including reviews by Benavides et al. [9], Kemp et al. [2], and Basher et al. [4]. They have been shown to be highly effective as soil conservation trees [11–13], and can be planted easily as 2–3 m unrooted coppiced poles with sheep and small cattle grazed immediately after establishment [2,14]. Nevertheless, a 40-year tree life is recommended as branch breaking is common [25], reducing the long-term soil conservation or carbon sequestration potential of each tree compared to if the tree was not felled. Additionally, the negative effects of poplars on pasture growth are well established [2,9] and there is little evidence they improve soil properties beneath their canopies [26,27].

In terms of other species, Devkota et al. [28] studied the canopy effect of Italian gray alder (*Alnus cordata* (Loisel.) Duby) on soil and pasture, and Australian blackwood (*Acacia melanoxylon* R.Br.) and Eucalyptus (*Eucalyptus* spp.) have also been studied in the context of timber production, pasture production, soil properties and landslide mitigation [11,29–31]. Many trees and shrubs have been researched for their potential use as fodder trees including research on poplars and willows (e.g. [32–34]), as well as tagasaste (*Cytisus proliferus* L.f.) and saltbush (*Atriplex halimus* L.) [35,36], among others [35]. Nonetheless, poplar and willow remain the dominant silvopastoral system in hill country, despite their constraints.

3.2. Kānuka

Kānuka is a native and successional genus that grows readily in New Zealand hill country [13], and has many attributes that mean it has the potential to perform well as a silvopastoral tree. Kānuka has been split into 10 endemic New Zealand species [37], although Heenan et al. [38] provides evidence that questions this 10-species description. Nevertheless, as of 2021, 10 are still recognised. These 10 species occupy different ecological niches and geographical extents [13]. Seven of these species (*K. amathicola* de Lange et Toelken, *K. ericoides* (A.Rich.) Joy Thomps., *K. linearis* (Kirk) de Lange & Toelken, *K. robusta* de Lange et Toelken, *K. salterae* de Lange, *K. serotina* de Lange et Toelken, *K. triregensis* de Lange) are trees that can reach greater than 10 m in height [37] and are the most suitable for use in a silvopastoral system. Most people collectively refer to these species by their common name, kānuka. This paper will use the term kānuka and is specifically referring to the seven kānuka species that are greater than 10 m in height when growing in native forest.

Figure 2. A typical North Island New Zealand hill country landscape 25 km north east of Dannevirke, in the Manawatū-Whanganui region. Willows can be seen space-planted in pastures at the bottom of the slope directly beneath the photographer. The photograph was taken by the lead author.

In most places, kānuka, along with mānuka and gorse (*Ulex europeaus* L.), are the first woody perennial species to colonise unmanaged pasture in New Zealand hill country [39,40]. When kānuka grows on this unmanaged pasture, the predominant practice is to clear the kānuka to produce treeless pastures [41]. However, this paper demonstrates that kānuka has many beneficial attributes in a silvopastoral system and that thinning instead of clearing higher density kānuka stands [13], or even space-planting the tree on hill country pastures, should be encouraged.

3.3. Reviewing Current Knowledge for Poplar and Kānuka

Drawing on existing research and knowledge, poplar, the most commonly planted silvopastoral tree in hill country, and kānuka are now reviewed and compared according to the framework tree attributes (Table 2) and system outcomes (Table 3). Information compiled in Tables 2 and 3 comes from different sources. The first are visible factors, such as the heights of unmanaged trees growing in hill country. This is information in Table 2 that has no references. The second are projected interactions that have been logically inferred based upon known tree attributes (e.g., an evergreen tree will provide more shelter in winter than a deciduous tree). These are sections in Table 3 under the label 'likely outcome' where there is 'no evidence' for a specific outcome. The final source is literature, either peer-reviewed scientific research or reports. These are labelled as 'evidence for' and 'evidence against' in Table 3. Table 2 does not contain 'evidence for' or 'evidence against' descriptions because tree attributes themselves are not positive or negative, but it is the resultant outcomes that are positive or negative to the user of the silvopastoral system.

Table 2. Tree attributes for poplar (*Populus* spp.) and kānuka (*Kunzea* spp.) in a New Zealand hill country silvopastoral system. Tree attributes have been adapted from Wood [15]. The photographs were taken by the lead author.

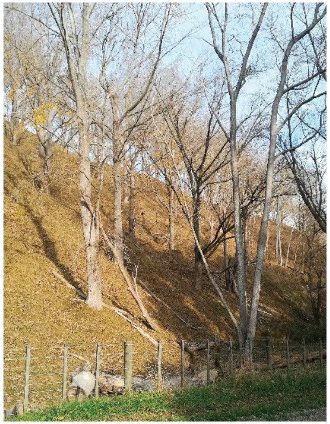
Tree Attribute	**Poplar (*Populus* spp.) Attribute**	**Priority Research Area**	**Kānuka (*Kunzea* spp.) Attribute**	**Priority Research Area**
Above ground tree habit and phenology	Current cultivars planted in the 1960s and 1970s are >30 m in height. Crowns are large and uncompact. Older cultivars often have large branches extended; some are multistemmed. Newer cultivars have been developed which grow as a single, straighter stem. Deciduous. 	Yes—an understanding of the form of newer poplar cultivars when they are fully-grown would be informative.	When growing isolated in hill country, kānuka are 8–20 m in height. Compact crowns. Stems can be multi- or single-stemmed. Many branches when unmanaged. The form of kānuka varies with tree density, growing taller and thinning in higher densities. Evergreen. 	No

Table 2. *Cont.*

Tree Attribute	**Poplar (*Populus* spp.) Attribute**		**Priority Research Area**	**Kānuka (*Kunzea* spp.) Attribute**		**Priority Research Area**
Below ground tree habit	For three 11.5-year-old poplar trees on a 17° hill country site at densities of 156 tree ha^{-1}, maximal lateral root extension ranged from 8.0–12.0 m. Mean tensile strength of 44.0 (minimum: 11.1 MPa; maximum: 114.3 MPa). The total root length of a 9.5-year-old poplar tree was found to be 663.5 m with a root biomass of 17.9 kg. The lateral root extension, root biomass and total root length of 'fully-grown' poplar trees on hill country > 25.0° would be valuable.	McIvor et al. [42,43]; Watson et al. [44]	No	Only kānuka growing in high density forest stands (~3000–16,000 stems ha^{-1}) have been studied. Fifteen 16-year-old trees growing at 12,800 stems ha^{-1} had a maximum root length of 4.5 m. Fifteen 32-year-old trees growing at 3900 stems ha^{-1} had a maximum root length of 6.1 m Mean tensile strength of 34.1 MPa (minimum: 18.2 MPa; maximum: 75.8 MPa). In another high-density stand (3000 stems ha^{-1}), the total root length of one fully-grown kānuka tree 9.5 m in height was shown to be 123.2 m, have a root biomass without the stump of 11.8 kg and a lateral root spread of 2.8 m.	Watson et al. [45,46]; Watson and Marden [47]; Watson and O'Loughlin [48]	Yes—research on the root distribution of kānuka growing at typical hill country silvopastoral densities (20–200 tree ha^{-1}) is required.

Table 2. *Cont.*

Tree Attribute	**Poplar (*Populus* spp.) Attribute**		**Priority Research Area**	**Kānuka (*Kunzea* spp.) Attribute**		**Priority Research Area**
Growth rate	On a 21–35° slope, the mean height of 268 poplar poles was just under 3.0 m after 12 months, ~3.5 m after 24 months and ~5.3 m after 45.0 months. Start heights were not given by the authors so yearly growth rates could not be calculated. 5, 7 and 9.5 years old trees had heights of 7.0, 9.5 and 13.3 m, respectively, on a 17° hill country site. This equates to a ~1.3 m year^{-1} growth rate (accounting for the 1.4 m start height of the poles).	Marden and Phillips [49]; McIvor et al. [42]	No	Initial growth rates are often 0.7–0.8 m year^{-1} in sheltered and high fertility sites, and 0.4–0.5 m year^{-1} in poorer sites. This data was collected from interviews, and was not stated to be quantitatively studied in the report.	Boffa Miskell Limited [50]	Yes—quantitative information on growth rates in contrasting conditions, as well as at 20–200 tree ha^{-1} densities, is required.
Water use	Four trees were shown to have an average water use of 180.1 L day^{-1} during spring, which equated to 1.2 mm day^{-1}. One of these trees had a water use of 417.0 L day^{-1}.	Guevara-Escobar et al. [51]	No			Yes—the water use of kānuka is unknown.
Response to pruning and cutting management practices	Responds well to pruning when the trees are young, as well as coppicing and pollarding.	Charlton et al. [25]	No			Yes—the response to management is unknown.

Table 2. *Cont.*

Tree Attribute	Poplar (*Populus* spp.) Attribute		Priority Research Area	Kānuka (*Kunzea* spp.) Attribute		Priority Research Area
Tree by-products	Wood—poplars can be pruned and harvested for timber. Fodder—leaves are excellent fodder for animals. Emissions trading scheme (ETS)—there is the potential for farmers to receive carbon credits (1 NZU = 1 tonne of sequestered CO_2) if the tree crown canopy is >30% in each hectare.	Charlton et al. [25]; Kemp at al. [2]; MPI [52]	Yes—research required to understand the density required to achieve a 30.0% canopy cover with poplar.	Wood—reported to be good firewood. Fodder—kānuka leaves are 0.5–2.5 cm, the tree doesn't have summer leaf flush as they are evergreen and the leaves are potentially bitter, so we tentatively suggest that the trees would be poor fodder quality. Honey—shown to have anit-bacterial, anti-viral, immunostimulatory and anti-inflammatory properties. Essential oil—kānuka essential oil has been shown to be an effective eco-friendly pesticide. Emissions trading scheme—potential exists for farmers to receive carbon credits (1 NZU = 1 tonne of sequestered CO_2) if the tree crown canopy is > 30% in each hectare.	Boffa Miskell Limited [50]; Bloor [53]; Gannabathula et al. [54]; Lu [55]; Tomblin et al. [56]; Kassimi et al. [57]; Park [58]; MPI [52]	Yes—research required to understand the density required to achieve a 30.0% canopy cover with kānuka.

Table 2. *Cont.*

Tree Attribute	Poplar (*Populus* spp.) Attribute		Priority Research Area	Kānuka (*Kunzea* spp.) Attribute		Priority Research Area
Site suitability (ecological range, hardiness, pests/diseases)	Exotic to hill country, although poplar in certain conditions can have a high survival rate when established in hill country. For 300 hill country poplar poles deaths after 45 months, site factors (site conditions, socketing etc.) contributed to 28% deaths, and animal damage contributed to 12% of deaths. After 6 years, survivability on six hill country farms ranged from 0% to 80% (slopes varied from 0% to 32% in the study). Although the reasons for death were not quantitively measured by the authors, reasons given include animal damage, poor planting, continued erosion, winter weather fronts and poor local site conditions. Fungus and rust can be issues, with more resistant clones the main mitigation strategy. As branch breaking is common due to high winds in hill country, and fungus and rust can be issues, best management practice suggests felling and replanting the trees after 40 years. An understanding of the survival rate of poplars on different slope classes (especially the steepest hill country slopes) and in different environmental conditions would be informative, as well as more detailed quantitative information on the reasons for the low survival rates.	Marden and Phillips [49]; McIvor et al. [59]; Charlton et al. [25]	Yes—an understanding of the survival rates of poplar poles on the steepest, most erosion prone, hill country slopes would be helpful.	Native to hill country and already grows readily throughout hill country. Kānuka is reported to potentially grow up to at least 160 years and possibly as old as 300–400 years. Kānuka can grow in unfertile and moisture limited areas of hill country. Kānuka are susceptible to myrtle rust as they are in the myrtle family, Myrtaceae. Data on the survival percentages of kānuka in varying soil conditions is required, as well as how susceptible a kānuka silvopastoral system would be to myrtle rust.	Spiekermann et al. [13]; Boffa Miskell Limited [50]	Yes—quantitative data is lacking on the age to which kānuka grow at 20–200 tree ha^{-1} densities in hill country, establishment survival rates and the system's susceptible to myrtle rust.

Table 2. *Cont.*

Tree Attribute	**Poplar (*Populus* spp.) Attribute**		**Priority Research Area**	**Kānuka (*Kunzea* spp.) Attribute**		**Priority Research Area**
Establishment method (seedling, cutting, pole)	Can be established as unrooted 1.0–3.0 m poles or stakes (0.5 m cuttings) which are sharpened and rammed into the ground. Sheep and small cattle can be grazed immediately. Large cattle can knock over and break poplar poles, so exclusion until the poles have established is recommended. Regular poplar poles that are planted in hill country normally take 2–3 years to produce, depending on the region, occupy a lot of land in their production and demand for them regularly outstrips supply. Understanding the establishment methods and survival rates of quicker to produce planting material (younger unrooted material or rooted material) that can be grown in a smaller amount of land with less water and lower costs would be helpful.	Marden and Phillips [49]; Phillips et al. [14]; Ian McIvor (personal communication, 26th October 2021) [60]	Yes—understanding the establishment of different planting material (younger unrooted material or rooted material) would be helpful.	With current planting technology and knowledge kānuka would need to be planted as seedlings and protected from animal browsing. Large cattle may require exclusion depending on the protection method. Protection with current technology would need to be strong 1.7 m plastic netting or a wire cage, supported by 2 Y posts for cattle, or by a Y post and a fibreglass rod for sheep. It is unknown at what age seedling protection can be removed.		Yes—little is known on the establishment of kānuka in hill country.

Table 2. *Cont.*

Tree Attribute	**Poplar (*Populus* spp.) Attribute**	**Priority Research Area**	**Kānuka (*Kunzea* spp.) Attribute**	**Priority Research Area**
Special qualities (e.g., nitrogen fixation, thorniness, bitter leaves)	No special qualities of note.	No	A key difficulty when establishing trees in hill country is livestock browsing or damaging the tree. Livestock exclusion from paddocks is often not possible. Some land managers state kānuka leaves are bitter, which may reduce or stop browsing by sheep and cattle during establishment. Evidence for this is kānuka is already found growing readily in many parts of unproductive hill country in the presence of animals. Fresh shoots or young seedlings from commercial nurseries are likely to be browsed.	Yes—more information on the relationship between kānuka leaves and livestock is required.

Table 3. Silvopastoral outcomes for poplar (*Populus* spp.) and kānuka (*Kunzea* spp.) in a New Zealand hill country silvopastoral system. Tree outcomes have been adapted from Wood [15].

Silvopastoral Outcome	Poplar (*Populus* spp.) Outcome		Priority Area for Research	Kānuka (*Kunzea* spp.) Outcome	Priority Area for Research
Influence of the tree on the pasture and soil	*Evidence against* Pasture reduction beneath the canopy between 12% and 65% for poplar greater than 15 years old. A relationship has been found between increased canopy closure and decreased pasture production. Leaf smother has been shown to depress autumn grass growth beneath poplar canopies. Poplars do not fix nitrogen. One study found 33.0% less soil moisture beneath poplars when compared with open pasture in summer and autumn. Another study found slightly more water in the top 15 cm in pasture away from poplar throughout the year, with the difference most pronounced in summer and autumn. As pasture production and soil moisture has been shown to reduce under poplar, there is no evidence that wind-run reductions caused by poplar facilitate water conservation in the soil. Found no evidence that poplar facilitate the build-up of organic matter, nitrogen, phosphorus or sulphate beneath their canopies between 0.0 and 7.5 cm at three sites with poplar trees > 28 years old. Found varied results of soil organic matter, phosphorus and sulphate beneath fully developed poplar canopies between 0.0 and 15.0 cm compared to open pasture at two sites. There is evidence that poplar increase exchangeable cations (calcium, potassium, magnesium, sodium) beneath their canopies, most likely because of the chemical composition of their leaves. Along with light interception and autumn pasture smother, the water use of poplar could be contributing to the reduced pasture production beneath their canopies.	Reviewed by Benavides et al. [9]; Wall et al. [61]; Douglas et al. [62]; Kemp et al. [2]; Douglas et al. [63]; Guevara-Escobar et al. [64]; Guevara-Escobar et al. [26]; Wall [27]	No—there is a good understanding of how poplar influences the pasture and soil.	*No evidence* *Likely outcome* There has been no research on pasture production, and the constraints to pasture production, beneath kānuka in hill country. More research is required to produce any likely outcome predictions for the influence of kānuka on pasture, livestock and soil. Kānuka are evergreen, so this may have varying influences on the system when compared to poplar. Kānuka do not fix nitrogen.	Yes

Table 3. *Cont.*

Silvopastoral Outcome	**Poplar (*Populus* spp.) Outcome**	**Priority Area for Research**	**Kānuka (*Kunzea* spp.) Outcome**	**Priority Area for Research**
Livestock shelter	*No evidence* *Likely outcome* Trees will most likely provide less shelter to animals in winter than summer (poplars are deciduous). The summer shelter will most likely be positive for animal grazing time in summer, and may reduce heat stress resulting in greater live weight growth of livestock. The influence of poplar stem and branches on wind-run in winter may have positive influences in terms of reduced deaths and increased livestock live weight growth by reducing wind chill.	Yes	*No evidence* *Likely outcome* As kānuka are evergreen it is expected the trees will provide good shade and shelter to animals in summer and winter. The summer and winter shelter will most likely be positive for animal grazing time throughout the year. The influence of kānuka on wind-run in winter may have positive influences in terms of reduced livestock deaths and increased livestock live weight growth by reducing wind chill.	Yes
Water and nutrient gains or losses	*No evidence* Hill country 20–200 tree ha^{-1} densities have not been studied.	Yes	*No evidence* It is unknown how kānuka impacts these system dynamics.	Yes

Table 3. *Cont.*

Silvopastoral Outcome	Poplar (*Populus* spp.) Outcome		Priority Area for Research	Kānuka (*Kunzea* spp.) Outcome		Priority Area for Research
Biodiversity interactions (excluding livestock and the forage crop)	*Evidence against* Poplar were found to either reduce or maintain earthworm populations compared to equivalent open pasture positions. The three most abundant earthworms found beneath poplars were all exotic (*Aporrectodea caliginosa*, *A. longa*, *Lumbricus rubellus*). *No evidence* As far as we are aware, nothing is known on how poplar influence bird, insect and fungi populations. *Likely outcome* Biodiversity value to native fauna is predicted to be small as poplar are exotic. As poplar are deciduous, predicted to have less value to biodiversity than an evergreen tree.	Guevara-Escobar et al. [26]	Yes	*Evidence for* 16 native and exotic bird species documented in high density (no density was given but the canopy was stated to be dense) native forest stands of kānuka. Higher density forest stands host diverse invertebrate populations. *No evidence* As far as we are aware, nothing is known about how kānuka influences fungi, bird or insect populations in a silvopastoral system. *Likely outcome* Although only high density kānuka stands (>1000 trees ha^{-1}) have been studied, a kānuka silvopastoral system is predicted to have a high biodiversity value to native fauna as the genus is native.	Williams and Karl [39]; Boffa Miskell Limited [50]	Yes
Greenhouse gas implications	*Evidence for* The above and below ground carbon pool of a poplar silvopastoral system was estimated to be 18.1 tonnes ha^{-1}. Nevertheless, the amount of carbon sequestered (above ground biomass) would reduce after the tree is felled. *Evidence against* No clear evidence poplars increase soil organic matter beneath their canopies. *No evidence* It is unknown how a poplar silvopastoral system may influence methane and nitrous oxide emissions.	Guevara-Escobar et al. [26]; Wall [27]	Yes	*No evidence* It is unknown how kānuka impacts soil conditions and the carbon pool of a kānuka silvopastoral system has not been estimated. Is unknown how a kānuka silvopastoral system may influence methane and nitrous oxide emissions. *Likely outcome* If kānuka can grow for > 100 years in hill country, it would be a long-term carbon sink in terms of above and below ground biomass when compared to hill country without trees.		Yes

Table 3. *Cont.*

Silvopastoral Outcome	**Poplar (*Populus* spp.) Outcome**		**Priority Area for Research**	**Kānuka (*Kunzea* spp.) Outcome**		**Priority Area for Research**
Soil conservation effectiveness	*Evidence for* Highly effective as soil conservation trees due to their large total root length, lateral root spread (even when not fully-grown), as well as their high root tensile strength. One study found poplar to have an average maximum effective distance of 20 m for landslide mitigation.	Hawley and Dymond [65]; Douglas et al. [66]; McIvor [12]; Spiekermann et al. [13]	No—the soil conservation effectiveness of poplar is well understood.	*Evidence for* Even though root systems of 20–200 trees ha^{-1} have not been studied, one study found kānuka to have an average maximum effective distance of 17.0 m for landslide mitigation. More research is required on the root distribution of kānuka growing at low densities (20–200 tree ha^{-1}) to gain a better understanding of the soil conservation value of a kānuka silvopastoral system.	Spiekermann et al. [13]	Yes
Time until the provision of a silvopastoral outcome	*Evidence for* Quick as poplar are fast growing.	McIvor et al. [42]	No	*No evidence* There is no quantitative information on the growth rate of kānuka or kānuka roots growing at low densities (20–200 trees ha^{-1}). *Likely outcome* Slower than poplar, as poplar are a fast-growing tree, and one qualitative study provides evidence that kānuka grows more slowly than poplar.	Boffa Miskell Limited [50]	Yes

Table 3. *Cont.*

Silvopastoral Outcome	Poplar (*Populus* spp.) Outcome		Priority Area for Research	Kānuka (*Kunzea* spp.) Outcome		Priority Area for Research
The ability of farmers to receive extra income streams from tree plantings	*Evidence for* Fodder—feeding poplar fodder to livestock is a practice undertaken by some farmers in summer drought conditions. Emissions trading scheme—poplars at 30% canopy are eligible for carbon credits. *Evidence against* Wood—although poplars can be pruned and harvested for timber, as of 2021, this isn't a regular practice in New Zealand.	Charlton et al. [25]; Kemp et al. [2]	No	*Evidence for* Emissions trading scheme—kānuka at 30% canopy are eligible for carbon credits. *No evidence* Timber—the commercial value of kānuka wood (for firewood and timber) is unknown. It is suggested that harvesting kānuka for timber is not a suitable practice for a kānuka hill country silvopastoral system because the tree density will be low (< 200 trees ha^{-1}) compared to a typical plantation density, plus when the trees are felled this would stop each tree's impact on other silvopastoral outcomes. Honey—high density stands of trees > 40 ha are generally required to harvest high purity kānuka honey so it is unknown if honey can be harvested from a low density (20–200 trees ha^{-1}) kānuka silvopastoral system. Further research is required. Essential oil—it is unlikely that a kānuka silvopastoral system would provide enough foliage for essential oil production because of the low density (20–200 trees ha^{-1}), although further research is required to confirm this.	Boffa Miskell Limited [50]	Yes—more information on the commercial potential of kānuka wood, honey and essential oil production is required.

Table 3. *Cont.*

Silvopastoral Outcome	**Poplar (*Populus* spp.) Outcome**		**Priority Area for Research**	**Kānuka (*Kunzea* spp.) Outcome**		**Priority Area for Research**
Ease of pruning, management and harvesting tree products	*Evidence against* Tall height and multi-branching habit mean management is difficult and often dangerous.	Charlton et al. [25]	No—there are other outcomes which have a higher priority.	*No evidence* *Likely outcome* The smaller and compact habit of kānuka compared to poplar suggests management would be easier.		No—there are other outcomes which have a higher priority.
Cultural values	*No evidence* As far as we are aware, there has been no research on the cultural value of poplar, despite there being a lot of research on the functional value of poplar. *Likely outcome* Poplar is an exotic genus so it is predicted to have less value than a native genus.		Yes	*Evidence for* Kānuka is a native and so has cultural significance. Nevertheless, more work is required to understand the cultural significance of kānuka compared to other genera (native or exotic) in New Zealand.		Yes
Aesthetics	*Evidence against* One study has shown that when people are informed that shelterbelts are exotic, they are preferred less than native shelterbelts. *No evidence* As far as we are aware, there have been no studies on how the preference of poplar compares to other genera.	Brown et al. [67]	No—despite little research, there are more important research priorities for poplar.	*Evidence for* One study has shown that when people are informed that shelterbelts contain native trees, they are preferred over exotic shelterbelts. *No evidence* As far as we are aware, there have been no studies on the visual qualities of specific trees within a native tree category, or on kānuka specifically.	Brown et al. [67]	No—despite little research, there are more important research priorities for kānuka.

Table 3. *Cont.*

Silvopastoral Outcome	Poplar (*Populus* spp.) Outcome		Priority Area for Research	Kānuka (*Kunzea* spp.) Outcome		Priority Area for Research
Longevity of the trees	*Evidence against* Tall height and multi-branching habit mean they are not very resistant against wind damage Best management practice suggests felling and replanting trees after 40 years (due to impact of wind on branches, and wood rot or leaf fungus). Above ground silvopastoral benefits are lost when the trees are felled. It is unknown how resistant new straighter cultivars are against wind as they have only recently been planted.	Charlton et al. [25]	Yes—an understanding of the resistance of new cultivars to wind damage is important.	*No evidence* *Likely outcome* The small and compact habit of kānuka compared to poplar, that they are native to windy hill country conditions, and are already found on many parts of hill country, suggests kānuka are highly resistant against wind damage. If kānuka can grow up to 400 years in hill country, even if only over 100 years, this means silvopastoral benefits will be lasting compared to poplar.	Boffa Miskell Limited [50]	Yes—confirming the longevity of kānuka is important.
Costs and ease of establishment	*Evidence for* Planting as unrooted poles is an efficient way of planting trees. Recommended practice is excluding large cattle for 2 years, but sheep can still be grazed. Survival rate is normally high for poplar. Costs $20–25 NZD to plant a pole as of 2021 (not including labour and transport costs). *Evidence against* The survival of poplar can be low, and more detailed quantitative information is required to understand the instances when survival rates can be low. *No evidence* More work is required to understand the establishment of poplar on the steepest hill country slopes.	Marden and Phillips [49]; McIvor [59]	Yes—more research is required on the establishment of poplar on steeper, more erosion prone slopes.	*Evidence against* The time required to plant seedlings and protect them is longer than when planting poplar poles. Cost of planting and protecting a commercially bought 50 cm kānuka seedling with protection is $20–30 NZD as of 2021 (not including labour and transport costs). *No evidence* Nevertheless, there is limited understanding into the methods of establishing kānuka in hill country, and more work is required to better understand kānuka establishment.		Yes—comparing the establishment ease of kānuka with poplar is a priority as it is an important outcome in hill country.

Table 3. *Cont.*

Silvopastoral Outcome	Poplar (*Populus* spp.) Outcome		Priority Area for Research	Kānuka (*Kunzea* spp.) Outcome	Priority Area for Research
Special qualities reducing animal interactions with the tree (thorniness, bitter leaves, etc.)	*Evidence for* Poplar can be established as unrooted poles which reduces the chance of grazing by livestock, as when leaves grow on the poles, they are normally above the reach of grazing livestock.	Marden and Phillips [49]	No	*No evidence* *Likely outcome* If kānuka are browsed less than other genera due to their leaves being bitter, establishing the seedlings or young trees may require protection for a shorter period of time than other more desirable browse genera.	Yes—understanding the interaction between kānuka and livestock will be useful information when attempted to establish kānuka.
Ability to refine the tree form for improved silvopastoral outcomes	*No evidence* *Likely outcome* Even though pruning, coppicing, and pollarding is possible that will reduce management in later life, this is only done sparingly by farms.		No—there are other outcomes which have a higher priority.	*No evidence* It is unknown how a refined form will impact hill county silvopastoral outcomes, or if tree management would be taken up by landowners.	No—there are other outcomes which have a higher priority.

4. Key Comparisons between Poplar and Kānuka

The following section explains in more detail the key comparative findings from the framework for important poplar and kānuka silvopastoral system outcomes.

4.1. The Interaction of Poplar and Kānuka with the Pasture and Soil

A disadvantage of poplar is the reduced pasture growth beneath their canopies [10]. There is no clear evidence whether poplar positively influence the water or nutrient dynamics of the agricultural system [26,27,63,64]. Possible attributes responsible for this competitive relationship with pasture could be their high-water use [51], their large and spreading form discouraging preferential grazing beneath their canopies, or their large canopy causing too much shading, in addition to their deciduous nature causing grass smothering [2,62], potentially reducing animal nutrient transfer in winter or reducing their influence on winter temperatures beneath their canopies [64]. Some of these factors are explored below.

Water use of fully-grown individually spaced poplar trees in hill country (37.2 stems ha^{-1}) was investigated by Guevara-Escobar et al. [51]. They found that average individual tree water use was 180.1 L day^{-1} during a spring study period, which equates to an equivalent water use of 1.2 mm day^{-1}. The maximum water use over their tree repetitions was 417.0 L day^{-1}. A review of tree water use for 67 species (including hybrids) by Wullschleger et al. [68] suggests that the average water use by poplars in the Guevara-Escobar et al. [51] study of 180.0 L day^{-1} is high. As well as having high water use, 6-month-old *Populus euramericana* (Guinier) trees were shown to have isohydric behaviour in which leaf water potential was maintained in well-watered, medium deficit, and severe deficit soil conditions [69]. Therefore, if the poplar cultivars planted in New Zealand also show isohydric behaviour, even in severe deficit soil conditions, they will have the same high water use as in saturated soil conditions [69]. Poplars cannot be compared with kānuka in terms of water use as the water use of kānuka is unknown. Nevertheless, if kānuka does use less water than poplar, this may be beneficial in terms of reducing tree-pasture water competition in the silvopastoral system.

Poplars are deciduous and lose their leaves in autumn, reducing the ability of the tree canopy to buffer air temperatures during winter months, influencing pasture growth and animal shelter effects. This was confirmed by Guevara-Escobar et al. [64] who did not find evidence that poplar buffer winter temperatures. Kānuka trees, however, are evergreen, and maintain their foliage year-round. Previous research presents examples of trees in agroforestry systems buffering winter air temperatures beneath their canopies. In Central-Western Spain, Moreno et al. [70] found the daily minimum air temperature to increase from 7.4 °C 1 m from the trunk to 6.3 °C 20 m from the trunk in the *dehesa* system of Spain. In a *Paulownia* spp. silvo-arable system in Eastern-central China, mean winter air temperature was 0.2–1.0 °C higher under trees compared with open cropping land [71]. Based on these findings, we postulate that having an evergreen tree canopy over hill country pastures in winter could buffer winter air temperatures, and this may result in increased pasture growth when temperature may otherwise limit growth.

The presence of tree canopies during winter is likely to attract more animals as they seek shelter from colder temperatures and wind. As animals are a key mechanism for nutrient transfer in hill country [72], if animals do preferentially spend time beneath kānuka in winter, this could have important implications for nutrient build-up beneath the canopy. Moreover, this should have animal health benefits, in addition to potentially reducing live weight losses as less energy may be used maintaining body temperatures. On the contrary, a canopy during winter will reduce the amount of light reaching the ground or pasture. If light limits growth during winter months, this could negatively affect pasture growth. Additionally, if animals spend too much time beneath winter canopies under certain trees, this may result in excess animal camping, potentially resulting in soil compaction and grass smothering.

In agroforestry systems, trees add leaves to the soil which can help build up soil organic matter (SOM) and nitrogen [73,74]. For *Populus maximowiczii* Henry × *P. nigra*

L. cultivars, Douglas et al. [62] recorded 1.7 t DM ha^{-1} $year^{-1}$ of leaf fall in unevenly planted poplar stands of 25–400 stems ha^{-1}. Douglas et al. [62] found open pasture to have more annual grass biomass (8.5 t DM ha^{-1}) than grass plus poplar leaf biomass under poplar (8.3 t DM ha^{-1}). The reduction in pasture growth beneath the canopies (6.6 t DM ha^{-1} $year^{-1}$) was not compensated by the 1.7 t DM ha^{-1} $year^{-1}$ addition of poplar leaves. Moreover, the nutritional value of recently shed poplar leaves have not been studied and although their fodder quality is good [25], after the leaves have begun to decompose they would most likely have a lower nutritional value when compared to green leaves in the canopy. Kānuka leaf fall has been measured in high-density unmanaged mixed stands of kānuka and mānuka (no density was given, see Figure 3) [75]. The two sites in the study had an average leaf fall of 2.2 t DM ha^{-1} $year^{-1}$. In contrast to poplars, this leaf fall occurred throughout the year, which may potentially reduce grass smothering during autumn, and as fewer leaves may be grazed by animals, increase the amount of organic matter that is recycled back into the soil.

Figure 3. A high-density mānuka-kānuka shrubland study site for the leaf fall study by Lambie and Dando [75] (pp. 612).

These factors suggest kānuka could have a facilitating relationship, as opposed to poplar's competitive relationship, with the hill country pastoral environment. If kānuka is found to positively influence soil conditions beneath their canopies, this may have important implications for the productivity of low producing hill country, as well as for soil erosion and the hydrology of the system. Comparing the agricultural environment beneath poplar with genera of contrasting attributes would be informative and help disseminate which attributes may be leading to the negative interaction between poplar and pasture.

4.2. Longevity

The 25 m or greater height and spreading branches of older poplar cultivars (high vulnerability to branch windbreak), and susceptibility to leaf rust and fungus, mean their longevity is low (~40 years) [25] when compared to holm oak (*Quercus ilex* L.) trees of the *dehesa* agroforestry system in Southern Europe (trees can grow for 100 to 250 years) [76]. This impacts the long-term influence of each tree and requires that trees are felled and replanted. This represents a cost to the farmer or taxpayer and likely reduces the long-term carbon sequestration potential of each tree. The framework presents evidence that kānuka may have a similar longevity to holm oak as (1) they can potentially grow up to 400 years old [50], (2) hill country is their ecological range, meaning that they may be less susceptible to disease (further research is required to understand the threat from myrtle rust) and (3) their relatively shorter height will most likely result in less branch windbreak. The form and longevity of new poplar cultivars that have been developed to grow in a straighter form is unknown.

4.3. Establishment

The ability to plant poplar as 2–3 m unrooted poles is a major advantage of the system, as sheep and small cattle can be grazed immediately after establishment and planting is quick in comparison to the planting and protection of commercially bought 50 cm kānuka seedlings. This is a major advantage of poplar, although if kānuka was adopted as a silvopastoral tree, planting technology would most likely improve with increased demand. The cost of planting and protecting 50 cm kānuka seedlings is comparable to poplar pole establishment (not including labour and transport costs).

4.4. Time until an Influence on the Agricultural Environment and Soil Conservation

Another advantage of establishing poplar poles is that they are already 1.5–2.5 m high when they are planted. This, in addition to their quick growth rate [49,59,77], means the time until they have an influence on the silvopastoral environment (above and below ground) is quick when compared to establishing kānuka seedlings. This quick growth rate in conjunction with their expansive root system means poplar are highly effective soil conservation trees [12,65,66]. Despite no research on the root systems of kānuka trees growing at a spacings of 20–200 trees ha^{-1}, tree influence modelling has shown kānuka to have an average maximum effective distance of 17 m, compared to 20 m for poplar [13]. This provides some evidence kānuka may be an effective soil conservation tree, as is the case for poplar.

4.5. Cultural Values

Kānuka is a native to New Zealand and as such has cultural significance. Kānuka presents an opportunity as a hill country silvopastoral tree that can potentially provide many beneficial utilisation outcomes alongside its cultural significance.

4.6. Bird Biodiversity

To the best of our knowledge, bird populations within poplar silvopastures have not been studied in New Zealand. This is also true of kānuka in pastured hill country, despite research showing the benefits to biodiversity of other global silvopastoral systems [3,78].

Agricultural landscapes in New Zealand hold great potential to harbour high diversity [79–82]. Blackwell et al. [79] found 'conventional' sheep and beef farms had significantly greater species abundance (total number of birds recorded) and diversity (number of different species) than all other studied landscape types—native forest, scrub, pine plantations, and kiwi-fruit orchards. However, there were two to three times fewer native species on the sheep and beef farms and kiwi-fruit orchards compared with native forest, pine plantation, and scrub. A similar conclusion was found for arable land in the South Island: species diversity was similar for native (16) and introduced (17) birds over a 2-year study, although species richness was much higher for introduced bird species (winter: 9.3 ± 0.4; breeding season: 11.2 ± 0.4) compared to native species (winter: 3.3 ± 0.2; breeding season: 1.7 ± 0.2) [80].

Although native bird populations have been shown to be smaller in productive landscapes, Blackwell et al. [79] found bird richness variation within sheep and beef farms. The number of native birds increased on farms which had more woody vegetation. Blackwell et al. [79] (pp. 70) conclude that there is great potential for "production landscapes to be flush with biodiversity" if there is more woody vegetation growing on New Zealand productive landscapes.

Williams and Karl [39] reported that a dense canopy of kānuka supported 15 bird species, with korimako/bellbird (*Anthornis melanura*), pīpipi/brown creepers (*Mohoua* *novaeseelandiae*), and riroriro/grey warbler (*Gerygone igata*) being most common in the kānuka stands compared to gorse stands. This study gives some evidence that the native and evergreen nature of kānuka may present an opportunity for enhancing the connectivity of New Zealand's forested ecosystems within agricultural landscapes.

4.7. Additional Income

Honey from mānuka has been medically popularised because of its non-peroxide anti-bacterial properties [83,84]. Kānuka also has anti-bacterial properties and can be used as an antiseptic on wounds [55]. In addition, kānuka honey has been shown to have anti-viral [53], immunostimulatory [54], and anti-inflammatory properties [56].

To produce un-diluted honey which maximises these beneficial properties, bees must harvest as much nectar as possible from the flower of interest. Mānuka is currently commercially produced at a large scale in New Zealand, requiring monocultures of mānuka greater than 40 ha to achieve desired honey quality [50]. If kānuka was growing singly-spaced within a pasture system, there is a high chance other flowers would be available to foraging bees, such as clover (*Trifolium* spp.) or gorse, diluting the quality of honey produced. Boffa Miskell Limited [50] (pp. 19) does state that some interviewed farmers suggested grazing adjacent pastures very low during the flowering season to reduce nectar dilution, although "there are no data to verify the effectiveness of this strategy".

Essential oil can be produced from kānuka leaves. Recent research has explored the use of this essential oil as an eco-friendly pesticide for aphid populations [57] and *Drosophila suzukii* [58] with encouraging results. Leaves and branches under 10 mm in diameter are harvested every 3 to 5 years from trees up to 7 years old, as these trees have the greatest leaf:shoot ratio and the tree height ensures ease of harvest [85]. It is unlikely that a silvopastoral system with a 20 to 200 trees ha^{-1} density of kānuka would provide enough foliage for economic essential oil production.

Landowners can earn credits for sequestering carbon (1 NZU = 1 tonne of sequestered CO_2) from the atmosphere through planting trees [52]. These NZUs can be traded based on a market-driven unit price. Although research is required to confirm this, it is likely that kānuka and poplar planted at 20 to 200 trees ha^{-1} would cover the 30% land area threshold required for farmers to be able to receive NZUs. As the NZU price increased by over 1000% from 2013 to 2020 [86,87], this could become a valuable revenue opportunity for farmers who wish to maintain their land in pastoral farming.

5. Evaluation of the Framework

A major benefit of this new framework is that it considers visible and known tree attributes so the potential benefits and costs of a particular genera can be assessed before research is undertaken. This is important in the case of kānuka, as it has received little research in a silvopastoral context to date, even though the framework provides evidence that kānuka has many benefits in certain outcomes when compared to poplar. This provides the means to 'screen' genera quickly before undertaking resource-intensive research. Moreover, it clearly highlights the tree attribute differences which may be causing alternate silvopastoral outcomes. Trees can then be more rigorously compared and selected based on these attributes.

As tree genera differ in their attributes and outcomes, it is apparent each genus will have distinct advantages and disadvantages. Viewing silvopastoral trees as a set of attributes and subsequent outcomes clearly shows them as 'a set of *trade-offs* rather than a real *solution*' [88] (pp. 14, emphasis in original). Kānuka will not be a panacea species, nor will any other. Nevertheless, by presenting species using this novel framework, with their advantages and disadvantages clearly conveyed, this will result in more informed silvopastoral research directions.

Species and cultivars within genera will also have different attributes, as outlined in a poplar and willow planting guide [25]. This will most likely be the case for the seven viable species of kānuka. Nevertheless, this was a level of detail beyond the scope of this review, although the framework could be used for within-genus comparisons.

A given tree's outcome may vary in differing growing situations, such as between pastoral livestock types, climates, topography or within-farm environments. The framework could also be used to compare the same species or genera in these differing environments.

One limitation of the framework being used as it is in this paper is the limited space within the tables. Using a table format does not present itself well to a more descriptive comparison between species for outcomes where little information is known. This was rectified in this paper by having a more descriptive comparison section below the tables. One solution to this would be to put the framework into a database, which could clearly show evidence for and against an outcome and provide an opportunity for more descriptive information in a notes section of the database.

Additionally, using the framework in a table format would be difficult when more than two species or genera were assessed, as the tables would most likely become cluttered with the information. Using the framework in a database would be very beneficial if more than two species or genera are compared.

When comparing the two genera, it would be helpful to add a common unit account for each of the outcomes so they can be quantitatively compared. Nevertheless, as stated in the introduction, this was beyond the scope of this review as the use of the framework in this paper is to review poplar and kānuka as silvopastoral trees and inform future research directions, not to provide a tool for quantitively evaluating tree planting decisions. This would be a valuable use of the framework, however, if enough information was available for specific species or genera.

Some of the outcomes could have had sub-categories, especially for 'above ground tree habit and phenology'. We decided not to use sub-categories because only this first outcome really warrants them, and we felt it was important to keep all the outcomes consistent. Moreover, the potential sub-categories such as 'impact of the silvopastoral tree on pasture', 'impact of the silvopastoral tree on the soil', and 'impact of the silvopastoral tree on water' are very much interlinked, as the soil is related to the availability of water, and both the soil properties and the availability of water are related to pasture growth. By maintaining one larger group, this allows for a summary statement at the end of each category, and makes it clear the holistic nature of this outcome.

Finally, as is the case in systems, many of the outcomes themselves interact with each other. For instance, 'the time until the provision of a silvopastoral outcome' interacts with 'the influence of the tree on the pasture and soil', 'livestock shelter', and 'soil conservation effectiveness', and 'the influence of the tree on the pasture and soil' interacts with 'water sediment and nutrient gains and losses'. Nevertheless, outcome-outcome interactions were not included in the framework as the focus of the framework is how the tree attributes relate to silvopastoral outcomes. We think research prioritisation and tree selection for researchers and land managers will be guided specifically by the presentation of the outcomes and their interactions with tree attributes.

6. Conclusions

Silvopastoralism is a land management tool that can offer holistic solutions to degraded agricultural landscapes. For silvopastoral systems to be researched, assessed, and compared in a holistic manner, a framework that outlines all their known silvopastoral outcomes is required. Moreover, by relating bio-physical tree attributes to these silvopastoral outcomes, tree selection for research and planting can be optimised based on a system's outcome needs.

The framework gives emphasis to the plethora of beneficial influences of trees to silvopastoral systems that are often not considered by New Zealand land managers, such as shelter provision, longevity, extra income from trees, the benefits of a winter tree canopy, the system's hydrology, and habitats for local fauna populations. This process clearly conveys the complexity of silvopastoral systems and extends the focus beyond more commonly researched outcomes (pasture production and soil conservation in the case of New Zealand hill country).

The framework was then used to review specific silvopastoral systems, highlighting research gaps and generating research priorities. In a New Zealand hill country case study, this paper shows the potential value of kānuka as a silvopastoral genus, a tree with a very different set of tree attributes to poplar, the most commonly planted silvopastoral tree in hill country. Kānuka may have improved outcomes in terms of pasture production, longevity, biodiversity value, shelter and ease of management due to its smaller size, evergreen nature and that it is native to hill country. Nevertheless, more research is required on kānuka to better understand these benefits and inform its use.

There also remain many outcome knowledge gaps for poplar used in a 20–200 trees ha^{-1} silvopastoral system such as biodiversity interactions, livestock shelter, greenhouse gas implications and water and nutrient gains or losses. This is surprising due to the amount of research that has been done on poplar and its widespread use. If poplar is to be fully evaluated and more fairly compared with other genera, researching these other silvopastoral outcomes is essential.

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Review

Mountain Watch: How LT(S)ER Is Safeguarding Southern Africa's People and Biodiversity for a Sustainable Mountain Future

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Abstract: Southern Africa is an exceptionally diverse region with an ancient geologic and climatic history. Its mountains are located in the Southern Hemisphere mid-latitudes at a tropical–temperate interface, offering a rare opportunity to contextualise and frame our research from an austral perspective to balance the global narrative around sustainable mountain futures for people and biodiversity. Limited Long-Term Ecological Research (LTER) was initiated more than a century ago in South Africa to optimise catchment management through sound water policy. The South African Environmental Observation Network (SAEON) has resurrected many government LTER programmes and added observatories representative of the country's heterogeneous zonobiomes, including its mountain regions. LTER in other Southern African mountains is largely absent. The current rollout of the Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON) and the Southern African chapters of international programmes such as the Global Observation Research Initiative in Alpine Environments (GLORIA), RangeX, and the Global Soil Biodiversity Observation Network (Soil BON), as well as the expansion of the Mountain Invasion Research Network (MIREN), is ushering in a renaissance period of global change research in the region, which takes greater cognisance of its social context. This diversity of initiatives will generate a more robust knowledge base from which to draw conclusions about how to better safeguard the well-being of people and biodiversity in the region and help balance livelihoods and environmental sustainability in our complex, third-world socio-ecological mountain systems.

Keywords: alpine and montane ecosystems; austral perspective; environmental sustainability; global change; long-term research; mountain observatories; multi-disciplinary research; social context; socio-ecological coupling; Southern Africa

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1. Introduction

Southern Africa is the southernmost region of Africa. This region is located in the mid-latitudes of the Southern Hemisphere at a tropical–temperate interface, resulting in a heterogeneous landscape and a dynamic climate characterised by strongly seasonal precipitation zones [1]. It has an exceptionally long geologic and climatic history [2] with its Barberton Greenstone Belt in the Makhonjwa Mountains of north-eastern South Africa credited as the oldest mountain range on Earth (ca. 3.2 Ga) [2,3]. Two mountain complexes dominate the region, the Great Escarpment and the Cape Fold Belt. The former is a 5000 km semi-continuous, passive erosional remnant of a receding continental margin stretching from Angola through Namibia, South Africa, Lesotho, Eswatini, Zimbabwe, and Mozambique [2,4] (Figure 1), and bisects the coastal belt from the colder and more seasonal interior [5]. The Great Escarpment arose from the rifting of the Gondwana super-continent and consists mostly of various sedimentary layers of the Triassic Karoo Supergroup overlain by younger basaltic lavas of the Early Jurassic at its highest elevations [6,7]. It covers an elevation range from ±1200–3482 m a.s.l. The significantly older Cape Fold Belt (or Cape Fold Mountains) is a 1300 km fold-and-thrust belt formed by the collision and subductive convergence of tectonic plates during the assembly of Gondwana, and is of Late Paleozoic age. It consists of sedimentary rock layers, mostly quartzitic sandstones and shales of the Cape Supergroup [6,8,9], which form a series of primarily east–west parallel ranges hemmed in between the Great Escarpment and the south-western and southern coastlines of South Africa, covering an elevation range from almost sea level to 2325 m a.s.l. (Figure 1).

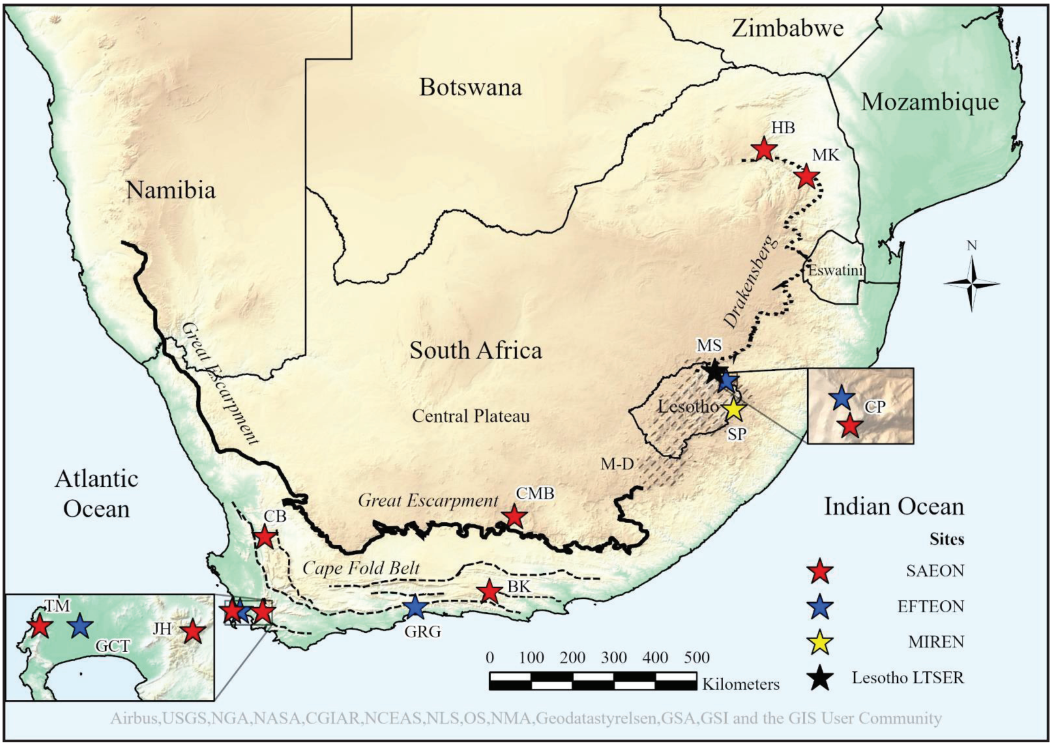

Figure 1. The location of the dominant mountain complexes and associated mountain observatories in Southern Africa. Observatories deployed by the South African Environmental Observation Network (SAEON, red stars) in the Cape Fold Belt: CB—Cederberg, Cederberg Mtns; TM—Table Mountain, Cape Peninsula Mtns; JH—Jonkershoek, Boland Mtns; BK—Baviaanskloof, Baviaans and Kouga Mtns. Great Escarpment: CMB—Compassberg, Sneeuberge; CP—Cathedral Peak, Maloti-Drakensberg; MK—Mariepskop, Mpumalanga Drakensberg; HB—Haenertsburg, Wolkberg section of the Limpopo Drakensberg. Proposed Expanded Freshwater and Terrestrial Environmental Observation Network landscapes (EFTEON, blue stars): GCT—Greater Cape Town; GRG—Garden Route Gateway; CP—Cathedral Peak, Northern Maloti-Drakensberg. Lesotho LTSER node (black star): MS—Mont-aux-Sources, includes the planned Global Observation Research Initiative in Alpine Environments (GLORIA) and Mountain Invasion Research Network (MIREN) sites. Current MIREN site (yellow star): SP—Sani Pass (extending to Kotisephola Pass). See Table A1 for site details. Sites relating to the Brotherton Fire Experiment, Nutrient Network, Soil Biodiversity Observation Network (planned), and MIREN (planned) are also/will be located at CP. M-D—Maloti-Drakensberg (indicated by cross-hatching). The "dashed" portion of the Great Escarpment refers to the Drakensberg section outside of the Maloti-Drakensberg. Not all mountain observatories are located on the escarpment edge. The less obvious extremities of the Great Escarpment in Angola and eastern Zimbabwe/western Mozambique are not shown.

Southern Africa's mountains account for almost half of the world's broad zonobiomes and a third of the world's global circulation systems [10]. They traverse a wide climatic gradient that includes subtropical arid (Namibia), Mediterranean (Cape region of South Africa), warm-temperate (eastern South Africa and Lesotho), and semi-arid tropical (Angola, Mozambique, and Zimbabwe) climate types. The Intergovernmental Panel on Climate Change has predicted that the region will be heavily impacted by climate warming [11], placing greater emphasis on our mountains as biodiversity refugia [12,13]. Increased frequency and intensity of droughts and floods, increasing temperatures, and decreased rainfall are specifically predicted, thus defining Southern Africa as a climate hotspot due to its existing vulnerabilities, poor adaptive capacity, under-development, and marginalisation [14]. Knowledge on the governance of climate change at a macro-regional level is lacking [15].

The rich biodiversity and ecosystem services of our mountains lend themselves to ecosystem-based adaptation [16] and nature-based solutions that encompass conservation, sustainable development, and restoration to reduce social and environmental vulnerabilities. Such approaches are critical as we foresee a greater demand for natural resources from our mountain regions [17], as well as greater competition for these resources amongst sectors of society [18]; such increasing pressures on mountain people and natural resources are typical of the developing world [19–22]. However, interventions aimed at balancing sustainable management of mountain-derived resources and human well-being should have a sound scientific basis in both the natural and social sciences [23,24].

Therefore, some of the most critical data for identifying and quantifying environmental changes, understanding long-term ecosystem dynamics for effective ecosystem management, understanding socio-ecological systems, informing environmental policies, and supporting global policy agendas, are those attached to long time-series from long-term ecological research (LTER) at local, regional, and global scales [25–28]. LTER is especially important for understanding episodic events (e.g., droughts and floods) and processes such as desertification, land degradation, and climate change, which do not operate over short-terms or small-scales [29–31]. Therefore, researchers need to establish high-quality, long-term collaborative and multi-disciplinary research networks aimed at understanding these drivers and patterns of environmental change in a coordinated and multi-site approach [25,26,32]. Two of the world's exemplary global LTER initiatives are the International Long-Term Ecological Research Network (ILTER) and the Group on Earth Observations Biodiversity Observation Network (GEO BON) [29,31,33]. The building blocks for LTER networks are site-based platforms or "observatories" such as Niwot Ridge (1980–present) in the Colorado Rockies (USA), Cairngorms National Park (2013–present) in Scotland, and Val di Mazia/Matschertal (2008–present) in the Italian Alps [34]. LTER is sometimes expanded to include the human dimension, which acknowledges close coupling between social and biophysical processes. Environmental problem solving should therefore view natural and human systems as a single entity through long-term socio-ecological research (LTSER) [35–37].

2. Aims, Materials and Methods

We present the first synthesis of the mountain observatories in Southern Africa and the collective value of long-term research from the region. The primary aim of this novel synthesis was to demonstrate the value of a diverse suite of process-orientated LT(S)ER initiatives in Southern Africa's mountain regions, framed by making reference to their contribution to human well-being, appropriate management of biodiversity, and environmental sustainability. A synthesis of this nature also generates broader statements gleaned by insight. A secondary aim, therefore, was to identify the strengths and weaknesses in Southern Africa's mountain-based LT(S)ER framework, and to make recommendations to enhance adaptive capacity and resilience to global change. For the first time, we contextualise the significance of our LT(S)ER from an austral perspective for the international mountain community.

This synthesis was based on an extensive and comprehensive literature review, as well as in-person institutional knowledge, given that both authors are personally involved in a number of these initiatives. Relevant published peer-reviewed scientific literature was sourced through Google®, Google Scholar®, ScienceDirect, and SpringerLink. Unpublished institutional grey literature, particularly from research institutions and governmental departments, and university theses were also consulted. This synthesis included key historical publications dating back to 1948, as well as the full spectrum of relevant literature up to 2021. A total of 164 references were consulted, most of which were then grouped into the focal areas relevant to this study. The literature was heavily focused towards the study area, namely the mountain regions of Southern Africa, but international publications were also cited where studies were relevant or comparisons needed to be made. A comprehensive and diverse set of LT(S)ER initiatives was selected based on objective selection criteria, as follows: (1) representations of the winter, summer, and all-year rainfall regions of Southern Africa; (2) research spanning a range of scales from local plot-scales to landscape-scales; (3) reference to above- and below-ground ecological processes; (4) research representing time frames ranging from earlier pioneering initiatives with significant historical value and long-term data sets to newer initiatives that address contemporary challenges not evident in the past (post-2000); (5) programmes championed by government and academic institutions; (6) inclusion of both montane and alpine elevations; and (7) the need to provide both scientific and practical demonstrative value to ensure a sustainable mountain future. These initiatives are discussed thematically in chronological order. We do not place emphasis on "how long is long-term" as some LT(S)ER initiatives are planned or recently established. They must be long-term by intention at establishment and repeatedly measured. Some of the initiatives refer to long-term monitoring as part of the gradient towards LTER or as part of the LTER framework. Our geographical focus is centred on two of Southern Africa's dominant mountain complexes, the Great Escarpment and the Cape Fold Belt. Despite the difficultly in defining and delineating mountains leading to different approaches [38], we followed the Global Mountain Biodiversity Assessment definition of mountains based on ruggedness criteria [39].

3. Discussion

3.1. Value of Historical and Current LTER Initiatives

3.1.1. Adaptive Management of Mountain Catchments for Water Security

Water is an essential resource that sustains almost all life on Earth. Southern Africa's water towers support millions of people in the region [40,41]. While climate scenarios show a significant decline in available water resources, socio-economic trajectories show an increase in water demand [42]. A supply shortfall in a water-scarce region may have social, economic, and environmental repercussions. It is therefore essential to safeguard and monitor our strategic mountain catchments to ensure a steady supply of clean water. South Africa has a history of long-term eco-hydrological research because mountain catchments were earmarked for large-scale afforestation using alien tree species, but the effects of this land use on water supply were unknown [43,44]. The country adopted a multiple-catchment design using entire catchments as experimental units to accommodate physiographic complexity, regarded as a world first [45].

Jonkershoek Valley LTER ("Jonkershoek"; 1935–1992 and 2010–present; with some rainfall gauging commencing in 1925; South Africa) is Africa's longest running catchment experiment [46]. It is located in a Mediterranean shrubland ("fynbos") catchment of the winter-rainfall Cape Floristic Region near Stellenbosch in the Boland Mountains of the Cape Fold Belt (Figure 1). It replaced South Africa's first LTER attempt at Jessievale in the Northern Drakensberg Escarpment (1910–1924), which failed due to lack of funding and poor management [47–49]. Jonkershoek uses gauged afforested catchments (and one natural fynbos catchment as the control) to ascertain the effects of afforestation on stream flow [50–52] (Table A1). Additionally, fire treatments and wild fires have been used historically to investigate the effects of fire on nutrient budgets [53] and hydrological responses [54,55].

Success at Jonkershoek led to similar LTER in the summer-rainfall Cathedral Peak Research Catchments ("Cathedral Peak"; 1948–1995 and 2012–present; South Africa), part of the greater Cathedral Peak Research Area in the Maloti-Drakensberg region of the Great Escarpment [44,52,56] (Figures 1 and 2). Gauged first-order catchments measure how stream flow in concert with sediment and nutrient exports are impacted by fire regimes in mesic montane grassland, and historically included a grazing and an afforestation treatment with alien trees [56–60] (Table A1).

These examples go far beyond demonstrating the significant impact of afforestation on streamflow and water yield. Wider application by scientists and policy makers to inform national catchment management and water policy in South Africa is arguably the finest example of science-driven policy from LTER in the country. These catchment experiments form the core of globally significant interdisciplinary research programmes that have shaped many environmental policies and practices relating to afforestation, biodiversity, fire, and water [46]. These policies were deconstructed from the late 1980s in favour of the National Water Act, which instead governs water-user rights among competitors. This Act looks past the sustainable management of catchments as ecosystems [49], but may be flexible enough for an adaptive management approach to climate change mitigation [61]. Policy changes often have deleterious knock-on effects. This LTER ceased because the nationally run catchment management programme was decentralised and handed over to conservation agencies in their respective provinces in the late 1980s, who failed to understand its value [49]. Fortunately, the LTER platforms at Jonkershoek and Cathedral Peak were resurrected from 2010 and 2012, respectively, under the gamut of the South African Environmental Observation Network (Table A1). They have evolved from long-term eco-hydrological monitoring platforms [62] to global change observatory catchments, encouraging more multi-disciplinary research using high-tech instrumentation [46]. Their value lies in understanding which land uses and management practices best support and optimise water supply in these sensitive and critical water supply areas, together with understanding the potential negative global change impacts. This knowledge is essential to building a resilient water tower and ensuring an adaptive management approach to water conservation in a water-limited region [62].

3.1.2. Fire Management and Policy That Optimises Grassland Biodiversity, Resilience and Water Production

Unlike the vast treed montane landscapes in many parts of the world [63,64], Southern Africa's mountains are covered largely by ancient, old-growth grasslands and shrublands. These highly flammable ecosystems have co-evolved with fire for hundreds of thousands of years [21,65], making fire one of the main ecological drivers and management tools [66]. Management objectives aimed at maintaining the stability of montane grasslands therefore need to incorporate their dynamic nature in response to fire [67]. Application of fire at the correct frequency and season is essential for optimising grassland biodiversity and condition, which minimises erosion and sediment losses to maintain a steady supply of clean water and maximise storage of soil organic carbon to mitigate climate change [68,69].

To understand these dynamics long-term, the Brotherton Fire Experiment (1981–1992 and 2015–present; South Africa; Figure 2) at Cathedral Peak in the Maloti-Drakensberg was established as a small-scale mesocosm-type fire experiment using 1-, 2-, 5-, and 12-year fire-return interval treatments to complement the larger research catchment-scale fire experiment discussed previously [69–71]. The experiment is generally sampled biennially, but occasionally on an ad hoc basis [71–73]. In 2004, a multi-disciplinary team of scientists used the fire experiment to convince the management authority of its importance by including a broader suite of biodiversity elements and the potential for climate change research [73].

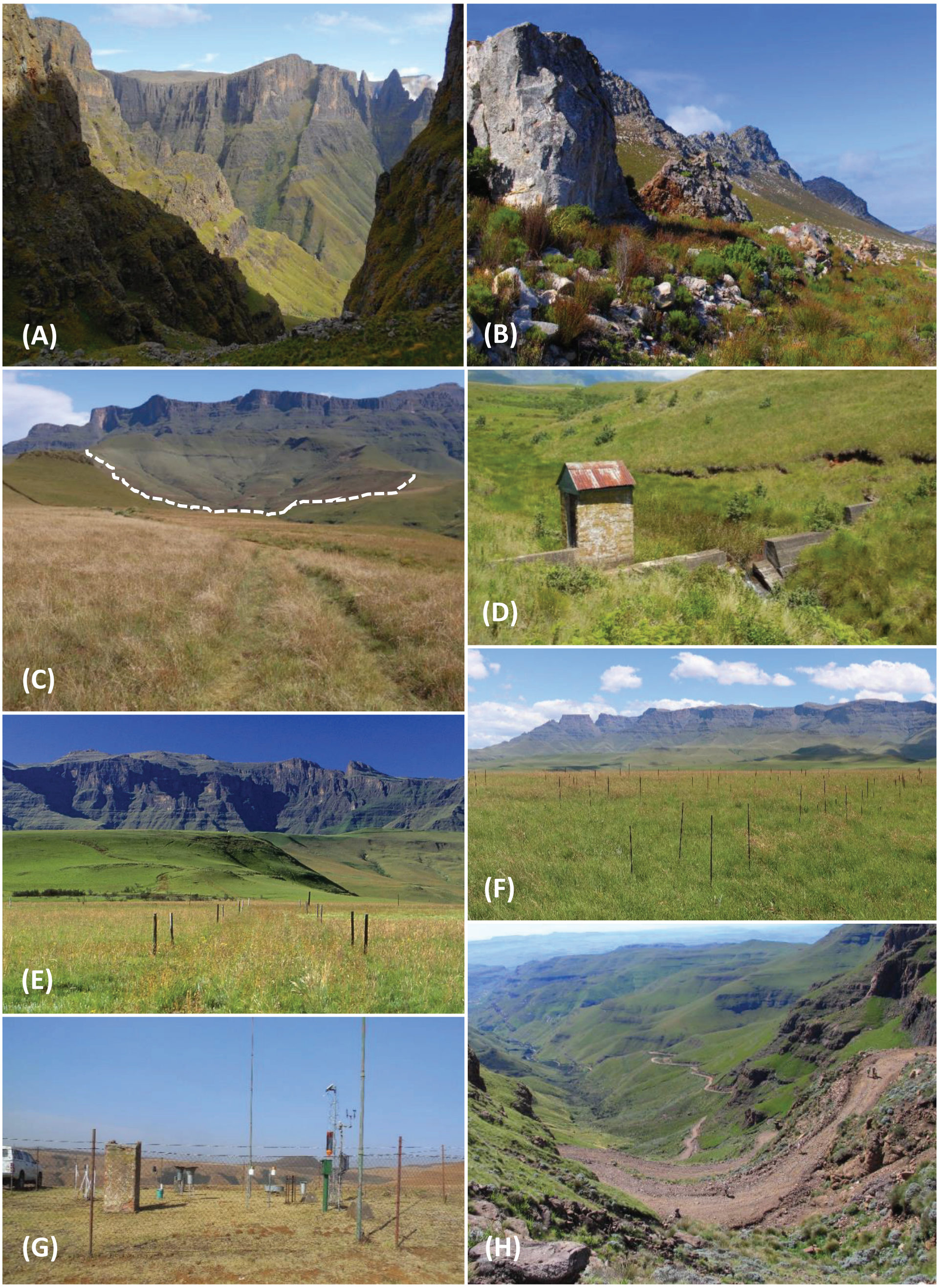

Figure 2. Photographic representation of LTER in Southern Africa's mountain regions: (**A**) Maloti-Drakensberg, Great Escarpment; (**B**) Cape Fold Belt; (**C**) Research Catchment II at Cathedral Peak (above dashed line) after the removal of alien trees; (**D**) V-notched gauging weir used to measure stream flow; (**E**) Brotherton Fire Experiment; (**F**) Nutrient Network site; (**G**) Campbell Scientific automatic weather station; (**H**) MIREN site at Sani Pass straddling South Africa and Lesotho. All photos by C. Carbutt.

The original aim was to assess the effects of pyrodiversity (varied fire frequency and seasonality treatments) on mesic montane grass structure (basal cover) and composition (diversity) [72], but has been expanded to test the effects of fire on forb species composition and diversity [66], soil properties and landscape functioning [74], invertebrate diversity and abundance [75], and multi-decadal changes in grass and forb species composition in concert [69,70]. It also hosts a warming experiment using open-top chambers [76]. All of these metrics are important indicators of grassland health [77] and biodiversity value [66]. Data from the long-term fire experiment are used to inform optimal burning practices in the Maloti-Drakensberg, established as regular biennial burning in the dormant season [69], supplemented with smaller patch burns at slightly longer fire-return intervals [70]. Biennial burns in late winter or early spring maintain grass bud banks and important grass species at desired levels of abundance [69,78] to ensure a long-term desired state of grassland equilibrium and stability that can resist change and maintain healthy and resilient grassland communities [69,78,79] and water towers [67,69]. Slightly longer fire-return intervals enhance plant diversity [70]. It has also been shown that excessively longer fire-return intervals (5–13 years) will shift grassland species composition and decrease vegetation cover, leading to greater soil exposure [69].

Although fire has rarely been included in experimental climate change research [76], the fire experiment will also provide a valuable means to detect and understand future responses to climate change as plant species are likely to shift their ranges, seasonal growth patterns, and responses to fire under changing mountain climates [69,76]. Understanding how montane grasslands will respond to climate change and associated changes in a fire regime is essential for protecting its profound biodiversity and functional value [76]. Such knowledge is now being entrenched as standard policy in the Integrated Management Plan and Fire Management Plan of the Maloti-Drakensberg Park World Heritage Site (in which this LTER site is located) [80] and in the management of mesic grasslands in general [81]. Such a fire experiment could also potentially inform the safest conditions under which to conduct controlled burning of fire-breaks and fire suppression, to limit the spread of life-threatening extreme fire events common to the Maloti-Drakensberg [68].

3.1.3. Resuscitating the National Government LTER Platform in South Africa

LTER rose to greater prominence in the South African scientific community in the mid-1990s, driven by renewed global interest in measuring anthropogenic climate change and concern for the socio-economic impacts of environmental stressors at scales and complexities not seen before. A national workshop in 1999 discussed prompts by the ILTER to establish a similar research network in South Africa, with particular focus on climate change and ecology [30,44,82–84].

The mandate of this emergent government-funded South African Environmental Observation Network (SAEON; 2002–present) is to understand human-induced global change impacts on the environment and ecosystem services and provide meaningful data for policy makers to manage South Africa's natural capital sustainably in a changing world [85]. SAEON maintains a network of platforms in both terrestrial and marine environments across South Africa. These platforms constitute long-tern research sites where repeated observations, experimental treatments, and related data are permanently maintained. SAEON is part of the Environmental Observatories Network (EON) and shares links with the Environmental Long-Term Observatories Network of Southern Africa (ELTOSA), designed to synergise LTER at a regional level, and the ILTER [82,86]. SAEON has partnered with academic institutions and other research facilities to rapidly engage an already institutionalised network to achieve a quick uptake in both scale and time. It makes use of historical platforms as well as establishing its own. SAEON operates as a number of research nodes distributed across the country's various zonobiomes, each anchoring participatory sites that serve as research stations and environmental change observatories. There are eight SAEON mountain observatories (four in the Cape Fold Belt and four in the Great Escarpment; Figure 1 and Table A1). SAEON has been instrumental at resurrecting earlier floundering government LTER programmes, for example at Jonkershoek and Cathedral Peak.

3.1.4. Early Detection of Mountain Invasive Alien Plants and Understanding Species Redistributions

Invasive alien plants are among the foremost threats to biodiversity on the planet [87,88]. The mountain regions of Southern Africa have not been spared this fate [89–92]. Some areas are accessible by road passes and are therefore highly susceptible to invasions due to anthropogenic disturbance and sustained propagule pressure [91,93,94]. This invasion threat necessitated a long-term intervention, and presented the opportunity for local actors to collaborate with the international Mountain Invasion Research Network (MIREN), established in 2005 as an initiative of the Global Mountain Biodiversity Assessment [89,95]. MIREN initially monitored the impacts of non-native plant invasions in mountains across the globe [95], but has expanded its focus to include the broader effects of global change on plant species' redistributions in mountain regions [27,96]. A sub-component, RangeX, seeks to understand the mechanisms and impacts of plants expanding their ranges due to climate warming [97]. These international programmes, with almost 30 participatory sites, are poorly represented in the Southern Hemisphere. Only eight sites are collectively represented by the Australian Alps, Southern African Maloti-Drakensberg, and South American Andes (Argentina, Chile, and Ecuador) [98]. Africa in particular is poorly represented; the second MIREN site is located in the Atlas Mountains of Morocco [98]. The region's first MIREN site, in the Maloti-Drakensberg, was established at Sani Pass, connecting South Africa with Lesotho (2007–present; Figure 2, Table A1) [89,91], and was later extended up into Kotisephola Pass in Lesotho [91]. Expansion of the MIREN network in the region is currently being facilitated through the Afromontane Research Unit of the University of the Free State at three sites ranging from montane to alpine elevations: Witsieshoek Pass and Sentinel trail, Cathedral Peak (Mike's and Organ Pipes Passes), and additional sites at Sani Pass in the Maloti-Drakensberg [99]. This LTER serves as an effective early detection strategy to mitigate the threat posed by alien plants [100] and helps understand how invasive alien plants and other range-expanding species are impacting biodiversity and ecosystem functions along elevation gradients, which, as competitors, are influencing species' responses to climate change through the establishment of novel communities [101,102].

3.1.5. Understanding the Effects of Nutrient Enrichment on Biodiversity and Livelihoods

The Anthropocene is marked in part by rapid changes to global nutrient budgets and the abundance and identity of consumers [103]. To quantify these global impacts, the Nutrient Network (NutNet; 2005–present) [104,105] has spread from the USA to about 130 grassland-dominated sites across the world [106]. This collaborative, distributed LTER network uses standardised methods to examine the relationship between two fundamental ecosystem properties on which ecosystem- and human-health both depend, namely diversity and productivity [105,107,108]. A primary effect of climate change on mountain ecosystems is shifts in species' distributions, diversity, and system productivity [109,110]. A mechanistic understanding of the diversity−productivity relationship is therefore fundamental to understanding how species dynamics shape community processes [103,111,112], which in turn can predict the conditions under which species can either buffer or exacerbate global change [103].

The NutNet site at Cathedral Peak in the montane belt of the Maloti-Drakensberg (2018–present; South Africa; Figure 2) is one of only two high-elevation sites in Africa, and is the only NutNet site within the geographical scope of this study. Similar to other LTER programmes covered in this synthesis, NutNet is poorly represented in the Southern Hemisphere, Africa, and the region. A NutNet site in the Maloti-Drakensberg is highly relevant because a long-term nutrient addition experiment manipulating multiple nutrients will be highly informative in a nutrient-limited system. Although basalt-derived soils of the Maloti-Drakensberg are intrinsically nutrient-rich (especially total carbon and nitrogen), they have a low nutrient availability due to highly constrained microbial activity mediated by cool temperatures and other soil-related factors [113]. Climate warming, leading to enhanced microbial activity and therefore increased nutrient availability, is expected to have a deleterious impact on the nutrient-limited flora of the Maloti-Drakensberg [114]. Additionally, atmospheric deposition of nitrogen and sulphur leading to ecosystem acidification is a further cause for concern. For example, Cathedral Peak in the Maloti-Drakensberg has the highest annual wet deposition fluxes of nitrogen (NO_3^- and NH_4^+) and sulphur (SO_4^{2-}) of any sites monitored in eastern South Africa [115]. High rainfall and recirculation patterns characteristic of a background site located downwind of large industrial areas are the most likely factors [115]. It is important to establish an additional site in the alpine belt of the Maloti-Drakensberg as the effects of nutrient enrichment through warming and deposition on a nutrient-limited alpine flora at this elevation are unknown. Furthermore, as some of our mountains are important rangelands supporting the livelihoods of shepherds practicing transhumance pastoralism [21], it is also important to gauge the potential effects of nutrient enrichment on the dynamics of grazed herbaceous systems.

3.2. Value of LT(S)ER Initiatives Under Development

3.2.1. Understanding How Climate Warming Will Affect Sensitive Alpine Habitat: An Austral Perspective

Although the alpine biome is represented across all continents and latitudes [116], it only covers about 3% of the Earth's terrestrial surface outside Antarctica [117]. Since 2001, the Global Observation Research Initiative in Alpine Environments (GLORIA), acknowledging the highly sensitive nature of alpine systems and their vulnerability to climate warming [118,119], established long-term alpine observatories across the globe for the comparative study of climate change impacts on mountain vegetation and its biodiversity [120,121]. A clear pattern has emerged in the distribution of GLORIA sites across the globe. Most are concentrated in the Northern Hemisphere (especially Europe, North America, and the Himalayas) [10]. While this may be in part due to the global alpine biome being far more represented in the Northern than the Southern Hemisphere [117], it also speaks to other factors such as historical bias, disparity in funding, and a historical disconnectedness between Northern and Southern actors. Interrogation of the Dynamic Ecological Information Management System (DEIMS) [34,122] revealed only 3% representation of alpine LTER-type sites from the Southern Hemisphere (viz. Australia, Bolivia and Ecuador; it is not known why the two New Zealand GLORIA sites do not appear in this database). This imbalance undermines the ability of GLORIA (and other LTER programmes) to generate representative data across all zonobiomes and global circulation systems. There are only two active GLORIA sites in Africa, in the Rwenzori Mountains and Mt. Elgon [123], both of which are located in Uganda in the Northern Hemisphere.

The upper reaches (ca. 2800–3482 m a.s.l.) of the Maloti-Drakensberg host the only alpine environment in Southern Africa [124] and the only alpine environment south of Mount Hanang in Tanzania, East Africa. It is small on a global scale (<12,000 km^2) [20] and poorly known from an international perspective. For example, key global alpine analyses did not include the alpine Drakensberg [125,126]. An exception included its inselberg alpine summits [127], which unfortunately are not representative of the "mainland" escarpment plateau due to their small size, and because of their almost free-standing nature, are spared the threats of livestock grazing, alien plants, and plant harvesting [128].

Africa's tropical and southern alpine systems are highly divergent biologically [21], and therefore necessitate separate LTER initiatives to measure potentially dissimilar responses to global change. Attempts were made by Prof. Stefan Grab from Wits University and the first author from 1999–2004 to redress the absence of GLORIA sites in Southern Africa and the paucity of sites in the Southern Hemisphere. Lesotho, supporting 90% of Southern Africa's alpine habitats [21], was chosen for this purpose. Support was provided in 2004 by a small New Zealand delegation from the University of Otago. The summits of Kotisephola Pass and Black Mountain were scouted in particular due to their accessibility. No suitable sites were located due to security concerns for equipment and inability to fulfil the multi-summit approach [121] due to topographic constraints. New localities are being sought by the Afromontane Research Unit of the University of the Free State, most likely in their planned Mont-aux-Sources LTSER node in the north-eastern Maloti-Drakensberg. Alternative possibilities in the Maloti-Drakensberg being considered are Letšeng diamond mine (Lesotho) and Ben Macdhui (Tiffindell Ski Resort; South Africa) [99]. In addition to understanding the effects of climate warming on a poorly known alpine flora, GLORIA sites in Southern Africa will ensure a more comprehensive and robust network by adding representations from the subtropic-alpine biome and maritime subtropical monsoon regional climate system in the mid-latitudes of the Southern Hemisphere, currently highly under-represented in the GLORIA network.

3.2.2. Soil Knowledge for the Management and Conservation of Soil Resources to Sustain Livelihoods and Safeguard Biodiversity

Soils are significant storehouses of global terrestrial biodiversity, which fulfil multiple critical ecosystem functions and services such as climate regulation, nutrient cycling, and food production [129–131]. Few long-term global soil biodiversity studies have been undertaken, leading to a lack of policies to support soil biodiversity conservation and governance [130,131]. Sustainable livelihoods in Southern Africa's mountains will depend heavily on well managed and conserved soil systems to support crop and livestock production. Unfortunately, populated areas in the Maloti-Drakensberg, for example, are degraded and not sustainably managed for food security [17,21]. Soil biodiversity is therefore under pressure from human activities [130]. Long-term studies relating to soil structure, fertility, and biodiversity are essential to optimising food production and ensuring environmental sustainability in the region. However, soil studies in the mountains of Southern Africa are limited, generally small-scale, and mostly non-repetitive [74]. The recently launched global Soil Biodiversity Observation Network (Soil BON), a thematic LTER network within GEO BON, aims to understand how changes to soil biodiversity and ecosystem function may affect the ability of people to sustainably manage and conserve soil resources to support livelihoods and safeguard soil biodiversity [132]. It is essential that the region is linked to this critically important international LTER programme and has a number of representative sites in its mountains. For this reason, a Soil BON site has been proposed for Cathedral Peak in the Maloti-Drakensberg, where paired sampling sites along a land use and degradation gradient ranging from protected area to communal land can be established.

3.2.3. Moving Towards Systems-Based, Landscape-Scaled LTSER

The region has an extremely poor track record with mountain-based LTSER, a great injustice given how important these mountains are to people. Perhaps the reason is because most long-term research in our mountains has historically taken place in sacrosanct protected areas managed for conservation, without having to take cognisance of a social context. People were simply fenced out. The world has changed significantly, and social dynamics are requiring formal integration given the complex social issues around land tenure, communal land practices, and degradation, as well as greater need for sustainability, food security, and more holistic management of socio-ecological systems. Southern Africa's third-world context necessitates a sensitive and strategic approach to addressing change in its mountain regions. Embracing its social environment through social engagement [133], public-assisted monitoring [32], and the crafting of innovative solutions for mountain futures [134] are key features to consider in future LTSER, given that mountains and their associated ecosystem services are critical for people [24,41,135,136] and are cradles of cultural and ethnic diversity [137,138]. The first pioneering form of mountain LTSER in South Africa took place in the impoverished rural Okhombe and Obonjaneni communities in the upper Tugela catchment of the northern Maloti-Drakensberg [139]. Individual projects were highly varied, ranging from erosion control monitoring of degraded catchments to implementing and monitoring intercropping systems for enhanced ecosystem services and food security [140]. There is a key need for South Africa to capacitate and support

LTSER initiatives with its neighbours, particularly where mountains are shared by adjacent countries (e.g., South Africa–Lesotho).

SAEON's highly networked infrastructure footprint has paved the way for a new ecosystems-based, socio-ecological initiative currently being established through the Expanded Freshwater and Terrestrial Environmental Observation Network (EFTEON; South Africa). This LTSER infrastructure comprises six socio-ecological "landscapes" accommodating gradients of land transformation to clarify the complex relationships between ecosystems and socio-dynamic systems under climate change [141]. Three EFTEON landscapes encompassing mountain environments are being established. The northern Maloti-Drakensberg EFTEON landscape proposes to make use of Cathedral Peak (Table A1), already a designated focal research and monitoring site in a protected area, as the "anchor tenant" from which to extend research infrastructure into lowland areas of both commercial and subsistence agriculture. The socio-economic and environmental importance of the Cathedral Peak area together with its geographic complexity and sensitivity to climate change inherent in a mountainous area makes it the ideal candidate for large-scale systems-based research [62]. Specifically, steep transformation gradients from almost pristine protected areas to degraded and impoverished community areas [142,143], a long historical record of meteorological and hydrological data [56,144], and its location in a transition area from C_3 to C_4 grassland and grassland/savanna count heavily in its favour for LTSER [145].

The second proposed EFTEON landscape, the Greater Cape Town (GCT) landscape, will link the Atlantic Ocean with the Boland Mountains Strategic Water Source Area in the Cape Fold Belt, covering steep climate and vegetation gradients in the Fynbos Biome. This environmental gradient traverses a rich socio-cultural footprint, which includes urban, agricultural, and natural land use types. The Table Mountain National Park ("Table Mountain") and Jonkershoek observatories are proposed components of this landscape [145] (Table A1). This landscape offers a direct link to the BioGrip Cape Point Atmospheric Monitoring (Global Atmospheric Watch) and Cape Town South African Population Research Infrastructure Network sites [145].

The third proposed EFTEON landscape of relevance is the Garden Route Gateway (GRG), which will be centred on short-reach, high-energy river systems draining the Baviaans and Kouga Mountains of the Cape Fold Belt into the Indian Ocean through an area of rapid urbanisation and agricultural intensification. The Baviaanskloof observatory is a proposed component of this landscape (Table A1). Both the GCT and GRG landscapes present source-to-sea opportunities involving upstream and downstream systems, which link terrestrial mountain catchments with marine ecosystems [145].

3.3. What about the Rest of Southern Africa?

South Africa has the most active and comprehensive LTER networks in the region. Other Southern African countries have limited long-term meteorological (rainfall and air temperature) and hydrological monitoring but it is not mountain-focused (see [146–150]). Two exceptions relate to Lesotho: a high-elevation rainfall and temperature series [151] and the MIREN programme (discussed previously). This almost absence of mountain LTER outside of South Africa is largely due to the region's remote and inaccessible complex terrain, shortage of institutional and human capacity, lack of funding, theft and vandalism of equipment, and poor data management systems [62,83,151,152].

One key intervention intended to facilitate LTER across Southern African countries was the ELTOSA network established in 2001. It aimed to connect member country EONs to study ecosystems and environmental issues traversing political borders [30,82,83], but has failed to materialise. A recent global review shows only South Africa and Namibia hosting LTER in the region—based on DEIMS, July 2017 [28]. The Namibian site, however, bears no relevance, as its research station is located in the Namib Desert. Failure to successfully implement a transnational network highlights the challenges of undertaking LTER in the region, hampered by pervasive funding constraints and lack of institutional capacity (both human and infrastructure) [30,82]. Fortunately, the African Mountain Research Foundation (AMRF), progeny of the International Mountain Society, was recently established to catalyse and extend LTSER beyond South Africa into the mountain regions of Angola, Lesotho, Madagascar, Malawi, Mozambique, Namibia, and Zimbabwe. It is essentially a fund-raising arm to establish LTSER with the Afromontane Research Unit of the University of the Free State as its beneficiary [153]. Previously, AfroMont (Research Network on Global Change in African Mountains) supported collaborative research in African mountains, but is now largely defunct.

3.4. Local Knowledge with Global Significance

This synthesis has enabled us to highlight the strengths and weaknesses of our mountain observatory networks (Table 1) and to underscore the collective value of our mountain-based LT(S)ER in terms of how it safeguards people and biodiversity for a sustainable mountain future. It also allowed us to contextualise and frame the significance of our mountain-based LT(S)ER from an austral perspective for the Northern Hemisphere-dominated international mountain community. This opportunity is essential to balancing the global narrative around how mountain people and biodiversity may be impacted by a rapidly changing world and can hopefully present workable solutions which may benefit other mountainous countries facing similar challenges.

Insights gained from our LT(S)ER offer a unique perspective due to our local mountain context, outlined as follows: (1) our mountains are not very high in elevation by global standards and do not occur at high latitudes. They therefore have no permanent snow and ice, no upper-alpine and nival zones, and no glaciers, suggesting that detecting changes may require a more subtle and nuanced approach (only periglacial signatures are present at the highest elevations). (2) Our mountains are not covered with montane forests and lack the characteristic alpine treeline tracking the 6 °C seasonal mean isotherm between alpine and montane belts [63,64], which as a thermal "marker" sensitive to climate warming can be used as an indicator of change. In Southern Africa's Maloti-Drakensberg, a more obscure treeline ecotone is depressed by almost a 1000 m due to a precipitous escarpment; this discontinuous treeline ecotone separates the upper-montane and lower-montane belts [114]. Changes here may not be as easily detected compared with the alpine treeline at higher elevation. (3) True to the global trend of mountain plant diversity peaking in the mid-latitudes [127], our mountains are hyper-diverse palaeo-centres of plant diversity and endemism. This diversity is largely accounted for by expansive and ancient old-growth grasslands and shrublands [124,154–156]. In contrast, our montane forests are small patches (1–10 ha) on south- and south-east facing slopes and in steep-sided valleys; they are species-poor with low levels of endemism [124,157]. (4) There are few examples of mountains located in the Southern Hemisphere mid-latitudes (together with the Australian Alps and central South American Andes), strategically positioned at a tropical–temperate interface, where warming and precipitation changes are expected. (5) The Great Escarpment and Cape Fold Belt are the region's most significant climate regulators–topographic influences that exert strong regional and micro-scale controls on precipitation, humidity, airflow and temperature [2]. (6) Our mountains include Africa's only non-tropical, Southern Hemisphere alpine habitat, and its small area and relatively benign relief by global alpine standards may offer alpine species under climate change fewer opportunities to migrate due to a limited mosaic of micro-habitats and thermal niches (see [158]). (7) Our mountains are characterised by strong moisture/aridity, temperature, and aspect gradients, and include almost half of the world's zonobiomes and a third of the world's global circulation systems. (8) Our montane grasslands are beginning to show different responses to climate change when compared with Northern Hemisphere systems [76]. (9) Our mountains are some of the oldest on the planet with interesting and complex geologic and geomorphic histories, with less of the "continental" influence experienced by Northern Hemisphere mountains. (10) Our mountains have their own unique Quaternary glaciation history [159] and are believed to have been affected by late

Quaternary climatic fluctuations [5,160]. (11) Our mountains host a sovereign country ("the Mountain Kingdom of Lesotho") entirely enclaved by South Africa; this is the only Southern Hemisphere example of an enclaved country and the only country in the world occurring in its entirety above 1000 m a.s.l. [161]. A nation accommodated entirely within a mountain context places extreme pressure on its natural resources—Lesotho's mountains are occupied by pastoralists with heavy dependence on communal rangelands, leading to landscape degradation and unsustainable resource use [21]. (12) In addition, there are still many learning opportunities to be experienced and lessons to be shared amongst a diverse suite of stakeholders in the building of a multi-disciplinary, multi-scale community of practice [27] to undergird adaptation and resilience policy.

Table 1. Strengths and weaknesses of Southern Africa's mountain observatory networks and LT(S)ER, as identified in this synthesis.

Features	Strengths	Weaknesses
LT(S)ER history	There is a long history of LT(S)ER in the mountains of South Africa dating back to some 111 years.	Despite a long history, LT(S)ER is relatively limited and currently overseen by a small community of organisations and researchers.
Historical focus	The earliest LTER in South Africa was all mountain-based eco-hydrology because it was needed to inform catchment management practices and water policy, highly relevant to a water-scarce country.	However, because of this one-dimensional legacy, purer forms of ecological LTER suffered historically.
Adaptive changes	LT(S)ER is evolving towards multi-disciplinary global change observation science.	This evolution has been a slow transition from long-term monitoring platforms.
Diversity of LT(S)ER initiatives	There is a diverse range of LT(S)ER programmes in Southern Africa. This diversity provides a larger and more robust knowledge base from which to draw conclusions about how to better safeguard people's well-being, appropriately manage biodiversity, and ensure environmental sustainability.	Having a diverse range of initiatives can also spread resources very thin, resulting in poorly replicated networks of each LT(S)ER type. There are some LT(S)ER types represented by solitary sites rather than the preferred distributed, coordinated, multi-site networks.
LT(S)ER capacity in Southern African countries (excluding South Africa)	These countries still have an enormous opportunity to design and capacitate the types of LT(S)ER networks that will serve their purposes to great effect, generating both quality science and the outcomes needed to address livelihood challenges in their mountain regions.	There is little to no LT(S)ER taking place in the mountains of Angola, Lesotho, Mozambique, Namibia, and Zimbabwe. LT(S)ER in Southern Africa is therefore unbalanced and not representative of the Great Escarpment. Africa in general is lacking mountain observatories, which contrasts markedly with its high population densities and socio-economic needs against a backdrop of accelerating environmental change [162].
LT(S)ER capacity in South Africa	South Africa has the most comprehensive LT(S)ER networks in the region and the best equipped mountain observatories. It therefore has a key role to play in capacitating and supporting its regional neighbours.	Notwithstanding South Africa's significant strides at LTER, the spread of sites in the country is not fully representative of its diverse mountain regions which traverse large moisture/aridity, aspect, and temperature gradients and consequentially a range of zonobiomes. The limited and uneven distribution of mountain observatories is also a global trend [162]. An example is the heavy reliance on Cathedral Peak in the Maloti-Drakensberg. This behemoth of LT(S)ER in Southern Africa's mountains accounts for the Research Catchments, the Brotherton Fire Experiment, a NutNet site and is proposed as a significant component of the forthcoming EFTEON LTSER landscape, as well as proposed MIREN and Soil BON sites.

Table 1. *Cont.*

Features	Strengths	Weaknesses
International connectivity	A number of collaborative partnerships with international LT(S)ER programmes are emerging, opening up significant opportunities for collaboration, lesson-sharing, and learning.	Southern Africa, Africa, and the Southern Hemisphere are poorly represented in international LTER programmes. LT(S)ER has suffered from a "silo mentality", whereby researchers have historically been working in isolation within the region and divorced from Northern Hemisphere colleagues and programmes. The Cape Fold Belt in particular lacks connection to such programmes, particularly MIREN and Soil BON.
Focal areas	There are still many research gaps and opportunities for scholarly study at all levels (graduate, post-graduate, and scholar). There is an opportunity for better integration of faunal, floral and soil-based LTER components towards more systems-based research.	There has been a historical bias towards certain spheres of study and certain taxonomic groups—faunas, soil biodiversity, and below-ground systems—are less studied than floras and above-ground systems at high elevation.
Elevational representation	Southern Africa has an alpine region that has great potential to host global change LT(S)ER.	Better use must be made of Southern Africa's alpine region, which remains very under-studied. Multiple alpine observatories are required for the GLORIA, MIREN, NutNet, RangeX, and Soil BON programmes, particularly in the colder and drier recesses of the south-eastern Maloti-Drakensberg. All observatories, with the exception of the long-term automated weather station on an alpine inselberg summit near Vulture's Retreat (3010 m a.s.l.), are montane (this site also hosts a long-term vegetation monitoring platform through fixed cameras; Table A1).

4. Conclusions

Southern Africa has the opportunity to host comprehensive mountain observatory networks that will contribute towards a more holistic and robust global network of mountain observatories inclusive of all relevant sciences. We conclude with a few recommendations to further capacitate Southern Africa's ability to manage its mountain systems sustainably and in a way that builds resilience to global change: (1) LT(S)ER should have its own unique flavour formulated around the region's socio-ecological realities, context, agendas, and policy frameworks. (2) The nations of the region not engaging in LT(S)ER should be encouraged to invest in a research infrastructure framework to advance their scientific footprint and skills base, and more importantly to understand global change impacts. (3) The smaller mountain complexes not part of the Great Escarpment, such as the Lebombo Mountains, Soutpansberg and Waterberg, may also warrant some attention in the future to ensure a more comprehensive understanding of our mountain systems. (4) The socio-ecological and socio-economic dimensions involving sustainable livelihoods, resource use, ethnic diversity, and culture linked to mountains need to be urgently incorporated in to LTER initiatives (LTSER). The establishment of the EFTEON landscapes in 2021 is a large step towards achieving this end. (5) Effective, clean governance is critically important to ensure sustainability, conserve natural resources and safeguard human well-being [163]. (6) Furthermore, global collaborations are key to tackling pressing global change issues that traverse spatial and temporal scales and require multi-disciplinary inputs across many fields. SAEON and the Afromontane Research Unit in particular are ensuring collaboration within the broader scientific community, with growing international partnerships emerging in the past few years. A few suggestions to foster deeper international connections include the hosting of appropriately themed mountain conferences (such as the first Southern African Mountain Conference 2022), focused workshops, greater use of digital resources to host online events, Special Issue journal publications, increasing the global visibility of international networks to grow membership across all hemispheres and disciplines, sabbaticals taken abroad, and more generally the reciprocal exchange of visiting delegations between countries. A good opportunity for synergistic interactions exists between the proposed Northern Maloti-Drakensberg EFTEON landscape and the Mont-aux-Sources LTSER node. (7) LT(S)ER in South Africa should continue to receive funding given its long LTER history, previous financial investments, long-term data legacies, and active strides being taken to advance its scientific infrastructural footprint. (8) LT(S)ER should be adaptive in nature, always seeking to remain relevant and supple enough to meet changing research questions and needs. It should also be designed with the end user in mind to inform "evidence-based policy" [26] primed for implementation. (9) Future placement of LT(S)ER sites to close knowledge gaps will require novel approaches, given that they may have to be located in remote and inaccessible areas that are difficult to establish and administer. (10) We have demonstrated the value of our LT(S)ER along thematic lines of research, however, they may obscure and limit our ability to characterise and mitigate global change impacts until they have been integrated through a holistic approach [162]. Our greatest challenge will be to integrate data from multiple thematic programmes into a single, clear mountain-specific adaptation policy for implementation. Smaller, focused steps will therefore be required to achieve this end. Since we already have water and fire policy informed by multi-decadal catchment and burning experiments respectively, a "nutrient policy" should also be established in the future that incorporates management interventions addressing the nutrient-enrichment impacts of global change on our mountain grasslands. (11) The current establishment of mountain observatories relating to the GLORIA, RangeX, Soil BON, MIREN, and AMRF programmes and the proposed EFTEON landscapes makes for an exciting new chapter of LT(S)ER in Southern Africa and an invaluable contribution to the international mountain community. This renaissance period is timeous given the many perils and pressures facing our mountain people and biota in the Anthropocene. It is therefore essential that LTSER generating high-quality data is conducted in the mountain regions of this uniquely positioned region of the Earth, whose context is largely unreplicated in other mountain regions of the world. This is our mountain watch for a sustainable Southern African mountain future.

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Appendix A

Table A1. Summary of the mountain observatories in Southern Africa. Atmospheric and hydrological research is included in the broader LTER framework to showcase the full suite of parameters measured long-term. Key environmental change drivers † and response variables * are indicated for each observatory [164]. Date ranges start with the earliest instrumentation/infrastructure for at least one of the data parameters listed. Mid-range dates are shown where the South African Environmental Observation Network (SAEON) resurrected earlier data collection. Data collection and recording frequency vary with changes in stations, instrumentation, or custodianship of the research platform. Elevation range at each observatory reflects the spread of data collection activities, not necessarily the topographic extremes (with the exception of the Mont-aux-Sources and Sani Pass sites).

Site and Affiliation	Mountain Range and Country	Management Authority	Biome and Rainfall Zone	Recorded Parameters and Attributes	Elevation Range (m a.s.l.)
Cape Fold Belt					
Baviaanskloof SAEON Fynbos node; proposed component of the Garden Route Gateway EFTEON landscape	Baviaans and Kouga Mountains, South Africa	Eastern Cape Parks and Tourism Agency	Intersection of Albany Thicket, Succulent Karoo, Fynbos; winter rainfall	Atmospheric parameters (2011–2015–current): air temperature, vapour pressure deficit, atmospheric pressure, precipitation, wind speed and direction Hydrological parameters (2012–current): groundwater and surface water elevation, depth and temperature, estimated streamflow Ecological parameters: vegetation surveyed in 1991/1992 and 2011/2012 † Land use/cover; disturbance; water abstraction * Hydrological functioning; biodiversity Baviaanskloof is affiliated with the Global Ecosystem Research Infrastructure (GERI) and the International Long-Term Ecological Research Network (ILTER). It is a LivingLands landscape and falls within the UNESCO Cape Floral Region Protected Areas World Heritage Site	174–985
Cederberg SAEON Fynbos node	Cederberg Mountains, South Africa	CapeNature	Fynbos, Succulent Karoo; winter rainfall	Atmospheric parameters (2015–current): air temperature, relative humidity, wind speed and direction, precipitation, solar radiation, atmospheric pressure Ecological parameters: vegetation relevés surveyed in the 1980s, targeted floral species monitoring † Climate change; disturbance * Biodiversity	1310–1576

Table A1. *Cont.*

Site and Affiliation	Mountain Range and Country	Management Authority	Biome and Rainfall Zone	Recorded Parameters and Attributes	Elevation Range (m a.s.l.)
Jonkershoek Valley ("Jonkershoek") SAEON Fynbos node; proposed component of the Greater Cape Town EFTEON landscape	Boland Mountains, South Africa	CapeNature	Fynbos, Afrotemperate forest; winter rainfall	Six gauged research catchments (five afforested with *Pinus radiata* + one control) Atmospheric parameters (1925–2013/2014–current): atmospheric pressure, precipitation, air temperature, fog, vapour pressure, dew point temperature, relative humidity, wind speed and direction, net radiation, leaf wetness; (2019–current): CO_2 and H_2O flux, short- and long-wave incoming and outgoing radiation, albedo, soil heat flux Hydrological parameters (1935–1992; 2010–current): runoff amount, surface water level, quality and temperature; (2013–current): soil moisture Ecological parameters: plant species turnover [†] Climate change; land use/cover; disturbance; alien organisms [*] Hydrological functioning; biogeochemical cycling Jonkershoek is affiliated with the GERI, ILTER and the TRY plant trait and BioTIME global databases and falls within the UNESCO Cape Floral Region Protected Areas World Heritage Site	239–1214

Table A1. *Cont.*

Site and Affiliation	Mountain Range and Country	Management Authority	Biome and Rainfall Zone	Recorded Parameters and Attributes	Elevation Range (m a.s.l.)
Table Mountain National Park (”Table Mountain”) SAEON Fynbos node; proposed component of the Greater Cape Town EFTEON landscape	Cape Peninsula Mountains, South Africa	South African National Parks	Fynbos, Afrotemperate forest; winter rainfall	Atmospheric parameters (1962–2013–current): precipitation, air temperature, fog, atmospheric pressure, net radiation, relative humidity, wind speed and direction, leaf wetness, and soil temperature Hydrological parameters (2013–current): soil moisture Ecological parameters: vegetation relevés surveyed in 1966, 1999 and 2010 † Climate change; land use/cover; alien organisms * Hydrological functioning; biodiversity Falls within the UNESCO Cape Floral Region Protected Areas World Heritage Site	40–966
Great Escarpment					

Table A1. *Cont.*

Site and Affiliation	Mountain Range and Country	Management Authority	Biome and Rainfall Zone	Recorded Parameters and Attributes	Elevation Range (m a.s.l.)
Cathedral Peak Research Catchments ("Cathedral Peak") SAEON Grasslands–Wetlands–Forests node; proposed component of the Northern Maloti-Drakensberg EFTEON landscape	Maloti-Drakensberg, South Africa	Ezemvelo KwaZulu-Natal Wildlife (previously Natal Parks Board, Department of Forestry/Forestek/Council for Scientific and Industrial Research)	Grassland; summer rainfall	Fifteen gauged research catchments (13–190 ha); one excluded from fire; one historically afforested with *Pinus patula* and one historically grazed by cattle Atmospheric parameters (1949–1995; 2012–current): atmospheric pressure, precipitation, dew point, relative humidity, air temperature, vapour pressure deficit, suspended solids, wind speed and direction, net radiation; (2019–current): CO_2 and H_2O flux, short- and long-wave incoming and outgoing radiation, albedo, and soil heat flux Hydrological parameters (1948–1995; 2013–current): surface water level, quality, temperature and volume, soil moisture Ecological parameters: vegetation relevés surveyed in 1975 and 1985 and by SAEON in 2013 † Climate change; land use/cover; disturbance * Hydrological functioning; biodiversity; biogeochemical cycling ** Long-term automated weather station and fixed camera vegetation monitoring site on an alpine inselberg summit near Vulture's Retreat Cathedral Peak is affiliated with the GERI and ILTER. The site falls within the UNESCO Maloti-Drakensberg Park World Heritage Site The Research Catchments are located within the Cathedral Peak Research Area which also hosts the multi-decadal Brotherton Fire Experiment (BFE), a Nutrient Network (NutNet) site as well as planned Soil Biodiversity Observation Network (Soil BON) and Mountain Invasion Research Network (MIREN) sites	1820–2463 3010**

Table A1. *Cont.*

Site and Affiliation	Mountain Range and Country	Management Authority	Biome and Rainfall Zone	Recorded Parameters and Attributes	Elevation Range (m a.s.l.)
Compassberg SAEON Arid Lands node	Sneeuberge, South Africa	Compassberg Protected Environment Group and SAEON	Nama-Karoo, Grassland; autumn rainfall	Atmospheric parameters (2016–current): precipitation, air temperature, relative humidity, wind speed and direction, net radiation, atmospheric pressure, leaf wetness, and soil temperature Ecological parameters: vegetation relevés surveyed in 2014 and 2016 † Climate change * Biodiversity	1200–2502
Haenertsburg SAEON Ndlovu node	Limpopo Drakensberg (Wolkberg section), South Africa	Limpopo Department of Economic Development, Environment and Tourism	Grassland, Savanna, Afrotemperate forest; summer rainfall	Atmospheric parameters (2014–current): air temperature, relative humidity, wind speed and direction, precipitation, net radiation, atmospheric pressure, and fog Ecological parameters: vegetation relevés surveyed triennially 2007–current, targeted floral species monitoring, high-resolution aerial imagery † Climate change; land use/cover; disturbance * Biodiversity	1350–1459
Mariepskop SAEON Ndlovu node	Mpumalanga Drakensberg, South Africa	Department of Forestry, Fisheries and the Environment/ Mpumalanga Tourism and Parks Agency	Grassland; summer rainfall	Atmospheric parameters (2000–current): air temperature, precipitation, fog Hydrological parameters (2019–current): water level, quality, temperature and volume Ecological parameters: vegetation relevés surveyed triennially 2018–current, high-resolution aerial imagery, fish composition (2012/2013, 2021) † Climate change; land use/cover; disturbance; water abstraction * Hydrological functioning; biodiversity Gazetted for inclusion in the Blyde River Canyon Nature Reserve	710–1947

Table A1. *Cont.*

Site and Affiliation	Mountain Range and Country	Management Authority	Biome and Rainfall Zone	Recorded Parameters and Attributes	Elevation Range (m a.s.l.)
Mont-aux-Sources LTSER node Afromontane Research Unit, University of the Free State [99]	Maloti-Drakensberg, South Africa and Lesotho	Ezemvelo KwaZulu-Natal Wildlife and Ingonyama Trust (South Africa); Basutho Royal Houses (Lesotho)	Grassland; summer rainfall	ca. 1200 km^2; establishment in progress; will include Global Observation Research Initiative in Alpine Environments (GLORIA) and Mountain Invasion Research Network (MIREN)/RangeX sites † Alien plants; climate change; land-use change; degradation; disturbance * Biodiversity; livelihoods The site falls partly within the UNESCO Maloti-Drakensberg Park World Heritage Site (Royal Natal section)	1300–3282
Sani Pass (South Africa) and Kotisephola Pass (Lesotho) Stellenbosch University; University of Johannesburg; University of Pretoria [89,91]	Maloti-Drakensberg, South Africa and Lesotho	Ezemvelo KwaZulu-Natal Wildlife (South Africa); Lesotho Government and Basutho Royal House (Lesotho)	Grassland; summer rainfall	MIREN sites established in 2007 along steep elevational gradients. Additional MIREN sites to be added by the Afromontane Research Unit † Alien plants; disturbance * Biodiversity The MIREN sites fall partly within the UNESCO Maloti-Drakensberg Park World Heritage Site (Cobham section)	1500–2874 2874–3200

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