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A Review of Small Farmer Land Use and Deforestation in Tropical Forest Frontiers: Implications for Conservation and Sustainable Livelihoods

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Abstract: Forest conversion for agriculture is the most expansive signature of human occupation on the Earth's surface. This paper develops a conceptual model of factors underlying frontier agricultural expansion—the predominant driver of deforestation worldwide—from the perspective of small farm households—the majority of farmers globally. The framework consists of four causal rubrics: demographic, socioeconomic, political–economic, and ecological. Following this approach, the article explores the current state of knowledge on tropical deforestation in tropical agricultural frontiers with a focus on Latin America, the region of greatest deforestation worldwide during recent decades. Neo-Malthusian arguments notwithstanding, in many tropical nations, deforestation has proceeded unabated in recent years despite declining rural populations. However, evidence from the global-to-household scale suggests that population size and composition are also related to farm forest conversion. Existing particularist or behaviorialist theories sometimes fail to capture key geographical and temporal dimensions, yet studies support the notion that certain cultural, individual, and household characteristics are crucial determinants of forest clearing. Conversely, while institutional arguments sometimes fail to emphasize that the ultimate land use change agents are local resource users, their livelihood decisions are shaped and constrained by policies governing economic subsidies, and market and infrastructure development. Further, although ecological change is usually modeled as an outcome in the deforestation literature, increasingly acute climate change and natural farm endowments form a dynamic tabula rasa on which household land use decisions are enabled. To more fully comprehend frontier forest conversion and to enhance protection and conservation while promoting vital local livelihoods, future research may fruitfully investigate the interaction of demographic, social, political, economic, and ecological factors across spatial scales and academic disciplines.

Keywords: land use/cover change (LUCC); livelihoods; deforestation; tropics; Latin America; agricultural frontier; population; environment; migration; human-environment relations; human dimensions of global environmental change; conservation

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1. Introduction

Forest conversion for agriculture inscribes the most extensive signature of human activity on planet Earth. The planet's intact old-growth forests have dwindled to approximately one-fifth of their original cover. Over a third of tropical forests have been eliminated with a net rate of 5.5 million hectares annually between 2010 and 2015; in 2019 alone an area the size of Holland was extirpated across tropical zones [1]. Understanding human-environment dynamics has increasingly been recognized as a research priority of the global environmental change community, yet what is known about tropical deforestation, despite hundreds of research articles across the social and physical sciences, remains limited by disjoined case studies at the micro scale, and by gross estimates of varying reliability relating forest cover to human drivers at the macro scale.

Some land use and land cover change (LUCC) literature describes the determinants of tropical deforestation as pertaining to underlying and proximate causes [2–5]. From

the research on tropical deforestation explicitly modeling proximate causes [3,6,7], three primary types of land use are noted: (1) agricultural expansion, (2) timber extraction, and (3) infrastructure development. Agricultural expansion, often facilitated by the other two land uses, emerges as the number one cause of deforestation on the planet, particularly in Latin America [1,3,8,9]. Whereas proximate causes are found locally—where LUCC is occurring—underlying causes tend to be further removed temporally and geographically (e.g., [3,10,11]).

Conceptual LUCC models framed in proximate and underlying causes have provided a helpful heuristic for conceptualizing the phenomenon of tropical deforestation (e.g., [2,3,6,12,13]). However, they require modification to address the more specific phenomenon of LUCC caused by frontier agriculture. This modification is expedient, given the disproportionate share of the forest clearing attributed to this phenomenon in recent decades [9,14,15]. While in recent years the share of deforestation attributed to large-scale export agriculture has increased (e.g., [5,9]), virtually all of the elimination of closed old-growth forest occurs along agricultural frontiers where such forests still exist. To date, the first step in this process is often the settlement by migrant farm families and the opening of land for crops and pasture.

Regarding deforestation conceptual models, some notable changes are necessary in order to develop a working framework of frontier LUCC. First, proximate determinant models sometimes confuse outcomes with drivers. In this paper, frontier deforestation is conceptualized as an outcome (as opposed to all deforestation as in, e.g., [3]) and the immediate causes of frontier forest conversion are considered as independent drivers of the phenomenon.

Second, traditional LUCC models have underrepresented the importance of physical geographical dynamics as drivers of ecological change. It is not, for example, considered a category of influence regarding environmental change in the (e.g., [3,12]) framework. Yet unfavorable environmental conditions can lead to extensive farming to compensate for declining yields, or to intensification if farm expansion is constrained. Therefore, in the framework proposed here, ecological conditions are modeled as a separate category of independent factors.

Third, while infrastructure expansion (e.g., urbanization and road building) represents a proximate cause of forest clearing in itself, recent models fail to emphasize that infrastructure development has a much greater role in tropical deforestation as a distal cause facilitating agricultural colonization, which then leads to forest conversion. Similarly, although urban expansion is a proximate cause of forest conversion, it claims a modicum of the world's total share of tropical deforestation and is therefore excluded from this conceptual model (urbanization relates to frontier forest conversion more as a distal cause, through demand for sowing more land in crops and pasture either on the frontier itself, or more likely, in long-established agricultural regions, which creates land pressures that foments frontier migration).

Fourth, the LUCC literature too often commits the ecological fallacy of conflating processes operating across different scales. This paper attempts to separate household factors (e.g., microeconomic and behavioral variables) from structural (macro) economic or political–institutional (most of which, as noted with an asterisk in Figure 1, are measurable at the community level or greater). Following these modifications, the proximate causes of frontier forest conversion are framed as nested within four categories: demographic, political–economic, socioeconomic, and ecological (Figure 1). A necessary underlying cause of frontier deforestation (i.e., migration) is modeled under the same rubric.

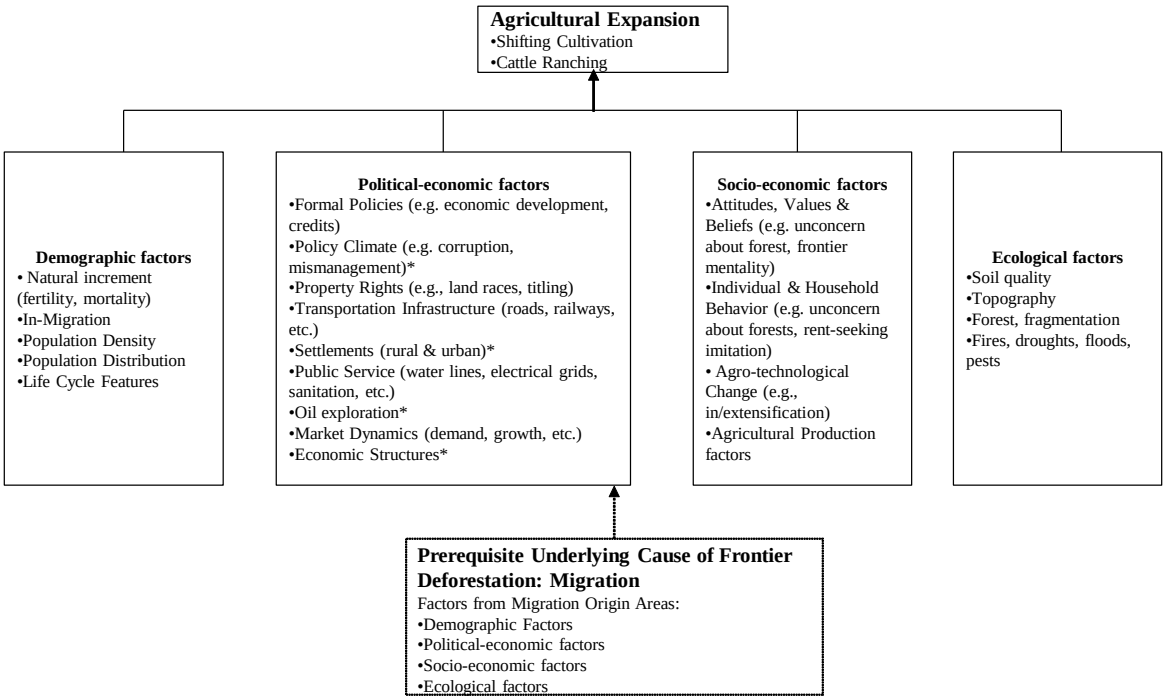

Figure 1. Factors affecting the proximate cause of deforestation in an agriculture colonization frontier: Colonist farmer land use (adapted from [7]).

Households that ultimately migrate to an agricultural frontier and clear forests to farm the land have done so only after exhausting or spurning other available options [16,17]. Frontier farming is not an ultimate outcome, and these households will continue to make decisions based on the degree to which available options enable or constrain their motives. Much LUCC and peasant studies literature investigates agricultural intensification, as indicated by the arrow pointing from Land Management to Agricultural Intensification. When referring to deforestation, the agricultural frontier literature examines the link represented by the arrow between Land Management and Agricultural Extensification (expansion of farmland—the opposite of intensification). Disciplines parse these topics, but households do not. Households can, and do, respond to demographic, political–economic, socioeconomic, and ecological conditions by acting in one or several ways, simultaneously or sequentially over time (i.e., multi-phasically, see, e.g., [18]). At the household level, deforestation is an outcome of agricultural extensification—most dramatically following rural–rural migration [7,19,20].

Following the conceptual models described above, in the following section there will be a review of the literature germane to the primary proximate cause of tropical deforestation, particularly in Latin America: small farmer agricultural expansion. The factors affecting forest conversion are framed by demographic, political–economic, socioeconomic, and ecological factors at the household and community levels. The conclusion consists of a consideration of the significance of the present state of knowledge on frontier LUCC to future research and policy efforts supporting forest conservation and rural development. Since a large share of the frontier deforestation worldwide occurs in Latin America, and the great complexities surrounding the phenomenon are somewhat simplified by controlling for regional effects, this review focuses on frontier deforestation in tropical regions of Central and South America.

2. Proximate Determinants of Small Farmer Land Use in Tropical Agricultural Frontiers

2.1. Demographic Factors

While it is clear that demographic factors interact with economic processes of supply and demand to explain much of global deforestation, less is understood about the relative influence of demographic vs economic drivers. A recent article goes so far as to claim that population-driven deforestation will lead to the collapse of sustainable human populations [21]. Regression analysis has suggested that population growth is positively related to agricultural expansion in Latin America [22], especially in areas of high poverty such as Central America and in the Andean nations [9]. However, along with economic processes, spatial and temporal discontinuities obfuscate links between population and environment interactions. Global and regional-level evidence of a positive link between population and deforestation would appear inconsistent with trends at the national level among many Latin American nations during recent decades, where rural populations have declined yet deforestation has continued, in some instances even accelerated [7,9,20].

Does this pattern cast doubt on global population-deforestation findings? Data remains inexact at the macro-scale due to inconsistent resolution and a continued inability to confidently match spatial pattern to process. Nevertheless, this apparent discrepancy is most likely explained by scale; a very small percentage of the global population—frontier farmers—are the agents of (if not directly responsible for, given their precarious political–economic situation) a disproportionate amount of the world's deforestation. Yet increasingly, forest conversion occurs not along a small-farmer settlement frontier but rather on large ranches and plantations where rural population density is low and declining as technical advances in productivity replace labor. Finally, population growth in urban areas and population-dense, forest-scarce rural regions can foment frontier deforestation through demand for forest and food products [6,9,15,23,24]. Increasingly, this demand is coming from abroad [9,11,24]. However, again, the agents of forest clearing in large parts of the Latin American and African tropics are not urban consumers or large export-oriented intensive farmers; they are small farmers in remote rural regions where large tracts of forest remain. Additionally, if rural populations are declining in most Latin American nations, how then is population associated with frontier forest clearing? As I will now discuss, in-migration, household size, household composition, and population density combine with economic and other factors to act in complex ways towards the retreat of frontier forests.

2.1.1. Frontier In-Migration

Rural–rural migration is not merely a demographic factor involved in forest clearing, it is a prerequisite to small-farm frontier deforestation [7,25]. Migration will remain a key driver of frontier LUCC. The potential for most future deforestation will not be on lands already settled, but rather on lands yet to be colonized beyond the forest fringe. Thus, an important point neglected in the literature is that demographic, ecological, and political–economic pressures elsewhere initially foment migration to the frontier.

In addition to promoting young and large households, resource abundance and labor scarcity characteristic of a frontier environment encourage in-migration—the primary source of agricultural frontier population increase. What is not yet fully understood is why some people from certain places choose to migrate to rural destinations as opposed to seeking other means of improving household security and well-being—such as migrating to urban areas, engaging in off-farm employment, or altering land management strategies. Whereas household size and composition have direct impacts at the farm level, the effects of colonization on already established farms is different than farmer colonists clearing unoccupied forest to create new ones.

Examples of rapid forest conversion at the regional scale following colonization are particularly abundant in the Latin American deforestation literature from the 1980s through the 2000s [3]. Most of the regions' forest clearing has occurred in the Amazon basin. This

process is well documented in Brazil (e.g., [26–28]). In the Ecuadorian Amazon, populations grew at annual rates exceeding 6% through the 1970s and 1980s—more than double the national average—as agricultural colonists claimed over one-third of the Ecuadorian Amazon region [29,30]. Central America shares a similar history of frontier colonization. The region suffered the highest rates of deforestation of any major world region during the 1990s. Much of the deforestation has been centered in the Maya Forest of northern Guatemala, Belize, and southern Mexico [31–33]. In Guatemala's Petén (the heart of the Maya Forest, representing 40% of Guatemala's national territory), fully half of the vast department's forestland had been cleared by agricultural colonization between the 1970s and the mid-1990s [34]. Increasingly, the migration connection has become more complex, with some second-generation colonists migrating to the US and sending remittances home, which in turn has distinct land change effects in origin areas yet to be fully understood [35].

2.1.2. Household Size

Although most of the accelerated population growth characteristic of agricultural frontiers results from in-migration, a large share is attributed to the exceptionally high-fertility of frontier migrants (e.g., [36,37]). High fertility in the remote frontier results from a combination of low demand for, and supply of, contraception options [38]. Among the scant statistical analyses of surveys collected from settler households with detailed population and land use data, studies from the Ecuadorian Amazon [37–39], Costa Rica [40], and Guatemala's Petén [41], found household size was negatively associated with forest cover on the farm.

Similar findings emerge from a pair of recent African studies. A statistical analysis of rural farm households in Tanzania found that larger families were associated with a greater demand for subsistence crops for household consumption as well as with more labor for clearing land to raise crops (e.g., [36]). A similar result was found through a regression analysis of over 500 households in central Malawi, with population size and poverty being the primary predictors of deforestation at the farm level [42]. Although these studies controlled for some household life cycle features, the relation between household demography and forest clearing is not simply a linear function of population size, but is part of a household maturation process, or family life cycle, associated with discontinuous pulses of forest clearing [37,43].

2.1.3. Household Demographic Life Cycle

Following Chayanovian peasant household theory [44], household age and sex composition affects labor availability and, therefore, land use and forest conversion [25,29,35,37,45]. Forest clearing tends to be high during the initial years of settlement as (typically) young families establish a farm, clearing forest for the production of subsistence grains, and to delimit farm boundaries to rebuff the squatter designs of new settlers [46]. As the household life cycle develops, maturing children augment household labor supply, while accumulated capital encourages adding perennials and/or cattle to the farm portfolio. Both processes can either increase or decrease the impacts of household demography on forest conversion, depending on the relative emphasis on each [16,37,45,47].

2.1.4. Population Density

Traditional frameworks of small farm household responses to population density (e.g., [48,49]) are essentially inapplicable to the frontier context. For frontier settlers at the edge of subsistence, many sorts of intensification are inefficient or risky [50,51]. And yet, population density plays a critical role in forest conversion [36,52–54]. Thus, during the early phase of frontier colonization, increasing population density leads mainly to agricultural extensification. As the frontier develops, transportation infrastructure improves, market integration increases, and land is consolidated among the "haves" and fragmented among the "have-nots". As predicted by peasant intensification theories in more population-dense rural environments, population growth on the frontier leads to

an increased labor-to-land ratio and dwindling forest cover, invariably followed by fallow compression and the use of agricultural inputs. However, contrary to the peasant land use literature, intensification on the frontier also frequently accompanies continued forest conversion when wealthy households simultaneously intensify and expand farm holdings—often for cattle ranching [55–58]. Where land consolidation is minimized by communally governed land and population density is attenuated by out-migration, as in parts of southern Mexico, fallow systems may remain a part of the agricultural mosaic and contribute to biodiversity [59,60]. Applying intensification efforts, informed from agricultural economics theory, without providing convincing incentives to do so on the ground, may not be a panacea for coupling conservation with rural sustainable development on the frontier where extensive land use remains attractive relative to other potential investments in land and labor.

As urbanization proceeds in earnest and fertility plummets in most regions of the globe (with notable exceptions such as the African Sahel), rural population should continue to decline. What is not known is what this process will mean for forest transitions. The globe's apparently inexorable demographic transition will not necessarily relieve population pressures on the tropical forest canopy. On the contrary, with increased economic globalization, reduced agricultural tariffs will likely encourage the continued expansion of cropland on large export-oriented agricultural lands. This will displace rural farmers, increase the number of rural inhabitants at risk for frontier migration, and promote the continued retreat of frontier forests. The magnitude and spatial distribution of these trends will ultimately be a function not so much of population dynamics, but rather of political and economic processes.

2.2. Political–Economic Factors

2.2.1. Neoclassical Economics

Most scholars agree that population is an intermediate variable rather than an ultimate cause of environmental change. For example, population growth would have a radically different—though not necessarily more benign (see, e.g., [61])—impact on forest ecologies if frontier settlers were beekeepers. Indeed, there are numerous cases in which population appears a less important determinant of deforestation than economic and political factors [62,63]. From a neoclassical perspective, land degradation results not from economic growth, but from market inefficiencies that undervalue natural resources and ignore long-term costs and externalities. In theory, an efficiently operating free market should benefit from population growth through an increase in both laborers and consumers, by way of reduced labor costs, and enhanced profit margins from greater economies of scale. Further, manufactured products can replace natural resources, while technology and human adaptation can evolve to more efficiently reap nature's bounty [64,65]. Natural resource scarcity can also attend a rise in demand, thus compelling the innovation of cheaper substitutes [64,66].

However, neoclassical economic approaches foggily mirror economic reality in several respects. First, resource substitution is not a given; it is not known whether innovation will forever compensate for increasing population growth and mounting consumption. Second, even in a "properly" functioning economy, short-term resource degradation may result during the lag between the demand for resource substitutes, or improved technology for resource use, and the adoption of new systems of production (e.g., [65,67,68]). Finally, if cheap substitutes for depleted resources are developed rapidly, environmental degradation may be considered an economically efficient use of resources (e.g., [69]). But then the question becomes meta-economical: is it ethically expedient to systematically destroy natural environments in the name of economic growth?

2.2.2. Macroeconomic Factors

Colonization fronts across the tropics are testament that impure capitalist economies have not optimally conserved natural resources but have occasioned systems of swift—

even terminal—exploitation [22,70]. Thus, political–economy theory may represent a more appropriate macro-economic heuristic for peripheral economies. In many regards, the internal economies of developing world nations mimic the core-periphery relationship they share with the developed world. This relationship has a spatial and temporal dimension.

Relative to the spatial dimension, consistent with international core-periphery models and globalization, developing countries have attempted to augment export earnings through agricultural expansion. As agricultural production is increasingly entwined in global commerce flows, prices for products and for investments in the means of production affect farmer decisions to expand or reduce cropland. This effect can be large. In a study from Mexico, from 1970 to 1985, maize and fertilizer prices were found to have the highest level of association with the expansion of cropped land [71]; see also [72]. The authors noted that the high cost of fertilizers may have decreased deforestation in market-oriented agricultural regions but increased it on the frontier; high costs of purchasing inputs served to catalyze frontier migration.

Thus, macroeconomic factors, apparently unrelated to frontier farmers largely marginalized from the global economy, can still lead to frontier forest conversion through incentives to expand export holdings which ultimately pushes small farmers to peripheral lands [20,22,73]. Some supply chains, for example, entail high deforestation with little benefit to small rural producers [74]. Some authors argue that tropical deforestation is part of the development process in which developing countries remain indebted to donor nations [75–77]. The Brazilian Amazon is a case where several authors have connected deforestation to debt owed to Western banks (e.g., [56,78–80]). However, this research has not been compellingly corroborated elsewhere (e.g., [81,82]).

A temporal dimension of core-periphery development is the purported Kuznetz curve association between economic development and forest transitions. According to this theory, forest impacts in early stages of peripheral economic growth are low, become accelerated during development, and are again attenuated at later stages of development when primary resource extraction is moved to a new, developing region [83–86]. This relation appears to apply to most tropical regions [22,83]. Such a relationship is evident, for example, in a comparison of deforestation over time in two Latin American countries of similar size and physical attributes: the "developing" El Salvador and the "developed" Puerto Rico [87].

2.2.3. Policy Incentives

In virtually all cases of frontier deforestation, road construction and other politically-sponsored activities play a prominent role. Indeed, one of the major criticisms of the popular "IPAT" formula of environmental change is the failure to include political and institutional factors. According to the I = PAT equation, environmental impact (I) is affected by population (P), affluence (A), and technology (T) [88]. Satellite imagery has indicated particularly high deforestation adjacent to roads throughout Latin America [89,90]; this has been documented, for example, in Brazil [91–95]; in Guatemala [34]; in Costa Rica [96]; in Ecuador [97]; and in Mexico [31,98]. Conversely, the importance of road access is highlighted in Bolivia where a dearth of roads and low population density has favored relatively lower deforestation [99–101]. Although roads impact protected and non-protected areas alike [102], Milien et al. (2021) [103] show that a protected area designation can reduce road-related impacts.

Nevertheless, road-building itself causes little deforestation relative to the land use stimulated around roads following in-migration. Formal policies in the form of taxes, credits, economic development plans—including finance, trade, investment, population, and land policies—are nearly always involved with deforestation at some level (and these will be affected also given the level of market integration following road construction and improvement). Some formal policies that promote forest clearing are indirect. For example, policies favoring urban consumers, such as the artificial depression of prices for basic grains produced by marginalized households on the frontier, may compel a response of agricultural extensification by the frontier settler [104].

Other policies more directly foster frontier forest conversion. For example, the National Institute for Colonization and Agrarian Reform (INCRA) in Brazil provided plots larger than 100 ha, as well as credit and food allowances, to early migrant farmers [26,80]. Tax incentives for cattle fanned a speculative land boom, with land in some areas appreciating at 100% per annum in real value [105,106]. Agricultural extension agents tended to promote a limited number of crops and to discourage diversified cropping—after all, their orientation is towards commercial agriculture—despite the importance of diversification in balancing diets and limiting susceptibility to pests, plagues, and crop failure [107]. Low gasoline prices further subsidized the use of chainsaws, road building, and agricultural machinery [108]. Meanwhile, loans from the Bank of Brazil favored farmers felling primary forest; yields were higher than those obtained from converted secondary forests [105]. Similar colonization laws in other parts of the Amazon (e.g., [109]) and in Central America (e.g., [110]) have also promoted rapid deforestation.

Property arrangements and land pricing distortions critically impact forest clearing throughout Latin America [22,111–115] as well as Asia [116,117]. When public lands are not valued in the same manner as private lands, the cost of public resource use is not incurred by the individual, but by the larger community. Such a land management system may lead to overexploitation of shared resources and, ultimately, to a "tragedy of the commons" [118–120]. Forests are artificially cheap to the squatter farmer who constantly faces the threat of new colonists invading his land, of park guards relocating him, or of absentee landowners reclaiming his land. Such uncertainties encourage land "mining"—rapacious land use for immediate benefit [92,113,121]. When a farmer is unsure if today's investments will be his to reap tomorrow, expansive agriculture replaces strategies of farm conservation (e.g, [113,114,122]). Indeed, since the possession of a land title is usually a prerequisite to obtaining credit, squatters may be unable to invest in land conservation strategies even if they wish to do so [109,110,113]. Most forestland in the tropics is public and administration is difficult to enforce. Maintaining a large amount of forest is risky, as it advertises unused land to invading squatters. Informal tenurial regimes that arise in this environment may promote deforestation as a means to establish land claims [51,113,116,123,124]. These land claims are not generally established to safeguard against the expansionist designs of neighbor farmers (informal tenure at the community level usually recognizes such claims); rather, these are to dissuade new in-migrants from homesteading.

In a regression analysis of forest clearing in Latin America from 1961 to 1994, improved property rights were associated with slower rates of forest conversion [22]. Case studies throughout the region support this finding [50,51,113,114,125–131]. For example, land tenure security was positively associated with the percent of a farmer's holdings in forests remaining within household farms in the Ecuadorian tropical forests [46]; see also [132]. Similarly, in Honduras, Humphries (1998) [133] reported that, in the absence of formal titles, early arrivals to the Honduran agricultural frontier established claims to land directly through forest clearing. However, highlighting the importance of local contexts, in Guatemala's Maya Biosphere Reserve, title was an important step towards sustainable development in reserve buffer zones [134], while in areas of greater land availability within the Reserve core zone, title was used as leverage for obtaining credit, which invariably was used to purchase cattle, thus leading to forest conversion [43,135]. Yet in the Amazon, land governance is considered by some researchers as a precondition to decreasing forest clearing [114]. Land titling in itself is unlikely to result in attenuation of pressures on tropical forests in the absence of incentives to leverage credit through farm ownership for intensive land uses, such as the planting of perennials rather than for extensive land uses such as cattle ranching.

Governments and non-government organizations (NGOs) spearheading land titling efforts must realize that secure land ownership enables farmers to broaden their suite of land management strategies—whether beneficial or deleterious to the environment. When development agencies promote technical assistance, yields can be enhanced while reducing

pressures on the forest [114,136–138] and where park boundaries are enforced (e.g., as in Costa Rica, [139]). For example, in the tropical Andes, Cuenca et al. (2018) [140] demonstrated that thousands of hectares were spared deforestation due to the implementation of a government conservation program. Similarly, some research finds that government interventions spurring rural electrification reduces deforestation due to the lower demand for forest-based electricity substitutes (e.g., [141]).

Conversely, poor administration of frontier lands will tend to lead to accelerated forest conversion [142,143]. For example, following governance reforms, deforestation in the Brazilian Amazon dropped by almost 80% between 2004 and 2012, since rebounding following relaxed government oversight and even incentives to deforest [144–146].

Corruption can also drive deforestation. Using panel data of Brazilian municipal-level deforestation and election data from 2002 to 2012, Pailler (2018) [147] found that deforestation rates increased 8–10% in election years with an incumbent mayor running for re-election. Rather than forest conversion being linked to democratically vetted government incentives, the link observed was to corruption and campaign financing, demonstrating the extent to which weak governmental institutions can have perverse impacts on forest cover.

While human population pressures on tropical forests operate through formal and informal political and economic processes, these pressures only explain part of the story. Where and when forest conversion occurs is often scale and place sensitive. When are small farmers pushed to the frontier as large plantation owners consolidate land, and when are they absorbed by plantation owners as workers or by urban labor markets? When do economic interests coincide with government decisions to build roads? When do land tenure regimes promote forest conservation rather than forest conversion? Ultimately, while enabled and constrained by macro-scale political and economic factors, farm households with independent agency make decisions to clear forest. Social and microeconomic characteristics associated with forest clearing at the farm level need to be incorporated in a full investigation of human impacts on tropical forests.

2.3. Socioeconomic Factors

2.3.1. Small Farmer Livelihoods

Economic and political theories insufficiently account for the broad range of small farmer responses to diverse environments. The decision whether a farm household decides to clear more forest or to reforest is typically part of a "mosaic of land uses across a landscape" consonant with a diverse livelihoods profile [148]. In addition, higher landscape diversity has been observed in the Brazilian Amazon to accompany reforestation in recent years as farmers avail themselves of better access to modern technologies and markets which allow for intensification of a portion of the farm while permitting some fallow land to return to forest [144].

One key factor in land use involves decisions regarding market versus subsistence production. The hybrid commodity and subsistence farmer is typical on the frontier. Such farmers tend to be risk averse, rather than risk takers [149,150]. The frontier agriculturists' first aim is family security rather than profit maximization [151]. Thus, a frontier farmer may be chary to replace traditional production strategies with new ones characterized by higher potential yields, but greater risk.

Nevertheless, some studies of frontier peasant households suggest that farmers work their land not merely for security and utility maximization, but to the extent that their available land, labor, and other resources allow [46]. Many Central American frontier farmers, for example, have remained risk-averse in sticking with one "tried and true" crop, as evident in the case of maize in the frontiers of the Maya forests [152,153]. However, frontier farmers are often vigorously market-oriented, producing a host of cash crops such as cocoa, coffee, and black pepper in tandem with subsistence staples, e.g., [46,136,154], and even intensifying livestock production [144].

The socioeconomic realities of the frontier sometimes hamper efforts to couple mutually reinforcing sustainable rural development with forest conservation. Poverty can be

a driver of deforestation, especially among subsistence farmers where there is also rapid population growth—the two often accompany one another–such as in the early stages of frontier formation (e.g., [11,42]). However, successful frontier farmers tend to deforest more than their poorer neighbors [41,46,155]. Land consolidation by livestock ranchers on the frontier drives much of the forest conversion in Latin America. Indeed, of the earth's total land area (of which approximately half is arable), approximately one-third is in agriculture and fully two-thirds of this is dedicated to livestock (FAO 2021).

However, even when shifting from sustainable forest extraction (e.g., the case of Bolivia [156,157]), the first stage of deforestation usually involves the activity of small farmers expanding existing agricultural fields. A typical story involves land consolidation followed by farm and forest conversion to pasture, pushing small farmers to convert forests for basic grain production in new frontiers. Colonists will harvest two or three crops in exchange for clearing the forest for cattle ranchers as the process begins anew. This process was described by Stewart (1994) [80] in Brazil, by Jones (1990) [110] throughout Central America, and more recently in remote areas of Central America and Andean nations [9].

2.3.2. Farm Space, Time Dimensions, and Frontier LUCC

Distance of settlements to a road and to a market are strong predictors of deforestation at the farm level. Agriculture that is produced in any given place is presumed to be a function of the relative value of the crop on different portions of land [158,159]. Controlling for exogenous factors, economic rent should decrease with distance to the market, creating a series of rings around the market in which the next outward ring represents a less intensive form of land use than the preceding one [158,159]. This model is generally supported by the predominantly extensive use of frontier land throughout the Latin American tropics relative to the intensive land use in regions more closely connected to markets. In the Ecuadorian Amazon, for example, Pichón (1997) [46] found that farms further than 9 km from the road had, on average, 79% forest cover compared with less than 50% for farms less than 3 km. Similar findings are reported in the Brazilian Amazon (Fujisaka et al. 1996; Barber et al. 2014; [144] and elsewhere in Latin America [34,73,94,98,101].

Since earlier colonists are at an advantage in selecting the land most accessible to a road, distance to the road is associated with the relative number of years a plot has been farmed. Harking back to Von Thunen [158], more accessible, older plots of land are more valuable and are unlikely to remain "idle"; in addition, farmers simply have had more time to clear forest on older plots, as evident in several regions, including the Ecuadorian [46,73] and Brazilian Amazon [144] regions.

2.3.3. Education, Origin Characteristics, Perception, Ethnicity

Farmers' decisions to grow crops for subsistence, or for market, and their relative success in doing so is not merely a result of economically efficient allocations to land and labor or simply a function of VonThunian location theory. Land use is shaped by farmers' perceptions that fire aspirations. These are molded by learned behavior whether through cultural mores passed down through ethnic traditions, by social networks, or by formal education. Recent research has pointed to the role of culture as a driver of human induced environmental change [160] and of land use/cover change [161].

Because deforestation patterns can vary with local cultural practices, perception of land use and deforestation is ultimately an important driver of land use behavior [162]. For example, in Los Tuxtlas Biosphere Reserve, Mexico, nearly two thirds of respondents believed they were responsible for deforestation, compared with less than one third of indigenous villagers [163]. This suggests the importance of perception of agency in managing land use and conservation. Similarly, cultural values associated with deforestation have been quantified in the Brazilian Amazon, including a culture with a proclivity towards cattle ranching [164]. The community scale must be included here, as indigenous communities have shown success in conserving forest land that impacts household land use towards decreased deforestation [165,166].

Education has been found to influence the frontier farmers' management skills and consumption aspirations (e.g., [167–169]). In the Ecuadorian Amazon, educational achievement of the household head was negatively associated with the percent of land in forest and positively related to land in pasture [46]. Murphy et al. (1997) [170] hypothesized this is because formal education poorly captures the skills and knowledge needed for success on the frontier; however, education was positively associated with soil conservation strategies in El Salvador, suggesting an attenuated impact on deforestation [171]. Garzón et al. (2020) [172] argue that education focused on ecological restoration can play an important role in decreasing frontier deforestation in the Colombian Amazon. Gimah and Bodo (2019) [173] come to a similar conclusion in Nigeria, asserting that environmental education can reduce deforestation and habitat loss.

If the concept of education is expanded beyond the formal type, to the extent more intensive farming is part of the learned (from origin communities) farming culture among frontier colonists, deforestation may be reduced (e.g., [80,125,174]). For example, Almeida (1992) [136] found that colonists from southern Brazil to the Pará frontier grew more perennials, sowed less pasture, and generally produced crops more intensively than other colonists—largely attributed to a greater experience in these strategies in the more developed south.

Ethnicity and frontier land use have been examined by several authors with mixed results. On the one hand, many successful colonist farming adaptations have come from indigenous groups in the Amazon [175,176]. Colonists along the trans-Amazonian highway, who followed the advice of mixed-race locals (caboclos) selected farms of higher soil quality and produced twice the yield per hectare of other colonists—reducing pressures on the forest [177]. Similarly, in Ecuador, Rudel and Horowitz (2013) [73] found that Shuar Indians cleared considerably less forest than colonists, partially because they had much less access to credit and were less likely to adopt cattle, unlike the neighboring Quichua [178]. In this case then, while the research question was framed around differences in land use among indigenous groups, the real issue was differential access to credit. In Guatemala's Petén, it has been debated (inconclusively) whether Q'eqchí Maya are more destructive of the forest than Ladino (mixed European and indigenous) colonists [43,179]. Finally, in western Belize, Steinberg (1998) reports that Mopan Maya land use has become ecologically destructive, marked by dramatically decreased fallow land and crop diversity as the Maya have been incorporated into the nation's market economy.

An ethnic-political driver of forest change emerges where certain ethnic groups are favored over others, resulting in various outcomes including land use/cover change. For example, in Malawi, areas with a large faction representing the same ethnicity as the president benefitted from more subsidized fertilizer. They were therefore able to intensify more successfully, and consequently deforested less compared with areas with other predominant ethnicities [180]. Similar links between ethnicity and power relations relating to forest cover change is reported from Kenya [181].

While the myth of the noble indigenous farmer hoeing rows of endemic crops in harmony with local ecosystems reflects as much of an essentialist straw-man as does the rapacious white cattle rancher, cultural traditions associated with learned behavior in origin communities, whether through ethnic traditions or dynamic social networks, impact land use decisions and must be considered in any informed research and policy concerning frontier land use and forest conservation.

This paper has discussed demographic, political–economic, and household-level socioeconomic links to frontier deforestation. Factors relating to frontier land use interact in complex ways across spatial scales and depend on local contexts. It still remains far from achieving a meta-theory of frontier deforestation given the vast contingencies of space, place, time, and individual agency. No one factor operates independently from others, and none is meaningful independent of the physical geographical context. Comprising the fourth category of analysis in the conceptual framework proposed here, ecological characteristics are not merely outcomes of human modification of the earth, they are also

important independent variables affecting human land use. After all, forest conversion is ultimately constrained by the relative virtues of the natural resource base on which farmers will inscribe their livelihoods.

2.4. Ecological Factors

The importance of ecological dynamics to agricultural change is noted by theorists who consider land use—and ultimately land degradation—as a function of dynamic environmental contexts (e.g., [182–185]). Good soil, low relief, and high water availability favor forest conversion to agriculture; however, since most such areas throughout most of tropical Latin America were denuded of forests centuries ago, most cases of recent forest conversion involve poor soil. This invariably leads to pasture creation, land degradation, and a continuation of a vicious cycle of frontier forest destruction [63,92,186]. Deforestation can impact soil function for years, including nutrient and carbon storage and recycling, erosion proclivity, and water drainage and filtration. Reforestation can reverse many of these effects, but restoration can take decades. If done appropriately, however, revitalizing impoverished soils through inputs can help reduce deforestation in situ and elsewhere [5,187].

In the early stages of frontier settlement, the best quality agricultural lands are selected first by large landholders or they are acquired during land consolidation when smallholders (including those with the initial fortune of finding good land) are forced off the land. Thus, agricultural extensification by small farmers often occurs on relatively poor soils and steep slopes, which may accelerate conversion rates to compensate for diminished yield capacity [184,188,189]. Large landholders may compensate small farmers for clearing land with the intention of later introducing cattle or market crops. Small farmers may remain and produce subsistence crops and often later introduce cattle, or they may rent from another landholder, or sell to another landholder.

In the latter stages of frontier development, land consolidation is associated with the sowing of pasture and soil compaction, which makes forest conversion irreversible and spurs further deforestation as soils are leached and land is abandoned [178,189,190]. A principal reason for soil degradation is that pasture impedes fallow re-growth, spurring the continued conversion of primary forest to maintain soil fertility [191]. Such soil degradation was largely responsible for the abandonment of up to 80% of pastureland in Brazil's Amazonia by the early 1980s [192], leading to the conversion of adjacent forests and those in new frontiers following migration [136].

Institutional planning forms a key link in the soil degradation-frontier LUCC connection. Colonization settlements are often planned hastily and with little regard for soil fertility or topography [107,189]. Roads are rarely built to coincide with the best soils for farming; for instance, poor planning in road construction has resulted in the failure to access the approximately 3% of soils in the Brazilian Amazon region thought to be sustainable for small farming with low and medium levels of technology [136].

Other ecological factors must also be considered when examining the determinants of deforestation in the bio-diverse tropics. Climate threatens to change the pace of deforestation for various reasons [9,193].

Aide et al. (2013) [9] show that northern-central Mexico and Northeast Brazil experienced reforestation during the first decade of the 21st century linked to increased rainfall consistent with human-induced climate change during the prior decade. Similarly, Pricope et al. (2013) [4] found climate change induced reduced rainfall connections to forest degradation in the African Horn region.

Other ecological processes affecting deforestation include disease and pest problems, which are much greater than in temperate regions [184,185]. In a diverse forest, same-species plants are spaced far apart, making it difficult for infestations to spread [80,184,194,195]. The preponderant reliance on one or two crops, typical of many frontier farming systems, strips the ecosystem of natural defenses against pests and diseases. Conversely, diverse cropping systems are more resilient than monocropping to pest and disease incidence. This has

been recurrently found, most recently for systems revolving around grains such as rice and maize [195] and for agroforestry systems such as those with cacao [194].

Another sort of pest is linked to deforestation. Malaria is endemic in many humid frontiers (Martine 1990; Hahn et al., 2014; [185]). Besides diminishing quality of life, malaria and other infections typical on the frontier such as gastrointestinal illnesses also cut into labor capacity, which can lead to declining yields and farm abandonment [196] and therefore, in some instances, reduce deforestation [185].

Ecological conditions form the tabula rasa on which frontier farmers will inscribe their livelihoods and land use decisions. These decisions are enabled and constrained by demographic, political–economic, and socioeconomic factors. The literature on frontier LUCC highlights the array of contingencies relating to space and place that hamper robust predictions of when and where forest clearing may occur. Despite continued population growth in the developing world, the percentage of the population serving as direct agents of forest clearing is declining yearly. Thus, political interventions to conserve tropical forests are as plausible now as ever. The next section will briefly review the major findings of this paper and propose a conceptual integration for informing research designs towards improving understanding of human-environment interactions that bear on efforts to improve rural livelihoods and conserve precious tropical ecosystems.

3. Discussion: Implications for Protection and Restoration

This paper has reviewed some of the literature regarding demographic, economic, political, household, and ecological factors associated with deforestation along tropical agricultural frontiers. These have been separated into discrete classes—only to clarify the contribution of each—with the intention of maintaining sensitivity to the inherently interconnected nature of the four categories. Nevertheless, despite relatively uniform conditions on the frontier in some regards, contradictions to theory are replete in the case study literature. Although the scholarly LUCC community has identified key factors relating to forest clearing, there has not been meaningful movement beyond the deforestation myths debunked decades ago in Hecht and Cockburn's (1989) [26] cogent narrative on deforestation in the Brazilian Amazon. We remain far from achieving a meta-theory of frontier deforestation, let alone of deforestation writ large. We are also far from prognosticating what this all means for conservation, protection, and restoration and human livelihoods. Perhaps such a goal is misplaced. Research suggests that efforts to achieve an all-encompassing theory will continue to pay attention to local context, to the mélange of physical and human geographies unique to each place, and to the fluid nature of space—especially when considering highly mobile human agents of change such as frontier migrants. The continued spate of research articles on the subject speaks to its importance, yet also suggests that key questions remain as to how, when, and where the political, socioeconomic, demographic, and ecological processes conspire to determine tropical deforestation. Nevertheless, the contours of some important spatially and temporally recurrent trends can be delineated.

3.1. Demographic Processes

Although a host of factors contribute to farmers' land use decisions on the frontier, a spatially and temporally recurrent demographic process underlying the first pulse of much of the globe's deforestation in tropical farm-forest frontiers is rural–rural migration (and accompanying high natural population growth) to forest margins and forest conversion to agriculture by poor colonists. This is usually followed by land consolidation by large ranch and plantation owners, a process of increasing note in recent years. It is the complex suite of determinants of this agricultural conversion process, the dominant driver of deforestation worldwide, that inspired this review and conceptual framework.

Population and forest cover change are rarely joined by a simple linear relation across scales. Neo-Malthusian arguments would appear inconsistent with the fact that, despite declining rural populations in many Latin American nations in recent years, deforestation proceeded unabated. The explanation is simple, requiring only a geographically acute

analytical lens. The population responsible for frontier forest conversion is a tiny fraction of all rural inhabitants; indeed, they represent a small portion of all migrants! If frontier forest clearing increases, either frontier farmers are clearing more forest or more migrant farmers are moving to the frontier. Neither of these outcomes necessitates overall (at the national scale) rural population growth. Conversely, Boserupian theory would predict that population pressures will induce technological innovations that lead to land intensification, slowing the incorporation of forests into farmland. However, on the frontier there is little population pressure to induce such intensification; indeed, in many cases it is the wealthiest farmers with the least population pressures but with greater market ambitions that intensify crop production. Increasingly, frontier dynamics are being played out on a global scale with farmer remittances and corporate investments flowing abroad into once nearly inaccessible regions (e.g., [11]).

3.2. Socioeconomic Livelihood and Political Processes

Economic and institutional arguments sometimes fail to recognize that the ultimate decision-makers who affect population and land use change are local resource users—even if their decisions are partly constrained by factors beyond their control. Road building is a necessary but insufficient cause of tropical deforestation. Road construction in itself causes little forest clearing; migration enabled by road construction has resulted in massive deforestation. For people to settle inhospitable remote areas, roads notwithstanding, something must be occurring in migrant origin areas to initially push them to the frontier. Similarly, once on the frontier, land insecurity and ample forestland sometimes encourages a rapacious "mining" of the land by settlers, followed by abandonment and the colonization of a new farm plot. However, granting frontier farmers land tenure will not in itself foster a conservationist ethos among farmers even as it increases the value of their land and extends their investment horizon farther into the future. Case studies illustrate that land tenure also unlocks credit from lending agencies, leading to cattle adoption and suddenly accelerated forest conversion. Policies enable and constrain land use decisions; they do not predict them.

3.3. Ecological, Geographic and Temporal Dimensions

Existing particularist or behaviorialist theories sometimes fail to capture key geographical and temporal dimensions or are not appropriate to agricultural frontiers. Cultural mores and learned experiences brought to the frontier affect land use following settlement; however, these aspirations are constrained by global and regional political–economic processes and local geographical conditions. How this develops will be place specific and rarely can be founded in broad generalities. For example, it cannot be claimed that indigenous farmers are more conservationist than farmers of European or mixed ancestry when evidence (e.g., from Guatemala and Ecuador) demonstrates that indigenous households are forest-demanding in resource-poor circumstances, but less so in others (and indigenous protected areas have had notable success). Similarly, sometimes intensive land uses learned in origin areas are maintained, as observed in parts of Brazil's Pará state [136]. In other instances, a culture of cattle ranching, as in Guatemala's Petén [135] and some regions of the Amazon [164,197], is exported to the frontier. No overarching theory will tell when this will, or will not, happen, yet any conceptual or empirical model must take into account cultural and social forces from origin and destination areas potentially affecting land use on the frontier.

Finally, the importance of ecological degradation in spurring further forest conversion is sometimes ignored, particularly as it relates to agricultural extensification on the frontier following out-migration. What is the connection? Good soil and flat topography attracts farm settlement. However, poor soil and steep, erosion-prone topography can spur farm abandonment and forest clearing elsewhere (e.g, [5,9,11]). These ecological priors, along with increasingly dynamic climate change, will also, therefore be important predictors of future potential restoration.

4. Conclusions

Aspects of the human-environment interface remain poorly understood using conventional frameworks insufficiently sensitive to local human and physical geographies, e.g., where remote sensing insufficiently replaces proximate sensing. Further research, informed by geographical, political, economic, social, and ecological processes and examined at multiple scales, is necessary to craft appropriate policy solutions to attenuate frontier forest conversion, restore and protect degraded lands, and ameliorate farm household livelihoods [65,198,199]. Although a large literature now exists on the wide range of demographic, economic, social, and ecological processes driving frontier forest conversion, disciplinary rigidity precludes the incorporation into research designs of the full suite of these cross-disciplinary factors. Economists study labor investments and market price fluctuations; demographers investigate fertility, migration, and life cycle features; ecologists examine environmental change; and political scientists research institutional processes governing resource use. Effective measurement of the relative strength of these factors will fruitfully incorporate integrated conceptual models, mixed methods and novel statistical and computational modeling approaches [200–202].

Regarding the issue of scale, the direction of association can be reversed when moving across spatial resolutions as illustrated in the relation between population and forest clearing. Rural population declined in many Latin American nations accompanied by continued high rates of forest clearing. At the local scale, the site of forest conversion, deforestation was positively related to population growth, yet the overall decline in rural population was a result of this process coinciding with a more general trend towards urbanization and international migration [11]. This is no paradox; it is simply an illustration of the importance of scale-dependency and of multi-scale political–economic factors. Reconciling scale and disciplinary deficiencies will inform improved research designs. This is ultimately necessary to better understand the greatest human impact on nature of all time, with the aim of effecting change beneficial to humans and nature.

Conservation and rural livelihoods need not be mutually exclusive. However, in order to reconcile potential competition between the two, a dual approach may be appropriate. First, identifying the population who most depends on rural livelihoods and has a proportionately large potential impact on and stake in conservation is critical. Locating the solution in people first helps us understand land change drivers, socio-cultural, demographic, and political—economic, within the context of livelihood choices. Second, the small farmer needs to be framed also within larger contexts encompassing land change science and sustainability.

On this second point, small scale farmers are not the only driver of deforestation. Additionally, not all small farmers are alike. To understand their relative role, the Drivers–Pressure–State–Impact–Response (DPSIR) framework could be particularly useful when nesting small farmers within a multi-scale institutional framework [203]. Similarly, to understand land change drivers writ large (and not just the role of small farmers), a land system science approach may be more suitable (e.g., [204]). "Middle-range" theory of land system change recognizes the gap between the surfeit of empirical studies and relative dearth of theory [74]. This gap remains, as an all-encompassing land change theory has remained elusive. Yet context can be generalized to describe causal chains of land change when bounding the range of phenomena that drive land change to a finite set of predominant categories. Pertinent to a "middle-range" framework in this paper, a focus on small farmers on agricultural frontiers fails to fully capture some of the issues of spillover, including land use displacement, and tele-connections, including spatially complex supply and demand pushes and pulls in an increasingly global economy. This is a limitation to this paper but also a potentially fruitful way forward for future integrated frameworks.

To more fully comprehend frontier forest conversion, restoration, and human livelihood potentials in forest frontiers, future research may fruitfully investigate the interaction across spatial scales and academic disciplines of demographic, social, political, economic, and ecological factors facing households as they aspire to enhance their livelihoods. Re-

searchers could successfully embrace integrated conceptual and methodological designs. Rural livelihood and forest restoration and conservation policies will ultimately only be as informed as the research which illuminates our understanding of where, how, and why people use land.

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