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Enhancing Security, Sustainability and Resilience in Energy, Food and Water

Edited by
Marko Keskinen, Suvi Sojamo and Olli Varis

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Special Issue Editors

Marko Keskinen
Suvi Sojamo
Olli Varis

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Special Issue Editors
Marko Keskinen
Aalto University
Finland

Suvi Sojamo
Aalto University
Finland

Olli Varis
Aalto University
Finland

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

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About the Special Issue Editors

Marko Keskinen is an Associate Professor in water resources management at Aalto University, Finland. He has also been working as a civil servant at the Finnish Ministry for Foreign Affairs, and has led several multidisciplinary and multicultural projects. Dr. Keskinen has around 20 years of experience from working on sustainability, the water-energy-food security nexus, integrated approaches, and science-policy-stakeholder interaction.

Suvi Sojamo is a Visiting Research Fellow at Aalto University, Finland. Dr. Sojamo has over ten years of experience in researching and developing principles and practices of sustainable water use and governance, having collaborated with academia, civil society, public and private sector organizations alike. She is among the leading scholars on corporate water stewardship internationally and has led the development of the Finnish Water Stewardship Commitment, which aims to make Finnish companies the most responsible water stewards in the world by 2030.

Olli Varis is the Aalto Distinguished Professor at Aalto University, Finland. Dr Varis is an internationally distinguished and recognised researcher in water and environmental issues, with a specialisation in global water resources as well as in the interaction between development and sustainability. He is especially renowned for his research related to Asia's growth economies. Dr Varis has led numerous international research projects and has a broad publication track record. He has also acted as an expert in numerous significant positions both in Finland and internationally.

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Editorial

Enhancing Security, Sustainability and Resilience in Energy, Food and Water

Marko Keskinen *, Suvi Sojamo and Olli Varis

Water and Development Research Group, Department of Built Environment, Aalto University, Tietotie 1E, FI-00076 Aalto, Finland; suvi.sojamo@aalto.fi (S.S.); olli.varis@aalto.fi (O.V.)
* Correspondence: marko.keskinen@aalto.fi

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Abstract: Our societies build largely on the concept of security and the ultimate justification for our present-day states is to ensure internal and external security of their citizens. While this task has traditionally focused on local and national scales, globalisation and planetary-scale challenges such as climate change mean that security connects also to a variety of sectors and has a stronger global dimension. Security is therefore increasingly connected with sustainability, which seeks to ensure that we as humans are able to live and prosper on this planet now and in the future. The concepts of energy security, food security and water security—as being used separately or together—manifest the burgeoning linkages between security and sustainability. This Special Issue brings together ten scientific articles that look at different aspects of security, sustainability and resilience with an emphasis on energy, food and/or water in the context of Finland and Europe. In this Editorial, we introduce the key concepts of the Special Issue, synthesise the articles' key findings and discuss their relevance for the on-going deliberations on security and sustainability. We conclude that ensuring sustainable security—or secure sustainability—requires systemic, structured processes that link the policies and actors in these two important but still distant fields.

Keywords: security; sustainability; resilience; nexus; linkages; energy; food; water; Finland

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1. Introduction: Security, Sustainability and Resilience in Energy, Food and Water

Security and sustainability are increasingly connected. Ensuring internal and external security continues to form the key justification for our present-day states. However, the use of security as a concept has broadened from national security concerns to other sectors and scales, extending to considerations of securities related e.g., to the planet, environment and climate [1–7]. At the same time, sustainability forms a critical objective for modern societies, as exemplified by several national and regional strategies (e.g., [8,9]) as well as by UN Sustainable Development Goals i.e., SDGs [10].

Sustainability and sustainable development (which is supposed to provide the pathway towards sustainability [11]) are traditionally closely linked to natural resources. Today, security policy is rapidly getting more and more intertwined with policies and practices related to the use of natural resources, as can be seen from the booming concepts of energy security (e.g., [12–15]), food security (e.g., [16,17]) and water security (e.g., [18–21]). While energy, food and water are critically important for societies, their availability is becoming more constrained, with drastic differences between regions and actors in accessing them (e.g., [22–24]]. Resource flows and value chains crisscross national boundaries, making their governance intersectoral and transnational by their nature (e.g., [25]). These three resource sectors are inherently linked, as is envisaged by different nexus approaches (e.g., [26–29]). All these features encompass the relevance of these resources for both security and sustainability, and call for systemic and future-orientated thinking to understand the complexities and challenges included in such connections.

Closely related to both sustainability and security is the concept of resilience. While security and sustainability can both be understood as goals, or even purposes, for a system (e.g., city, state or planet earth), resilience designates certain characteristics of a system that makes it work. Resilience is thus a measure of a system's ability to survive and persist within a variable environment that sees different kinds of changes over time [30]. The resilience concept is used regularly in relation to socio-ecological systems when describing their ability to withstand and respond to changes—whether environmental, economic, social or political (e.g., [31,32]). Yet, resilience as a concept has been actively used in other fields as well [33], and it is increasingly being used also in relation to (national) security under concepts such as state resilience or societal resilience (e.g., [34–40]).

Despite their centrality to our societies, systematic coupling of sustainability and security remains rare. Instead, both have their own policies and practices, and related actors and scales. We see that the broadened interpretations of both security and resilience can help in analysing and understanding the intricate and fundamentally important linkages between security and sustainability (see also [41–43]). This means that instead of focusing on global development challenges or national security threats separately and through detached policies, the concepts can help to build bridges between them. At the same time, their broadened conceptualisation has arguably allowed different interpretations by various actors, making their practical implementation prone to political loadings.

The call for this Special Issue, "Enhancing Security, Sustainability and Resilience in Energy, Food and Water" in the Sustainability journal was open for multi-, inter- and transdisciplinary research articles that study security, sustainability and/or resilience with a focus on energy, food and/or water. These three concepts and three themes were also the focus of our Winland research project that was funded by the Strategic Research Council at the Academy of Finland (http://winlandtutkimus.fi/english). Many of the Special Issue's articles are therefore linked to that project [6,44,45].

2. Key Findings from the Special Issue Articles

The Special Issue includes ten articles, all looking at the concepts of security, sustainability and/or resilience in relation to energy, food or water. In terms of study contexts, the articles focus on Finland or Northern Europe, primarily at a national scale, providing possibilities for comparison and complementary findings. In this section, we briefly summarise the main contexts and key findings for each article. Their joint findings and related conclusions are then discussed in the next section.

The first article, by Jaakko Jääskeläinen et al., focuses on energy security, looking at energy trade between Finland and Russia [46]. The authors focus on Finland's dependence on Russian energy and its possible security implications, noting that Finland's complex relationship with Russian energy trade has raised concerns over whether the dependence on one supplier forms an energy security threat. Applying energy policy scenarios and an interdependence framework to analyse the countries' energy systems and strategies, the authors found no acute energy security threats related to the energy trade between the two countries. At the same time, the authors note the critical economic and political importance that energy has for Russia. This makes energy a strategic asset for Russia, indicating that it has close linkages with the country's geopolitical considerations as well as other strategic sectors such as the military. The authors also note that the energy relations and the related concept of energy security between the countries go beyond the flow of fuels and electricity, highlighting the critical societal, political, and economic aspects of energy production and trade.

Ossi Heino et al. look at the role that critical infrastructure has for the security and resilience of modern societies [47]. Defining critical infrastructure as systems whose disruption or collapse would lead to serious consequences and crises of social order, the authors make use of a stakeholder workshop to look at two case studies related to energy (nationwide electricity grid disruption) and water (intentionally contaminated water supply in a city). The authors emphasise the importance of the interdependencies between critical infrastructure systems, noting that such interdependencies occur in various ways, namely between different systems, between different stages of system development, and between different operational and maintenance phases of those systems. The authors conclude that producing security requires typically continuous interaction and creation of meanings between varying actors and logics. This, in turn, implies a need for changes in thinking—in particular related to problem definition across conventional administrative structures, geographical boundaries and conferred powers.

Elina Lehikoinen et al. study the role that food production in water-abundant areas could have in combating global water scarcity and resource-efficient food production, focusing on the export potential of water-intensive cattle production from Finland [48]. Using four different scenarios, the authors calculated Finland's virtual water net export potential through a combination of domestic diet change and reallocation of the present underutilized agricultural land. The results indicate that the greatest potential to net exports of virtual water could be achieved when local feed production was maximized for domestic use and export, and bovine meat consumption in Finland was replaced with a vegetarian substitute. This scenario would correspond annual virtual water consumption for food of about 3.6 million people. The results emphasise how water-intensive production in water-rich areas could have a significant impact on global water savings, enhancing both water security and food security.

Related to the previous article, Elina Lehikoinen and Arto O. Salonen look at food preferences in Finland, focusing on sustainable diets and their differences between consumer groups [49]. Building on the notion that food consumption is not just caloric intake but a profoundly personal matter based on individual preferences, the authors assessed how sustainable food choices vary among Finnish citizens based on extensive questionnaire data. The results indicate differences in personal preferences between men and women, as well as between different age and income groups, with middle-aged men with high incomes being the most reluctant group to adopt sustainable diets. The authors conclude that transition towards more sustainable diets among Finns works out best if people feel that they can combine altruistic factors (e.g., ecological benefits) and hedonistic factors such as health or weight loss in their diet.

Noora Veijalainen et al. carry out a national scale drought impact analysis for Finland, assessing the effects of a severe drought on water resources in Finland [50]. The analysis includes three main phases: simulating water levels and discharges during a severe reference drought, estimating how climate change would alter droughts, and assessing their impact on key water use sectors such as hydropower production and water supply. The results indicate that drought can be a risk multiplier for the water–energy–food security nexus even in water-abundant conditions such as those in Finland. The authors also recognise practical possibilities to enhance resilience to drought in different sectors, and recommend the inclusion of drought into selected regional preparedness exercises that are regularly organised in Finland to enhance preparedness and enhance collaboration between relevant sectors and actors.

Lauri Ahopelto et al. build on the work by Veijalainen et al., identifying areas of Finland that are water-stressed and vulnerable to drought [51]. The authors apply a water use-to-availability analysis that makes use of national water permits and databases, and compares them with estimates from global models on Water Depletion Index. The results indicate that while most areas in Finland would have enough water also during drought, South and Southwest Finland would have difficulty securing sufficient water availability for all sectors, requiring water use prioritisation. As a result, the authors recommend that to enhance water security, Finland's water resources management system should include Drought Management Plans in most drought-prone areas. The most convenient way to do this would be to incorporate such plans into the EU River Basin Management Plans.

Emma Hakala and her co-authors contributed two articles to the Special Issue, both analysing the concept of environmental security and its linkages to general security discourse in Finland and Sweden. Their first article looks at the environmental threats through a novel three-level framework that brings analytically together local, geopolitical and structural impacts related to such threats [52]. Through exploration of the interactions between environmental change and society at different levels, the authors emphasise the importance of geopolitical and structural factors. The authors note that environmental security impacts have an interesting dual nature: while they unquestionably influence societal security, they cannot be understood strictly as a matter of security policy. As a result, new kinds of (environmental) threats indicate that the security sector should adopt new modes of action, utilising, for example, risk assessments and preparedness activities as a means to take into account the security implications of environmental change.

In their second article, Hakala et al. use their three-level framework to study environmental security policies in Finland and Sweden and propose practical ways for developing more effective measures to tackle environment-related threats [53]. While acknowledging that environmental issues—and first and foremost, climate change—have become an increasingly established part of security and foreign policy discourse, the authors argue that the value of environmental security as a concept for policy practice has not gained the momentum it would deserve. Based on their analysis, the authors call for a development of a new policy approach to tackle environmental security impacts in a comprehensive manner. Such an approach should build on close interaction between different sectors as well as between researchers and policy-makers, should make use of risk assessment and scenario processes, and would ultimately require strong strategic intent due to multi-sectoral character and novelty of the concept of environmental security.

Mika Marttunen et al. look at the concept of water security, arguing that policies promoting it should build on a systemic understanding [54]. Consideration of the current and future state of water security as well as its linkages to food security and energy security are all needed. To facilitate this, the authors developed a novel assessment framework that defines water security through a criteria hierarchy consisting of four main themes, and then studies these in terms of their current state and trends, functionality of legislation as well as water–energy–food security linkages. Applying the framework to a national water security assessment in Finland, the authors note that the framework provides a systematic and visual way to assess water security. The authors conclude that using the framework collaboratively with different stakeholders enables identifying issues that may not otherwise be covered, facilitating discussion on water security and, importantly, recognising actions needed for its improvement.

The article by Antti Belinskij et al. focuses on the role that regulation has in the governance of water–energy–food linkages [55]. Building on the adaptive governance theory related to common pool resources, the authors look at how regulation can both enable and prevent innovative solutions for sustainability. The authors focus on one bottom-up solution, namely the plans of Finland's largest dairy processer to establish novel manure treatment facilities. Such facilities would enhance the overall sustainability of animal agriculture by enabling biogas and fertilizer production, and reducing agricultural loading to waters, providing one example of synergies between water, energy and food security. Such plans would, however, also change the regulatory framework applied for manure treatment, as a treatment facility is a point-source pollution source that is regulated more strictly than diffuse pollution sources. The authors conclude that traditional top-down regulation related to food security in EU-Finland seems not to have the adaptive capacity to facilitate new, bottom-up solutions. This, in turn, points out the need to rethink some of the regulative practices related to environmental protection and food security and, more broadly, to water-energy-food security nexus.

3. Discussion and Conclusions: Ensuring Secure Sustainability and Sustainable Security?

What can we conclude jointly from the ten Special Issue articles—and more generally, from our Winland research project [44]? Our conclusions are threefold; related first, (thematically) to energy, food and water and their role for security and sustainability; second, (theoretically) to the connections between the concepts of security and sustainability; and third, (methodologically) to the need to address the security–sustainability connection in a systematic, structured manner. We next discuss these three aspects separately, and then conclude with some synthesising thoughts with Finland, the main study context in most articles, as a reference context.

First, it is clear that the three "resource sectors" of energy, food and water are closely linked, with each of them having strong implications to the other two sectors. While most of the articles focused on just one or two of these sectors, practically all of them also emphasised the close connections that the three sectors have. Such a finding puts further emphasis on the significance of so-called nexus approaches that aim to find synergies and enhance policy coherence between these (and other) themes and their governance [25–27,56].

The articles also emphasise that energy, food and water have linkages to both security and sustainability, providing possibilities for connecting the two concepts. While all three sectors are in the core of sustainability, they are also critically important for societies' security, including preparedness and resilience to future changes. Related to this, the articles note that climate change, increasingly portrayed as a climate crisis or climate breakdown (e.g., [57]), puts an additional future pressure on the three themes. Climate change can even be seen to manifest itself through the energy–food–water nexus. While climate change mitigation depends critically on energy transition to a carbon neutral and carbon negative society, the main impacts from climate change will be felt through changes in the hydrological cycle and a major adaptation challenge is caused by its negative impacts to food security.

Second, the findings from the articles support the hypothesis of the Special Issue that security and sustainability are increasingly connected—and that such connections are particularly strong in relation to energy security, food security and water security. While most articles do not explicitly address the security–sustainability linkage, a great majority of the articles considers both sustainability and security related to energy, food and/or water, focusing on the use and management of these three resources for the well-being and development of societies.

The articles can thus be seen to link to the concept of the security–development nexus [1], and, in particular, to the period of development that has, during the 21st Century, been characterised by increased globalisation and emphasis on sustainability [2,10]. In this way, the Special Issue's articles also contribute to the discussion of the scale of security–sustainability linkages. While security and sustainability increasingly connect (and arguably also conflict) at a global scale, the articles remind us that such connections are pertinent also at lower scales, from regional to national and local.

Consequently, we conclude that resilience can be used as one connecting factor between security and sustainability. We have studied the different dimensions of resilience in our Winland research project [44,58–62], noting that resilience seems to have an increasingly important, although partly contested, role in both sustainable development and security discourses. Given that both sustainability and security policies need to address different changes, resilience as a system characteristics (and as a boundary object [63]) provides, therefore, one possible connection between security and sustainability.

Third, the findings documented in the articles support the idea that addressing security and sustainability, particularly if addressed together, requires systemic views and comprehensive policy approaches. While both security and sustainability cross several sectors and scales, the current policies focus too easily on local and national scale implications and largely neglect broader (and more complex) geopolitical and structural/systemic aspects [53]. Such a focus is, as such, understandable, as assessing comprehensively just one thematic area, such as water security [54], requires a major effort that is also subject to many interpretations and therefore easily contested. This indicates that instead of one fixed framework, comprehensive policy approaches promoting security–sustainability linkage should build, first and foremost, on enhanced interaction and co-creation between different actors, with such interaction being focused through common activities and shared interests [6] as well as strong strategic intent.

Establishing this kind of comprehensive policy approach embracing sustainability–security linkages is by no means easy. Yet, we see that Finland, the main study context of this Special Issue, is well-positioned to develop and promote such approaches. Finland already has advanced policies related to both sustainable development [64] and comprehensive security [7,65], and close collaboration between different societal sectors—many of whom are engaged in both sustainability and security-related planning and policy making. We hope that findings from this Special Issue will, for their part, encourage paying closer attention to the security–sustainability linkages, both in Finland

and more broadly. It is clear that our current challenges do indicate the need to enhance such linkages, be it under the synthesising concept of sustainable security or secure sustainability.

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Finland's Dependence on Russian Energy—Mutually Beneficial Trade Relations or an Energy Security Threat?

Jaakko J. Jääskeläinen [1], Sakari Höysniemi [2,*], Sanna Syri [1] and Veli-Pekka Tynkkynen [2]

1 Department of Mechanical Engineering, School of Engineering, Aalto University, P.O. Box 14100, FI-00076 Aalto, Finland; jaakko.j.jaaskelainen@aalto.fi (J.J.J.); sanna.syri@aalto.fi (S.S.)

2 Aleksanteri Institute, Faculty of Arts, University of Helsinki, P.O. Box 24, FI-00014 University of Helsinki, Finland; veli-pekka.tynkkynen@helsinki.fi

* Correspondence: sakari.hoysniemi@helsinki.fi; Tel.: +358-50-3148944

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Abstract: Studies on energy security in the context of relations between European Union (EU) and Russia tend to focus on cases, with an open conflict related to supply, such as "hard" energy weapons, or on only one fuel, often natural gas. However, there is a need to understand the long-term impacts that energy relations have politically, economically and physically, and their linkages between resilience, sustainability and security. We analyse the Finnish-Russian energy relations as a case study, as they are characterised by a non-conflictual relationship. To assess this complex relationship, we apply the interdependence framework to analyse both the energy systems and energy strategies of Finland and Russia, and the energy security issues related to the notable import dependence on one supplier. Moreover, we analyse the plausible development of the energy trade between the countries in three different energy policy scenarios until 2040. The findings of the article shed light on how the trends in energy markets, climate change mitigation and broader societal and political trends could influence Russia's energy trade relations with countries, such as Finland. Our analysis shows that Finland's dependence on primary energy imports does not pose an acute energy security threat in terms of sheer supply, and the dependence is unlikely to worsen in the future. However, due to the difficulty in anticipating societal, political, and economic trends, there are possible developments that could affect Finland.

Keywords: energy security; energy trade; import dependence; energy policy; Russia; Finland

1. Introduction

The crises associated with the supply of natural gas in 2006 and 2009 stimulated the European Union (EU) to develop a European energy security strategy in 2014 [1]. One of the key concerns of the strategy is that member states have not placed similar emphasis on security of supply compared to other energy policy areas. To enhance energy security, the EU has made reducing dependence on imported fuels and dominant suppliers its key targets, thus advancing the EU-level energy market and infrastructure integration and coordination among member states. Increasing the share of renewable energy sources and implementation of energy efficiency measures are also key targets that link energy security with climate policy [2,3]. Regardless of the EU targets, national policies and responses tend to vary not only because of differing energy infrastructures, but also due to differing perceptions of threats and risks.

Finland is an interesting example of the EU-Russia energy trade in several ways. Firstly, Finland ranks among the most energy-intensive countries in the world [4] due to its cold climate and energy-intensive industry. Secondly, Finland has practically non-existent domestic fossil fuel and uranium resources. Consequently, Finland imports almost two thirds of its primary energy [5], the vast majority of which comes from Finland's neighbour in the east, Russia. This has sparked debate in Finland concerning whether the low self-sufficiency in energy and the high dependence on one supplier are in fact threats to energy security or merely a sign of mutually beneficial trade relations. Compared with, for example, the East European states, and issues related to outdated energy infrastructure or a lack of connections to global energy markets, securitisation of energy has remained limited in Finland, as has consideration of energy as a foreign policy tool. For instance, the Nord Stream I and II natural gas pipelines (that are not linked to Finland's gas supply) have only been a subject of environmental regulation. At the same time, the pipeline has become a political issue in many other EU countries [3].

In contrast to Finland, Russia is often portrayed as an energy superpower with abundant fossil fuel and uranium resources. Energy exports comprise a notable share of Russia's gross domestic product (GDP), and hence, the Russian economy is strongly affected by the global demand and market prices of energy. Academic interest has broadened due to the Russia-Ukraine gas disputes and increasing politicisation of energy issues [6–9]. Furthermore, as Kustova [8] notes, there is still a tendency to assess energy in the context of Russia's relations with the EU or its member states either as an openly traded market commodity or as a tool for foreign policy influence. One of the ways to provide a more nuanced understanding could be to assess both energy security threat perceptions and physical energy relations in the operational milieu [8,10]. Energy security is a multi-dimensional issue and thus cannot be neatly simplified into an issue of supply or market optimisation. Therefore, assessments of societal, (geo)political and technical development are also equally vital.

Finnish energy policy or, more specifically, energy security has been studied widely. One part of the literature has assessed public debate and political processes related to energy. Valkila and Saari [11] and Ruostetsaari [12] have studied Finnish energy elites and decision-making. In terms of specific energy forms, inter alia Teräväinen et al. [13], Ylönen et al. [14], Vehkalahti [15], Laihonen [16] and Aalto et al. [17] assessed the public debate and political processes concerning nuclear power. Similarly, Huttunen [18] and Kivimaa and Mickwitz [19] have studied the debate on bioenergy. In terms of energy security, Lempinen [20] studied the ways energy security, including threat perception of Russia, have been used as a rhetorical tool in the marketing of peat, while Karhunen et al. [21] provide a survey-based assessment on the governance of security of supply for combined heat and power (CHP) plants. Another significant part of the literature has assessed the Finnish energy system with techno-economic analysis (e.g., Reference [22]). Zakeri et al. [23] and Aslani et al. [24] have assessed the integration of renewable energy into the current Finnish energy system. Saastamoinen and Kuosmanen [25] applied a quality frontier model to measuring the quality of domestic electricity supply security. Pilpola and Lund [26] used a national energy system model to assess policy risks related to nuclear power and biomass. Excluding the studies of Aalto et al. [17] and Ochoa and Gore [27], the analysis of Finnish-Russian energy relations is typically based on historical analysis focusing on oil (e.g., References [25,28]) and nuclear power (e.g., References [29,30]). Compared to previous research, this article concentrates on the current system and on future trends relating to Finnish-Russian energy relations and Finland's resilience against external shocks.

This article uses an interdisciplinary approach to analyse Finland's resilience regarding primary energy import dependence and the plausible energy security risks related to the notable dependence on Russian energy trade beyond import-related aspects. First, Section 2 reviews the current literature on energy security, including key approaches, disciplines and Russia's energy policy. Section 3 introduces the applied methods that combine energy policy, energy system and energy technology analyses. Section 4 analyses the dynamics of Finnish-Russian energy trade currently, and Section 5 analyses the future of Finnish-Russian energy trade through three different scenarios. Section 6 discusses the findings and finally, Section 7 draws conclusions.

2. Literature Review

In the literature, energy security remains a slippery or polysemic concept that varies contextually, culturally, politically, temporally, spatially and in terms of energy source [31,32]. The concept has traditionally been linked to securing supply and demand of oil and gas, but climate policy goals and increased use of renewables have resulted in electricity playing a growing role in the framing of energy security concerns [33,34]. Energy security can be loosely considered as secure supply for countries lacking primary energy resources, while for countries with an abundance of energy, it is commonly framed through the (external) demand side dynamics [35,36]. However, a general disciplinary consensus on what energy security is or how it should be assessed is still missing.

One of the reasons for the lack of agreement could also be the disciplinary divide. Cherp and Jewell [37] categorise energy security research into three perspectives: 'Sovereignty', which has commonly been studied by social science approaches, such as security studies and international relations; 'robustness', with the key research coming from natural sciences and engineering; and 'resilience' analyses of economics and the complex systems approach. The sovereignty perspective focuses more on external issues and geopolitics, such as the policies and actions of exporting countries or their respective companies, and the stress is placed more on threat perceptions rather than on physical supply. The robustness perspective assesses energy security through quantifiable factors, such as demand, scarcity or infrastructural capacity. The resilience perspective assesses more generic characteristics of energy systems by combining political, technical, and economic elements and qualitative and quantitative assessments that enable more nuanced anticipation of known and unknown risks [38]. With its focus on risks, this perspective brings the concept closer to the broader debate on sustainability [39].

Considering also that energy mixes and societal and political dynamics vary significantly across countries and regions, the meaning of energy security could be deepened with an assessment of country interactions [40]. The literature also notes that market-based assessment alone is not sufficient, and energy security is often considered as an element of (national) security in general [38,41]. It is hence tied to societal and (geo)political development, making it difficult to assess through one discipline. As Mayer and Schouten [42] note, energy security is more like a specific assemblage that consists not only of perceptions of (in)security, including political and market trends, but also material flows and physical infrastructures. This comes close to the concept of "vital systems security", linking the level of domestic control over an energy system with the systemic capacity to respond to disruptions [33]. This paper follows the proposal of Cherp and Jewell [38] that defines energy security as "low vulnerability of vital energy systems". That is, energy security is a temporally specific construct based on the power of associated institutional interests tied to specific infrastructures [43].

The gap between physical infrastructure reliability and the perception of energy security [42] can vary significantly not only between energy experts and the general public, but also within the expert audience across countries [44–46]. In other words, experts tend to frame the concept in more narrow terms than the public. Among experts, the argumentation often falls between a liberal, market-orientated world-view and a more nationalist or geopolitical world-view stressing sovereignty that can establish completely opposing outlooks, which are hard to reconcile [47].

One common theme in the literature is that strategies of resilience between consumers and producers are likely to differ—and the latter, especially, may tend to use strategies of resistance [48]. For instance, price-setting [49] by producer countries or individual companies are strategies enabling governance or the spread of influence 'at a distance' [50] or 'co-optation' [51], i.e., seductive or covert use of power. Strategies of energy transition (i.e., aims to achieve a low-carbon energy system by increasing renewable energy production and energy efficiency), as well as the introduction of shale oil, and shale gas, as well as liquefied natural gas (LNG) into the global energy market [52] can bring about a significant shift.

Although the shelves are full of research that has assessed whether Russia would use a so-called energy weapon, i.e., using energy trade for political leverage with direct or indirect issuance of threats, it still remains an issue of dispute in research [31,53,54]. This could be due to the division in international relations scholarship between realist and liberal schools of thought, which also reflects social scientific analyses of energy security and trade [8,55]. The former perceives the world as an anarchic place where states are key actors pursuing security, often with military means. There is also consideration of little cooperation among the actors operating at the international level, while the economy is only one of the spheres of foreign policy influence. The latter stresses that economic interdependence and free trade are sources of political integration and increased security. States and other actors perceive cooperation as a key goal to strengthen wealth instead of political power. Therefore, law and institutions are also of high value. In Europe, energy dependence is often perceived as a symmetric alignment, in which both the EU and Russia are dependent on the continuation of trade relations. This does not necessary apply to the situation with individual countries or companies, which can be subject to occasional or systemic use of the "energy weapon", i.e., differing pricing or contractual terms [56,57].

This has also partially led to an analytical bias, as Russian state-owned or controlled companies make energy contracts not with the EU, but with individual member states and their respective energy companies under national ownership or control [54,57]. In contrast, the argument this paper aims to develop is that energy trade relations in the context of Russia's influence on Western countries are best understood through the analysis of threat perceptions and the ability to substitute current incomes from other energy forms [17,24,26]. Although Russia may not behave as a liberal actor as the EU [58], it may still operate through spheres of trade. That is, instead of issuing direct threats, Russia aims to influence via geoeconomic measures [59]. In contemporary Russia, it is therefore not security of supply, but security of export or demand that is constructed around the principle of sustaining and increasing energy export revenues [60].

In the sphere of broader security and international relations, there is a trend towards weakening relations between Western countries (the EU and US) and Russia via the increased use of sanctions. This may hinder the development of the Russian energy sector, but it is still highly likely that the EU and Russia will retain their status as key trading partners. For example, in the sphere of natural gas contracts last until the 2030s and penalties on both sides sustain a relationship based on interdependence [3]. That is, energy infrastructure and supply chains built over many decades are sustaining the dependence of key Russian trading partners on Russian energy not only through trade but also through infrastructure as an element of geopolitical influence [61]. However, both EU countries and Russia have a growing interest in establishing alternative energy export and import routes. This may force Russia and its energy companies to react strategically to sustain security and resilience, but also to consider applying soft energy weapons, such as price-setting, that could sustain dependence [57]. Finally, Casier [53] argues that increasing threat perceptions of the EU energy security are not so much a result of increased import dependence from Russia, but are due to increased competition and geopoliticisation of EU-Russia relations in general. That is, perceptions are reproduced in the energy sector that may lead to a reductionist and simplified geopolitical frame and physical import dependence should not be directly conflated as political dependence [62].

3. Materials and Methods

This section introduces the applied methods and data used to analyse Finnish-Russian energy trade and its plausible future trends. Section 3.1 introduces the key materials and Section 3.2 provides the methodology applied to analyse the current state of relations. Section 3.2 introduces the approach to the scenario analysis.

3.1. Materials

Our research uses both qualitative and quantitative data in order to demonstrate how 'vital energy system' is defined in Russian and Finnish contexts, and what trends and risks could emerge in different scenarios. In terms of qualitative data, we assess the Russian and Finnish energy strategies, namely Finland's Climate and Energy Strategy up to 2030 and, on the Russian side, Russia's Energy Strategy up to 2030, the Draft project up to 2035 and a Forecast of scientific and technological development by the Ministry of Energy. This is triangulated with a literature review and an assessment of Finnish and Russian newspaper articles discussing key issues related to energy trade between Finland and Russia.

3.2. Interdependence Framework

Here we apply the 'interdependence' framework loosely, but expand it beyond assessment of bilateral energy relations in the sphere of natural gas [10,54] to any given energy type. Interdependence is considered to apply between trading partners when intensive transactions across the border bring certain expenses that prevent one side from fulfilling its aims due to high dependence on what the other side makes. There are two assumptions in this framework. The first one is that cooperation establishes possibilities to benefit from the given relationship. The second is that the actors become dependent on each other, which decreases their ability to act autonomously. The relationship can be symmetric or asymmetric, with the latter being more common. The analytical goal is thus to define whether the relationship is about dependence or interdependence [54]. The model consists of three dimensions, which are physical energy relations, the dominance of the energy agenda in mutual relations, and the influence of the European Union. Physical energy relations are studied by analysing the flow of fuels and electricity between Finland and Russia and the infrastructure that connects the energy systems. In line with the critiques of the framework [62], we would like to stress that the influence of Russia cannot be reduced to simple import dependence, and therefore the second dimension is important. The dominance of energy in mutual relations is analysed with a content analysis of key strategic documents and official statements by looking at the perceptions actors give for energy (in)security. Finally, the influence of the EU is examined through an assessment of the extent to which a given member state has aligned with EU policy, but also how the sanctions have impacted. Compared to the aforementioned studies, our main focus is on the first two dimensions while we also take a closer look at the internal dynamics within Russia and Finland and at the global market trends that are equally important when assessing Russia's ability to exercise power [63].

In our analysis, we combine assessment of threat perceptions with the development of physical energy relations. As the framework suggests, power or the ability to influence through energy trade should not be reduced to physical import dependence. Rather, the focus is on the role of substitutability in fossil fuels and uranium in the context of the changing energy landscape, which includes the emergence of renewables and unconventional fossil fuels, namely LNG and shale gas, but also fourth generation nuclear power.

3.3. Scenario Analysis

Future development of the Finnish-Russian energy trade is analysed through three global energy market scenarios. The first of these is the market trends scenario, which is based on current market trends. That is, it comprises planned and decided climate actions, limiting global warming to 3–3.5 degrees Celsius. The second is the low carbon scenario, an optimistic scenario in terms of climate change mitigation, where global warming is limited to two degrees via substantial reduction of global CO_2 emissions. The third is the high carbon scenario, a scenario where global climate policy has failed, and CO_2 emissions continue at an unsustainable growth rate. In this scenario, the global consumption of energy together with Russian exports of fossil fuels, uranium and energy technology are on the rise. The scenarios are based on inter alia energy strategies of Finland and Russia, the International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC) scenarios, and previous studies by the authors. The scenarios are developed until 2040 and presented in more detail in Section 5.

The way in which we use the scenarios comes close to the thought experiment approach [34], i.e., our main interest is not the likelihood of a given scenario, but to provoke the imagination of a reader [64]. Predicting global energy market trends in the future is challenging—not only because of the uncertainties related to technological development and demand for energy, but also due to political trends and global ambitions related to climate change mitigation.

4. Finnish-Russian Energy Trade

Finland has a long history of energy trade with Russia. The trade is practically one-directional, as Finland lacks domestic fossil fuel reserves in comparison with its substantial demand for energy, whereas Russia has significant export volumes. In order to map plausible vulnerabilities related to Finland's dependence on Russian energy, this section analyses the relations of Finland and Russia with regard to energy trade. Furthermore, this section aims to develop a synopsis of the most relevant energy security-related data and political and security aspects of Finnish-Russian energy trade. Sections 4.1 and 4.2 introduce the Finnish and Russian energy systems, respectively. Section 4.3 takes a deeper look into the dynamics of the Finnish-Russian energy trade. With regard to the interdependence framework, Sections 4.1, 4.2.1, 4.3.1 and 4.3.2 deal with the first dimension, i.e., the physical relations, while Sections 4.2.2 and 4.2.3 unpack the political debate and the influence of EU via sanctions.

4.1. Energy in Finland

Section 4.1.1 reviews the demand for energy in Finland and Section 4.1.2 deals with the supply side. Unless otherwise mentioned, Finnish energy policy targets and future development of the Finnish energy system are based on the Policy scenario of the new National Energy and Climate Strategy of Finland from late 2016 [65].

4.1.1. Demand

Finland has substantial energy consumption per capita due to its cold climate and energy-intensive industry. The most significant sectors of (primary) energy consumption in 2016 were industry (45%), space heating (26%) and transport (17%) [66]. Figure 1 presents the Finnish primary energy consumption and energy sources in 2007–2016 [66], 2020 and 2030 [65]. Primary energy consumption is expected to reach 418 TWh by 2030 [5].

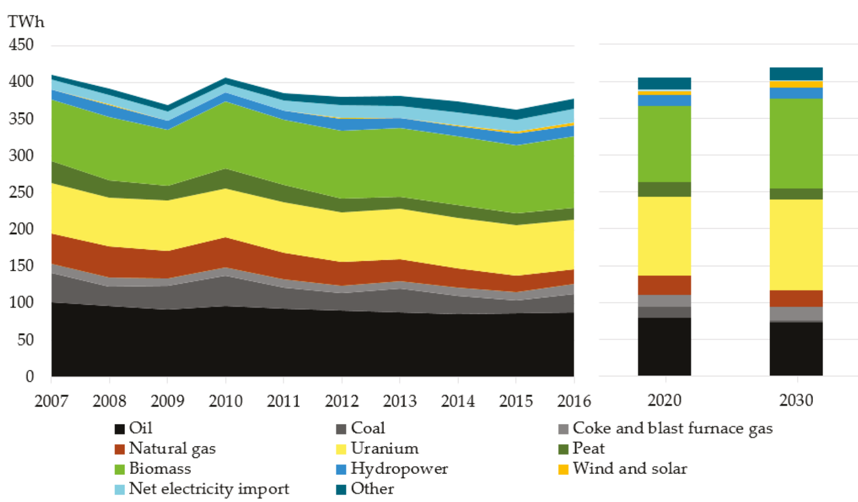

Figure 1. Primary energy consumption and energy sources in Finland in 2007–2016, 2020, and 2030.

Demand for electricity has remained at around 82–85 TWh/a in Finland in the 2010s. During the past decade, the demand has been lower than expected due to the financial crises and exceptionally warm weather. However, the annual electricity demand peaks in Finland have grown, reaching an all-time high in early 2016 (15,105 MWh/h) [67]. This has spurred debate on generation adequacy in Finland [68,69]. The main sectors of electricity consumption are industry and construction (47%, 2016 figures), residential and agriculture (27%), and the public sector (23%), with transmission and distribution losses covering 3% of electricity use in 2016 [66]. In 2030, the Energy and Climate Strategy estimates an annual electricity consumption of 93 TWh and an upper limit of 16,235 MWh/h for the annual demand peak in Finland [5].

In addition to the high demand for electricity and space heating, a noteworthy feature in the Finnish energy system is the role of district heating and cogeneration in particular. Demand for district heat was approximately 33.6 TWh in 2016, i.e., 46.1% of total space heating [70]. Approximately 70% of the district heat was based on combined heat and power (CHP) production. Demand for district heat is expected to remain approximately at its current level until 2030 [5].

4.1.2. Supply

As illustrated in Figure 1, the most important primary energy sources in Finland are biomass (25.9%, 2016 figures), oil (23.2%) and uranium (18.2%) [66]. Finland imports practically all of its fossil fuels, and a vast majority of the imports come from Russia. In total, imports comprised 64.0% of the total primary energy supply in 2016, of which the majority originated in Russia (Table 1). The imports are presented in more detail in Section 4.3. The most notable domestic primary energy sources in Finland are biomass (71%, 2016 figures), peat (15%) and hydropower (10%) [66]. Figure 1 presents the development of primary energy supply in Finland in 2007–2016 and the political targets for 2020 and 2030.

Finland has a highly diversified electricity production mix. During the past few years, electricity supply in Finland has been distributed between thermal power (29.6%, 2016 figures), nuclear power (26.2%), hydropower and wind power (21.9%), and net import (22.3%) [71]. Installed power capacity in Finland in early 2018 was approximately 17,400 MW [72]. However, as some of the capacity is allocated in system reserves and the availability of, for example, wind and hydropower vary according to external conditions, the highest electricity production peak in Finland in 2016, for example, was approximately 11,600 MW [67]. This corresponds to the estimate of Fingrid, the national transmission system operator, regarding the available domestic power capacity during the winter peak-demand period in 2016 [66]. Thus, Finland is highly dependent on electricity imports for supplying the annual demand peaks. The cross-border transmission capacities from Sweden, Russia, and Estonia are approximately 2700 MW, 1400 MW, and 1000 MW, respectively; resulting in a total import capacity of 5100 MW. This is more than one third of the record high demand peak.

Finland has set a target of self-sufficiency in annual electricity production by 2030 [65]. However, two new cross-border transmission lines are being planned and constructed between Finland and Sweden, and Finland's dependence on imported electricity to supply the annual demand peaks might thus even grow by 2030 [69]. In addition to the new transmission lines, the most significant foreseeable changes in the Finnish energy system by 2030 are the following:

- Two new nuclear power plants: Olkiluoto 3 (1600 MW, deployment in 2019) and Hanhikivi 1 (1200 MW, deployment after 2024).
- Phasing out coal in normal energy use and halving the use of imported oil.
- Increasing the share of renewable energy sources to 50% and self-sufficiency to 55% of final energy consumption.

The Finnish energy system comprises a variety of capacity and energy reserves. In addition to the peak load reserves (currently 729 MW of power plants and demand response [73]), Fingrid controls different frequency restoration reserves, which comprise inter alia approximately 1000 MW of fuel oil powered gas turbines. The Finnish legislation on imported fuels (28.11.1994/1070) obliges parties importing or utilising coal or natural gas to store fuel for three months' consumption and parties importing or utilising oil to store fuel for two months' consumption. However, in practice natural gas storages are substituted via storing fuel oil. Uranium is excluded from the legislation, but nuclear power producers store uranium for 1–2 years' consumption. In addition to the obligations for importers and producers, the Finnish National Emergency Supply Agency (NESA) has emergency fuel storages.

4.2. Energy in Russia

Due to the very different characteristics of the Finnish and Russian energy sectors, we also analyse energy in Russia with a different approach. Russia is the world's largest country in terms of land area and its energy market is much more scattered than that of Finland. In terms of energy security in Finland, energy generation capacity and energy infrastructure outside western Russia are of lesser importance. Therefore, in addition to the direct linkages in the Finnish-Russian border, this section will concentrate on Russia's role as an energy exporter and its energy strategy. Section 4.2.1 reviews the demand for and supply of energy in Russia, Section 4.2.2 analyses the strategic role that the energy sector has in Russia, and Section 4.2.3 analyses the impacts of the EU and US sanctions on the Russian energy sector.

4.2.1. Demand and Supply

Russia has the world's fourth largest primary energy consumption after China, USA, and India, covering 5.2% of global energy consumption in 2016 [74]. The annual consumption in 2016 was 689.6 Mtoe (~8020 TWh). In addition to the Russian consumption, the global demand for primary energy has a vital role in the Russian energy market due to Russia's role as an energy exporter: Russia was the world's largest exporter of oil and natural gas in 2016, exporting 74% of its produced oil, 33% of produced natural gas, and 54% of produced coal [74]. Russia's primary energy consumption, fuel reserves, domestic production and exports in 2016 are presented in Table 1. Uranium is not traded as openly, and hence its production and export figures are absent from the table.

Table 1. Russian primary energy consumption, fuel reserves, domestic production and exports in 2016 [74].

Energy Source	Consumption (TWh/a)	Share	Reserves (TWh)	Global Share	Production (TWh/a)	Global Share	Net Export (TWh/a)
Natural gas	4201.9	52.4%	~348,000	18.0%	5900	16.6%	2070 [4]
Oil	1773.6	22.1%	~169,000	6.3%	6470	12.7%	4770 [5]
Coal	1037.4	12.9%	~892,000 [2]	15.5%	2260	5.3%	1220 [6]
Uranium	517.5	6.5%	~70,000 [3]	8.9%	-	-	-
Hydropower	486.1	6.1%	-	-	-	-	-
Other [1]	3.5	0.0%	-	-	-	-	-
Total	8020.0	100%	-	-	-	-	-

[1] Including wind and solar power; [2] At the end of 2017; [3] A rough estimate based on 507,800 tons of uranium reserves [75] and a heat value of 500 GJ/kg [76]; [4] Including pipeline and liquefied natural gas (LNG) trade; [5] Including crude oil and oil products; [6] Including anthracite, bituminous and lignite.

In 2010, the Russian government implemented a mechanism called the capacity delivery agreement (CDA) in order to incentivise investment in power capacity [77]. Due to lower-than-expected demand for electricity after the financial crises around 2010, the mechanism has resulted in a notable surplus of generation capacity in Russia. Power production capacity in Russia is approximately 240 GW, of which 68.0% is thermal power, 20.1% hydropower, 11.6% nuclear power and 0.23% renewables other than hydropower [78]. Russia's gross electricity production, electricity consumption and net electricity imports in 2016 were 1071 TWh, 900 TWh and 15 TWh, respectively [79].

4.2.2. Energy as a Strategic Asset in Russia

Energy plays an important role in the Russian economy. It is often more than a commodity and it is linked with other strategic sectors, such as the military [80]. Hydrocarbons in particular are also considered a tool for construction of the energy superpower identity [81,82]. As a result, broader security and strategic concerns are openly expressed and they are closely tied to geopolitical considerations [83]. The most recent finalised document remains the Energy Strategy up to 2030 [84], while the yet to be finalised Energy Strategy is in the project stage [85]. This is remarkable, as other key Russian security strategies have been updated during 2014–2016 [80]. Equally important is a forecast of scientific and technological development by the Ministry of Energy [86].

Recent energy strategies in Russia have not functioned as blueprints for action, but rather served as 'documents for documents', i.e., the Russian government uses interlinked documents to govern energy sector development [87]. Therefore, the energy strategy itself provides little detailed information about the exact measures, but rather describes risks and key strategic objectives. Furthermore, according to previous research, the estimates for fuel and energy balance, as well as domestic technological capability are rather optimistic and, depending on the fuel, can significantly differ from global estimates [88–90]. Furthermore, there is variation on how different documents illustrate the development of politics. The energy strategy project does not discuss issues, such as geopolitics very much, while the forecast of technological development perceives energy as a tool for political influence and considers that the USA and the EU are, in cooperation with their allies, conducting a new kind of war with Russia [91].

The draft version of the energy strategy assesses the development of the Russian energy sector through "optimistic" and "pessimistic" scenarios, of which the former is one of our sources for the high carbon scenario in Section 5. Both scenarios in the draft focus on the development of fossil fuels and have a rather optimistic annual GDP growth of 2–3% [85,91]. At the moment, the (external) energy security question for Russia is how to best manage fluctuations in energy prices, as half of the Russian budget comes from energy revenues (80% oil and 20% natural gas) [87]. Nuclear power is expected to become a more significant source of revenue, but also to replace domestic natural gas consumption for export [88]. Russia aims to double its nuclear energy production by 2030 [85] and to turn nuclear power into a major export industry [17,88].

The importance of developing a more balanced economy that is not based only on fossil fuels or energy revenues is also acknowledged [84,85]. A forecast of scientific and technological development by the Ministry of Energy [86] considers it risky for Russian energy companies to focus only on the development of large scale fossil fuel projects. However, previous research shows that progress has remained limited [92,93]. In contrast, energy efficiency measures have had a stronger foothold strategically, and they are assumed to save up to 40% of the domestic production and enable an increase in export revenue [94]. Furthermore, one of the issues the strategy highlights is technological dependence on Western technology and it sets the target of having energy equipment produced 85–90% (previously the target was 95–97% by 2030 [84,95]) domestically by 2035 [85]. Under the current Russian policy targets, the critical challenges in terms of (internal) energy security are finding sufficient investments, increasing the technology level, increasing energy and economic efficiency to keep up with global levels, and developing energy infrastructure [87]. With current and even higher oil prices, it is difficult to sustain the societal security without broad restructuring of society. That is to say that current financial security mechanisms, such as welfare funds are running out, and without new income new energy infrastructure investments are also hard to finance [91].

If carbon reduction targets increase significantly, uranium and also natural gas, due to its lower carbon intensity, could play an even more significant role than today [57]. In terms of natural gas, there are three important factors: (1) How the EU market integration continues and what is the level of ambition regarding climate policy; (2) how the demand for natural gas in India and in China will evolve [60]; and (3) how the LNG market will develop. The global production network for LNG has more than doubled between 2002 and 2015. Furthermore, establishing a new kind of pricing regime that could reduce the power of traditional long-term contracts is equally important [52].

4.2.3. Impact of Sanctions on Russia

The EU, the US and some other countries have introduced sanctions on Russia since spring 2014, after the annexation of Crimea. Economic sanctions have so far affected mostly new greenfield projects and especially the oil sector [96], which is the most vulnerable due to its dependence on foreign technologies [95]. Furthermore, the sanctions have also influenced diplomatic relations at the EU level. For instance, the EU-Russia Energy dialogue has not organised any high-level meetings, since the introduction of sanctions [96]. It is peculiar, however, that the nuclear power sector has been left outside sanctions, although there are many greenfield projects in Europe [91].

The sanctions have the most notable impact financially and technologically. In the financial sphere the sanctions have resulted in depleted access to long-term loans and a decrease in credit ratings for key Russian energy companies [97]. In the oil sector, the difficulty in brownfield projects is to retain current volumes. In greenfield projects, the development of new projects has slowed down or been postponed due to difficulties in cooperation [95,97], although the use of non-Western technology has helped slightly [98]. It is also worth noting that in addition to sanctions, the Third Energy Package of the EU with the key strategic goal of liberalising the natural gas market has forced Gazprom to unbundle distribution from production [3]. Gazprom is currently trying to solve this issue via World Trade Organisation (WTO) arbitration, but if the decision favours the EU, it could strengthen the impacts of sanctions.

The impact of sanctions has been less remarkable for natural gas, as the Russian reserves are at a high level and the long-term nature of trade contracts mitigates short-term risks. However, politically one possible result is that the experience of sanctions will push Gazprom's newer European customers towards LNG and other energy sources [96]. If the sanctions continue, the difficulty for Russian LNG could be to keep up with more modern and cost effective methods, while non-Russian companies could gain a larger market share in Europe [97].

The likely impact of the sanctions could be twofold: On the one hand, they reduce demand and highlight the dependence on Western technology, while on the other hand, they provide a push towards internal renewal and economic modernisation [90]. However, due to Russia's significant economic and political dependence on oil and gas, this type of internal development is challenging. That is, the Russian regime needs to take corporate interests into account. Domestic interest groups could, for instance, push for strengthening energy sector subsidies and a strategic focus on it [99]. The societal impact could be the increased control of citizens due to a simplification of economy and centralisation of power. If the broader Russian economy stalls, this could even lead to citizen protests [57].

4.3. Energy Trade Relations between Finland and Russia

Despite the concerns and public debate on Russia's reliability as a supplier of energy, there has in practice been no noteworthy disturbances in energy flows from Russia to Finland in the last few decades. The debate mirrors Finnish-Russian relations in general, and the perceptions of threat related to Russia [15]. On the one hand, the debate has thus been about security in general and whether Russia could reach its foreign and security policy goals via energy trade. On the other hand, there has also been liberal consideration that free trade enables positive interdependence and cooperation in Russia [17,57]. The latter is more dominant in the Finnish energy strategy and related documents [5,65], but also in diplomatic meetings with the Russian president [100,101]. Key politicians and industry representatives have also argued against energy trade having political or security implications [102]. Consequently, despite Russia's significant role in supplying energy to Finland, the new energy strategy of Finland does not mention Russia even once, and the background report only mentions Russia briefly when discussing the opening up of the Finnish natural gas market.

As noted in the previous section, the Russian energy sector is one of the strategic sectors, and therefore market-based rationale can be neglected if the state security or foreign policy needs are more important. In Finland, the major energy companies operate on the basis of market logic, although energy is, to some extent, always an object of strategic considerations. Therefore, most of the large Finnish energy companies are also partially state-owned [57].

4.3.1. Primary Energy

Finland imported 64.0% of its primary energy in 2016 and 63.0% of this amount originated in Russia, i.e., 40.4% of the total primary energy in 2016 was of Russian origin. Table 2 presents the primary energy imports from Russia in more detail. The value of Finnish primary energy imports in 2016 amounted to 7128 MEUR, of which 67.7% was related to trade with Russia [66].

As shown in Table 2, the most notable energy sources from Russia are oil, uranium, coal and natural gas, respectively. Natural gas is the most sensitive in terms of security of supply, as practically all the natural gas consumed in Finland still comes through a single pipe from Russia. Moreover, unlike other imported fuels, there are practically no natural gas storages in Finland. However, consumption of natural gas in Finland has decreased significantly in the 2010s due to its declining economic competitiveness [66], and the natural gas market in Finland is about to open up via LNG terminals and a new pipeline between Finland and Estonia, Balticconnector.

Table 2. Primary energy sources in Finland and the share of Russian imports in 2016 [66].

Energy Source	Consumption (TWh/a)	Share	From Russia (TWh/a)	Share of Total	Share of Imports
Biomass	99.5 [1]	26.3%	10.9 [2]	11.0%	91.5%
Oil	88.1	23.3%	67.4 [3]	76.5% [4]	76.5%
Uranium	67.5	17.9%	26.6 [5]	39.4%	39.4%
Coal and coke	35.3	9.3%	21.6	61.2%	61.2%
Natural gas	20.3	5.4%	20.3	100%	100%
Net electricity import	19.0	5.0%	5.9	30.9%	30.9%
Hydropower	15.6	4.1%	-	-	-
Peat	15.6	4.1%	0.1	0.5%	52.5%
Recycled and waste energy	8.1	2.1%	-	-	-
Heat pumps	5.9	1.6%	-	-	-
Wind and solar	3.1	0.8%	-	-	-
Other	0.3	0.1%	-	-	-
Total	378.2	100%	152.7	40.4%	63.0%

[1] Including all wood-based fuels, black liquor, biogas and other bioenergy; [2] Natural Resources Institute Finland [103]; [3] Including crude oil, middle distillates, heavy fuel oil, LPG, methanol and other petroleum products; [4] Estimated figure, as some of the oil is refined in Finland and exported; [5] Based on fuel sources and production volumes of Finnish nuclear power producers in 2016. Due to the relatively easy storability of uranium, consumption of uranium is a better indicator than the imports of a single year.

As mentioned in Section 4.1.2, Finland aims to halve its oil imports and phase out coal in normal energy use by 2030. Moreover, the global markets for crude oil and coal are liquid. Uranium, on the other hand, is not traded as openly, but there is still a variety of suppliers globally. All of the aforementioned three fuels (oil, coal and uranium) are relatively easy to transport and store. Furthermore, due to the obliged storages of imported fuels, disruptions in their supply would not cause acute shortages for end users of energy.

Finland is much less significant a purchaser of energy from Russia than what Russia is to Finland as a supplier. Of all Russian hydrocarbon exports in 2016, 1.4% of oil (Neste's refinery actions excluded), 1.0% of natural gas and 1.7% of coal were exported to Finland [66,74].

4.3.2. Electricity

Russia is not a part of the Nordic wholesale electricity market, Nord Pool, but is connected to it via two DC links and an AC line on the Finnish-Russian border. There are two modes of power trade between the countries, which are bilateral trade (1160 MW RU-FI and 180 MW FI-RU) and direct trade capacity (140 MW) [104]. In addition, Fingrid has reserved 100 MW of transmission capacity between the countries for system reserve. The lack of electricity market coupling between Finland and Russia has a few consequences. First, experiences of uncoordinated capacity remunerative mechanisms indicate that integrating different market mechanisms pose challenges and result in under-usage of capacity and welfare losses [77]. Secondly, the bilateral trade volumes need to be confirmed before the closure of the Nordic spot market, which complicates trade between the countries. Moreover, in contrast to the Nordic energy-only market model with zonal prices, Russia's market design is an energy-plus-capacity market with nodal prices, i.e., electricity prices are defined separately for each location of the grid. Nodal pricing is typically applied in systems that have congestion within the system and high transmission losses.

Along with the investment subsidies, Russia implemented capacity payments for electricity sales in late 2011, which significantly decreased the flow of electricity between Russia and Finland. As shown Figure 2, a majority of Finland's net electricity imports came from Russia until 2011 [66]. Since 2012, electricity has been imported from Russia mostly during peak demand periods, and the majority of imports come from Sweden. In 2016, approximately 40% of Russian net electricity exports were imported by Finland [66,79], which indicates that Russian electricity exports are far lesser in volume than those of energy fuels.

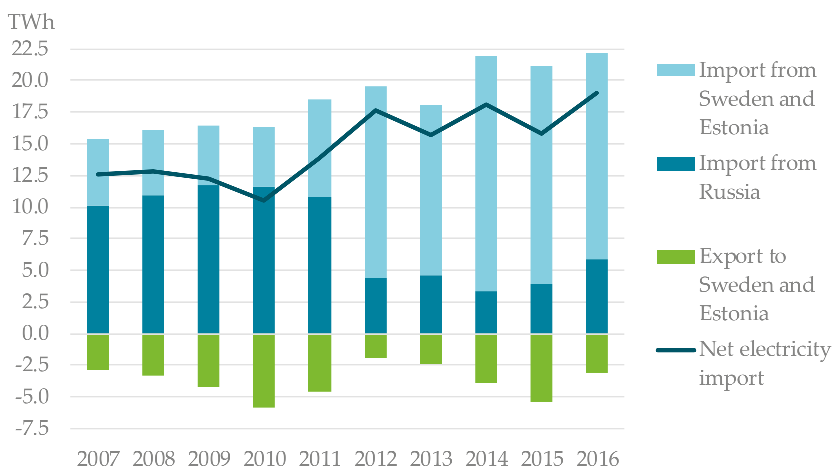

Figure 2. Electricity import and export in Finland in 2007–2016 and the decline of Russian electricity imports in 2012 [66].

Due to the notable subsidisation of power capacity in Russia, it is highly unlikely that electricity trade between Russia and Finland could be hindered by a lack of available capacity in western Russia. The power capacity in western Russia exceeds the annual demand peaks by almost 70% [105].

4.3.3. Political and Security Aspects of Finnish-Russian Energy Trade

In addition to supplying fuels and electricity to Finland, there are a few other connections rooted between Russia and the Finnish energy sector through corporate ownerships and technology transfer that have been the object of political debate. The key companies on the Finnish side are the half state-owned oil company Neste and the energy company Fortum, as well as a more recent actor, the Fennovoima nuclear power company. On the Russian side, they collaborate with the mostly state-owned companies Rosneft, Gazprom, and Rosatom. The Russian state has been cautious with regard to allowing foreign companies to operate in sectors it considers strategic, namely the energy sector [98], but Finnish companies are somewhat of an exception to this. However, there could be a possibility of trade with small enterprises, e.g., in biomass with less political risk, as they are mostly private businesses [99]. The two countries differ significantly as energy producers, and Finland's relations with Russia could be characterised more through asymmetric dependence. Yet, there are also elements of interdependence that are particularly evident in technology transfer enabled by Fortum.

Neste has operated in the oil business since the 1940s, and has been developing its portfolio towards biofuels. Nowadays, it could be considered a rather depoliticised case, but historically the company has been an object of political leverage from great powers, including Russia [28,106,107]. In the case of Neste, Russian influence comes from the fact that its processes are optimised for Russian Urals oil quality. This is also a topic acknowledged in the EU energy security strategy [1]. Therefore, fully changing to, for example, Norwegian Brent quality would bring significant economic loss [91]. The company is roughly 50% state-owned and it was an object of taxation worth 3.8 billion euros in 2017 [108]. Therefore, changes in the supply or profitability could have a fiscal impact on the Finnish government. Finland's Climate and Energy Strategy up to 2030 focuses only on domestic consumption of oil, but it is worth mentioning that the company exports oil products worth around 3 billion euros. Thus, regardless of domestic targets Neste could continue trading oil products to other countries.

Fortum used to be part of Neste as well, but it has grown through acquisitions from a domestic and Northern European company into a medium-sized global operator. The acquisition of Russian heat and power company TGC-1 in 2008 was the largest Finnish investment in Russia [109], and it allowed Fortum to gain a role as a regional player in Russia. Fortum also recently established the Wind Development Investment Fund with Rusnano, which is a subsidiary of the Russian nuclear company and agency Rosatom [110]. The joint project won a tender in 2017 to build 1000 MW of wind power capacity [111]. The expected income based on a guarantee price would be close to half a billion euros annually. Compared to the Nord Pool spot average price of 30–35 EUR/MWh in the recent years, while the guarantee price of 115–135 EUR/MWh in Russia is substantial. In a strategic sense, this project enables technology and knowledge transfer for Rosatom and allows Fortum to strengthen its market position in Russia. However, the recent Uniper acquisition by Fortum [112] is probably the most remarkable case. The acquisition links Fortum with the politically contested Nord Stream II gas pipeline [113], but it also makes Fortum a notable player in the Russian energy market, as Uniper is the third largest private utility in Russia. This has also opened some Russian concerns. For example, a politician and an economist, Mikhail Delyagin, even considered Fortum as a threat to national security in a Russian governmental newspaper [114]. Fortum disagreed with these comments, proceeded with legal actions and argued that energy is only about trade, not politics [115]. The Russian minister of energy also disagreed with this statement in the same newspaper and considered the company to be one of the greatest investors in the Russian energy sector [116].

Nuclear power has played an important role in Finland and is, generally speaking, widely accepted among the public [117]. However, Fennovoima continues to be an object of political dispute [29,118], with one of the reasons being Russian ownership and the contract for purchasing uranium from Russia for ten years after completion of the power plant. Although Russia has been a reliable supplier, this is a political victory at a time when the relations between Russia and the EU have deteriorated. Fennovoima is an important case from the perspective of Russian security of demand or energy diplomacy in general, as it would be the first Western project—something that Rosatom is currently lacking [17,89]. The EU energy strategy [1] has also raised concerns that member states should not be dependent on the Russian uranium supply and therefore diversification should be a key criterion in the new nuclear power plants. Rosatom is a fully state-owned corporation established in 2007 by the Russian Atomic Energy Ministry and continues to fulfil strategic objectives of the state [57]. Unlike, for example, Rosatom's Western counterparts, the company is part of the Russian armed forces and a central guarantor of Russia's Great Power position via nuclear threat, but it also provides expertise and regulation for the full nuclear power production cycle, from mining to nuclear waste. As the joint project with Fortum demonstrates, Rosatom is also aiming to broaden its portfolio to renewables and energy storage [119].

However, the way in which events have proceeded with Fennovoima has left questions in the public debate. One of the themes is that the Russian actors have been accused of pressuring the

Finnish government to make decisions in favour of Rosatom. For instance, the Finnish president Sauli Niinistö has been accused of pressuring Fortum to become a partner of Fennovoima [120], while the former minister of economic affairs, Olli Rehn, changed his position unexpectedly from opposing the project to full support. As he noted, the project could even have been cancelled in the summer of 2015. This would have significantly harmed Finnish-Russian relations, as Finland had at that time refused to obtain visas for Russian diplomats for participation in a meeting of the Organisation for Security and Cooperation in Europe due to EU sanctions, which led to a minor diplomatic issue [121]. That is, in line with the argument of Casier [10], the threat perception from security or foreign policy could have spilled over into the sphere of energy policy. In the early stages of the Fennovoima project, Russia was perceived in a negative fashion and Russian nuclear technology was perceived as outdated. Moreover, the Russian option was not included in the Decision-in-Principle. As Vehkalahti [15] notes, the debate on Finland's (external) energy security is always mirrored against Russia. The debate is coherent as long as Russia stays on the negative side. It has been discursively and politically challenging to frame Russian ownership as positive. For instance, the chairman of the board of Fennovoima, Esa Härmälä, argued that Fennovoima reduces Finland's dependence on Russia [122]. A more balanced argument could be that the power plant improves generation adequacy in Finland, while over the next decades Finnish dependence on Russia will remain more or less the same, which can be difficult to justify at the EU level with consideration to the EU energy security strategy [1].

If we place these cases and events in the interdependence framework, they show that energy is a dominant topic in mutual relations, although in terms of physical energy relations the risks are manageable. Finnish actors are balancing their interests with Russian ones, but also with the EU policy. It is relevant to note that regardless of the EU sanctions, Finnish companies have actually increased their cooperation with Russian actors, especially in the cases of Fortum and Fennovoima. With regard to oil, the Finnish energy and climate strategy focuses mostly on reducing domestic consumption, which means that the refinery activities of Neste are mostly unaffected.

5. Finnish-Russian Energy Trade in the Future

This section analyses the future of Finnish-Russian energy trade in three different scenarios: Market trends scenario, low carbon scenario and high carbon scenario.

5.1. Scenario 1: Market Trends

The market trends scenario is based on currently decided and implemented energy policy and climate actions. This scenario is in line with Pöyry's Basic scenario [91], which is in turn based on the scenarios of the World Energy Council (WEC), IEA, Energy Information Administration (EIA), McKinsey and BP. Despite the brief optimism and consensus regarding climate change mitigation after the Paris agreement, concrete actions to tackle the increasing amount of CO_2 in the atmosphere have been vastly inadequate. The uptake of renewables (and nuclear power) continues, but the global warming by the end of the century will be 3–3.5 degrees Celsius.

The energy transition proceeds as in the 2010s. That is, wind and solar power will retain their significant growth rates of around 7.5%/a, but a majority of the increasing demand for energy is covered with fossil fuels. Global consumption of fossil fuels thus increases, particularly in developing countries. Coal consumption peaks in 2025, but the consumption of natural gas and oil keeps increasing by approximately 1%/a until 2040. Development of the Finnish energy sector proceeds according to the Finnish energy and climate strategy from late 2016 until 2030. After 2030, the Finnish energy system develops according to its climate roadmap until 2050, i.e., towards 80–95% CO_2 emission reduction compared to the level in 1990 [123]. Despite the production costs of wind and solar power becoming much lower than those of fossil fuels by 2030, technological development of electricity storages is not fast enough to enable more rapid penetration of renewables.

Russia retains its role as an energy exporter. The increasing demand for fossil fuels in Asia compensates for the decreasing demand in Europe. The Russian economy continues to grow, but only slowly, by around 1–1.5% annually. Russia includes climate change mitigation in its policy, but this is not actively implemented. In terms of influence, Russia's ability to act will remain the same or decreases slightly. As energy incomes do not increase significantly, hard methods of influence, such as issuing threats, are unlikely.

Development of Finnish-Russian Energy Trade in the Market Trends Scenario

Table 3 presents the development of Finnish energy imports from Russia in market trends scenario. Biomass and peat are excluded from the table, as Finland has abundant domestic resources of both.

Table 3. Development of Finnish energy imports from Russia in the market trends scenario.

Energy Source (TWh/a)	2016	2020	2025	2030	2035	2040
Oil	67.4	65.0	50.0	33.7	28.0	24.0
Uranium	26.6	26.6	26.6	25.6 [1]	25.6	25.6
Coal and coke	21.6	20.0	16.0	8.0 [2]	6.0	3.0
Natural gas	20.3	17.0 [3]	14.0	10.0	10.0	10.0
Electricity [1]	5.9	3.0 [4]	1.0	1.0	1.0	1.0
Total	141.8	131.6	107.6	78.3	70.6	63.6

[1] Loviisa 1 and 2 are decommissioned and Hanhikivi 1 is deployed; [2] Coal is phased out in normal energy use. However, some of the industrial consumption remains; [3] The consumption of natural gas remains quite steady, but the Balticconnector and developing LNG markets reduce imports from Russia; [4] Finland becomes self-sufficient regarding electrical energy via the new nuclear power plants. However, Finland will continue to import electricity from Russia during annual demand peaks.

As shown in Table 3, energy imports from Russia decrease notably by 2040. This is mainly due to Finland's reduction of fossil fuels in its energy mix, and the largest decreases are in consumption of oil and coal. Finnish primary energy consumption reaches around 410–420 TWh/a by 2020 and remain roughly at that level until 2040. Therefore, assuming there are no biomass or peat imports in 2040, approximately 16% of Finnish primary energy consumption in 2040 is of Russian origin (comparing to 40.4% in 2016).

5.2. Scenario 2: Low Carbon

In the low carbon scenario, a strong global consensus and political will are achieved regarding climate change mitigation. In terms of world politics, this is achieved via a rather peaceful world without much confrontation among the great powers, as they are the ones with the most significant emissions. This scenario is in line with the 450 scenario of the IEA and Pöyry's Fast development scenario [91]. The scenario develops according to the aims of the Paris agreement, but inadequately in terms of limiting global warming to 1.5 degrees. Despite the prominent global growth in wind and solar power capacity and the reduction in consumption of oil and coal, global warming is 2 degrees Celsius by the end of the century.

The production costs of wind and solar power fall below those of fossil fuels in the 2020s. Furthermore, technologies for electricity storage develop quickly, allowing for faster penetration of variable renewable energy technologies. Global wind and solar power capacity growth rates are around 10%/a. Electric cars develop rapidly, which leads to a decrease of 1%/a in the use of oil. Demand for coal decreases by 2–3% annually. In addition to cheap wind and solar power, the increasing demand for energy in developing countries is met mostly with natural gas-based production. Therefore, demand for natural gas increases significantly by 2030, after which it retains a steady growth of around 0.5%/a.

Russia is still a prominent energy exporter in this scenario. However, the decreasing demand for coal and oil along with the consequent reduction in their market prices and growing emission allowances prices reduce Russia's incomes from energy exports notably. The increasing demand for natural gas, particularly in Asia, is not rapid enough to compensate for the reduction in demand for oil. In terms of influence, Russia's ability to act decreases notably. Russia increases its domestic consumption of coal and nuclear energy as the role of natural gas exports increases.

Development of Finnish-Russian Energy Trade in the Low Carbon Scenario

Table 4 presents the development of Finnish energy imports from Russia in the low carbon scenario.

Table 4. Development of Finnish energy imports from Russia in the low carbon scenario.

Energy Source [TWh/a]	2016	2020	2025	2030	2035	2040
Oil	67.4	62.0	47.0	30.0	24.0	20.0
Uranium	26.6	26.6	26.6	25.6 [1]	25.6	25.6
Coal and coke	21.6	20.0	13.0	6.0 [2]	4.0	3.0
Natural gas	20.3	17.0 [3]	12.0	8.0	7.0	6.0
Electricity [1]	5.9	3.0 [4]	1.0	1.0	1.0	1.0
Total	141.8	128.6	99.6	70.6	61.6	55.6

[1] Loviisa 1 and 2 are decommissioned and Hanhikivi 1 is deployed; [2] Coal is phased out in normal energy use. However, some of the industrial consumption remains; [3] The consumption of natural gas decreases, and the Balticconnector and developing LNG markets reduce imports from Russia; [4] Finland becomes self-sufficient regarding electrical energy via the new nuclear power plants. However, Finland keeps importing electricity from Russia during annual demand peaks.

As shown in Table 4, energy imports from Russia decrease slightly faster than in scenario 1 by 2040. The difference in the scenarios comes from the more rapid reduction in the use of oil and natural gas in Finland. Assuming no biomass or peat imports in 2040, approximately 13% of Finnish primary energy consumption in 2040 is of Russian origin (compared to 40.4% in 2016).

5.3. Scenario 3: High Carbon

The high carbon scenario is based on the IEA's RCP8.5 scenario [124], the Slow development scenario of Pöyry [91] and the Optimistic scenario in Russia's draft energy strategy up to 2035 [85]. The energy transition that started in the 2010s stagnates and global climate goals are abandoned. Instead of working on a systematic reduction in emissions, decision-makers keep prioritising national short-term economic growth and arguing over whether nuclear power or renewables are better for addressing the challenges related to climate change. The share of renewable energy in global power production mix keeps growing, but slowly. Growing scarcity of rare earth metals combined with slow development of electricity storage technologies hinder the cost reduction and penetration of wind and solar power. Electric vehicles remain much more expensive than those with internal combustion engines, and thus no electric vehicle revolution takes place before 2040. Demand for energy and the use of fossil fuels keep growing particularly in Asia. Energy trade with both the EU and China increases and, consequently, the Russian economy grows at an annual rate of 3% (compared to the current growth of around 1% per year). Russia's political leverage via energy trade strengthens significantly.

This scenario is in stark conflict with global climate change mitigation targets. However, the scenario also comprises increased demand for Russian uranium and nuclear power technology, and nuclear power is seen as a plausible tool for decreasing global CO_2 emissions [125,126].

Development of Finnish-Russian Energy Trade in the High Carbon Scenario

Table 5 presents the development of Finnish energy imports from Russia in the high carbon scenario.

As shown in Table 5, Finnish energy imports from Russia decrease slightly by 2040. Finland abandons its ban on coal for security of supply reasons, but the use of coal decreases as some of the power plants reach the end of their technical lifetime. Natural gas utilisation decreases slightly due to deployment of the Balticconnector and LNG terminals. However, as Estonian natural gas also originates in Russia, most of the natural gas eventually comes via the pipeline from Russia. Biomass and peat imports in 2016 remain at the same level until 2040. Therefore, approximately 32% of Finnish primary energy consumption in 2040 is of Russian origin (compared to 40.4% in 2016).

Table 5. Development of Finnish energy imports from Russia in high carbon scenario.

Energy Source [TWh/a]	2016	2020	2025	2030	2035	2040
Oil	67.4	66.0	65.0	64.0	63.0	62.0
Uranium	26.6	26.6	26.6	28.6 [1]	31.6	34.6
Coal and coke	21.6	20.0	18.0	16.0 [2]	14.0	13.0
Natural gas	20.3	17.0 [3]	15.0	15.5	16.0	16.5
Electricity [1]	5.9	4.0 [4]	4.0	4.0	4.0	4.0
Total	141.8	133.6	128.6	128.1	128.6	130.1

[1] Loviisa 1 and 2 are decommissioned and Hanhikivi 1 is deployed. TVO starts to purchase a growing share of its uranium from Russia; [2] Due to security of supply concerns, coal retains its role in the Finnish energy market; [3] The consumption of natural gas increases slightly, but the Balticconnector and developing LNG markets reduce imports from Russia; [4] The new nuclear power plants reduce electricity imports slightly.

6. Discussion

At the time of writing, it is still unknown how long the sanctions on Russia are going to continue and whether they will be broadened. Finnish companies are mostly cooperating with the state-owned Russian companies that have been the key targets of sanctions. In response to the broadening sanctions, Russia could, for instance, establish a stricter policy for foreign companies in the energy sector. This could increase the political risk for Fortum due to its ownership of Russian energy infrastructure. Furthermore, if sanctions were extended to the nuclear sector, they could weaken Rosatom's organisational and technological capacity to finish the Fennovoima power plant. As we have noted, both of these companies have been mentioned in high-level diplomatic meetings, meaning that the Russian side also acknowledges their importance and benefits. Russia's energy sector development is also closely tied to the interests of the regime of President Putin. If the regime shift occurs peacefully, the impacts on the Russian energy market will probably be minor, but if it does not, the political and economic risks could increase significantly.

The most relevant dimensions of energy security in our analysis were resilience regarding self-sufficiency, security of supply, affordability and the environmental impacts of energy supply. System balance is also an increasingly vital component with the growing share of variable renewable energy sources, and hence the role of, for example, demand side management [127], electrical energy storages [128], and power-to-fuel technologies [129,130] will become more important in the future. However, system balance has not been a major issue in Finland due to, e.g., the significant hydropower capacity in the Nordics. Despite the recent concerns about generation adequacy during electricity demand peaks in Finland [68], no threats have materialised so far. Therefore, particularly with regard to Finnish-Russian energy trade, the dependence on primary energy is a more compelling issue. Energy in general also continues to be a dominant topic on the diplomatic agendas of both countries.

One difficulty in terms of generalising results in energy security-related research is the unique nature of national energy systems and their corresponding trade relations. The analysed phenomena are so interdisciplinary and varied in nature that no single indicator can capture the complexity and define the specific level of (in)security. For example, the severity of the longer-term impacts of climate change are very difficult to compare with risks related to one country's political leverage on another via energy trade. However, on a global sustainability perspective, each passing year seems to raise the risks related to climate change higher on the list of acute energy security threats to be addressed.

As noted earlier, climate change mitigation is not high on the Russian agenda. However, inclusion of Russia in the global climate policy is important, as it produces roughly 5% of global CO_2 emissions. Another key question is what kind of procedures the climate change mitigation regime would enact for those countries that do not commit to the rules. For instance, France has proposed a carbon border tariff for those that do not commit to the Paris agreement [131]. If the EU proposed similar measures, would Finland follow the rules or try to retain good relations with Russia?

The scenarios in Section 5 should not be considered attempts to predict the future, and none of the scenarios is likely to materialise as such. Due to the growing urgency around climate change mitigation, it is anyhow advisable that the future is closer to the low carbon scenario than the high carbon scenario. It should be noted, however, that in the global perspective the low carbon scenario grows more unlikely by the day, as no consensus concerning the mitigation methods has been reached. Preferences on the mitigation methods vary between inter alia wind and solar power, nuclear power, and carbon capture and storage (CCS) [132]. It is not clear that any of these methods alone would suffice anymore [132,133], but rather a deep transition beyond current energy system optimisation is required [134]. Moreover, the currently planned and pledged climate actions result in emissions that are far higher than those required to limit the warming to two degrees [135,136] and the investment needs to fulfil the gap are substantial [137].

One subject of future research is the more thorough inclusion of embodied energy in intermediate trade, as Russia is among the largest net exporters of it [138]. Finland both imports and exports energy-intensive goods and, for example, Neste's refineries are optimised for Russian oil. Another subject of future research could be to calculate the marginal costs of increasing the self-sufficiency in energy supply in Finland. That is, at what cost could a self-sufficiency of 40–100% in primary energy supply be obtained. A third possible subject is a more systemic comparison of threat perceptions within a timeframe of multiple years and multiple energy forms, or case studies, e.g., to expand the research on public debate over Fennovoima to cover other energy companies, such as Neste or Fortum.

7. Conclusions

Finland's complex relationship with Russia regarding energy trade has raised concerns over whether the dependence on one supplier is in fact an energy security threat for Finland. In order to address this concern, we have analysed the energy systems and energy strategies of Finland and Russia and the Finnish-Russian energy trade including key aspects of recent public debate by loosely applying the interdependence framework. Furthermore, we have analysed the societal and (geo)political aspects of the energy trade, as the trade relations cannot be understood only through techno-economic analysis. We have also outlined three global energy market scenarios in order to analyse the future of Finnish-Russian energy trade.

Through purely techno-economic analysis, we found no acute energy security threats related to the energy trade, despite the fact that Finnish-Russian energy relations are constantly being discussed in Finnish and Russian media and in diplomatic meetings. Finland does import all of its natural gas and significant shares of its oil, coal, uranium and electricity from Russia. Of these, disturbances in the supply of natural gas and electricity are the most tangible, as they are connected to the existing pipelines and transmission lines, respectively. However, consumption of natural gas in Finland and Russian electricity imports have decreased significantly during the 2010s. For coal, oil and uranium, there is a variety of suppliers globally. Moreover, Finland stores an amount equivalent to at least several months' consumption for all of these fuels. There are no natural gas storages in Finland, but the critical demand for natural gas can be substituted with oil. Therefore, disturbances in the fuel supply would not cause an immediate energy crisis.

However, as noted in the literature, the energy relations and the concept of energy security go beyond the flow of fuels and electricity. Finnish policy has traditionally focused on retaining good relations, but not everything can be controlled by Finland. The energy sector plays a vital role in the Russian economy and it is entrenched deep within Russia's political strategy. If a strategic shift occurs, spill-over effects to Finland or Finnish companies are possible. The Finnish and Russian energy strategies are also very different in nature. Finland aims for carbon neutrality and self-sufficiency while retaining its security of supply, whereas Russia aims to strengthen its role as a global energy supplier. In other words, Russia is more concerned with the security of demand. Apart from the Fennovoima project, Finland's energy policy is thus directed towards decreasing dependence on Russian energy, while Russia's energy strategy would prefer the opposite.

We studied the development of Finnish-Russian energy trade until 2040 in three global energy market scenarios: Market trends, low carbon and high carbon. The share of Russian imports in the

Finnish primary energy mix decreases in each scenario, comprising 16%, 13% and 32% of the Finnish energy supply by 2040, respectively. This is mainly due to decreases in the use of oil, coal and natural gas in Finland. The scenarios inevitably vary in terms of how the Finnish-Russian energy trade develops, but the more significant differences are in their impact on the global climate and the Russian economy. The Russian economy generally benefits from the increasing global demand for fossil fuels and uranium. Apart from uranium and nuclear power technology, what is beneficial for the Russian economy in terms of energy can be detrimental to climate change mitigation. As the market trends scenario is already dubious with regard to climate change mitigation and the plausible multiplicative effects caused by climate change, realisation of the high carbon scenario could result in challenges far greater than the slower development of Finnish self-sufficiency in energy supply.

In conclusion, Finland's notable dependence on Russian energy has so far not resulted in the materialisation of any security of supply threats, and the dependence is unlikely to worsen in the future. All the analysed scenarios result in a reduction in the use of fossil fuels in Finland, and, consequently, also in energy imports from Russia. However, as we are currently experiencing turbulent times, in terms of societal, political, and economic trends, there are possible risks and feedback loops that could affect Finland.

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Critical Infrastructures: The Operational Environment in Cases of Severe Disruption

Ossi Heino [1,*], Annina Takala [2], Pirjo Jukarainen [1], Joanna Kalalahti [1], Tuula Kekki [3] and Pekka Verho [4]

1 Research, Development and Innovation, Police University College, P.O. Box 123, FI-33721 Tampere, Finland; pirjo.jukarainen@poliisi.fi (P.J.); joanna.kalalahti@poliisi.fi (J.K.)
2 Faculty of Built Environment, Tampere University, P.O. Box 600, FI-33014 Tampere, Finland; annina.takala@tuni.fi
3 Research and Development, The Finnish National Rescue Association (SPEK), Ratamestarinkatu 11, 00520 Helsinki, Finland; tuula.kekki@spek.fi
4 Faculty of Information Technology and Communication Sciences, Tampere University, P.O. Box 692, FI-33014 Tampere, Finland; pekka.verho@tuni.fi
* Correspondence: ossi.heino@poliisi.fi

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Abstract: The functioning and resilience of modern societies have become more and more dependent on critical infrastructures. Severe disturbance to critical infrastructure is likely to reveal chaotic operational conditions, in which infrastructure service providers, emergency services, police, municipalities, and other key stakeholders must act effectively to minimize damages and restore normal operations. This paper aims to better understand this kind of operational environment resulting from, for example, a terrorist attack. It emphasizes mutual interdependencies among key stakeholders in such situations. The empirical contribution is based on observations from a workshop, in which participants representing the critical services and infrastructures in Finland discussed in thematic groups. Two scenarios guided the workshop discussions; nationwide electricity grid disruption and presumably intentionally contaminated water supply in a city. The results indicate that more attention should be paid to the interdependencies between critical infrastructures, as well as to the latent vulnerabilities hidden inside the systems. Furthermore, producing security seems to require continuous interaction and creation of meanings between extremely different actors and logics. This implies a need for changes in thinking, particularly concerning the ability to define problems across conventional administrative structures, geographical boundaries and conferred powers.

Keywords: critical infrastructure; resilience; interdependencies; water; energy; terrorism

1. Introduction

Today, approximately half of the world's population lives in urban areas, and it is assumed that urbanization will accelerate so that only one third will live outside urban areas by 2050 [1]. This development raises a variety of challenges that also impact the infrastructures, the reliable and effective functioning of which will determine how cities are able to respond to the demands of quality of life [2]. Some of these infrastructures are called 'critical' as societal well-being is fundamentally built on their reliability. They can be understood as the backbones of societal sustainability, safety and security of supply. The functioning of critical infrastructure impacts directly and indirectly on the prices of goods, economic competitiveness, public health, education, potential to fulfill oneself, and through all of these also societal resilience, i.e., the ability to cope and recover after crises [3–5]. Critical infrastructures provide people with access to a wide range of commodities, the availability of which is essential to the resilience of communities [6,7].

Alongside urbanization, technological networks that enable 'normal' and 'aspired' quality of life have grown in number and density while their importance has also been accentuated. As interconnectedness and interdependencies also grow, this means that the critical infrastructures are more vulnerable to systemic risks and the possibility of unpredictable and extensive failures [8]. The 'criticality' of critical infrastructures implies that more attention has to be paid to their security. Disruptions to critical infrastructures can have such strong and widespread effects that they can also deteriorate the public sense of security and trust in the structures and institutions that uphold social stability. Severe disruptions of critical infrastructure services can seriously challenge the general public's trust in the systems that have generally been seen as reliable and are expected to function efficiently in recovery after a crises [9].

This is where the interconnection of sustainability, security, and resilience is displayed in the context of critical infrastructure. Without delving too deeply into the meanings of these much used, and in many ways blurred, concepts, it can be said that their interconnections lie at the heart of societal development. Resilience has succeeded in bringing a new perspective to security discourses in which, instead of the classical probabilistic worldview, the underlying instability and the root cause of uncertainty are taken as the starting points [10]. Then again, resilience has often been applied too uncritically and as automatically good, whereas some safety investments made in the name of resilience have in fact reduced safety or hidden the resilient nature of various negative threads [11,12]. The concept of resilience has helped in understanding sustainability, and as a result, it has been possible to enhance the sustainability of systems by reinforcing their resilience. On the other hand, strong resilience has been shown to be the reason for the unsustainability of some systems [13]. It is also possible that sustainability and security can be pursued by reducing redundancy, which, as one of the essential aspects of complex infrastructure systems resilience, has produced systemic vulnerability and thus resulted in completely the opposite outcome [13]. Thus, resilience can be said to be focused on the adaptability of the system over a relatively short time span, while security and sustainability are broader and more far-reaching phenomena. The relationship between them is ambiguous. In any case, the infrastructures of urban environments are interesting in the sense that they are material compositions at the very heart of urban development, creating and modifying the ways and conditions of human co-existence [14]—they are the hard core of sustainability and security.

Severe disruption caused by humans, including terrorism, targeted at critical infrastructures undoubtedly shakes understandings of secure and sustainable living environments. Because of the essential role of critical infrastructures in society, it is easy to understand that an attack on them would match the terrorist modus operandi of causing severe disruption to societal stability. Furthermore, critical infrastructure has not been planned and built to take into account these kinds of human-induced threats. As Koppel maintains, it is difficult to add security aspects afterwards to a system that has not originally been planned to take these into account [15]. It is probable that in the case of intentional attacks and attempts to influence critical infrastructure, conventional risk preparedness will not suffice as the authorities' and utility service providers' operational environment will be considerably altered due to human threat. Thus, the central motivation of this paper is to better understand the operational environment in a situation where critical infrastructure is the target of terrorist activities or other intentional disturbance.

From the point of view of terrorism, urban environments are particularly tempting targets because cities can be seen as the nodes on the networks where people, value streams, ideas and information meet [16]. Coaffee argues, that particularly after the 9/11 terrorist attack, modern megacities have become the central scenes of terrorism as they offer a wide spectrum of economically, socially, and symbolically valuable targets and a suitable context for terrorism [17]. New forms of terrorism have revealed the vulnerabilities of urban areas and incited new forms of security production. Accordingly, it can be argued that terrorism is nowadays a part of urban redevelopment.

In addition to the fact that the operational environment is tainted by an ever more complex risk landscape, the actor network involved in preparing and responding to risks is also increasingly complex [18]. One key issue is how authorities and utility service providers are able to provide safety and security and restore normality after a severe disruption to critical infrastructure. An attack on critical infrastructure would expose unpredictable interdependencies and cause cascading effects that do not align according to the conventional structures and hierarchies of risk and safety management [19–22]. This kind of attack would challenge the vulnerabilities embedded in the conceptions of preparedness and the ability to respond both as separate entities and as part of a collaborative effort [23]; this kind of situation would, rather, necessitate self-direction, extended mandates, or even unauthorized solutions and require unforeseen capabilities within unusual roles. It would, e.g. urge authorities to exceed conferred powers, which is strictly forbidden and not even necessary in normal situations. Emergency management is primarily based on bureaucratic procedures; the strict orders, legal regulations, contingency plans, and operational guidelines are an important part of their justification and authorization. As discussed, severe disruption in critical infrastructure would challenge these premises and it is topic of interest in this paper.

This paper can be characterized as an examination of theory that is guided by empirical observations. The first goal of the paper is to illustrate the mutual interdependencies revealed by severe disturbances of critical infrastructure and thus to perceive the multi-actor situations that open up. The second goal, based on the preceding one, is to describe some of the key requirements of the main actors that emerge as a result of a serious disruption to critical infrastructure. As the paper progresses, excerpts from the empirical material are used to guide and concretize the theoretically oriented discussion.

The theme of this paper will be approached by first discussing the role and characteristics of critical infrastructure in modern societies. The empirical contribution of this paper is based on the KIVI project workshop focused on the vulnerability of critical infrastructure and the operational capability of authorities. The context and methodology are described in section three. The KIVI ("Vulnerability of critical infrastructure and operational capability of authorities") project aims to enable the anticipation of and preparedness for crises and disturbances of human origin, related to authorities and service providers of critical infrastructure. Results are discussed in section four by presenting an exploration of the key components of critical infrastructure from the point of view of severe intentional disruption. Lastly, the findings of this study are concluded in section five.

2. Critical Infrastructure as the Foundation of Normality and Security

To begin with, it is necessary to define what is meant by infrastructure and why some of it is considered to be socially critical. In this section, the definitions and most important aspects of critical infrastructure will be discussed.

2.1. Producing the Mundane

By definition, infrastructures refer to structures that form the underlying base or background, enabling activities that happen in the front or above this base [24]. Infrastructures maintain the vital functions of society and regeneration, and make our everyday life foreseeable, safe and healthy. Infrastructures provide resources for the creation and renewal of everyday practices. They are, therefore, the material compositions that shape the spectrum of social practices. In shaping the dynamics of a daily life course, they impact what is considered to be normal and sufficient [25,26]. However, their wide-ranging benefits to societal and sustainable development do not always get the attention they deserve in decision-making processes [27]. As the impact of infrastructure has been embedded in mundane practices when they function as expected, they are simultaneously everywhere but not really anywhere.

The interweaving of infrastructures and social life—or the co-evolution of infrastructures and the society surrounding them [28]—results in the fact that the convenience, safety, and healthiness of everyday life are bound to, and our societal processes rely on the access to, infrastructures and their impeccability. Societies are thus increasingly vulnerable to disruptions in these infrastructures.

In other words, the more unreservedly everything relies on infrastructures, the more damaging their failures [29,30]. Infrastructures can thus become critical in relation to those who rely on them. Concretely, the criticality of an infrastructure can be assessed in the event of a disturbance, which reveals, in addition to technological vulnerabilities, how unreservedly the reliability of infrastructures is trusted. This is of particular interest because infrastructures are in many ways, and on many levels, interconnected and dependent on each other's existence and performance.

2.2. Criticality of Infrastructures

Some infrastructures are called critical when referring to their particular relevance or necessity. The US National Infrastructure Protection Plan 2013 [31] uses the following formulation to define critical infrastructure: "Systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters". Following this definition, critical infrastructure plays an essential role, for example, in processes that are crucial for the functioning of society. They are therefore systems whose disruption or collapse would lead to serious consequences and crises of social order. Their criticality can be assessed by outlining the importance of a system for citizens, the economy or the ability of service providers to function. In this case, the factors to be taken into account in the assessment are factors related to the duration, extent, and absorption capacity of the system in case of disruption [32]. Criticality assessment can also be done by paying attention to, for example, system preparedness, interdependencies, dependence of people and activities on the systems, and relevant risks [33]. On the other hand, the definition of the criticality of infrastructures has expanded so that the systems can be called critical quite loosely. For example, Fjäder quite rightly asks: if everything is considered critical, is anything really critical anymore [34]? A similar position is maintained by Riedman, whose case studies suggest that in some cases the worst scenarios related to the so-called critical infrastructures, did not, in reality, cause particularly dramatic damage [35].

In Finland criticality is defined, for example, in the Criminal Code of Finland [36], according to which a sentence of criminal mischief is given for person who causes serious danger to "power supply, public health care, defense, administration of the law or another corresponding important societal function". Also in relation to data and communication offenses, the Criminal Code defines, with slightly different wording, actions that could endanger "the energy supply, general health care, national defense, the administration of justice or another function that is important to society and that is comparable to these".

2.3. Interdependencies

The aforementioned interconnection of systems is often referred to as interdependency, which, in the case of infrastructure systems, may occur between different types of systems, between different stages of system development, and between the different operational and maintenance phases of systems [37]. Interdependencies have a significant impact on the disruption dynamics of critical infrastructure. Due to the interdependencies, an abnormal event in one system may cause an impact somewhere else, which in turn may still cause further effects both to the original system and to other systems that are connected to it. Due to the interconnections and the socio-technical nature of critical infrastructure, disturbances can be very nonlinear and unforeseen. Interdependencies can act as an intensifying structure as they transport effects from different levels and places to others [38]. It is also worth noting that the diversity of systems, together with the interdependencies between them, make urban areas vulnerable to cascading effects [37].

Without discussing comprehensively cascading failures, it is worth mentioning some examples. The floods in Europe in 2002, the volcanic ash cloud created by the eruption of Eyjafjallajökull in 2010 and Hurricane Sandy in 2012 are all examples of cases where external shock caused by natural forces has caused significant cascading effects in addition to direct destruction. The power outage in Italy in

September 2003 and the Northeast blackout in the same year are examples of cases where a relatively small fault in the power plant, such as a software bug that activated in the alarm system, has had far-reaching effects. As Helbing points out, extreme events do not necessarily need a massive external shock to happen, but also the internal aspects of the system can transfer and escalate effects [8].

The interdependence of infrastructures was first highlighted in 1997, when the pioneering report Critical Foundations: Protecting America's Infrastructures was published by the President's Commission on Critical Infrastructure Protection (CIP). The report noted that national security, prosperity and social well-being depend on reliable infrastructures that are increasingly complex and interdependent [39]. For example, the National Infrastructure Protection Plan 2013 [31] defines dependency as "The one-directional reliance of an asset, system, network, or collection thereof—within or across sectors—on an input, interaction, or other requirement from other sources in order to function properly" and interdependency, respectively, as mutually reliant relationship between entities; the degree of interdependency does not need to be equal in both directions. Although 'dependencies' and 'interdependencies' are conceptually simple, as a phenomenon they are apt to increase the overall complexity of critical infrastructures dramatically and to impact the qualitative aspects of the risk and vulnerability landscape: First, the potential of cascading and escalating effects is increased. Second, it brings forth new kinds of vulnerabilities that are hidden in the qualities of interdependencies and the functionalities of various interfaces. Third, possibilities for intentional harm are also increased [40–42]. Various interdependencies may arise unnoticed when systems are designed, built and developed partly on the reliability of existing structures. In other words, it is not evident how and which other systems a system is dependent on.

Because interdependencies are a characteristic of critical infrastructures, they should also be perceived from a system-of-systems (SoS) perspective. SoS outlines the understanding of critical infrastructure as a joint formation of different components, each of which are large scale systems in their own right and can operate autonomously both technically and administratively. However, each subsystem is exposed to effects resulting from an impact to one or more other subsystems [43]. From this point of view, interaction is more important than the autonomous function [43], which motivated by systems and complexity theories, emphasizes the emergent interaction between the parts and the whole. Maier [44] emphasizes communication as a defining element of a SoS and information exchange as a prerequisite for its ability to organize. In this case, the focus is on the interfaces between different systems. The interactions and interdependencies of complex SoS systems also explain how a micro-level phenomenon can trigger dynamic processes leading to macro-level consequences [43,45,46].

In practice interdependencies are manifested, for example, when a seemingly insignificant disruption in one technical component is transmitted from one system, service, and process to another, eventually causing a severe threat to health and safety. It becomes obvious that a component level disruption may, in a suitable situation, trigger a chain reaction the final effects of which will only be seen after the interdependencies have materialized [47]. Pescaroli and Alexander outline a new perspective for understanding the vulnerability of critical infrastructures [48]. They apply the concept of panarchy referring to the dynamic interaction of the different layers of hierarchical systems. The disruption of critical infrastructure cascading to disaster can result from the vulnerabilities nested on various levels of the system. The connections in interdependent systems reinforce the structural weaknesses of these systems as they transmit these weaknesses from one level to another. In other words, a situation that escalates into a catastrophe does not need to be caused by a massive external shock, but a suitable combination of inner systemic vulnerabilities suffices [8,48]. A locally restricted component-level disruption may result in a series of non-linear development paths where the progression of the disturbances may occur faster than the recovery, and the scale of the consequences no longer correspond to scales of origin of the disturbance. In this sense, the issue of critical infrastructure security is also becoming a part of global economic and security themes [47]. Nonetheless, it is worth pointing out that the positive causal relationship between interdependencies and vulnerabilities is not always as self-evident as is implied, because of the impact of the topology of networked structures, cascade mechanisms, and interconnections of vulnerabilities between systems. In other words, it is possible that the increase in interdependencies actually reduces the risk of cascading failures [49].

2.4. Systemic Resilience

When examined from the point of view of intentional disturbance it is worth noting that the interdependence of systems forms critical nodes whose adept exploitation can cause large-scale and profound consequences to the social order and trust with relatively small effort [50,51]. Thus, critical infrastructure needs to be included in the debate on terrorism and the means of combating it. Adapting Ulrich Beck's idea of a 'risk society', a rather fertile ground has been created for extensive intentional disturbance. It is important to note that the effects of critical infrastructure disruptions may today be different from those a few decades ago as the functions and processes, which rely on critical infrastructures, have increased and become more complex. Critical infrastructures as socio-technical systems not only provide security, healthiness, and convenience, but also increase the operational reliability of those processes that manage the interoperability of different systems. It is thus part of society's system for resilience.

In this context, the resilience of critical infrastructure is seen as the system's ability to absorb disruption effects and to reorganize to maintain crucial functions, the most necessary structures and identity [52]. According to Little, the magnitude and intensity of the consequences of critical infrastructure disruptions depend on the quality of the interference, the number, and nature of the interdependences, the redundancy in the systems and the available capacity to produce countermeasures to restore the situation [53]. In this sense, the issue is also linked to the management of critical infrastructure as it has a crucial effect on the systemic vulnerability of systems with interdependencies [18]. Resilience cannot therefore be seen solely as a technocratic or sector-specific reduction, but rather as a cross-border and socially charged concept [54]. Referring to "the tragedy of the commons" phenomenon, Haimes examines the resilience of interdependent infrastructure systems from the SoS perspective, and illustrates how the different missions, goals, and schedules of different actors alone constitute a collection of human factors whose discordance with other interdependent systems' can have a significant impact on the functioning of a given SoS [43]. In this sense, the challenge is precisely to see the integration of one's own activities into entities of which no one has complete knowledge.

The impacts of management solutions are not always obvious. There are latent vulnerabilities and resident pathogens that occur during the design, construction and operation of critical infrastructures. They are hidden inside the systems for long periods of time and appear as unexpected components when disruptions cascade and the situation escalates [55–57]. In other words, there are always causal factors of a severe disruption embedded in critical infrastructure. These are invisible and inactive in normal conditions but still embedded in the depths of the socio-technical systems, waiting to be triggered when the conditions are favorable. These latent vulnerabilities determine the spread and escalation of the consequences of disturbances [8,48,58]. As Pescaroli and Alexander point out, in a system susceptible to cascade effects the magnitude of systemic vulnerabilities is more defining than the magnitude of the original phenomenon [38]. Although the triggering of cascading disruptions cannot generally be predicted, their potential can be integrated into preparedness and resilience thinking. In this respect, resilience is also the ability to ensure that the system is not overwhelmed by latent vulnerabilities.

3. Methodology

The main empirical material for this paper was collected in a workshop organized at the Police University College in Tampere, Finland, in January 2018 in association with a steering group meeting of the KIVI project. The workshop was facilitated by a modified Open Space method. As an orientation to the workshop, the participants were introduced to two different scenario-based exercises that reflected the model for comprehensive security defined in the national Security Strategy for Society [59] and related to the vulnerabilities identified in the National Risk Assessment 2015 [60]. In the first scenario, participants tackled a case in which a nationwide electricity grid disruption occurs in the freezing conditions of late December. The second scenario presented a situation where presumably intentionally contaminated drinking water causes serious illness and disease in a city. Both cases were severe, abnormal situations but not (yet) formally defined "states of emergency" which would have an impact on the powers of the authorities.

Unlike the original Open Space method participants did not suggest topics for discussion; instead they were invited to discuss under four preliminary prepared topics. Three of these derived from the Security Strategy for Society: formation of situation picture/awareness, competencies and resources in crisis management and crisis communications [59]. In addition to these participants were invited to provide support for the development of a new kind of self-assessment tool in terms of continuity management. In line with the Open Space method, participants were allowed to move freely between the topics (discussion groups). Researchers from the KIVI project facilitated, recorded and later analyzed and transcribed the discussions.

The workshop participants represented the following Finnish organizations: Energy Authority, Fingrid (Finland's electricity transmission system operator), Finnish Energy, the Finnish Red Cross, the Finnish Water Utilities Association, Helsinki City Rescue Department, Police University College, National Emergency Supply Agency, Tampere University of Technology, the Finnish National Rescue Association, the National Cyber Security Centre of Finnish Communications Regulatory Authority, the National Police Board, the Pirkanmaa Safety and Security Cluster, and the Security Committee. The total number of participants was sixteen. The participants represented the key actors who would be involved in scenarios such as those discussed in the workshop.

Although this paper does not deal with the case of Finland per se, it is appropriate to briefly describe the concept of security in a Finnish context, as this can be assumed to contribute to the shaping of the workshop participants' thinking processes and methods. In 2012, the Government of Finland gave a Resolution on Comprehensive Security, which emphasized the networking of society, the interconnection of threats and the consequent difficulty of forecasting. According to this, securing of critical societal functions should be carried out in collaboration between the authorities, the business sector and citizens. The Government Resolution on Comprehensive Security covers the management of disruptions, including measures taken by the responsible authority, mutual assistance between authorities, and ensuring the information exchange between the various parties to produce up-to-date situational awareness and make relevant decisions. However, Branders, in her doctoral dissertation, points out that the idea of comprehensive security takes a view that all identified security threats could be managed [61]; this differs from our view in this paper, which emphasizes systems' ability to cope in general and in particular with unpredictability.

As the workshop participants were experts responsible for preparedness actions, civil protection and/or represented organizations vital for the security of supply, much of the collected information is confidential or security sensitive. Protecting such information is an absolute prerequisite for carrying out research, and has an impact on the publishing of the results [62] (pp. 257–264). Therefore, in this paper, phenomena are treated in a way and at a level that respects the requirements of enhanced security but still strives to deepen our understanding of the phenomena being examined.

One more thing needs to be taken into account. The kinds of phenomena that are of interest in this paper are such that there is limited amount of experience of them. Thus, the situations that emerge from the workshop scenarios are novel, and discussion is based on the creative adaptation of prior experience and knowledge. It is assumed, that the workshop experts, with their vast experience, have a sophisticated understanding of many of the structural features related to critical infrastructures and their disruptions. However, the analysis provides only a limited view of the development needs for preparedness. Rather, this paper contributes to the preliminary analysis and exemplification of the research topic. Ultimately, this paper seeks to find the building blocks of the logic that determines either success or failure in the case of a severe disruption of critical infrastructure.

4. Critical Infrastructure in the Face of Severe Disruptions

In this section we examine the results based on the workshop discussions. Direct excerpts from the empirical material provide examples of the discussions and thus concretize the theoretically oriented results. First, attention is turned to the challenging operational environment that emerges as a result of severe disruptions to critical infrastructure. Second, the role and formation of situational awareness in decision-making are considered. Third, the new challenges facing critical infrastructure sectors are explored and their impact on vulnerability is discussed. Fourth, the potentiality of critical infrastructure as a target of terrorist attack is given serious consideration.

4.1. Disruption Requires an Innovative Search for Resources and Competencies

As mentioned earlier, the convenience of modern everyday life is based on many self-evident structures. A good example of this is critical infrastructure that as a collaborative socio-technical system helps to produce normality. When it works as expected, no single service, function, or actor is distinguished from the whole that it is a collaborative part of. Such a requirement for collaboration exists in both normal and exceptional situations, but it is noteworthy that the participating actors may vary depending on the situation. An actor that is perceived as an 'outsider' in normal situations can become an important collaborator in exceptional situations. In the workshop, participants discussed the multi-actor situation emerging from the scenarios:

> "This isn't only for the police, but it is for multiple authorities. Even if there was a crime committed and that belongs in police jurisdiction there is still stuff that concerns public health, social services and what not. This would require all sorts of arrangements. I mean, this whole [city district] would be uninhabitable. And public health services, one hospital cannot cope with all these patients. This would require a collaborative effort from several authorities to get people to some habitable place."

It is noteworthy that exceptional circumstances necessitate effective collaboration even if the actors are institutionally fragmented. Critical infrastructures have been the subject of substantial reform and change over the last decades. As part of fragmented urbanism, the management of critical infrastructures has shifted to the hands of highly specialized professional groups [63]. This has enabled each group to focus on maintaining and enhancing their own area of expertise. The underlying problem of this development is that the understanding of systemic vulnerabilities has deteriorated.

Through fragmentation, the security and resilience of critical infrastructures are largely seen as an inter-organizational issues, i.e., processes formed in various contractual networks and interaction relationships. Then again, the deterioration of the understanding of systemic entities suggests that connections to the meta-strategies of comprehensive security are weakened. If this is true, seeing infrastructure management as part of the context of internal and external security, the prevention of terrorism and crisis management become increasingly distant. To counteract this, the Nordic countries, for example, have been striving to reinforce the principles of comprehensive security and a broader concept of security that interweave public administration, business, non-governmental organizations, and citizens to improve the resilience of society [64]. The role of such actors may be vital in exceptional situations; they may be essential for continuity even if they are not thought to be relevant when designing systems or managing them in normal situations.

A further feature of a severe disturbance in critical infrastructure is that many of the resources needed by key actors will become inadequate with respect to the level of needs in the situation. At the same time as the available resources and information seem inadequate decisions should be taken to manage the situation and to protect citizens. One example of this was manifested as the workshop participants discussed the congestion of the emergency response centre and the decision-making pressure in the water scenario.

> "112 [emergency number] will probably be congested just by the relevant phone calls, as there will be so many of them. And then the capacity, I have to get back to the fact that there is no such resource that if in real life an area of this size was badly polluted that there would be any chance to have a system to treat the patients. [...] Of course, there are antidotes for the poison, but how quickly can they be taken into use, well, I suspect it won't be very quick."

> "In these situations, there's a need to make big decisions very rapidly. Prohibition of water use, closing water taps, moving people, full mandatory evacuation at some point ... well, I wouldn't want to be the one making these decisions."

4.2. Shared Situational Awareness and Collaborative Sense-Making Are a Necessity

One major theme in the workshop discussions was the formation of a situational picture and awareness. In normal situations much of the information is such that one specific actor can keep it to him or herself, but in a case of disturbance this information must be efficiently shared so that decision-making can be based on appropriate understanding of the overall situation. Participants in the workshop maintained that the formation of more or less uniform situational awareness is a key prerequisite for decision-making. It is noteworthy, however, that the preconditions for the shared situational awareness are formed long before the real need for information exchange and joint analysis materializes; preconditions are comprised of operational practices and cultures, levels of trust, judicial frameworks, and their interpretations.

> "It would be absolutely essential that we could make the right conclusions. After the right conclusions have been made, it is a different story what happens then. But the point is how to reach the [conclusions], you will most definitely need information from other actors. [...] Once we have formed the right situation picture and awareness only then can action proceed and the right measures be taken. Before that it is quite unclear."

> "This comes down to the fact of how well the cooperation between the healthcare, the police and the rescue has been built, so that a situation picture can be formed. Environmental health [department], water utility, all these [actors]."

> "And then, how can this be identified as regional or local. So, how do different provinces and hospital districts talk to each other? So, the formation of a kind of nationwide picture of this, on top of everything."

Multiagency situational awareness and a picture are the essential elements in decision-making when talking about the ability of key actors to function in dynamically changing operating environments such as in the case of critical infrastructure disruptions. For example, Pescaroli emphasizes the importance of access to information and the preconditions for establishing a dialogue in coordinating cooperation [19]. Baber and McMaster talk about 'collaborative sensemaking' highlighting that it is important not only to participate in the information gathering and sharing processes, but also to understand who should be involved in these processes [65] (p. 14). It is necessary so that the key actors can effectively focus scarce resources on the most important issues. Baber and McMaster further point out that the idea of collaborative sensemaking is not to ensure that each actor has the same schema and knowledge structure as the knowledge needs and the responses generated based on the information are actor-specific [65] (p. 66–69). In other words, it needs to be noted that the situational awareness has a tendency to develop from interaction between actors, and each actor has their own interpretation of the emerging patterns and no one can claim sole ownership for them. One workshop participant discussed this issue in the following way:

> "This is an important question. We have been thinking about this a lot in our organization. Should an authority that is generally responsible for leadership in the situation be sharing its own situation picture or an overall shared situation picture? If it shares its own picture, other actors may not understand anything about it. [...] When every sector has their own language (and mode of action) that others do not understand. It would be good to get them into understandable language and to all the important actors. But it really requires that you are in touch with each other and talk about what the situation actually is. If one authority, let's say rescue, tries to make a situation picture of its own, then it goes down the drain."

As can be seen in the above citation, the multi-actor situation opened up by the severe disruption of critical infrastructure also causes management challenges. The widespread nature of the effects of disruption complicates the division of tasks and responsibilities, especially in situations where no prior experience exists. But above all, the difficulty is accentuated by the change of context: if, in a normal situation, critical infrastructure systems can be seen as technical objects severe disruption forces them to be examined anew. Working in the framework of comprehensive security, collaboration and shared situational awareness is not just a continuation of normal activities, but a different way of thinking. It was also emphasized that, instead of exclusively sector-specific tasks and responsibilities, key actors also have common requirements necessitating collaboration. A severe disruption brings forth actors whose ability to contribute to a collaborative set-up is essential to the system's ability to recover. Such capabilities are determined as the disruption is triggered and the scale and severity of the situation begin to become evident. As Boin and Smith point out, it is not even always evident from the beginning, which infrastructures and actors prove to be critical in a particular case [66]. The disruption reveals actors whose functional capacity is essential for the recovery and functioning of the entire system of collaboration.

The communication and information processing practices adopted by organizations are also latent factors in the system, which may, in the face of severe disruption weaken the collaborative capabilities of actors [56]. Their consequences may become tangible when collaboration is needed, even though they might have previously been difficult to identify and out of the reach of the established ways of thinking and traditional risk management. When looking at the communication of organizations, the focus should therefore be on the interdependencies, collaborative sensemaking and the presence of ignorance and unpredictability [65,67]. Workshop participants illustrate the difficulty of sharing information with an example of health care in a situation where information related to the state of health and symptoms should be rapidly dispersed:

> "If we are now thinking about the health side of things, for example. When in a situation described by the scenario, the patient is brought in, so he trusts that information will not be revealed, but that health issues are kept secret. There may be a big threshold to give out information."

> "And what really interferes with much of the cooperation, even between authorities, are these privacy protections; they cannot share information about people with each other. It is a continuous problem, especially in major accidents. Help does not reach those in need because of these information security challenges."

4.3. Threats against the Cyber Domain Have Increasingly Serious Repercussions in Urban Environments

In addition to the characteristic interdependencies of critical infrastructures, it needs to be noted that due to the development and strengthening of automation and telecommunications technology, the systems are ever more merged into the ubiquitous 'social fabric'. With smart technologies, the Internet of Things (IoTs), automation of transportations, and so on, algorithms that guide telecommunications and operations have become part of the foundation of modern living. At the same time, they offer additional opportunities for intentional criminal mischief and terrorist acts. One workshop participant describes a denial-of-service attack and points out, for example, how individual households may unintentionally become part of the attack.

> "There was recently this one case where a boiler had supposedly been hacked. But in reality the case was that the boiler was directly connected to the Internet, and when it was online, a malware that scanned only IoTs with vulnerabilities, got access to the boiler and started a denial-of-service attack on the other side of the world. And as the boiler is not designed for that, it crashed. So, there needs to be no direct cyber influence on the boiler, but it can still be involved with something else inadvertently. And the big problem is that when the number of devices online is growing so damn fast, and no manufacturer of refrigerators has probably done any software before, they are bound to repeat the mistakes made by IT experts a long time ago. So the quality of the software can go back to the beginning of the 1990s and all the same basic problems will return. Then we have a terrible pile of crappy devices. And, as a result of these enormous amounts of devices, the attack potential will become huge. Denial-of-service attacks can be made with a large number of inefficient devices."

The effects of the development of telecommunications technology are most evident in urban environments. A person in the city is inadvertently served by a number of different IT systems. Industrial systems that are controlled over the Internet have also been incorporated into critical infrastructure management. Simply put, increasing numbers of people, devices, and objects are interconnected. The structural functionality of modern cities is thus also defined by the underlying algorithms, software and their security. Due to this threat, discussion of management and safeguarding of critical infrastructure has incorporated terms like cyber warfare and cyber terrorism [68,69].

This development has provided undeniable benefits, but it has also increased the potential for hybrid influencing in densely populated urban environments, where attacks on computer networks and infrastructures are not only harmful due to increased dependency of digitalized services, but can also be effectively combined with other methods of hostile influencing. Hybrid influencing refers to the coordinated use of economic, political or military means such as cyber, physical, and economic operations. The term hybridity emphasizes the attempt to combine two or more commonly separately used systems to produce the desired synergistic effects [70]. This also manifests the fact that critical infrastructure is seen as a potential target and in some cases an instrument of terrorism.

4.4. Potential Terrorist Target

As a severe disruption of critical infrastructure is likely to cause widespread and profound implications for the convenience and security of everyday life, inflicting disruptions can be seen as a means of causing deliberate harm [71]. In addition to direct and immediate impacts, attacks on critical infrastructure would undermine the stability-maintaining structures and create a climate of insecurity; it would be a psychological shock that would have an impact on people's sense of fear and attitudes towards governance to a much larger extent than the actual attack [72–74]. Like any purposeful organization, terrorist groups seek to find cost-effective solutions that could produce the desired effect, such as harnessing the leverage of social structures to advance their own agenda. Critical infrastructure, with all its interdependencies, forms a metasystem of societal welfare, and by intervening in its functionality, it is possible to turn the system against itself [75,76]. Thus, the sophistication of society also means increasing its vulnerability; the strength, progression, and capacity of a system are at the same time its Achilles heel [76].

If one thinks about water services, the context of one of the scenarios covered in the workshops, modern societies have invested heavily in order to organize water services so that that they cover as large a part of the population as possible, and the quality is high. People can trust the quality of the water services. Intentional contamination of drinking water, for example, biologically or chemically would alter the systems producing public health and mundane convenience to a system spreading disease, death, mistrust, and fear in a way that would make it one of the most effective instruments for terrorism [75,77,78]. From a mechanical point of view, the system would work impeccably, but its ultimate purpose and quality would have been manipulated. According to Meinhard, the intentional contamination of water would also cause unforeseen difficulties for health care [79]. This kind of a situation would create an operational environment where the central actors have hardly any prior experience, and where the element of surprise is of considerable proportions [80].

> "As a citizen, I think that this would cause such horror. When there is no clear cause [of illnesses and deaths] known, then that is the most horrible situation. And the doubt of whether I can count on the authorities to tell me the truth. One starts to doubt everything. [...] Then the rumors break out that this is terrorism or what is it?"

Critical infrastructure can thus be seen as a structure that intensifies disruptions and social distrust, and therefore it is an interesting instrument from the point of view of terrorists [81–86]. In this regard, one dimension when assessing the criticality of critical infrastructure should be the extent of impact one can achieve by changing the functional identity of the system. By exploiting critical infrastructure, terrorists can manifest and symbolize the vulnerability of social order. At the same time, the influence would target structures that are present in the formation of everyday well-being and terrorists would thus be able to convey a psychologically important message that no one is safe [73].

The potential of critical infrastructure to be the target is increased by the terrorist tendency to attack so-called soft targets, the tendency to increase the complexity of attacks, and the tendency to maximize the number of victims [66,87–90]. When targeting critical infrastructure, the aim would be to cause disruption to services that people strongly rely on, and to undermine citizens' confidence in the ability of government to protect citizens [72]. This has been manifested by the terrorist attacks in Madrid in 2004 and a year later in London. In this sense, it is not particularly surprising that according to intelligence data the water services networks, in addition to other critical infrastructures, have been identified as objects of interest for terrorist organizations [91,92]. The participants of the working group note that the intentionality of the disruption impacts the way it is handled:

> "Yes, this is a really tricky case, even though one could identify the toxic substance, but to identify the cause to be able to do something about it. But the reason behind it will also impact what is to be done, what to prepare for and what places to protect."

> "The nasty thing when dealing with human beings is that if they don't get caught, then they can continue. In that sense, the cause does not disappear before that person has been found."

If critical infrastructure were the target of a terrorist attack, this would mean a very different kind of operational logic in comparison to cases with disturbance caused by, for example, a storm, malfunction, or human error. When the cause is of intentional human origin, then the cause responds actively and intelligently at least in the light of its own purpose. As a result, restoring the situation becomes essentially more difficult. Awareness that the attacker is intentionally trying to cause damage has an impact on the restoration process. In addition, scarce resources would be needed not only to deal with the acute disruption and its effects in a life-threatening environment, but also to anticipate and prepare for possible future strikes. For example, the terrorist attacks in Paris in November 2015 illustrated how in the case of one attack, the authorities had to focus their attention on the potential for subsequent strikes that could occur, for example, on the other side of a metropolis. Moreover, because of the human origin of the disturbance, the possibility of hybrid operations cannot be excluded; concrete physical attacks can be prepared for a long time by a continuous means of influence to maximize the desired effect.

5. Conclusions

Looking at urban environments and critical infrastructures as their central components, it can be seen that sustainability is linked to securing the preconditions of continuity and development. The focus is on the creation and maintenance of vitality, and avoidance of societal collapse, whether it is a fast or slow process [93]. Adapting Romero-Lankao et al. [94], it can be said that urban sustainability, security and resilience surface from a dialogue about desired futures. This paper has examined this very broad and complex issue in the context of critical infrastructure vulnerability and disruption. It is time to sum up the key findings of this paper and reflect on the future directions they provide in the framework of security, sustainability, and resilience.

First, it is necessary to underline the intensification of complexity, the importance of which is particularly emphasized in urban areas. Interconnected systems construct fertile soil for disruptions to spread through cascade-effects. For example, Helbing describes this phenomenon through the concepts of systemic risk and hyper-risk, where the number of possible cascade paths and non-linearity are characteristic [8]. The situation is twofold in the sense that, on the one hand, there is a strong aspiration in society, with the help of risk management and contingency planning, to prevent the emergence of catastrophes and curb their adverse effects. On the other hand, this orientation, together with the development of society, lays the groundwork for even worse vulnerabilities. This is mostly a matter of improving performance in the field of modern threat scenarios and the realities of the operational environment, which differs from the more traditional risk management field in which critical infrastructure producers and other key actors have demonstrated their capacities [95]. In this regard, it could be argued that strengthening resilience requires understanding that the traditional way of tackling vulnerabilities through identification, knowledge and management does not do the trick in a world of systemic and interdependent vulnerabilities.

Second, this paper illustrated the socio-technical nature of critical infrastructures. A severe disruption in the system can go beyond geographical, organizational, and administrative boundaries, thus activating a multifaceted set of actors whose ability to collaborate is required to restore the situation. The workshop discussions illustrated some of the challenges associated with the coordination of various human subsystems. For example, the importance of reliable, up-to-date information from other key actors was highlighted throughout the discussions as a driving force for their own actions. The primary guiding principle seems to be that taking the necessary action requires the presence of sufficient certainty. In this regard, it is argued that strengthening resilience requires understanding that the information available in a situation of severe disruption to critical infrastructure may inevitably be undesirable both in quantity and quality, but still the expectations and requirements for the effective management of the situation remain. The required activity may not be able to claim legitimacy from established administrative-legal institutions, so the ability to cross different conventional boundaries becomes one of the factors determining the resilience of the overall system. Producing security requires continuous interaction and creation of meanings between extremely different actors and logics.

Third, the importance of the preparedness and contingency thinking is emphasized. As Kachali et al. point out, a preparedness perspective going beyond sectoral boundaries should be integrated in the development of activities [18]. The challenge is that the development of the activities is often driven by the calculations between the inputs and the benefits gained, but the benefits of taking the preparedness perspective are not realized in concrete sense. Their realization is, at best, that the unwanted does not happen. In general, the causal relationships between inputs and non-occurrence are not easily perceived. In addition, even when the benefits are manifest, they are not known at the investment stage. From the point of view of the input-output perspective, preparedness may at worst appear as a no-win situation. In this regard, it can be stated that the strengthening of resilience requires understanding that the development of functions from the point of view of normal situations does not necessarily say much about the capacity to perform in exceptional circumstances. As noted in the workshop discussions, the severe disturbance of critical infrastructure is likely to create an operational environment in which many of the things that are taken for granted in normal circumstances are called into question. These observations also align with the SoS-perspective formulated by Haimes, according to which such complex SoS emergent properties should guide the processes of strategic preparedness, response and recovery. These emergent features are "system features that are not designed in advance, but rapidly evolve based on sequences of events that create the motivation and responses that ultimately develop into features characterizing the Complex SoS." [43] (p. 667).

Fourth, the paper also emphasized that the sectors of critical infrastructure should be prepared to fight and also to face the attacks organized by a malicious actor whether it be of governmental origin or something else. Producing security and sustainability in this context would seem to require the ability of key players to perceive themselves as a networked organization. However, the idea of a networked organization is not easily adopted by the authorities, infrastructure producers and other key players. In line with the SoS typology by Maier [44], the issue is, especially for the authorities, how essentially 'directed' systems that are based on the implementation of specific goals in a centralized manner, are able to adapt the methods of 'collaborative' systems, where systems have to work more or less voluntarily on a common goal. However, the need for a more networked 'defense' is emphasized in the face of the development of threats such as organized crime, hybrid action and terrorism in an increasingly networked, diverse and technically sophisticated direction. For example, Simon argues that the next wave of terrorism will be heavily technology-inspired, turning the power of society's own technological advancement against itself [96]. Information and communication technologies are one aspect of this; i.e., cyber terrorism, whereby interest is focused firstly on cyber-attacks against the critical infrastructure control systems, and secondly, on "cyber facilitated" terrorism, in which the idea is to utilize cyber in the planning of a traditional attack and to enhance its impacts. In this sense, enhancing the resilience of a system necessitates new ways to protect and produce safety. The introduction of critical infrastructure into the context of terrorism reflects the idea discussed throughout this paper that what makes our society stronger also weakens it. It should also be noted that the established ways of producing security are not necessarily suited to the new challenges. To conclude, it can be said that societal development itself has inspired an operating environment in which the limitations of systemic understanding can become the main vulnerability of our time.

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sustainability

Article

Cattle Production for Exports in Water-Abundant Areas: The Case of Finland

Elina Lehikoinen [1,*], Tuure Parviainen [2], Juha Helenius [2,3], Mika Jalava [1], Arto O. Salonen [4,5] and Matti Kummu [1,*]

[1] Water and Development Research Group, Aalto University, P.O. Box 15200, FI-00076 Aalto, Finland; mika.jalava@aalto.fi
[2] Department of Agricultural Sciences, University of Helsinki, P.O. Box 27, FI-00014 Helsinki, Finland; tuure.parviainen@helsinki.fi (T.P.); juha.helenius@helsinki.fi (J.H.)
[3] Ruralia Institute, University of Helsinki, Lönnrotinkatu 7, FI-50100 Mikkeli, Finland
[4] Faculty of Social and Business Studies, University of Eastern Finland, P.O. Box 1627, FI-70211 Kuopio, Finland; arto.salonen@uef.fi
[5] Finnish National Defence University, PL 7, 00861 Helsinki, Finland
* Correspondence: elina.lehikoinen@aalto.fi (E.L.); matti.kummu@aalto.fi (M.K.)

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Abstract: Water scarcity is a severe global threat, and it will only become more critical with a growing and wealthier population. Annually, considerable volumes of water are transferred virtually through the global food system to secure nations' food supply and to diversify diets. Our objective is to assess, whether specializing water-intensive production for exports in areas with an abundance of natural resources, would contribute to globally resource-efficient food production. We calculated Finland's virtual water net export potential (four scenarios) by reallocating the present underutilized agricultural land and combining that with a domestic diet change (three scenarios) to maximize the exports of cattle products. Assessed scenarios indicate that the greatest potential to net export virtual water (3.7 billion m^3 $year^{-1}$, 25-time increase to current) was achieved when local production was maximized with domestic and exported feed, and bovine meat consumption in Finland was replaced with a vegetarian substitute. This corresponds to annual virtual water consumption for food of about 3.6 million global citizens (assuming 1032 m^3 cap^{-1} $year^{-1}$). Therefore our results suggest, that optimizing water-intensive production to water-rich areas, has a significant impact on global water savings. In addition, increasing exports from such areas by decreasing the domestic demand for water-intensive products to meet the nutrition recommendation levels, saves water resources.

Keywords: cattle production; diet change; land use; reallocation; trade; virtual water; water-intensive products

1. Introduction

The world is facing a severe dilemma—how to feed the population sustainably in the future [1–3]. Global population is expected to exceed 9 or even 10 billion by 2050 [4,5], and this creates a tremendous pressure to provide enough food for everyone. In many parts of the world, natural resources for food production are already scarce [6,7] and unevenly distributed, especially relative to the population.

Mekonnen and Hoekstra [8] specified that in general, the highest water scarcity occurs in areas where the population density is high or agriculture is heavily irrigated, or both—often combined with low natural water availability. Around 4 billion people are facing water scarcity for at least some time of the year [8]. On average, the global water footprint for an average consumer was around 1385 m^3 cap^{-1} $year^{-1}$, of which the water footprint related to consumption of agricultural products was 92% (total virtual water 1274 m^3 cap^{-1} $year^{-1}$, of which green and blue virtual water contribute to

1032 m^3 cap^{-1} $year^{-1}$) over the years 1996–2005 [9]. Therefore, food production is the key focus point in tackling water scarcity.

Existing studies have shown that international trade often leads to global water savings (see e.g., [10–16]), and thus can also be used as a measure to lower the overall pressure on natural resources. The same applies locally: A recent study by Porkka et al. [17] shows that a majority of the sub-national areas facing scarce green-blue water resources, increased their food imports to secure the local food supply. It has been estimated, that since the mid-1980s to 2009, the percentage of world food production that is internationally traded on international markets rose from 15% to 23% [18].

Use of key natural resources for food production has exceeded sustainable limits (see e.g., [6,19–21]). At the same time, measures, such as diet change, a reduction of food losses and a yield gap closure can, if used together, sustainably increase the global food availability by 100–200% [6,22,23]. Kummu et al. [23] found that in Europe and Northern America, among the measures mentioned above, diet change plays a key role in increasing food availability without increasing resources use. This is due to a high share of animal products in the diets, and hence these diets have several times higher resource use per unit of nutrition produced than plant-based diets (see, e.g., [24–27]).

In addition to the global overviews, there are local studies about the agricultural land use efficiency comparing the outsourced and (re)localized production to meet the domestic food demand (see e.g., for the UK, Reference [28]; Sweden, Reference [29]; USA, Reference [30]; Finland, Reference [31]). However, not much is known about an export potential of specializing water-intensive production to countries with an abundance of natural resources.

In this present study, we take a different angle to increase the understanding of food production and study the reallocation of global water resources. To the best of our knowledge, we conduct the first detailed study about the reallocating global water resources by specializing water-intensive cattle production in water-rich areas, and turning that into virtual water exports to potentially easing global water scarcity. We build scenarios based on reallocations potential in domestic land use combined with domestic diet change towards lower water intensity. We acknowledge that the global, and even local, food system forms a complex net that has multiple economic, environmental and social aspects to consider. Our study focuses on the environmental and natural resources perspectives, providing knowledge about the possibilities of reallocation that can be used as a foundation for further research focusing on, for example, economic feasibility or social acceptability.

We aim to form a better understanding of practical actions that can be done at the national level towards more sustainable global food production. Kummu and Varis [32] presented data showing that in the northern latitudes, water resources are rich and populations low. We chose Finland as our case study, since it is a typical northern country with the presented characteristics of rich water resources and low population [33,34]. Still, Finland annually imports a considerable, and increasing, amount of water-intensive products [35]. Finland's external water footprint is 47%, and a majority of it is caused by agricultural production [36]. While importing virtual water, Finland is also outsourcing negative environmental impacts. Sandström et al. [37] discovered, that over 93% of the land use related to biodiversity impacts of Finnish supply, is external [37]. However, Finnish natural resources are underused [38], and there is potential to decrease imports of arable food crop commodities to Finland by domestic production. Sandström et al. [31] studied, that the replacement of imported rice, soybeans and rapeseed with domestic crops, would reduce embedded blue water requirement by up to 16% and green water by almost 30% of the total crop related virtual water imports [31]. As complementary to the current national studies, our research focuses on increasing Finland's virtual water net exports related to cattle production.

We focus on cattle production for four main reasons. First, the global water footprint of bovine meat is very high with an average of 15,415 l kg^{-1} [39,40]. Thus, cattle production should be in close focus in redesigning food systems for water efficiency. Second, the rich freshwater resources in Finland are underused for agricultural production [41]. Third, there are agronomic and environmental needs to diversify arable land use in Finland, to which leys and pastures, as well as domestic protein feeds, would contribute positively [42]. At the moment, Finland is a net importer of bovine meat [43], although its prerequisites are met to increase domestic cattle production and to become a net exporter. Fourth, Finns consume animal products, especially red meat, beyond national [44], regional [45] and international [46] dietary recommendations. Currently, it is part of the national food policy to reduce meat-based meals by increasing the proportion of plant-based meals [47].

Therefore, we hypothesize that Finland has a potential for, and multiple benefits to be gained from, a strategic specialization to water-intensive cattle products for exports as a contribution to a globally fair share of limited water resources. Further, we hypothesize that shifting towards a more sustainable diet would increase this export potential.

After presenting the motivation for and aim of this study in Section 1, Section 2 focuses on introducing the relevant materials and methods used to test our hypothesis. Since our study focuses only on one country, we provide the main benefits and limitations for cattle production in Finland already at the beginning of the paper. In Section 3, we present how our scenarios would impact the land use in Finland and abroad, and the potential for Finland to export virtual water. We then discuss the benefits and disadvantages of cattle production in Finnish and global contexts in Section 4. We also acknowledge the limitations of our study while making suggestions for future studies. Finally, we draw our conclusions in Section 5.

2. Materials and Methods

This study was designed and conducted as follows (Figure 1):

- Step 1: Calculating the potential of reallocation cattle production to the presently underutilized share of grass leys maintained in arable farmland in Finland;
- Step 2: Laying the baseline for current Finnish cattle production and cattle product consumption;
- Step 3: Creating four cattle production scenarios (a current production, productions with current and future domestic feed potentials, a maximum production), and three diet scenarios (current consumption, 50% reduction of bovine meat consumption and 100% reduction of bovine meat consumption) in Finland;
- Step 4: Calculating the domestic and outsourced land use requirements for cow feed in different cattle production scenarios, and calculating the need for an agricultural land replacing the bovine meat protein with a vegetarian substitute in the different scenarios;
- Step 5: Estimating the potential to increase the cattle product net exports with a scenario-matrix, considering the feed trade and diet changes;
- Step 6: Converting the scenario-matrix into water footprints and calculating the potential to net export virtual water.

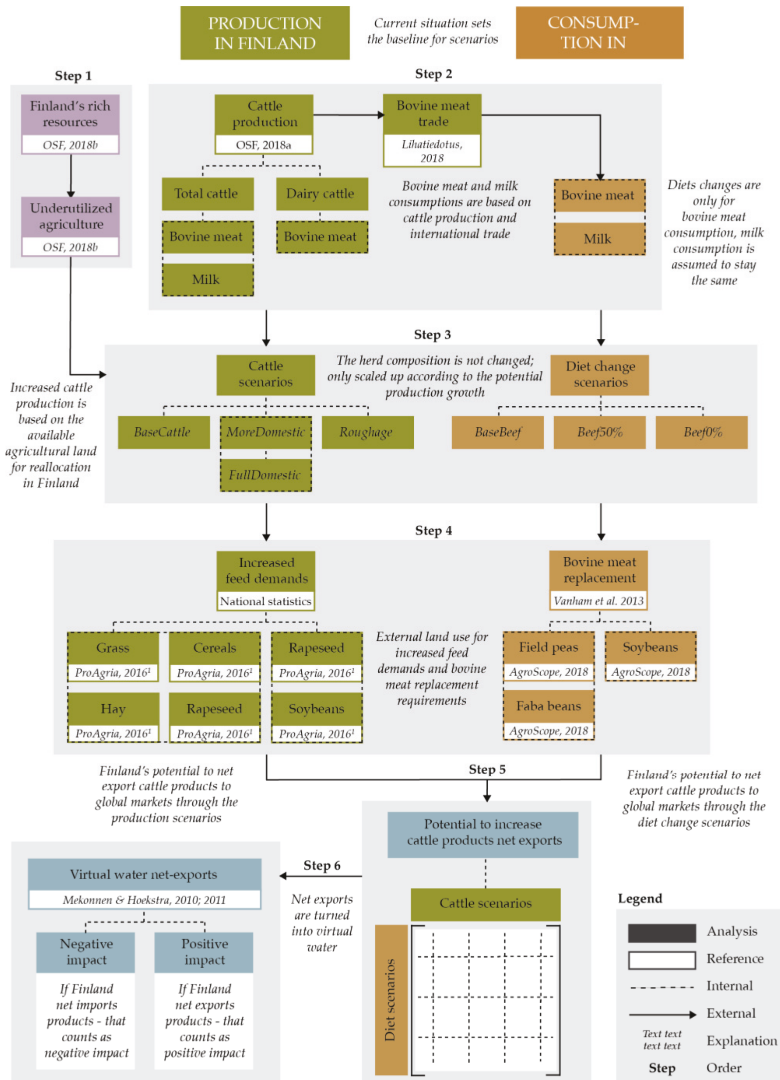

Figure 1. Flowchart of the study. Finland's vast and underused natural resources create the baseline for this study (Step 1). The calculation is divided into separate assessments of cattle production and cattle products consumption in Finland (Steps 2–4). Cattle production and feed use scenarios are combined (Step 5) and turned into virtual water to calculate the potential net exports (Step 6). [1] Data for ProAgria is based on a personal communication with professor A. Huuskonen (Natural Resources Institute Finland) and researcher O. Niskanen (Natural Resources Institute Finland) 16 June 2016 [48].

2.1. Reallocation of Agricultural Land (Step 1)

We did not assume any changes to the current extent of agricultural land. The concept of underutilized leys—which refers to arable land that is sown to grasses or mixtures of species of grasses and dicotyledons—is maintained as a measure of an agri-environmental scheme or as fallow, and is only partially or not at all used as a pasture or for silage [49]. Seppälä et al. [49] estimated that the Finnish underutilized ley potential was 472,000 ha in 2013. This estimation matches relatively well to the data from OSF [50], where the total available land for reallocation was calculated to be 480,200 ha on average over the baseline period 2012–2017 [50]. Potentially, the underutilized leys might be even higher, since year by year the number of animals is decreasing and hence, idle leys are increasing [49].

Further, Finland also imported (53,000 tons year^{-1}) and exported (660,400 tons year^{-1}) of cereals on average over the baseline period 2012–2017. We assumed that the net export (607,400 tons year^{-1}) of cereals could also be partly used for cattle feed, if needed, and thus the potential for additional cow feed requirements already exists. In our scenarios, cereal exports refer to wheat, barley and oats, since those are the main crop commodities to be traded.

2.2. Baseline of the Cattle Production and Cattle Product Consumption (Step 2)

2.2.1. Current Cattle Production

Beef and dairy production systems are very interlinked, and changes in the dairy system might cause alterations in the beef production system [51]. Hence, no changes in the relative size of beef to dairy cattle husbandry was assumed, and the ratio between the dairy and meat products was kept at the present level. On average over the baseline period 2012–2017, the total cattle herd size was 909,400 heads, of which the dairy cattle was 282,400 heads. The baseline for the annual production was 83,400 tons of bovine meat and 2327 million litres of milk based on the 5-year average [52]. A special characteristic of Finnish cattle production is the comparatively low share of bovine meat production, since a large part of the cattle is specialized on milk production.

2.2.2. Current Consumption of Cattle Products

We studied bovine meat consumption at the national level, and took into consideration international trade. The national bovine meat consumption was calculated as the sum of cattle production and net imports (imports–exports). The cattle production data was available over the years 2012–2017 [52], and the trade of bovine meat until the year 2016 [43], that was scaled to correspond to the year 2017. On average, the annual bovine meat consumption at the national level was 102,700 tons, resulting around 19 kg cap^{-1} year^{-1} (carcass meat).

2.3. Cattle Production and Diet Change Scenarios (Step 3)

2.3.1. Local Constraints to Cattle Production

Finland is a large country that is sparsely populated. Figure 2 presents the current cattle production areas and the agricultural land uses in Finland, relevant to our study [50,52]. Cattle production is focused in the western and middle regions of the country, where the landscape is mainly plains. The utilized agricultural land for feed production is focused in the southern and western parts of the country. Leys and fallows are focused in the same areas as cattle production, meaning that the majority of the feed is close to cattle production. However, farmers' decision-making for chosen crops and animal numbers is based on market prices and agricultural policies, which were not part of our assessment.

Cultivation of rapeseed competes with peas and beans cultivation in the southern and south-west regions [50]. However, based on the estimate by Peltonen-Sainio [53], there is an increased cultivation potential for rapeseed and legumes. The realistic combined potential for rapeseed and legumes, taking into account the crop rotation, currently is around 201,000 ha (baseline for the year 2011, using mean figure for cultivated area in the 2000s) and in the future could be around 392,000 (baseline for the year 2055, using mean figure for cultivated area in the 2000s). When looking only at the rapeseed cultivation, the increased potential is currently around 258,000 ha (baseline for the year 2011, using mean figure for cultivated area in the year 2000s) and in the future could be around 445,000 ha (baseline for the year 2055, using mean figure for cultivated area in the 2000s). In addition, when looking only at the legume cultivation, the increased potential is currently 242,500 ha (baseline for the year 2011, using mean figure for cultivated area in the 2000s) and in the future could be around 444,500 ha (baseline for the year 2055, using mean figure for cultivated area in the 2000s). The current potential was estimated only for areas that have manageable production risks and the future potential, induced by a prolonged growing season attributable to projected climate change, was estimated for 30 year period according to 19 climatic models [53].

European Union banned the use of neonicotinoid (pesticide) in 2018, and hence the production of rapeseed cultivation is challenged in Finland [54]. The Finnish rapeseed yields are already declining but the situation is constantly changing, and thus we decided not to consider this in our calculations. Overall, the yields in Finland are lower than in Central Europe, mostly due to the shorter growing season. In the future, better cultivars, which have adapted to long days in the northern hemisphere, might offer high-yielding varieties also in the north [55].

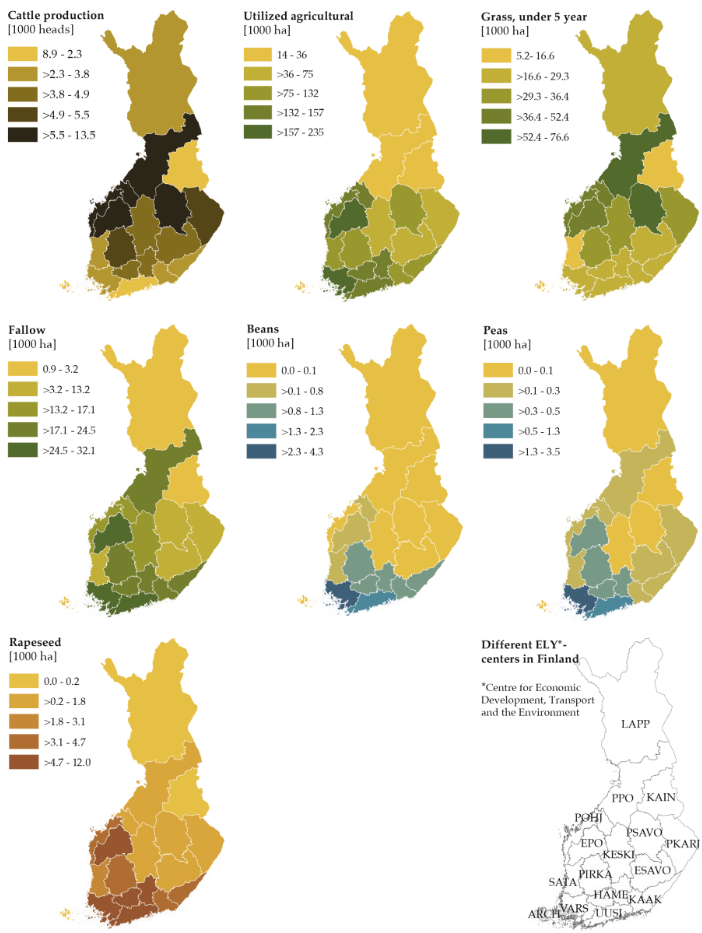

Figure 2. Cattle production and different agricultural land uses in Finland that are relevant to our study [50,56]: UUSI, Uusimaa; VARS, Varsinais-Suomi; SATA, Satakunta; HÄME, Häme; PIRKA, Pirkanmaa; KAAK, Kaakkois-Suomi; ESAVO, Etelä-Savo; PASAVO, Pohjois-Savo; PKARJ, Pohjois-Karjala; KESKI, Keski-Suomi; EPO, Etelä-Pohjanmaa; POHJ, Pohjanmaa; PPO, Pohjois-Pohjanmaa; KAIN, Kainuu; LAPP, Lappland; ARCH, Archipelago (Åland Islands).

2.3.2. Cattle Production Scenarios

We created four cattle production scenarios based on the availability of underutilized Finnish agricultural land for reallocation (Table 1). In all scenarios, the herd composition (dairy to beef animals ratio, number of lactations of dairy cows) was not changed. The production was simply scaled-up in its current structure to meet the potential for growth. The estimations for the increases in feed demand were based on the current feed consumption from ProAgria data [48]. The industrial by-product energy feeds (such as molasses and glycerine) were omitted, since these dietary supplements are produced as by-products from industry, and therefore do not directly compete with agricultural land use. Moreover, those are not a significant proportion of the cattle diet.

The first cattle production scenario (*BaseCattle*) presents the baseline situation. Rapeseed and soybean feed imports are based on the current use, and the underutilized agricultural land has not been reallocated for feed production. The trade of cereals also remains the same as currently.

The second and third cattle production scenarios focus on improving the feed self-sufficiency by replacing soybean feed imports with domestic rapeseed feed protein. The replacement is done by a conversion factor 1.37 (protein replacement factor is based on the soybeans (0.52 [57]) and rapeseed (0.38 [57]) protein content). In the second cattle production scenario (*MoreDomestic*), the current domestic rapeseed cultivation potential of 258,000 ha [53] is utilized, and the rest of rapeseed protein feed is imported. In the third cattle production scenario (*FullDomestic*), the future domestic rapeseed cultivation potential of 445,000 ha [53] is utilized, and no feed imports are needed. In *MoreDomestic* and *FullDomestic*, the currently underutilized land has been claimed for also growing the other cattle feed (such as pasture, grass for silage, hay, and barley). In both of these scenarios, no extra land is needed for agricultural production—only the potential in underutilized cultivation potential is reclaimed, and the cereal net exports are exploited domestically.

The fourth cattle production scenario (*Roughage*) describes the grass feed self-sufficient production, where the production is based on the maximum cultivation potential of domestic pasture and grass silage. This is supported with increased rapeseed and soybeans exports in the same proportions as in the *BaseCattle* to meet the feed requirements.

Table 1. Cattle production scenarios (*BaseCattle, MoreDomestic, FullDomestic, Roughage*), including the assumptions for land use and feed trade.

Limitations	Assumptions			
Cattle production scenarios	*BaseCattle*	*MoreDomestic*	*FullDomestic*	*Roughage*
Underutilized agricultural land	Non-productive/ biodiversity	Leys/Rapeseed	Leys/Rapeseed	Leys
Availability of cereal feed (for cattle)	Current	Current or increased	Current or increased	Current or increased
Rapeseed imports allowed	Current	Imports allowed	No imports	Growth allowed
Soybeans imports allowed	Current	No imports	No imports	Growth allowed
Soybeans replaced with rapeseed	No	Yes	Yes	No

2.3.3. Diet Change Scenarios

We used three diet change scenarios to estimate the potential impact of reducing bovine meat consumption. The first scenario (*BaseBeef*) presents the current diet, where no changes are done. In the second diet scenario (*Beef50%*), the bovine meat consumption is reduced by 50%, and in the third diet scenario (*Beef0%*), the bovine meat consumption is reduced by 100%. The replacement of bovine meat with vegetable foodstuff was calculated based on equal protein content [58]. The consumption of milk and milk products were assumed to remain at the current level, and hence no replacement was needed.

The Finnish average daily bovine meat protein intake is 7.8 g cap^{-1} day^{-1} (on average over the years 2008–2013) [59]. At the national level, this equals 15,590 tons year^{-1} of bovine meat protein. This bovine meat protein needs to be replaced partly or fully with vegetable substitute protein in *Beef50%* and *Beef0%* scenarios. To do that, we created a vegetable substitute protein (*VegSubPro*) mix based on the global consumption of soybeans, peas, and beans (on average over the years 2008–2013). First, we collected the global average for the food (kg cap^{-1} $year^{-1}$) supply quantity of soybeans, peas, and beans, and then calculated the relational share of consumption for those. This analysis provided us with a general reference of how the replacement could be. For the imported protein replacements [57], we used the dried soybeans (*Glycine max*), and for domestic protein replacements, we used dried green peas (*Pisum sativum*) and dried faba beans (*Vicia faba*). Based on the relative share of consumption and protein content, we calculated the *VegSubPro* has the protein content of 297 g kg^{-1}.

2.4. Land Use Requirements for Cow Feed and Diet Change (Step 4)

For calculating the land use need in cattle production and cattle products consumption scenarios, we developed a land use model that accounts for the interactions between the changes in the agricultural land use and plant yields, cattle production and diet change scenarios, and trade for both human foodstuff and cattle feeds products. The calculation was done in a mass balance basis and then converted to land use according to the local and global yields. The agricultural land was allocated first to the domestic feed and food production, and only after that to the cereal exports. If the domestic supply could not suffice cattle production or diet change scenarios, global yield estimates were used to calculate the land use in aboard on per plant basis [60]. The land use requirements were calculated using the following equation (1):

$$\begin{aligned} \text{Land use requirements } &= plant\ production - human\ demand * \\ diet\ change\ modifier &+ cattle\ demand * cattle\ scenario\ modifiers + imports - \text{ exports.} \end{aligned} \tag{1}$$

2.5. Potential for Cattle Products Exports (Step 5)

We created a scenario-matrix, using cattle production and domestic diet change scenarios. This scenario-matrix was based on the following principles:

- Finland exports and imports bovine meat: The bovine meat net imports were always first replaced with domestic products, and only after that, the potential for bovine meat exports was allowed;
- Finland also exports and imports milk and milk products: The current milk production was taken as a baseline level and the increased production seen as potential exports;
- The *VegSubPro* was included in the trade as well: Only soybeans were imported, since beans and peas were cultivated domestically.

2.6. Virtual Water Net Export Potentials (Step 6)

The water footprint is defined as an indicator of freshwater use that takes into account both direct and indirect water use of a consumer or producer [61]. We used the global water footprints for crops [39] and animal products [40] in order to calculate the impact, that Finland could have in the global markets.

The water footprint is divided into blue, green and grey water. Blue water refers to the fresh surface and groundwater used in the production, while green water refers to the amount of rainwater consumed, and grey water refers to the amount of fresh water needed to assimilate the pollutants to meet specific water quality standards [61]. Blue and green water consumption is inherent to the production of crops and livestock—biomass cannot grow without a certain amount of water. Grey water is much more avoidable by agricultural management practices, and therefore was neglected in this study.

The potential for virtual water net exports of the different scenario combinations was accounted for Finland's international net trade of cattle products and feeds needed for the production. Finland's net imports of virtual water are given as negative values, since then Finland is consuming the already scarce global water resources. Finland's net exports of virtual water result in a positive virtual water contribution, since then Finland is providing virtual water for the global markets. The water footprint for domestic cattle production and consumption in Finland was not counted to the virtual water trade balance, as it does not affect the virtual water trade balance. The virtual water net exports were calculated using the following equation:

$$Virtual\ water\ net\ exports = exports * virtual\ water\ footprints - imports * virtual\ water\ footprints. \quad (2)$$

Yet, it is vital to recognize that not all Finland's consumed global water is from scarce water resources—therefore not all virtual water net exports ease the global water scarcity. Nevertheless, when calculating the number of global citizens that net exports from Finland could sustain, we used the value of 1032 m^3 cap^{-1} $year^{-1}$ [9] for the global average of virtual green and blue water footprints for food consumption per capita. It is also good to acknowledge, that we looked at only the net exports of cattle products, not Finland's overall net exports.

3. Results

3.1. Cattle Production and Diet Change Scenarios

From *BaseCattle* to *MoreDomestic* and *FullDomestic* scenarios, the number of total cattle increases by 42.9%, and from *BaseCattle* to *Roughage* increases by 134.0%. Since the herd composition in the scenarios was kept unchanged, the production of milk and beef products increases by the same proportions. The annual bovine meat production increases from 83,400 tons $year^{-1}$ in *BaseCattle*, to 119,200 tons $year^{-1}$ in *MoreDomestic* and *FullDomestic*, and to 195,100 tons $year^{-1}$ in *Roughage*. While the milk production increases from 2.3 billion litres $year^{-1}$ in *BaseCattle*, to 3.2 billion litres $year^{-1}$ in *MoreDomestic* and *FullDomestic*, and to 5.3 billion litres $year^{-1}$ in *Roughage*.

In the baseline diet scenario (*BeefBase*), no substitutions for proteins derived from animal products are required. In *Beef50%*, annually 26,800 tons $year^{-1}$ of *VegSubPro* replace the reduced domestic bovine meat consumption (51,300 tons), of which 10,700 tons $year^{-1}$ of soybeans (4300 tons of dry matter) is imported and rest 16,100 tons $year^{-1}$ of legumes (6100 tons of dry matter) is domestic. In *Beef0%*, 53,600 tons of *VegSubPro* is required to replace 102,700 tons $year^{-1}$ of domestic bovine meat consumption. For this amount of *VegSubPro*, 21,400 tons $year^{-1}$ of soybeans (8600 tons of dry matter) is imported and the remaining 32,100 tons $year^{-1}$ of legumes (12,100 tons of dry matter) is domestic.

3.2. Land Use Scenarios

In *BaseCattle*, 78% of the feed use is domestic (593,900 ha; including hay, grass and silage, cereals, rapeseed, peas and beans) and 22% is outsourced (171,300 ha) (Figure 3). Rapeseed feeds dominate the imports, having a share of 87% of the total outsourced land use. In *MoreDomestic*, 89% of the feed is domestic (1,020,900 ha) and 11% is outsourced (132,500 ha). In this scenario, 97% of the outsourced land use is for rapeseed cultivation, as the soybeans imports are replaced with the rapeseed imports. In *FullDomestic*, all the feed production (1,117,900 ha) is 100% domestic and only soybeans replacement for bovine meat reduction is outsourced (3800 ha). In *Roughage*, 72% of the feed use is domestic (1,179,800 ha) and 28% is outsourced (453,800 ha). In this scenario, rapeseed imports dominate with a share of 82% (408,400 ha) of the total outsourced land use, and soybeans for feed and food are outsourced for 45,400 ha.

In all the scenarios, domestic agricultural land use changes mainly take place in the presently underutilized agricultural land (Figure 3). *BaseCattle* leaves 21% (474,300 ha of the total of 2.3 million ha) of the land underutilized. Of the other scenarios which resort to the underutilized land based on the rapeseed cultivation potential, *MoreDomestic* decreases it to 9% (191,400 ha), *FullDomestic* to 4% (94,400 ha), and *Roughage* to 3% (65,800 ha). The share of other agricultural crops remains relatively unchanged.

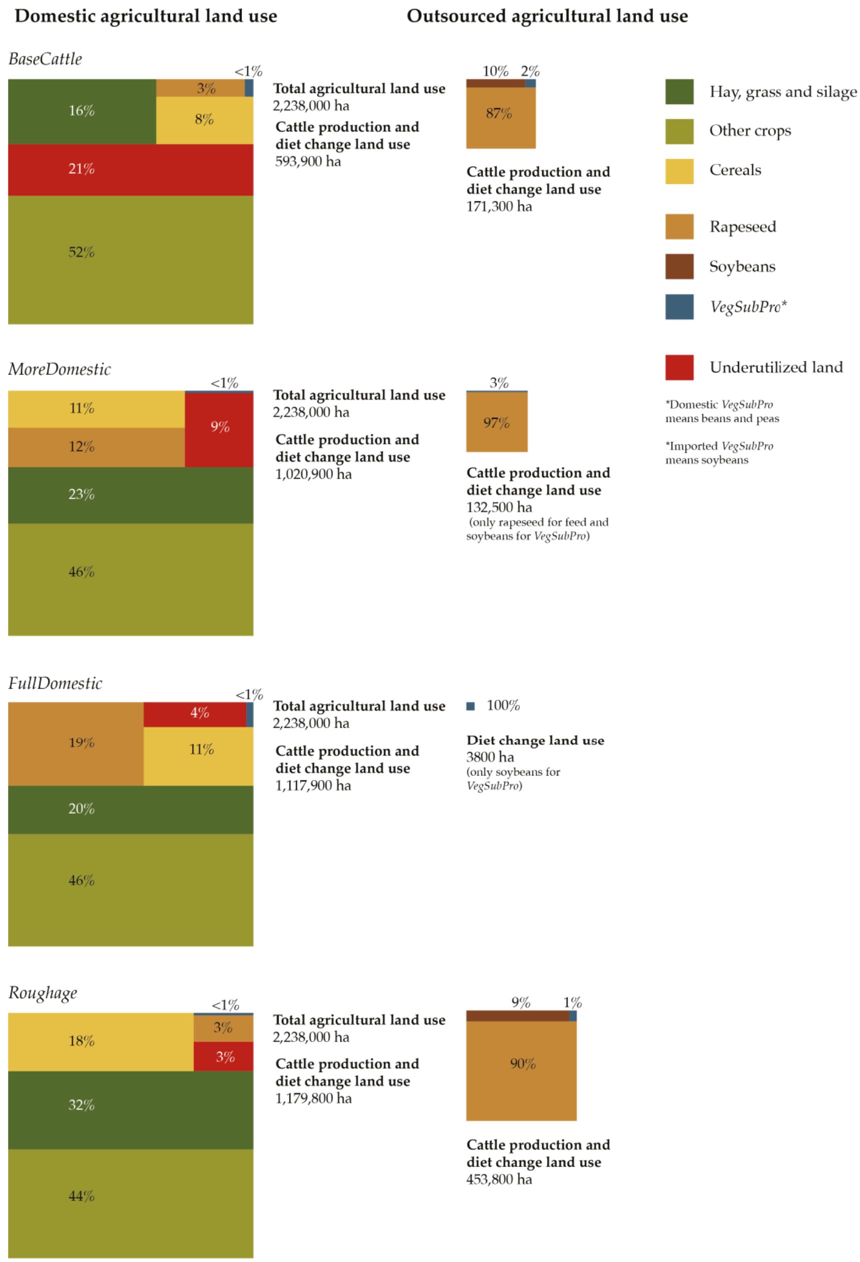

Figure 3. Land use for different cattle production scenarios. The domestic part of the analysis demonstrates how the different cattle feed and *VegSubPro* requirements change the land use (with the total land use being constant at 2,238,000 ha and the 'other crops' specify the other agricultural production). The outsourced land use assessment presents how much external land use the cattle feed and *VegSubPro* imports require. Due to the rounding, not all percentages add up to 100%.

3.3. Cattle Products and Feed Trade

The most significant increase in net exports is in milk. The annual net exports increased tremendously in all scenarios, from 975,200 tons up to 3,139,800 tons. Relatively, the net exports of bovine meat increase in relative terms even more, from −19,300 tons to 175,800 tons (Table 2). The trade of harvested crop products is also variably affected. In *MoreDomestic* and *FullDomestic*, the majority of underutilized agricultural land is used for rapeseed cultivation, and the potential for exports of grain cereals remains modest. This is an opposite case in the *Roughage*, in which the majority of the underutilized land can be used for cereals, and due to animal feed imports, plenty of grain cereals are available for exports. In *VegSubPro*, a variation between the scenarios in need for imports for *VegSubPro* is relatively minor (ranging from 4300 tons to 8600 tons), but accountable.

Table 2. Finland's international net trade of bovine meat under the diet change scenarios (*BaseBeef*, *Beef50%*, and *Beef0%*), milk, as well as for cattle feeds (cereals, rapeseed, soybeans) and vegetable substitutive protein (*VegSubPro*) in different cattle productions scenarios (*BaseCattle, MoreDomestic, FullDomestic* and *Roughage*). The net trade is calculated at Finland's border, and negative values indicate imports and positive values indicate exports.

Product	*BaseCattle*	*MoreDomestic*	*FullDomestic*	*Roughage*	Unit
BaseBeef					
Bovine meat	−19,300	16,500	16,500	92,400	tons year^{-1}
Soybeans (*VegSubPro*)	0	0	0	0	tons year^{-1}
Beef50%					
Bovine meat	22,400	48,500	48,500	124,500	tons year^{-1}
Soybeans (*VegSubPro*)	4300	4300	4300	4300	tons year^{-1}
Beef0%					
Bovine meat	64,100	99,900	99,900	175,800	tons year^{-1}
Soybeans (*VegSubPro*)	8600	8600	8600	8600	tons year^{-1}
Milk	0	975,200	975,200	3,139,800	tons year^{-1}
Feed					
Cereal	607,400	372,900	372,900	275,400	tons year^{-1}
Rapeseed	−258,500	−222,300	0	−705,300	tons year^{-1}
Soybeans	−39,700	0	0	−93,000	tons year^{-1}

3.4. Virtual Water Net Exports

When assessing the potential of different scenarios to increase virtual water exports, it can be seen that despite that *Roughage* is importing feed the most, maximizing cattle production has the greatest potential to increase net export virtual water (Figure 4). At the same time, this scenario also consumes global water resources the most, that needs to be taken into account when calculating the overall trade-offs.

When solely looking at the trade of virtual water, it can be seen that only *FullDomestic* does not consume global water resources (apart for the soybeans imports in the *VegSubPro*), because the share of domestic feed has a high impact on virtual water net exports. The production of cattle products is the same in both *MoreDomestic* and *FullDomestic*, but as domestic feed has a higher share in *FullDomestic* (Figure 4), it also leads to a higher virtual water net export potential.

The role of diet changes also plays an important role when calculating the potential to increase virtual water net exports: The less bovine meat Finnish people eat, the more virtual water can be net exported. The *Beef0%* has on average, 0.9 billion m^3 year^{-1} higher potential for net exports compared to the *BaseBeef*, despite the chosen cattle production scenario.

Finally, we estimated what the virtual water net exports would mean regarding the average water footprint for a global citizen (Figure 4). Thus, the above-explored potential to increase virtual water net exports of different scenarios, would provide virtual water for more than half of the population of Finland. In the scenario maximizing the net exports of virtual water, *Roughage* combined with the radical of domestic consumption (*Beef0%*), the exports would meet with annual virtual water needs for food of 3.6 million global citizens. Even if *Roughage* was combined with the nutritionally recommended cut in domestic beef consumption (*Beef50%*), it would still sustain 3.1 million global citizens for their virtual water needs for food consumption.

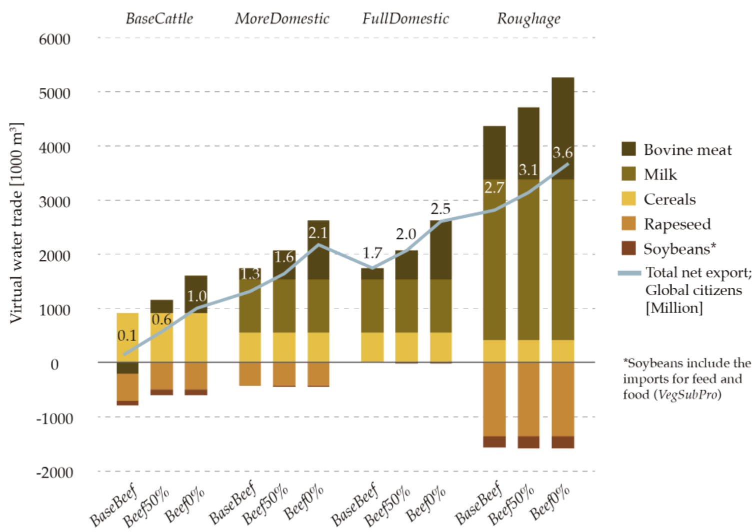

Figure 4. Finland's potential to net export virtual water in combinations of scenarios for cattle production and domestic diet change. Bars indicate the product-specific imports (negative values) and exports (positive values), while the line represents total net exports (exports–imports). The estimation of how many global citizens could be provided with annual virtual water for food production is given as a number on top of the line (in million people).

4. Discussion

Based on these results, we argue that on top of efforts in reducing water use by conventional methods (e.g., food loss reduction, yield gap closure, improved irrigation efficiency), water consumption could be directed to areas with a surplus of water, and exported as virtual water to relieve water demand in areas with water scarcity, for example. In this study, we assessed Finland's potential to increase virtual water net exports by intensifying water-intensive animal production in an area with rich water and farmland resources, and combining that with a diet change towards less water-intensive protein sources. There have been previous studies on Finland's negative external water footprint [31,36] and agriculture's negative outsourced environmental impacts [35,37]. However, in this study, we wanted to estimate the positive impact, that Finland could have with its rich water and farmland resources.

4.1. Dependency on Imported Agricultural Inputs and Products

Finland, like a majority of countries, is a net importer of agricultural products and, therefore, has an external water footprint surplus [36]. The Nordic climate sets certain restrictions for agricultural production, such as one and short growing season, late spring and early autumn frosts, low degree days, and albeit long daylength during the growing season, low temperatures, and low solar radiation intensity [62,63]. It is thus understandable, that Finland imports part of the food consumed by its population, especially items that help with meeting the dietary requirements over the winter period [44].

Our analysis explored cattle production scenarios under current agricultural production conditions, assuming current yields and current practices of cattle husbandry. Even though there is potential to increase cattle production in Finland with domestic feed, dependency on the global markets remains through other imported agricultural inputs [64,65], which is important to keep in mind when estimating the vulnerability of Finnish food system.

We expect the scenarios to have political relevance in terms of the economics of farming in Finland—structural change from a high number of small family farms to a low number of bigger, more entrepreneurial farms has been fast, and is still ongoing [66]. At the same time, the price margin between farmer prices of agricultural products and the price of food is increasing, and farming is hardly profitable [67,68]. In this situation, any sustainable scenario for increasing exports of agricultural products attracts attention. For any country, finding its sustainable role in the globalizing food system is serving the maintenance of human resources, infrastructures, social capital and institutions for maintenance domestic food supply and food security.

4.2. Diet Changes for Humans and Animals

Finnish red meat consumption has increased alarmingly in recent years, as it has in a large part of the other Western and Northern European countries [45,59,69]. Finland's recent national food policy suggests reducing meat-based meals by increasing the proportion of plant-based meals [47]. However, it is vital to recognize that livestock production is more than just meat production, and beef production is closely associated with milk production in Finland. Our analysis demonstrated that the exports of milk (products) also had a significant role, when calculating the potential to net export virtual water of the large production potential in various scenarios (Figure 4).

Consumers can adapt more easily to a diet that contains some meat rather than to an entirely meatless diet [70]. Our diet change scenarios only reduced the consumption of bovine meat, and otherwise the meat consumption remained the same. Based on the current polls on Finnish consumer habits, there is a modest increasing trend on favouring plant-based meals [71], and therefore our diet changes could be realistic in the long term.

The scenarios did not include changes in feed protein sources to monogastric livestock (e.g., poultry and pigs); in these, a change to domestic sources may cause negative effects to growth and productivity [42,72,73]. Regarding the feed for bovine livestock, Peltonen et al. [42] explained that Finland has a great potential to shift towards fully domestic protein sources, including legumes in grass mixtures and rapeseed meals, but also more marginally malting residues, pea and faba bean [42,74,75]. As Finland only has one growing season, and agriculture has been characterized as a monoculture [42], diversifying the domestic legume cultivation—for food and feed—would enrichen the agriculture and landscape [31].

In our scenarios, cereal cultivation and trade played a notable role. Especially in *Roughage*, virtual water net export increased substantially when the underutilized land was used for cereal cultivation, and the cereals were first consumed domestically along with the increased feed imports, and then exported mainly as feed (the quality might vary, and hence we assumed the exports to be feed such as barley, oats and what). Our analysis showed that there are two different ways to achieve increased animal production—either to increase the overall net exports in the expenses of partly outsourced environmental impacts via partly imported feed as in *Roughage*, or to have more moderate virtual water net exports with hardly any outsourced environmental impacts as done in the *FullDomestic* scenario.

4.3. Global Impacts of the Reallocation of Land and Water for Cattle Production

While our study provides new information on how a country can increase its virtual water net flows and have a positive impact in the global markets, this study does not consider how this trade would affect the global markets and what kind of impacts it would have on current production countries. Theoretically, there is a potential to minimize the land and water needed globally by reallocating production to countries with high land and water efficiencies [12], but there are also several challenges and risks regarding the reallocation. We used Fader et al.'s [12] statements for assessing our results against the current situation in Finland and the global context (Table 3).

Table 3. Challenges in reallocating water-intensive production (Fader et al., 2011) contrasted to the current situation in Finland, and against global impact.

Challenges in Reallocating Water-Intensive Production by Fader et al. 2011	Situation in Finland Based on Our Research and Cited Literature	Global Impact Based on Our Research and Cited Literature
Importers would increase their dependency on other countries [12].	Finland already imports around a third of its consumed food [64], but the increased cattle production exports could act as a buffer against certain global shocks.	Population growth and meat consumption are increasing rapidly, and therefore water-scarce countries could focus on growing less water-intensive products (e.g., vegetarian protein) [39,76], that can be used for animal and human consumption. Finland's exports could then only meet the increased demand for cattle products.
Many countries do not have the financial means to import the goods they would need, and are already today involuntarily out of the virtual land and water markets [77].	Finnish primary production has high expenses, due to the climatic constraints, and the country is very dependent on subsidies [78].	Due to the high productions cost [79], Finnish cattle products might not be accessible in the countries that would benefit most of the virtual water embedded in the trade.
Increasing imports, especially in countries with poorly developed rural infrastructure, could favour urban consumers, while putting pressure on the domestic agricultural sector, causing rural poverty and rural-urban migration [16].	Finnish agriculture is going through structural changes [66], and increasing cattle production would empower agriculture and enrich the landscape.	Our study focused only on the environmental aspect, and excluded the social and economic viewpoints. These should be studied in detail, together with needed legislation and political will, to understand the potential of our scenarios fully.
Increasing exports could lead to increasing deforestation and land and water contamination [80].	Even though the quantity of fresh water is not the limiting factor to increased cattle production in Finland [33], quality problems, such as increased pollutants and nutrient leaching [81], still need to be taken into consideration.	Quantifying net global environmental impacts would require an analysis of the impacts of increased production in exporting locations and impacts of reduced production in importing locations.
High water and land productivities are frequently linked to high input use (fertilizers, pesticides), potentially leading to high pollution rates if not properly regulated [77].	Regulation and sustainable agricultural practices are needed to guide farmers and consumers towards more sustainable production and consumption.	There is a potential to increase production in current areas with an inefficient production by closing the yield gap and by integrated farm water management [23], and therefore optimizing water savings on water-stressed locations would be beneficial.

4.4. Water Scarcity Impacts in Finland and Globally

Finland has on average (2008–2013) 237 billion m^3 of renewable water resources [33]. This puts Finland at the top of EU countries if measured as the water resources per capita [82]. Based on our scenario-matrix, the greatest potential of net export virtual water (blue and green) was 3.7 billion m^3 year^{-1}. This is on average only 1.6% of all renewable freshwater resources in Finland, and thus can be assumed that Finnish freshwater resources would not be endangered by the increased net export volumes under the normal conditions.

Although on average, water is abundant in Finland, various parts of it are also experiencing droughts, which have been studied less than the more frequently occurring floods [83]. One of the recent severe droughts occurred in 2002–2003 when Finland's water deficit was at its worse (about 60 billion m^3). According to Kuusisto [82], almost half of the deficit was in groundwater stores, a quarter in soil moisture storage and the remainder in lakes. There were severe drought conditions over the growing season 2018, causing prominent (ca. 30%) reduction in harvest compared to the 2017 year's harvest, and the final estimations have not yet been assessed [56]. Even though most of the Finnish crop production is rainfed, Peltonen-Sainio et al. [41,84] state that climate change will create challenges. Especially, frequencies of extreme weather events are expected to increase, which might require the development of irrigation systems for comprehensive water management [41]. Our scenarios did not include assessment for future climatic conditions, but it is obvious that any changes in water resources and agricultural production conditions are relevant.

Finland could increase the net exports of virtual water of cattle products from 0.1 billion m^3 year^{-1} to 3.7 billion m^3 year^{-1} (Figure 4), depending on which scenario combination that is chosen. When putting these net exports into practical measures, this means providing annual agricultural virtual water to up to 3.6 million global citizens (when assuming 1032 m^3 cap^{-1} $year^{-1}$ water consumption for food). Even though greater volumes of virtual water would be required in order to make a powerful influence on the 4 billion people impacted by water scarcity, it is good to put this into a wider perspective—Finland has a population only of around 5.5 million people [34], and it could provide additional virtual water for more than half of a population of its own size. Our study provides a practical example of what one country can do, and if scaling the same scenarios for other water-abundant countries, this might have a considerable impact globally and contribute to the globally fairer sharing of resources.

4.5. Limitations of the Study and Future Directions

Despite the vast freshwater resources, Finland is already facing the challenge of eutrophication in the rivers and lakes that are close to agricultural production, in particular through nitrogen and phosphorus loadings [85,86]. In addition, the entire Baltic Sea is already affected by eutrophication, due to the intensive use of the sea itself and anthropogenic activities [87,88]. Our research focused only on the water quantities, but the future research should expand the assessment also to a water quality analysis. Another significant and negative environmental impact is caused by greenhouse gas (GHG) emissions [89], to which methane from ruminant livestock metabolism has a significant global contribution but which were not considered in our study. Even though the carbon footprint of cows in Finland is smaller (reference level of that in Sweden [51]) than for example in the United States [90,91]) or in Brazil [92], the GHG emissions are an important consideration going beyond our assessment. Further, when evaluating the overall sustainability of increased cattle production in Finland, all positive—but also all negative—impacts, such as economic influence, transportation emissions, degradation of wildlife habitats, eutrophication and deforestation, need to be considered in more detail in the future studies, before constituting the comprehensive understanding.

In the future, population growth and increasing meat consumption are adding more pressure to already limited natural resources. Bringing additional virtual water to global markets does not directly reduce agricultural water consumption in water-stressed areas, due to the increased consumption demand, but rather might keep the scarcity level at the same level. Unfortunately, scarce resources are often depleted in one way or another, as people are understandably seeking ways to secure their income. Thus, instead of suggesting the reduction, or phasing out, of agricultural production in water-stressed areas—alternatively, we are suggesting that less water-intensive products and livelihoods would have to be introduced together with support for efficient and just water resources management.

5. Conclusions

Water scarcity is globally a critical challenge, and the international trade of agricultural products connects a majority of the countries, including water-rich Finland, tightly to it. Case studies are needed to understand how an individual country could implement the existing knowledge and contribute positively to a globally resource-efficient food production in practical matters.

In this paper, we assessed the potential to ease water demand in water-scarce areas by assessing the increase of water-intensive production in areas with a surplus of freshwater, such as Finland. We took into consideration Finland's land use requirements that are embedded in agricultural production and trade. We combined the production scenarios with diet change, and calculated Finland's total potential to net export virtual water in the form of cattle products.

Our analysis demonstrated that there is a potential for reallocation of water use to water-rich areas through the exports of water-intensive products, and replacing partly or fully the bovine meat protein with vegetable protein sources. Finland has vast water and land resources, and hence the increase of water-intensive production does not consume the existing natural resources in the same ratio than in some other production areas, already suffering from water scarcity. Based on these findings, we argue that it is more important to consider where water is saved rather than looking merely at volumes that are saved.

Future case studies could have a combination of global trade and spatial analysis to provide further insights on where the water should be saved and where the natural resources are underutilized. In order to solve the global dilemma of food production with limited resources, the detailed system-wide spatial approach is necessary for this alarming problem.

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Food Preferences in Finland: Sustainable Diets and their Differences between Groups

Elina Lehikoinen [1,*] and Arto O. Salonen [2,3]

1 Water and Development Research Group, School of Engineering, Aalto University, P.O. Box 15200, FI-00076 Aalto, Finland
2 Faculty of Social Sciences and Business Studies, University of Eastern Finland, P.O. Box 1627, FI-70211 Kuopio, Finland; arto.salonen@uef.fi
3 Finnish National Defence University, PL 7, 00861 Helsinki, Finland
* Correspondence: elina.lehikoinen@aalto.fi

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Abstract: The world is facing the great challenge of how to feed the increasing and wealthier population sustainably in the future, with already limited natural resources. The existing literature reveals the negative impacts of animal-based diets, and thus global diet changes are required to ensure future food availability. Nevertheless, it is important to acknowledge that food consumption is more than caloric intake—it is based on personal preferences. We assessed how sustainable food choices vary among Finnish citizens. The respondents (n = 2052) answered nine statements about their consumption behavior. We applied quantitative and qualitative methods, and our results indicate that favoring plant-based diets was the highest among people under 30 and above 60 years old. Middle-aged men with high incomes was the most reluctant group to adopt sustainable diets. Health-related issues and origin of food were the most preferred reasons for food choices, while environmental awareness was ranked lower. The key to mainstream sustainable diets lies in the co-benefits —transition towards more sustainable diets among Finns could be possible, if people felt that they can combine the selfish, hedonistic factors (e.g., health, weight loss) and altruistic factors (e.g., ecological benefits) in their everyday diets.

Keywords: animal-based diets; consumer behaviour; co-benefits; diet change; food culture; plant-based diets; sustainable diets

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1. Introduction

The world is facing a great challenge of how to feed the population sustainably in the future. Natural resources for food production are already scarce in many parts of the world, and the population is expected to reach 9 or even 10 billion by 2050 [1,2], which exacerbates the pressure on an already worrying global situation. Fortunately, there are existing studies that present how to increase food production sustainably with the current resources. Dietary changes towards healthier and plant-based diets, improvements in technologies and management, reductions in food loss and waste, are assessed to be the main contributors to increasing the global food availability without expanding the agricultural land use (see e.g., [3,4]).

In this study, we focus on diet change, since for citizens, it is the most effective and easiest way to influence the environment. Food and eating combine the elements of nature and culture [5], but the way we are eating changes constantly [6]. Wahlqvist and Lee [7] explained that the sense of local and regional food culture have existed throughout human development. In the past, the food culture altered relatively slowly, but current global phenomena, such as rapid population changes, global trade, displacements and migrations, and variances in affordability, has accelerated these changes. Nevertheless, it is important to understand that food consumption is about more than just nutrition—eating enjoyment is based on manifold personal preferences, and attitudes might greatly differ among the people living in regions where there are multiple meal options and financial means to choose the preferred diet [8].

Hartmann and Siegrist [9] highlighted that a behavioral change is needed in more prosperous countries to reduce substantial environmental damage caused by food consumption. Sabate and Soret [10] also specified that the drastic diet changes are complex, which implicates behavioral and policy challenges at many levels. Therefore, dietary recommendations should be tailored to regional conditions for preserving cultural eating habits and contributing to more environmentally friendly consumption [11]. There are already Western country-scale studies about citizens' behaviors and attitudes towards meat consumption and sustainable diets (see e.g., Belgium: [12,13], Finland: [14,15], Germany: [16], Netherlands: [17,18], Scotland: [19], United States: [20]). However, the information about nutrition, food safety and dietary recommendations is increasing and changing constantly, and thus diet changes among citizens constitute a heterogeneous and dynamic research area.

This present study supplements the existing knowledge about the people's dietary preferences, and assesses the potential to mainstream diet changes towards a more sustainable direction at a country level. In the long term, the demand for livestock is projected to grow by 70–80% between 2005 and 2050 [21,22], and it is crucial to change this direction. For example, in Nordic countries, the consumption of meat has almost doubled in the past 50 years, being one of the highest in the world [11,21]. Our research focuses on Finland—a typical affluent country with a low population and high animal protein consumption [23]. Even though Finnish meat consumption (kg cap^{-1} $year^{-1}$) is slightly lower than in other Western European countries and stabilized in the recent years [24], the consumption is still beyond the national recommendations [25,26]. Since there is not only one single reason as to why people would choose less animal-based and more plant-based diets [9], we study the variance of different socio-demographic characteristics, such as age, gender, living area and income, as they relate to dietary habits. In addition, we also assess personal preferences, environmental awareness, and activity to influence when making food-related decisions, in an order to understand the main drivers and key obstacles related to choosing plant-based and domestic meals.

2. Diet Choices in Everyday Life

2.1. Sustainable Diets Regarding People and the Environment

Sustainable diets are described as consumption that is nutritious, safe and healthy in both quantity and quality. The food also needs to be economically, environmentally, socially and culturally sustainable for the present and future generations. For food to be sustainable, it should not threaten the needs of others but should be protective and respectful of biodiversity and ecosystems (see e.g., [10,27,28]). There are four main factors that make plant-based diets recommendable for transitioning to a sustainable society: global food security, human health, environment and animal welfare [29].

Sabate and Soret [10] state that the current food consumption and environmental changes, food security and food sustainability are on a collision course. The world has enough food, but it is produced and distributed unevenly. To find a balance in this situation, several consumer studies have been published in relation to ecological food choices and consumption, including more sustainable food consumption and plant-based diets (see e.g., [3,4,13,30–36]).

The increasing knowledge about negative health issues associated with meat consumption has concerned nutrition experts. Despite meat being an easy and important way to meet dietary protein requirements [37,38]—processed red meat intakes can contribute to increases in total mortality, cancer mortality, and cardiovascular disease mortality as well as the risks of contracting type 2 diabetes [39–43]. Even though the WHO (World Health Organization) and the World Cancer Research Fund (WCRF) recommend plant-based diets, they also acknowledge that a moderate amount of red meat can be acceptable if it is not processed [44,45].

At the same time, livestock production consumes considerable volumes of water [46] and occupies significant areas of farmland [47] that could be used more efficiently for the cultivation of alternative protein resources. In addition, livestock production is a substantial greenhouse gas producer and contributor to eutrophication of waterways [47], among other negative environmental impacts. Yet, it is central to acknowledge the current importance of meat protein and therefore, more attention needs to be paid for the suitable production areas of livestock where there is a surplus of water and land [48,49].

Despite the harmful impacts, meat consumption is increasing globally as the population is getting wealthier [23]. At the global level, the main drivers for the increased meat intake are manifold, such as an increased income, urbanization, changes in trade policies and consumer attitudes [50]. At the same time, the main reasons to reduce meat intake are equally multiple, including population growth, ecosystem deterioration and public health risks [2,39,51,52].

2.2. Features Behind Choosing Sustainable Diets

2.2.1. Motivation for Personal Food Consumption

Hartmann and Siegrist [9] stated that citizens' preferences form a complex net with multiply reasoning for personal diets, especially in the western countries. Järvelä et al. [14] explained that people often describe their food choices in terms of avoiding or favoring. This division itself already includes what one considers to be good or bad choices. The strategy of avoiding seeks to eliminate the threats of food quality and safety from own's eating habits. The strategy of favoring seeks to consume food that is believed to be safe and health-promoting [14].

There are clear differences in meat consumption between women and men. In general, women have expressed more concern for the environment [9,53–55] and are more likely to reduce their meat consumption [18,35,56,57]. Men appear to be less willing to reduce their meat consumption, and in addition, they prefer larger meat portions [17,35]. De Boer and Aiking [56] discovered that people who prefer plant-based meals and white meat also have a lower appreciation for the taste of red meat. More precisely, favoring plant-based diets is linked with concerns over animal welfare, and favoring white meat is linked with pickiness about meat [56]. Even though people have different attitudes towards meat production, often it is not strong enough to directly influence consumption behavior [6].

Research also suggests that older people have more sustainable ways of living than younger citizens [58,59], and meat consumption is expected to decline with age [60–62]. The reasons behind the decline in meat consumption can be manifold such as the changes of taste, higher cost of meat, poor dentition, digestive issues or simply personal preferences. Increasing health awareness and concern might eventually even lead to a declining appetite [62].

Improved incomes or lower food prices have led to the increased consumption of animal-based diets and processed foods [50,63], but this might not directly correlate with personal choices. It seems that people with higher levels of education (often also correlated with higher incomes), have lower levels of meat consumption [62]. Thus, income is not a straightforward determinant of food consumption. At the same time, rapid urbanization has impacted food consumption patterns significantly. Globally urban areas often are characterized by higher caloric intake, including higher consumption of animal products and food fat [50,64], but this might refer mainly to the urban poor.

2.2.2. Environmental Awareness in Food Choices

Hartmann and Siegrist [9] discovered that the environmental impacts of food consumption are often unknown to people, especially in various Western countries. Only a small minority of citizens are aware that a plant-based diet is more environmental friendly than an animal-based diet [16]. It also seems that even if citizens acknowledge the negative environmental impact of meat consumption, generally there is an underestimation of it [12,17]. The negative environmental impacts are often projected to packaging, food waste, transportation of food, production and processing of the food, rather than to actual meat consumption [19,50].

Individuals often can adapt more easily to the environmentally friendly behavior that is effortless or has a low cost (e.g., recycling), than to behavior that is potentially more inconvenient or has a high cost (e.g., vegetarian diet) [53,65,66]. Also, people might feel that they have already reduced their meat consumption and hence do not see the reason to change their dietary habits any further [19]. Only a minority of the citizens are willing to change their diets towards a more plant-based one for ecological reasons, while health-related reasons are more prominent [9,19]. Salonen et al. [67] discovered that sometimes pursuing personal interests is a strong driving force to choosing diets.

2.2.3. Activity to Influence on Food Consumption

The world is changing constantly, along with the various information regarding food, diets and dietary recommendations. Holm and Palojoki [68] stated that the problem is not the lack of information, rather the difficulty to digest it all. People often know a lot about food-related issues, but at the same time, they acknowledge the inability to implement those in their daily routines [14]. Järvelä et al. [14] also discovered that citizens often feel overwhelmed by the increasing new information that conflict with the previous information, or there might be even feelings of despair and doubt if citizens' personal actions would have any significant difference [19]. In addition, some citizens are not willing to change their meat consumption habits because they are sceptical about the scientific relevance, or have formed a mistrust towards the constantly changing information flow [69].

It seems that changes in taste and preferences are usually linked with long-term shifts, while the short-term changes are more frequent and often affected by negative information [62]. The popularity of local, sustainable and organic food has increased over recent years [50], and the origin of food is considered to be important to people because these foods are believed to be simply better [6]. Organic and local foods are commonly associated with economic benefits and transparency [70], as well as health and freshness of food [20]. Yet, it is worth noting that the benefits are focused more on personal gains rather than concerns about the environment [20]. Järvelä et al. [14] added that, for example in Finland, if the statements about the importance of the local food were fully put into practice, the selection in stores would be different that it is currently. Therefore, we can make only limited assumptions based on the surveys. Overall, the knowledge about more sustainable food choices is related with a higher willingness to change meat consumption behavior [9,17,71].

2.3. Research Questions for this Study

In this paper, we focus on sustainable diets from citizens' perspectives, and study the potential transition towards more sustainable diets. Our research questions are: (a) How do sustainable food choices vary among Finnish citizens' everyday lives? and (b) What kind of transition potential towards more sustainable diets can be identified in Finland? We analyze a variation of age, gender, living area and net-income because socio-demographics factors other than gender or cultural background have rarely been examined [9]. Sabate and Soret [10] stated that food behavior is determined also by other factors than just socio-demographics characteristics, such as attitudes, norms and culinary traditions. Therefore, in order to comprehend the driving forces behind Finnish citizens' dietary habits, we also assess personal preferences, environmental awareness and activity to influence everyday food choices.

3. Materials and Methods

Data used in this research was part of a wide national survey that focused on Finnish citizens' sustainable behavior, and our research used the data related to sustainable diet choices. Figure 1 presents how our study was conducted—it was divided into quantitative and qualitative analyses. The quantitative analysis focused on variances between different groups of citizens when choosing a sustainable diet, and the qualitative analysis studied the main drivers and key obstacles when choosing plant-based meals.

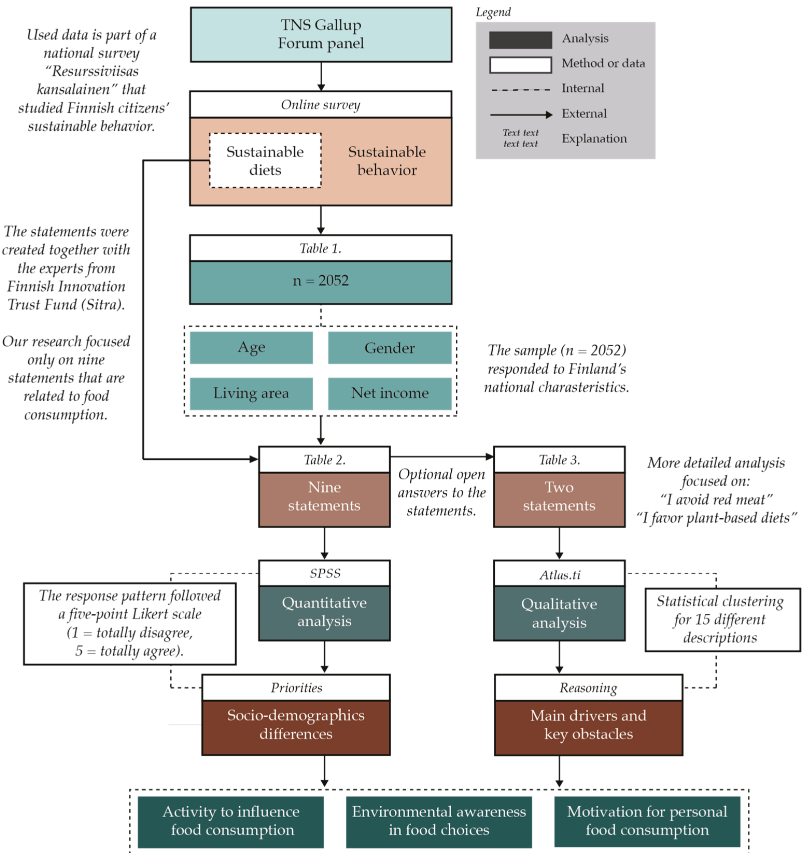

Figure 1. Flowchart of the study. Our quantitative analysis focuses on variances between different groups of citizens when choosing a sustainable diet, and the qualitative analysis studies the main drivers and key obstacles to choosing plant-based meals.

A sample (n = 2052) was collected in April 2017 via an online questionnaire from the TNS Gallup Forum-panel. The panel serves different national research surveys containing 40,000 respondents that represents the population of Finland (18–79 years old), excluding Åland region, while the population of Finland is around 5.5 million people [72]. Table 1 presents socio-demographic characteristics of the sample (left) and Finland's national socio-demographics (right) for the year 2017 [72–77] when the survey was conducted.

Table 1. Socio-demographics characteristics of the sample (n = 2052) and Finland's socio-demographics for the year 2017 [72–76].

Sample's Socio-Demographics	n	%	Finland's Socio-Demographics
Gender (n = 2052)			
Female	1048	51.1	50.7%
Male	1004	48.9	49.3%
Age (n = 2052) [1]			
<30	210	10.2	33.9%
30–39	236	11.5	12.8%

Table 1. *Cont.*

Sample's Socio-Demographics	n	%	Finland's Socio-Demographics
40–49	429	20.9	12.0%
50–59	310	15.1	13.3%
60–69	529	25.8	13.4%
>70	338	16.5	14.7%
Living area (n = 2052)			
Metropolitan area	521	25.4	20.8%
Other cities/towns	1062	51.8	50.1%
Countryside	469	22.9	29.1%
Net income of the respondent in € (n = 1694)			
<10,000	189	11.2	17.9%
10,001–20,000	331	19.5	23.1%
20,001–30,000	428	25.3	20.2%
30,001–40,000	342	20.2	16.5%
40,001–50,000	210	12.3	9.4%
>50,000	194	11.5	12.9%

[1] The sample accounts for respondents only from the age group between 18–79 years old, while the national socio-demographic characteristics present the whole age group, starting from 0 years old until >100 years old [74].

The statements were developed together with the experts from the Finnish Innovation Fund Sitra. The original questionnaire had a wide range of statements regarding different attitudes and actions that related to sustainable consumption and sustainable behavior. The unambiguity of the claims in the questionnaire was pretested by students of Metropolia University of Applied Sciences, Finland. On the basis of the feedback, ambiguous claims were removed or reduced to more unambiguous ones. The response pattern followed a five-point Likert scale (1 = totally disagree, 5 = totally agree).

Our analysis focused on nine statements regarding sustainable food consumption in citizens' everyday life (Table 2). In order to identify variances between groups, we applied a one-way ANOVA with post hoc procedures by SPSS. Levene's test results were significant which means that the assumption the homogeneity of variance was broken. According to Tabachnick and Fidell [78] problems created by unequal group sizes, however, are relatively minor. Moreover, we applied Brown-Forsythe *F* because it gets around this challenge by weighting the group variances by the inverse of their sample sizes [79].

Table 2. The statements that the participants were asked to respond to (a five-point Likert scale).

Category	Statements
Motivation for personal food consumption	I favor a plant-based diet I avoid eating red meat (beef, pork, lamb) I like to try new healthy and environmental friendly foodstuff
Environmental awareness in food choices	I favor locally produced food I take into account the origin of food while shopping I choose a pro-climate meal in a restaurant
Activity to influence food consumption	I actively influence what I eat I change my eating habits as I get more information I try to minimize the environmental cost of my diet

The respondents were also able to explain in more detailed why they considered the specific statement—a way of food consumption—to be important for them. By analyzing open answers based on the statements, it was possible to get complementary information to be added to the quantitative analysis. The qualitative analysis was done to two statements in the questionnaire: "*I avoid eating red meat (beef, pork, lamb)*" and "*I favor a plant-based diet*".

Initially, the statement related to avoiding meat had 421 open answers but after cleaning the data, we analyzed 326 open answers. Also, the statement related to favoring a plant-based diets initially had 632 open answers but after cleaning the data, we analyzed 417 open answers. The neglected open answers either stated plain "*yes*" or "*no*" and did not provide any additional information, specified unwillingness to answer the open question or the content of the answer was not clear. Many of the neglected open answers also included descriptive information about the content of meals, time-related specifics, overall willingness to change consumption habits without further explanation or otherwise included information that did not respond to the statements.

The open answers were clustered according to Table 3 by using Atlas.ti. The same clustering was used for both statements in an order to assess the differences and similarities in avoiding red meat or favoring plant-based diets. Often the open answers had multiple descriptions, and hence there were more answers related to statements than the overall number of open answers. The multiple reasons were analyzed with a code co-occurrence tool. The c-coefficient value indicates the strength of the relation between two codes similar to a correlation coefficient. The c-coefficient varies between 0 and 1. Zero means that these codes do not co-occur, meanwhile 1 means that the two codes co-occur wherever they are used. However, the database is qualitative, and therefore no p-values are provided [80].

Table 3. Clustering the open answers for "*I avoid eating red meat*" and "*I favor a plant-based diet*".

Code	Descriptions
Challenge	Refers to challenges or difficulties, doubts or questions to choose a particular diet.
Diversification	Refers to a desire to change or diversify consumption habits or diets.
Environment	Refers to concerns about the environment, climate or energy consumption.
Ethics	Refers to concerns about animal welfare or refers to personal ethical reasons.
Exception	Refers to particular occasions for choosing or avoiding a particular diet.
Family	Refers to an impact of a family or household member; either positive or negative.
Finances	Refers to financial reasons; either expensiveness or affordability.
Health	Refers to health-related concerns or limitations; either positive or negative.
Meat replacement	Refers to replacing the red meat with other meat and vegetable substitutes.
Origin	Refers to the origin of the food as well to its seasonality.
Other	Refers to multiple and diverse reasons for choosing or avoiding a particular diet.
Science	Refers to science, research, recommendations or general beliefs.
Taste	Refers to personal preferences on the flavor of food.
Vegetarian	Refers to already being a vegetarian.
Weight	Refers to losing weight or lightening the diet.

4. Results

4.1. Descriptive Statistics

According to the descriptive statistics, locality (mean 3.98) and origin of the food (mean 3.48) were important to Finns (Figure 2). Finns also actively influenced their everyday food choices (3.68), although new information was not considered to be so essential (mean 3.18). Choosing a pro-climate restaurant meal (mean 2.26) scored the lowest along with avoiding red meat (mean 2.48) and favoring plant-based diets (2.92). When environment was related to health (mean 3.29), it scored higher than when solely related to reducing the environmental impacts (mean 2.99).

All these mean averages present sustainability as a multidimensional phenomenon that combines support for the locality, environmental friendliness, health issues and willingness to change behavior. In all of these dimensions, women's eating choices received higher scores than that of men.

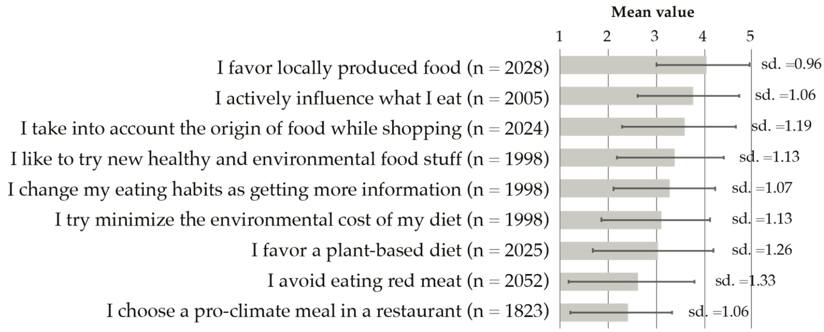

Figure 2. Descriptive statistics of the statements related to food consumption, from the highest to lowest mean (with standard deviation, sd.).

4.2. Differences between Groups

In all nine statements, there was a statistically significant difference ($p < 0.001$) among men and women, so that women had systematically higher scores than men. Thus, women prefer more sustainable food than men in Finland.

When taking a closer look at the differences between groups in *favoring plant-based diets,* we recognized that the differences among different age groups were statistically very significant, $F(5, 1500) = 6.89$, $p < 0.001$. Plant-based diets were most common among citizens under 30 years and over 60 years old which means that the behavior was demonstrated in an inverse bell curve. In addition, favoring plant-based diets received high scores until the personal yearly income reached 30,000 euros. Having more money seemed to decrease favoring plant-based diets. Among citizens earning more than 30,000 euros, favoring the plant-based diets decreased significantly, $F(5, 1416) = 3.74$, $p = 0.002$. Regarding the place of residence, there was a statistically significant difference, $F(2, 1523) = 3.11$, $p = 0.045$, when favoring plant-based diets. We recognized that favoring plant-based diets was highest in the metropolitan area and decreased towards the countryside.

Avoiding red meat varied such that the of 40–49-year-old age group avoided eating red meat the least and, interestingly, the age group of over 70 years old avoided red meat the most. Between the different age groups, there was a statistically very significant difference, $F(5, 1618) = 5.66$, $p < 0.001$ Statistically, a significant difference also occurred among the different living areas, $F(2, 1551) = 6.11$, $p < 0.002$. Citizens in the metropolitan area avoided red meat the most, and citizens in the countryside avoided red meat the least.

Regarding the *willingness to try new healthy and environmentally friendly foodstuffs*, there were no statistically significant differences among the socio-demographics groups, apart from gender, $F(1, 1986) = 111.0$, $p < 0.001$. Women were more willing to try new foodstuffs than men. Nevertheless, willingness to try new foodstuffs decreased with age, but it was not statistically significant ($p < 0.061$).

When considering the *willingness to minimize the environmental impacts of the diet*, the differences between different age groups were statistically very significant, $F(5, 1606) = 7.65$, $p = 0.000$. Finns in the 40–49-year-old group were the least interested in minimizing the environmental impacts of the diet and those over 70 years old were the most interested. Thus, these tendencies were demonstrated by the inverse bell curve. In addition, we detected that personal net income influenced willingness to minimize environmental impacts positively until 40,000 euros. When personal yearly net income is above 40,000 euros, citizens become less interested in the environmental impacts of their diets. The difference was statistically very significant, $F(5, 1391) = 3.99$, $p < 0.002$.

Choosing a pro-climate restaurant meal had a great diversity of responses. Statistically, a significant difference $F(5, 1423) = 5.77$, $p < 0.001$ was found among different age groups. We recognized that the age group under 30 years old had a relatively low interest in choosing pro-climate restaurant meals.

Also 30–40-year-old Finns were very unlikely to choose a pro-climate restaurant meal. When personal income level increases, choosing a pro-climate restaurant meal is reduced as well. After personal net-income reached the level 30,000 euros, the decrease was steep. The difference between different income groups was a statistically significant, $F(5, 1287) = 2.65$, $p < 0.03$.

When comparing the *activeness or passiveness to influence diet*, there was a statistically significant difference between the metropolitan area and other living areas, $F(2, 2002) = 3.11$, $p < 0.045$. In the metropolitan area, the activity of people was higher than people living in other areas. Regarding the age groups, we recognized that 30–39-years-old Finns were the most active in influencing their diets. Respectively, 40–49-years-old Finns were the most passive in influencing their diet. Between the different age groups, there was a statistically significant difference, $F(4, 1619) = 2.76$, $p < 0.02$.

4.3. Reasoning of Food Choices

Health-related issues were the most common reasons either to avoid red meat (25.5%) or to favor plant-based diets (36.8%) (Figure 3) When avoiding red meat, answers included multiple concerns such as a fear of cancer, increased cholesterol or abdominal problems—the respondents were mainly reducing their red meat consumption because of the feared negative impacts. Respectively, the open answers emphasized the personal well-being and a desire to live healthier as the primary reason when favoring plant-based diets—the respondents were mainly increasing their vegetable consumption because of the hoped positive impacts.

Next to health-related issues, were concerns about the state of the environment, climate change and the exploitation of environmental resources for avoiding red meat (16.2%) or for favoring plant-based diets (12.4%). The content of these open answers was similar for both statements, but the respondents did not fully specify whether the concerns were related to Finland or to the global situation.

Personal preferences or taste were mentioned as the fourth most common reason (10.2%) to avoid red meat and as the third most common reason (11.9%) to favor plant-based diets. Again, the reasons to avoid red meat were often seen negatively such as disliking the taste of meat, and respectively, the plant-based diets often received embraces for the flavors of vegetables. Third most commonly (12.5%) respondents avoided or reduced their red meat consumption by eating white meat or vegetables, indicating that there is already an increasing movement towards favoring plant-based diets.

After the third or fourth most common reasons, there was more dispersion between the reasons to avoid red meat or to favor plant-based diets. Ethics, such as the concern about the animal welfare or welfare, was relatively high for the respondents either to avoid red meat (9.7%, the fifth most common reason) or to favor plant-based diets (5.2%, the sixth most common reason). In the open answers, some of the respondents felt very strongly about this, and the diets were considered as an important way of living or as a personal statement. Interestingly, the desire to lighten the diets or lose weight, was the fourth most common (10.6%) reason to favor plant-based diets but the tenth most common (1.9%) reason to avoid red meat. This linked closely to the health-related issues, especially for favoring plant-based diets, where the aim was to live healthier.

The respondents did not have any significant challenges or difficulties, doubts or questions either to avoid red meat (1.9%, the 11th most common) or to favor plant-based diets (1.6%, the 13th most common). In addition, the Finnish consumers seemed to be independent decision-makers, since family was mentioned only as the 14th most common reason (1.4%) to avoid red meat or as the ninth most common reason (2.2%) to favor plant-based diets.

Some of the answers (Figure 3) had multiple reasons whether to avoid red meat or to favor plant-based diets. When looking at the main reasons to avoid red meat (Figure 4), the highest connections were between the environment and ethics (c-coefficient 0.17), and between the environment and health (c-coefficient 0.14). There was also a correlation between health and ethics (c-coefficient 0.09), and between the origin of the food and particular occasions (c-coefficient 0.09). The particular occasions were often related to holidays meals, such as Christmas or Easter, or the respondents described that they consumed red meat only during exceptional occasions such as dinners in restaurants or meals hosted by someone else.

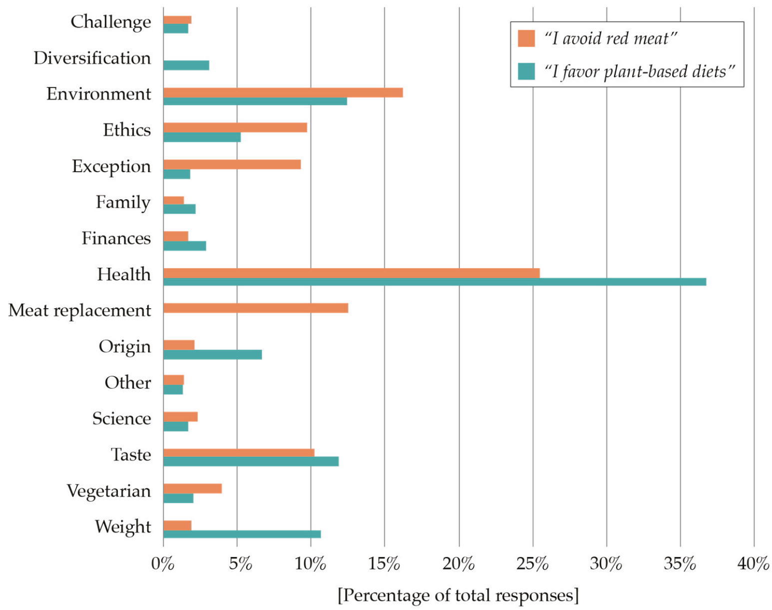

Figure 3. Different reasons for avoiding eating red meat (orange color) or favoring plant-based diets (green color) expressed as a percentage of total responses, if the respondents evaluated that they agreed (Likert scale 4) or totally agreed (Likert scale 5) with the given statement.

When looking at the connections between the main reasons to favor plant-based diets (Figure 4), health-related reasons connected with environmental concerns (c-coefficient 0.13) and with weight control (c-coefficient 0.10). Respectively, the environment had a high connection with ethics (c-coefficient 0.15) which was often explained by a common concern about the environment and animal welfare.

The challenges and difficulties for avoiding red meat or favoring plant-based diets, presented an interesting study area that reflected also respondents' attitudes. Women sometimes specified that they were reducing their red meat consumption but their spouses were not. Nevertheless, this was not explained as a challenge—rather only as a remark, and therefore there is not a connection between family members and challenges when avoiding red meat. This was opposite in the favoring plant-based diets, where the connection between family members and challenges was the highest (c-coefficient 0.17). Again, sometimes women were answering that they would increase their vegetable consumption but found it difficult because the resistant in the family. Nevertheless, it is good to acknowledge that the overall the family influence was not ranked high (Figure 3), and therefore the connection (Figure 4) seems higher than it might actually be.

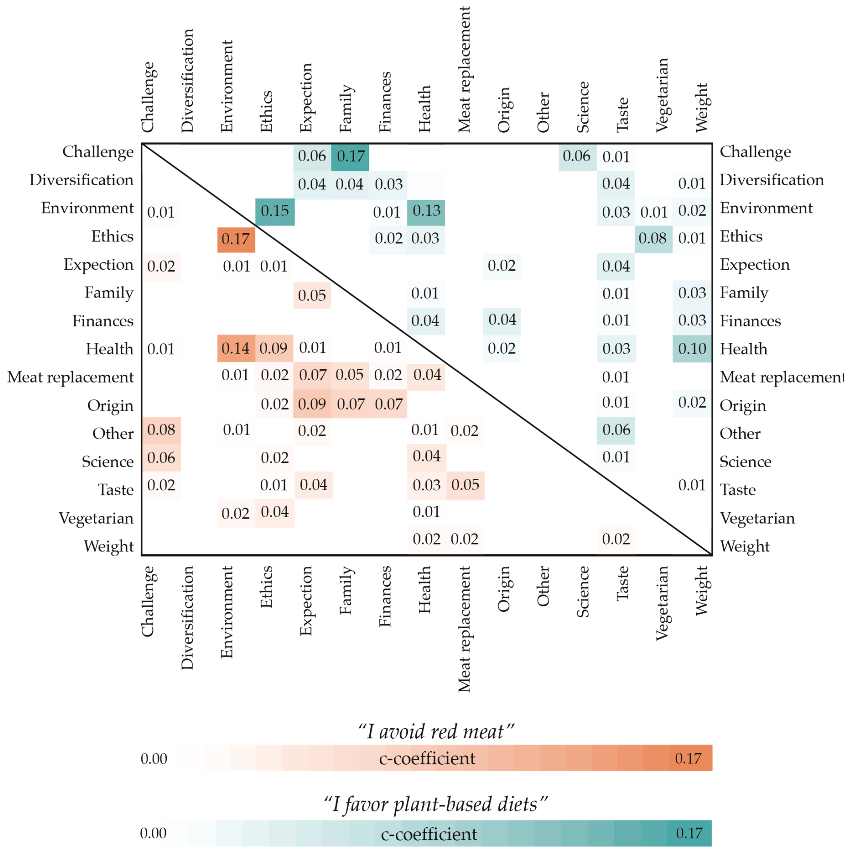

Figure 4. Interconnections between the clustering for favoring plant-based diets based on the c-coefficient values (meaning that the multiple reasons were given for the same answer).

5. Discussion and Concluding Remarks

5.1. Progressive Urban Women and Wealthy Middle-Aged Men

Similar to previous studies [53–55], our results also indicate differences between men and women. In general, women's lifestyles are more ecologically and socially sustainable than men's in western countries [15,81,82]. We also discovered that Finnish women were more environmentally aware and more willing to try new environmental and healthy foodstuffs. As a general assumption, women also are often more responsible for households and cooking, and our analysis presented that there is a connection between the challenge of favoring plant-based diets and being influenced by family members (Figure 4). Similar findings were discovered in Scotland, where some women stated that they found reduction of meat consumption problematical because of their husbands or partners [19].

We discovered that the age group over 70 years old avoided red meat the most, which is also supported by a decline in appetite with ageing found by Verbeke et al. [62]. In Finland, like in other Nordic countries, the consumption of meat has increased significantly over the last decades [11,21] and meat is not anymore considered as a luxury product like it used to be centuries ago [8]. It might simply be that the older generation is not used to eating meat as it is consumed averagely in Finland today for several reasons such as the cost of the meat, poor dentition and digestive issues. Overall, the older generation's attitudes towards meat might be more conservative than the younger generation.

Respectively, the age groups under 30 and over 60 years also favored plant-based diets the most. Finnish younger generation is more exposed to vegetarian options because of the changes in the food culture and international trade [83], that has diversified the traditional diets with imported foodstuff. Previous studies have presented that offering more meat-free meals would increase their selection [9,53]. This might also be explained by the geographical differences among metropolitan areas, other cities and the countryside in Finland: there are more vegetarians options, including vegetarian restaurants, in the cities than in the countryside. This was opposite to the global assumption that the animal protein consumption increases in the cities [50], but applies to a hypothesis about the saturation levels in meat consumption, where Henchion et al. [84] explain that the external reasons such as climate change, obesity, technology advancements and changes in lifestyles might be changing the policy initiatives as well consumer behavior towards reduced or levelled meat consumption.

Our results also displayed that the taste of food was important for Finnish people and was ranked relatively high, whether when avoiding red meat or favoring plant-based diets. This emphasizes the power of personal choices and motivation that Finnish people have over their food consumption. On average, Finnish citizens spend around 10% of the expenses for food (reference on the year 2016)—for low-income earners that is the second highest expenses group and for high-income earners that is only the fifth highest expenses group [85]. It is still important to acknowledge that this presents only the average, and there is an increasing number of people who are dependent on food aid [86,87]. Thus, people do not always have the option to choose their preferred diets but are tied into the existing conditions and surrounding restrictions. However, it seems that people who consume meat more frequently and have a positive attitude towards meat consumption, are also less willing to reduce their meat consumption [9].

In Finland, the average annual net-income is around 29,000 euros (Table 1). Our results present that when personal net-income was higher than 30,000 euros, favoring plant-based meals decreased significantly. On average, men earn more in Finland than women, and are more active in the working life [88]. Thus, it can be speculated that on average the people groups earning more than the average income, are far in their career path and therefore also middle-age or older. This is supported by the data showing, that the age group of 40–49-year-old favored red meat the most.

Based on these findings, we can reason that the women living in the metropolitan areas are more progressive and willing to change their diets towards more sustainable options. An opposite conclusion can be assumed: currently it is less likely that middle-aged men, with higher incomes, will change their diets. Nevertheless, based on the previous results and our findings regarding age and global trade, we can assume that the entire food culture is in a transition, and that future generations will dictate its direction.

5.2. The Potential Towards More Sustainable Diets in Finland

Based on previous research [14], it seems that Finnish people have enough information about food-related issues. Nevertheless, science or official recommendations scored averagely when people explained their specific reasons to avoid red meat or favor vegetables. Macdiarmid et al. [19] discovered that the increasing information about diets does not always guide people, and this seems to be the case in our study as well.

Respectively, open answers related to personal health and well-being scored the highest in both statements (Figure 3). It seems that knowledge is more related to a personal well-being rather than the environmental impacts of food production. Losing weight was emphasized as one of the main reasons to favor plant-based diets. As an example, in the statements (Figure 2) "*I like to try new healthy and environmental foodstuff*" scored higher than "*I try to minimize the environmental cost of my diet*", which implies that the environmental impacts alone do not seem too important for Finnish people. Our hypothesis is therefore that health benefits, such as lighter meals, weight control and diversifying diets, would be effective ways to decrease red meat consumption and increase plant-based meals in the Finnish context.

Previous studies presented that the environmental impacts, when even recognized, are more known and associated with packaging, food waste and transportation, rather than food consumption [19,50]. Furthermore, the impacts of global food crises might also seem very distant to Finnish citizens, although Finland benefits significantly from global trade [83,89,90]. Thus, it might be that Finnish citizens are simply not aware of their environmental impact in local or global contexts.

Nevertheless, it is good to acknowledge the local context—Finland has vast natural resources for agricultural production compared to many other countries [91,92]. In addition, a majority of Finnish people live in urban settings [93], and thus primary production might feel alien to the majority of citizens. Finnish primary production is going through structural changes, like in the rest of Europe, and farm sizes are increasing while the number of farms is decreasing [94]. In the midst of these changes, it is good to acknowledge that locality could bring economic benefits to certain production areas. Max-Neef [70] argued that the economic sustainability creates local employment and business opportunities when money stays within the specific areas and countries. Our results also emphasized the importance of local food to Finnish people, and preference for local food was considered high (Figure 2) [15]. However, this is not often reflected in the real purchasing situation at grocery stores [14], and people tend to make to their buying decisions based on something else, such as price. We can therefore assume that the appreciation of domestic food is important to Finns, yet is not reflected in everyday life.

Consequently, we state that there is a realistic potential to mainstream sustainable diets, but it relies on people's knowledge and personal motivations to change their diets. As stated, the Finnish citizen does not follow the typical consumer model regarding personal income—rather, consumption habits are shaped by personal preferences.

5.3. Limitations of the Study and Future Research

We applied variance analysis as a quantitative research method. ANOVA is a fairly robust research method in terms of error rate [78]. However, violation of homogeneity of variance was our challenge. All the inspected groups were no equal-sized. In order to take care of this challenge, we reported Brown-Forsythe *F*-ratios. By doing so, we reduced the impact of large sample sizes with large variance. This was important because we know that *F*-ratio tends to be conservative in a situation where groups with larger sample sizes have large variances than the groups with smaller sample sizes [79].

Even though our analysis provided valuable new and current information about Finnish citizens' consumption habits, the phrasing in the questionnaire may have influenced respondents' presumptions and answers. The respondents were asked to estimate their behavior regarding how they "*avoid red meat*" or "*favor plant-based diets*". This could have already directed what generally is considered to be good or bad choices [14]. Therefore, the respondents might have understated or exaggerated their behavior or consumption habits based on the phrasing in the questionnaire.

It is also important to acknowledge that not all the participants (n = 2052) explained their statements by open answers, and therefore the qualitative analysis supplemented only partly to the original sample. The qualitative analysis was also done in Finnish and translated into English, and therefore some of the deeper cultural content was needed in the interpretations that might have also impacted on the clustering (Table 3).

The neglected open answers indicated that many of the respondents were already reducing their red meat consumption or increasing their vegetable consumption. This provided information supporting the idea that a transition towards more sustainable diets is possible, and is actually happening, but it did not indicate the state of the current consumption level. As studied by Macdiarmid et al. [19], if people feel that they are already doing something different compared to their ordinary consumption habits, they do not have any further need or desire to change their diets. More specified questions and answers regarding the reduction or increased quantities (e.g., g cap^{-1} $week^{-1}$) of meat consumption would help to understand the current state. In addition, it is also important to consider what is meant by meat or by red meat. Globally, consumption of meat has increased but a considerable amount of increased meat consumption is consumption of poultry [50]. Our research focused only on red meat—consumption of poultry was not within the scope of this study.

This research focused only on citizens and their personal preferences, but future research should also focus on the politicians or municipal officials responsible for public procurements [95]. Vinnari and Tapio [24] suggested that the taxing products at a higher rate is not sufficient as different groups would need to be persuaded in different ways regarding the benefits of altering their diets and beliefs. Finnish legislation guarantees pupils and students the right to free meals during school days from pre-primary and basic education until the completion of upper secondary education [96]. Therefore, we suggest that there is a great chance to direct people's consumption habits toward more sustainable diets through public procurements.

6. Conclusions

We found that choosing sustainable diets is a multiform phenomenon where health and environmental reasons were mentioned as a first priority, but other reasons such as taste, ethics or losing weight were emphasized as well. In addition, the different socio-demographic indicators, such as gender and age, impacted clearly personal choices. Finnish society is relatively wealthy by global standards, and citizens are able to choose their diets based on personal preferences. Finnish people do not perhaps see the connection between their food consumption and nature depletion, while the connection between diets and well-being is more subjective and known to Finns. Emphasizing health impacts and weight control is highly valued among Finns, and directly influences diet choices such as whether to avoid red meat or favor plant-based diets. Environmental awareness also appears in the background but it is not perhaps strong enough to be the leading driver to change diets to be more sustainable. Thus, our conclusion is that the potential transition towards more sustainable diets among Finns is the most powerful when people can combine the selfish, hedonistic factors (e.g., health, weight management) and altruistic factors (e.g., ecological benefits) in their everyday diets. The key to mainstream sustainable diets lies in the co-benefits.

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Severe Drought in Finland: Modeling Effects on Water Resources and Assessing Climate Change Impacts

Noora Veijalainen [1,*], Lauri Ahopelto [1,2], Mika Marttunen [1], Jaakko Jääskeläinen [3], Ritva Britschgi [1], Mirjam Orvomaa [1], Antti Belinskij [1] and Marko Keskinen [2]

1 Finnish Environment Institute, Latokartanonkaari 11, FI-00790 Helsinki, Finland; lauri.ahopelto@aalto.fi (L.A.); mika.marttunen@ymparisto.fi (M.M.); ritva.britschgi@ymparisto.fi (R.B.); mirjam.orvomaa@ymparisto.fi (M.O.); antti.belinskij@ymparisto.fi (A.B.)

2 Department of Built Environment, Aalto University, 02015 Espoo, Finland; marko.keskinen@aalto.fi

3 Department of Mechanical Engineering, Aalto University, 02015 Espoo, Finland; jaakko.j.jaaskelainen@aalto.fi

* Correspondence: noora.veijalainen@ymparisto.fi

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Abstract: Severe droughts cause substantial damage to different socio-economic sectors, and even Finland, which has abundant water resources, is not immune to their impacts. To assess the implications of a severe drought in Finland, we carried out a national scale drought impact analysis. Firstly, we simulated water levels and discharges during the severe drought of 1939–1942 (the reference drought) in present-day Finland with a hydrological model. Secondly, we estimated how climate change would alter droughts. Thirdly, we assessed the impact of drought on key water use sectors, with a focus on hydropower and water supply. The results indicate that the long-lasting reference drought caused the discharges to decrease at most by 80% compared to the average annual minimum discharges. The water levels generally fell to the lowest levels in the largest lakes in Central and South-Eastern Finland. Climate change scenarios project on average a small decrease in the lowest water levels during droughts. Severe drought would have a significant impact on water-related sectors, reducing water supply and hydropower production. In this way drought is a risk multiplier for the water–energy–food security nexus. We suggest that the resilience to droughts could be improved with region-specific drought management plans and by including droughts in existing regional preparedness exercises.

Keywords: drought; hydrological modeling; water security; climate change; groundwater; water–energy–food security nexus; preparedness; Finland

1. Introduction

Drought is one of the most costly natural hazards, causing diverse and cascading impacts on different economic sectors [1]. Europe has been hit by several large droughts during the last hundred years [2,3], with the average cost of drought in EU countries estimated to have been 6.2 billion euros per year in 1990–2006 [4]. Drought costs are, however, difficult to assess comprehensively due to their complex nature, and particularly the fact that indirect costs are seldom properly captured [5]. The lack of data and multitude of methods used in cost assessment make it difficult to compare the results and to estimate the cost and benefit of action against droughts [5]. Studies of drought severity and impact have used a variety of methods, including the use of different drought indices [6,7], and the estimation of the economic impacts of recent droughts [4,8]. The sectors affected directly by drought include energy (particularly hydropower), transportation (water transport affected by low water levels), agriculture (crop yields and livestock), forestry, buildings (e.g., the subsidence of clay soils and the consequent damage to buildings), water supply, industry, tourism, and recreation [8,9].

Water security in Finland is regarded as being at a very high level due to favorable natural conditions, including abundant water resources, as well as good governance and long-term water conservation efforts [10]. Water security can be defined in many ways [11]. We use the definition by UN Water, which states that "water security is the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" [12].

Droughts in Finland are infrequent, and rainless periods are relatively short. Severe drought would impact different parts of Finland differently, as water resources and water use are not equally distributed. The northern and eastern parts are more water-rich than the coastal areas that have a denser population and more intensive water use. Therefore some areas are potentially more vulnerable to droughts, and severe drought could cause serious damage and problems to several sectors [8]. While drought would directly impact water security, its negative effects on hydropower and agriculture mean that it also has the potential to affect both energy security and food security [13].

Despite this, no comprehensive, national or even regional scale analysis on the impacts that a severe drought would have on Finland has been carried out. The economic impact of drought on the whole of Finland has been estimated only for the drought of 2002–2003, which was estimated to have cost 102 million euros in direct damage [8]. The largest damage was caused to hydropower, building foundations, agriculture, and water supply for industry. Although severe and intense, the 2002–2003 drought was not particularly long-lasting and occurred mainly during wintertime, which limited the effects on agriculture. After the drought of 2002–2003, it was suggested that one way to prepare for future droughts could be to simulate the impact on water resources of last century's most severe drought, which occurred in 1939–1942 [8], but until now this evaluation has not been carried out. During the drought of 1939–1942, the precipitation was well below average for three and a half years and the observed water levels in major lakes and rivers were at record lows.

Legislation sets the foundation for future drought preparedness and management as well as related responsibilities. Climate change adaptation aspects are already included in Finnish and EU law, including the Finnish Water Act (587/2011) and Water Services Act (119/2001), as well as the EU Floods Directive (2007/60/EC). However, neither Finnish nor EU legislation requires specific drought management plans. In Finland, only the Water Act includes actual provisions on drought preparation and management. According to the Water Act, drought justifies the review of water permits and the restriction of water abstraction to avoid significant harm or damage (Ch. 3, Sec. 21; Ch. 4, Sec. 10). The Water Act also mandates a state authority to prepare a report on the measures needed to minimize the harmful impact of droughts (Ch. 18, Sec. 3), and thus directs the authority toward drought management planning. At the European level, the Common Implementation Strategy of the Water Framework Directive (2000/60/EC) [14] guides the Member States to consider drought preparation in the context of river basin management planning, which can be seen as a wide enough spatial scale for drought risk management.

Climate change has increased the interest in drought and its possible impact. The hydrological regimes in Finland will be affected by climate change, as changes are expected particularly in seasonal variability due to warmer winters [15]. Precipitation is expected to increase and the length of dry periods to decrease in winter, while changes in summer dry periods are more uncertain [16,17]. While meteorological drought periods are estimated to remain relatively unchanged in length due to climate change [18], climate change can still cause hydrological drought to become more severe in some regions. Warmer temperatures increase evaporation and cause earlier and smaller spring floods, which result in lower discharges during late summer and early autumn [19]. To date, there have been few strong observed changes in drought trends in the Nordic countries [20,21]. Climate change projections made with large-scale models predict decreases in drought severity for either the entire Finland [22] or Northern Finland, with no significant changes in Southern Finland [23].

The aim of this study was to develop and test a methodology for a national-scale drought analysis in Finland, and in this way to improve the understanding of droughts and their impacts on key water-related sectors. This paper was written as part of the same research project as the paper by Ahopelto et al. [24], which estimates water availability and water stress in Finland during a severe drought. Ahopelto et al. [24] used monthly discharges (without climate change) as input for their water stress analysis, whereas this study estimated the daily discharges and water levels during a severe drought and the consequent impacts on water resources, water supply and hydropower production in Finland, while taking into consideration spatial variance within the country. In addition, the impact of climate change on droughts was estimated. Based on these results, we discuss the ways that long-term drought should be taken into account in a water-rich country like Finland.

2. Materials and Methods

2.1. Finland's Water Resources and Climate

Finland's water resources amount to approximately 20,000 m^3 per inhabitant, making Finland the second most 'water-rich' country in the EU [25]. On average, only 3.5% of the renewable water resources are abstracted, but variation between regions and seasons is high [26,27]. Water resources are also important, as water-intensive industries, such as the paper and pulp industry, are rather extensively practiced in Finland. Approximately 10–20% of electricity is produced by hydropower [28], which is also important in balancing energy production [29].

The Finnish climate is cold with no dry season [30], moderate precipitation amounts, and moderate evaporation. The observed average annual precipitation sum for 1981–2010 varied from 450 mm in Northern Lapland to around 750 mm in Southern and Eastern Finland [31]. The normally prevailing westerly winds bring moist air to Finland and long-term meteorological droughts are rare [18]. Periods of no or very little precipitation are relatively short. The maximum length of a period with less than 10 mm precipitation with a return period of 20 years is 50–65 days, and is slightly longer in winter than in summer [17].

Climate and hydrology in Finland are characterized by seasonal variation, with snow accumulation in winter and snowmelt during spring. A high percentage of the land area is forests (75%), with agricultural land accounting for 8%. Finland can be divided into three main hydrological regions: the lake district in the east and center, small coastal rivers in the south and west, and the northern area with large rivers. The lake district in particular includes many lakes (Finland has a total of 187,887 lakes), which decreases flow variability. The northern area has large rivers and a short summer with relatively small evapotranspiration amounts and therefore has a relatively small drought risk. The coastal area of Finland has fewer lakes, smaller rivers and more variable discharges, and groundwater recharge is somewhat hindered in areas with thick clay soils partially or totally covering aquifers. At the same time, water use is intensive due to the larger population and active industrial and agricultural activities.

Finnish watersheds generally have two periods of low discharge: late winter or early spring before the beginning of runoff from snowmelt, and late summer, when evapotranspiration, which in summer is greater than precipitation, has decreased the runoff. In Southern Finland, the annual lowest discharge most commonly occurs during summer, while in Northern Finland the winter discharges are the lowest [32].

2.2. Study Area

The study area includes the whole of Finland. Transboundary watersheds in Russia, Sweden, and Norway were also simulated when they affected discharges and water levels in Finland, but results beyond the borders of Finland are not presented. Figure 1 shows the major rivers and lakes in Finland. The five largest lakes in Finland, namely Lake Saimaa (greater Saimaa), Lake Inari, Lake Päijänne, Lake Pielinen, and Lake Oulujärvi are shown with different colors in Figure 1. In addition, the locations of the discharge observation sites in the largest rivers in Finland used for comparison with 1939–1942 (Section 3.1) are shown (Figure 1).

The groundwater level was modeled for 18 groundwater stations where good quality water level data was available, and the groundwater model functioned relatively well. Three of these stations were selected for closer study, namely Perniö (South-Western Finland), Akonjoki (Central Finland) and Sodankylä (Northern Finland) (Figure 1). These were selected to represent different parts of the country and different types of groundwater areas to produce an overview of the impact of drought on groundwater tables in smaller aquifers where the hydrological cycle is shorter. Akonjoki is situated in a small moraine formation with finer and mixed grain soil, and Sodankylä is located in a small glaciofluvial formation of coarse-grained soil. Both the Akonjoki and Sodankylä stations provide an outlook on groundwater availability in areas with scarce groundwater reservoirs. Many private wells in rural areas are situated in these types of conditions. Perniö station is located in a smaller esker with coarse and mixed gravel and with better groundwater recharge and reservoir conditions that represent the conditions in areas where many smaller water companies extract water.

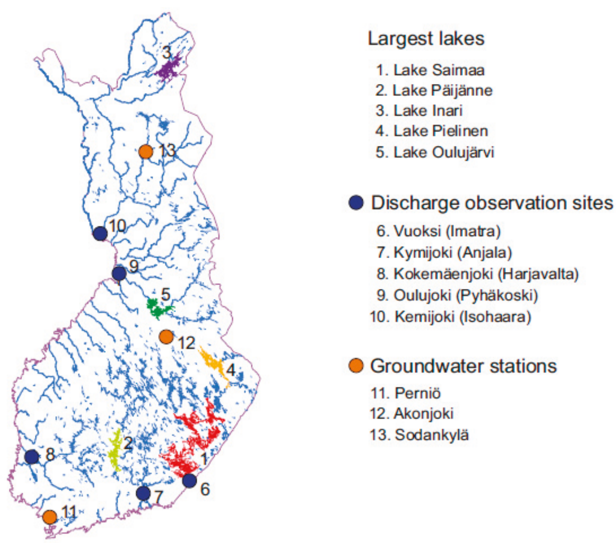

Figure 1. The major lakes and rivers in Finland. The location of the five largest lakes, the discharge observation sites used for comparison in this study, and the three groundwater stations analyzed are shown on the map.

2.3. Study Methodology

The drought impact analysis used in this study included three main phases. The study methodology can be seen in Figure 2. The first study phase included the hydrological modeling of the water levels and discharges during the reference drought in 1939–1942 (Section 2.6) and the control period 1981–2100, using the observed meteorological input variables (Section 2.4) and the hydrological Watershed Simulation and Forecasting System (WSFS) model (Section 2.5). The second phase includes an estimation of the impact of climate change on drought during the reference drought and during the control period using the delta change approach and seven climate scenarios (Section 2.7). In the third phase, the impact of drought on hydropower and the water supply from groundwater were analyzed (Section 2.8) and the policy implications discussed.

To simulate the impact of a severe drought on water resources, the worst drought in recent history (since reliable observation has been available) as the reference. This drought occurred in 1939–1942 (Section 2.5). This drought was selected because it was severe and long-lasting in most of Finland,

and its impacts have not been previously estimated. For most of Finland it was the worst drought for which meteorological observations are available. A real drought event is more realistic and easier to justify for stakeholders than an artificial drought generated using a hydrological model.

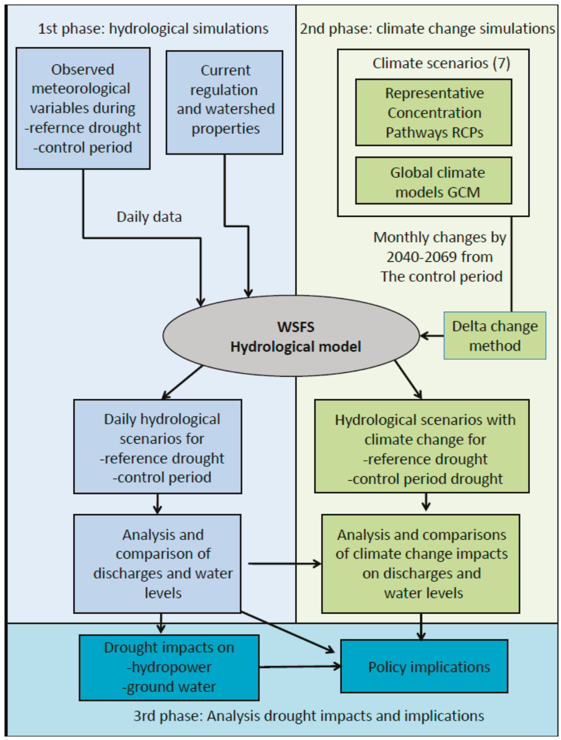

Figure 2. Flow chart of the study methodology used. WSFS: Watershed Simulation and Forecasting System.

2.4. Observations and Materials Used

Observations of the daily precipitation, temperature, relative humidity and wind speed that were used as input into the hydrological model were obtained from the records of the Finnish Meteorological Institute (FMI). The meteorological observations from 1938–1942 were used to simulate the reference drought from the period 1939–1942 and meteorological observations from the period 1980–2010 for the simulation of the control period 1981–2010.

For the simulation of the reference drought of 1939–1942, we used data from 35 precipitation stations (four of these did not contain all years), 32 temperature stations, 33 cloudiness observations, six stations for relative humidity, and six for windspeed. Observations were available only for Finland, and therefore the simulation of cross-boundary watersheds was more uncertain. For the simulation of the control period 1981–2010, we used data from approximately 240 temperature measurement stations, 470 precipitation measurement stations, 140 cloudiness observations, 180 wind speed observations and 220 relative humidity observations from the FMI. However, the observation network varied during this period and different numbers of stations were used during different years (the most recent number was from the year 2000). Additionally, observations from approximately 11 temperature and 16 precipitation observation stations in Norway, Sweden, and Russia were used. As can be seen from the number of observation stations, the observation network was considerably sparser in 1939–1942 than 1981–2010.

All precipitation observations contain gauging errors and the catch error for snow are especially significant and need to be corrected [33]. The observations for 1981–2010 were corrected with aerodynamic, evaporation, and wetting corrections based on air temperature and wind speed observations [34]. However, in 1939–1942 the precipitation measurement devices differed from the current devices used, with a Wild wind shield in use in the 1930s and 1940s. The Wild windshield had poor aerodynamic properties and therefore the catch error for snow was large [35]. For 1939–1942 the observed precipitation was corrected using a simpler method than that used for 1981–2010, since the aerodynamic, evaporation, and wetting correction factors were not available for the Wild windshield, and since there were too few wind observations to be used for the correction. For the 1939–1942 period, constant corrections for snow and rain were used. The estimates for these corrections for the Wild type wind shield were based on the literature, and the factors were 1.43 for snow and 1.05 for rain [35].

In addition to meteorological observations, water level and discharge observations were used to evaluate the results for 1939–1942. Since we used present-day land use and lake regulation practices in the hydrological model simulations, the daily simulated results for the 1939–1942 weather may differ from those observed in 1939–1942. However, over a period of one year or longer the impact of regulation decreases (since water is mainly stored seasonally and inter-annual storage is small) and the average observed discharges can be compared with the corresponding simulated discharges (Section 3.1).

2.5. First Analysis Phase: Hydrological Model

In the first phase of the study, hydrological modeling of the reference drought and the control period (used for comparison) was carried out using the Finnish Environment Institute's Watershed Simulation and Forecasting System (WSFS) hydrological model [36,37]. The same model was also used to estimate the changes projected by climate scenarios (Section 2.6). WSFS is used as the national hydrological forecasting and flood warning system in Finland, and also for regulation planning and research purposes, such as climate change impact assessment [15,38,39]. The rainfall–runoff model in the WSFS is based on the HBV model developed by the Swedish Meteorological and Hydrological Institute (SMHI) [40].

The input data for the model were the observed daily temperature, precipitation, wind speed, humidity, air pressure and cloudiness (Section 2.4). From the point measurements of the observation stations, an areal value for each sub-basin was calculated based on the three closest stations with observations for each day. These areal values were then used in the water-balance simulations for each sub-basin. The outputs from the WSFS model included the daily snow amount, soil evaporation, and runoff for each sub-basin, the discharge for sub-basin outflows and water levels, lake evaporation, and outflows and inflows for each modeled lake.

The water-balance simulations in the WSFS hydrological model were conducted at the sub-basin scale, with over 6000 sub-basins of varying size (approximately 20–500 km^2) [36]. From each sub-basin the water was then routed to the following sub-basin based on the river and lake network. Present day lake regulation rules and water structures were used. The WSFS includes all lakes in Finland with an area over 1 km^2 (approximately 2600 lakes).

For the hydrological simulations, a new and more physically-based version of the WSFS hydrological model was applied (Figure 3). This version includes an energy-balance-based snow model, a rainfall–runoff model with a two-layer soil moisture model and lower groundwater storage and evapotranspiration and lake evaporation models. Other sub-models in the WSFS include a precipitation model and models for lake and river routing (Figure 3).

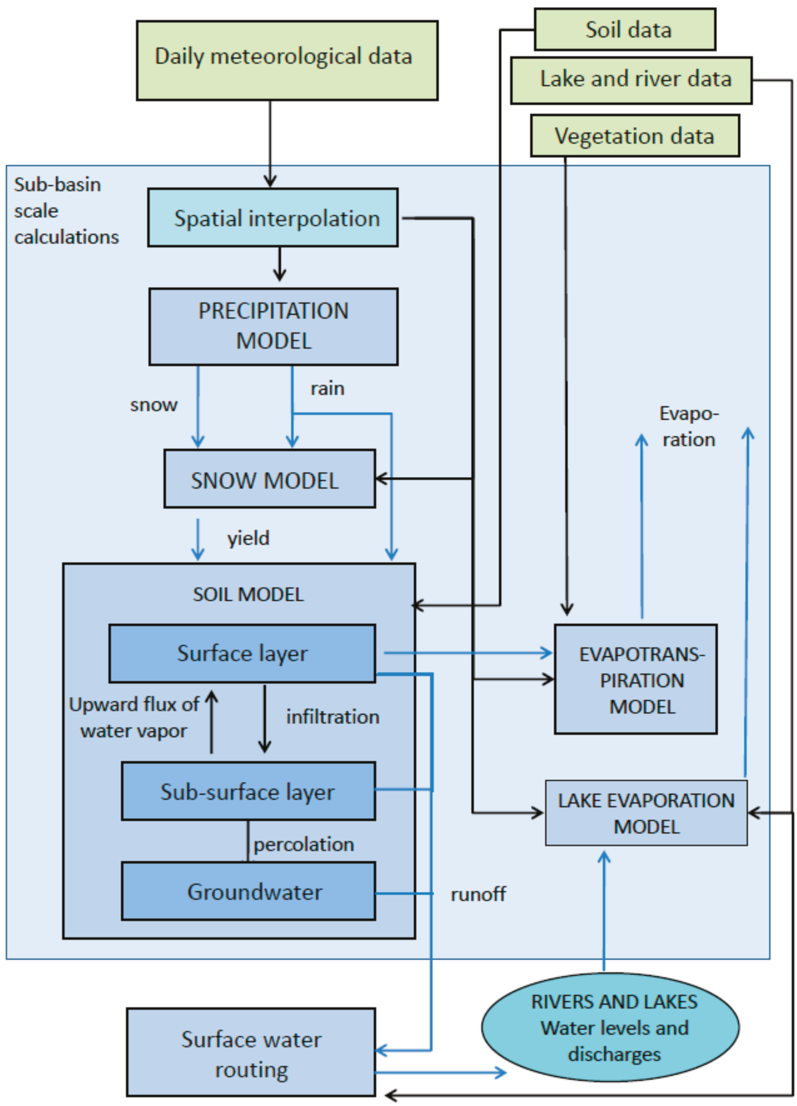

Figure 3. Schematic representation of the hydrological WSFS model.

The snow model is based on the energy balance of the snowpack (RTOT, Equation (1)), which determines the snowmelt. It has been described in detail by Vehviläinen [37].

$$\text{RTOT} = \text{RSN} + \text{RLN} + \text{RLAT} + \text{RSEN} + \text{RP} + \text{RG} - \text{CO} \quad (1)$$

where

RSN = net shortwave radiation
RLN = net longwave radiation
RLAT = latent heat flux
RSEN = sensible heat flux

RP = heat content of liquid precipitation
RG = heat exchange of the soil surface
CO = heat deficit of the snowpack (cold content)

In the evapotranspiration model, the evapotranspiration of a reference crop is calculated based on the Penman–Monteith formula for each land use class [41,42]. The total evaporation of a sub-basin is calculated as a weighted average of the evaporation of different land use classes in the sub-basin.

The soil moisture model that has been described in more detail by Jakkila et al. [43] was applied. The soil moisture model is divided into two layers, a surface layer and a sub-surface layer. These layers produce runoff to the rivers and lakes, and the sub-surface layer produces percolation to groundwater storage. The soil properties used by the soil moisture model include soil porosity, field capacity, wilting point, and hydraulic conductivity [43].

These more physically-based sub-models improve the reliability of the model, especially during drought (when evapotranspiration is more important than in normal situations), as well as during climate change simulations. When using the Penman–Monteith formula, changes in potential evaporation depend not only on changes in temperature and precipitation, as was the case in previous studies [39], but also on changes in wind speed, relative humidity, and radiation or cloudiness. Simple estimation methods for potential evaporation can overestimate the increase in evapotranspiration due to climate change [44], while more physically-based methods offer more reliable results.

Groundwater was modeled for the whole of Finland using the simple groundwater model of the WSFS, which calculates groundwater storage. For groundwater stations, the groundwater levels are simulated based on the effective porosity calibrated against observed groundwater levels [45].

The WSFS model parameters were calibrated against observations of the snow water equivalent, the extent of the snow-covered area, snow depth, lake water level, and discharge. The period used for model parameter calibration was 1980–2016. The automatic calibration procedure used a modification of the direct search Hooke–Jeeves optimization algorithm [46] to find an optimal set of parameters. The same model parameters were used in all the simulations.

2.6. The Drought of 1939–1942 as a Reference Drought

The reference drought of 1939–1942 was used to estimate the drought impact. The observed uncorrected annual precipitation sum was the lowest recorded in 1941 (precipitation observations start from 1844 and the observation network became comprehensive in the 1910s). The precipitation level in 1941 for Finland was on average 394 mm, which is 40% lower than average of 1981–2010 and corresponds to a return period of approximately 100–150 years [47,48]. In addition, 1939 and 1940 were among the twenty driest years of the 20th century. Tree ring data (dendrochronology) [49,50] and estimates of inflows [51] show that 1939–1941 was a dry period in the entire Nordic region. The first half of 1942 was also drier than average, while during the second half precipitation was above average. The years 1940–1942 were colder than average and during the winters of 1940–1941 and 1941–1942 the amount of snow was large. In South-Eastern Finland, tree ring data from the 9th century onwards indicate that the early summer periods of 1940 and 1942 were among the ten driest in the data and clearly the driest in the 20th century [50].

The area influenced by this drought covered most of Finland; only Northern Finland had precipitation levels close to average. The observed water levels and discharges were in many locations the lowest recorded. Kuusisto [48] estimated that in 1941 the average discharge from the rivers in the Finnish territory to the sea or neighboring countries was the lowest of the 20th century, at approximately half of the average value. In Lake Saimaa, where there have been water level observations from 1847 onwards, the lowest observed water level was in 1942, and the second lowest in 1941. The return period of the water levels and discharges during the drought was different in different parts of the country, in the most severe locations in Central Finland the estimated return period was greater than 150 years [47].

The drought in 1939–1942 had a large impact on food production. The hay harvest was only half the normal size and the cereal harvest was only two thirds of the usual size [47]. However, the impact of the drought is difficult to distinguish from the impact of the Second World War, which hindered adaptation, took resources (e.g., manpower and horses from agriculture) and reduced the possibility to import materials such as fertilizers.

2.7. Climate Scenarios

The second phase of the analysis looked at how climate change would alter the simulated minimum discharges and water levels during the control period and during a severe drought with different climate scenarios. Climate change will alter the hydrological regime in Finland and also the seasonal distribution of water. The implications of climate change for droughts and low water levels in the period 2040–2069 were assessed using the delta change method [52] and seven climate scenarios (Table 1). In the delta change method, monthly changes in precipitation, wind speed, relative humidity and solar radiation are multiplied by observed variables from the control period or the reference drought period (see Equation (2), which is similar to the equation for calculating precipitation). To obtain the temperature, the temperature change was added to the observed temperature, and a seasonal temperature-dependent component was also included to account for different changes in different parts of the temperature distribution (Equation (3)) [53].

$$P_{mod} = P_{obs} * \Delta P \tag{2}$$

$$T_{mod} = T_{obs} + \Delta T = T_{obs} + s_m(a_s T_{obs} + b_s) \tag{3}$$

where

P_{mod}/T_{mod} = the modified daily precipitation/air temperature
P_{obs}/T_{obs} = the observed daily precipitation/air temperature
$\Delta P/\Delta T$ = the precipitation/temperature change
s_m = the monthly scaling factor
a_s, b_s = the coefficients of the seasonal linear transfer functions

Table 1. Climate scenarios used in the study.

Abbreviation	RCP	GCM	T Change 2040–2069	P Change 2040–2069
Average RCP2.6	2.6	average of 28 GCMs	1.9 °C	5.8%
Average RCP4.5	4.5	average of 28 GCMs	2.5 °C	7.4%
Average RCP8.5	8.5	average of 28 GCMs	3.4 °C	10.6%
Warm and wet [1]	4.5	MIROC-ESM-CHEM	4.1 °C	14.2%
Warm and dry [1]	4.5	HadGEM2-CC	2.9 °C	7.0%
Cold and wet [1]	4.5	CESM1-BGC	2.1 °C	7.4%
Cold and dry [1]	4.5	CESM1-BGC	1.5 °C	0.8%

[1] Selected from an ensemble of 28 scenarios.

The climate scenarios used were based on the Global Climate Models (GCM) used in the IPCC Fifth Assessment Report [54], which used the representative concentration pathways (RCPs) for scenarios of future greenhouse gas concentrations [55]. Three RCPs, namely 2.6, 4.5, and 8.5 were selected for use. The scenarios included an average scenario, calculated as the average in the 2.5 degree (lat/long) grid over Finland used by FMI, and based on the results of 28 GCMs for the three RCPs [16]. Additional results from four individual GCMs for RCP 4.5 were selected from an ensemble of 28 climate scenarios to represent the extremes of changes. These scenarios represent warm and wet, warm and dry, cold and wet, and cold and dry conditions for RCP 4.5, where greenhouse gas concentrations by the end of the century are moderate (Table 1). From the gridded values of the GCMs the changes were interpolated for each sub-basin based on the four closest grid points.

2.8. Analysis of Drought Impact on Key Water-Use Sectors

The third phase of the analysis aimed at understanding the potential societal and economic impact of drought, focusing on water supply and hydropower as key water-related sectors. A brief analysis to assess the impact of drought on hydropower and water supply at the national scale was carried out. The economic impact on other key water-related sectors (e.g., agriculture, forestry, navigation, recreation), as well as the potentially substantial environmental and societal impact are beyond the scope of this analysis and were therefore not assessed (but will be briefly discussed).

Water supply is considered a critical infrastructure, as both societal well-being and resilience is fundamentally built on its reliability. Groundwater is essential for water supply in many parts of Finland. Of the municipal water supply, 63% is dependent on groundwater, in addition Finland has approximately 600,000 private wells [56]. Water supply companies using surface water are usually less prone to drought since they usually use water from large waterbodies. Industry would also experience some difficulties with water supply during a drought, although most of the water-intensive industries (i.e., the paper and pulp industry) have been built close to large lakes and rivers with ample supply. Mines (39 operating mines in Finland in 2016) are located next to the ore deposits, which can be next to head water and smaller water bodies. Water demand and availability during the same reference drought is assessed in more detail by Ahopelto et al. [24].

The impact of drought on discharges and hydropower production was simulated with the WSFS hydrological model using current hydropower capacity and daily discharges simulated for the location of the 57 largest hydropower plants in Finland (all plants with a capacity of 10 MW or more). The simulated discharges, capacities and maximum outflow capacities were used to estimate weekly average hydropower production during the reference drought using the weather in the period 1939–1942. The same results have been analyzed by [13] in regard to the impact on energy sector power adequacy during the peak demand period (i.e., a cold period with high demand for electricity) in January.

3. Results

3.1. Hydrological Results: Impact on Surface Water and Groundwater

3.1.1. Surface Water

Comparisons of the observed discharges of 1939–1942 and the simulated discharges for the reference drought of 1939–1942 were carried out in five large rivers for which observations were available (Table 2, for locations see Figure 1). All these watersheds have undergone land use changes and changes in the regulation of lakes since the 1940s, and the daily observations were therefore not comparable to the simulated values. The regulation of previously natural state lakes has begun in several places, and in Lapland new reservoirs have been built. The comparison of long-term averages showed that the difference between the simulated and observed values varied from –8 to +10% (Table 2). Taking into consideration the changes in watershed land use since the 1940s and the uncertainties in the simulated discharge, the results can be considered to be in relatively good agreement with the observations. The uncertainties included possible errors in the observation of discharge and meteorological variables (including considerably sparser observation networks especially influencing uncertainties in estimating the areal precipitation, and older types of precipitation gauges), and limitations in the hydrological model simulation. These uncertainties had no effect on the achievement of the study’s objectives, because our purpose was not to exactly replicate the drought in 1939–1942, but to assess the impact of a similar reference drought in present-day and future conditions for current water resources.

Table 2. Comparison of the simulated discharge for the reference drought and the observed average discharge in 1939–1942 in the five largest rivers in Finland (for locations see Figure 1).

River, Observation Point	Observed Discharge (m^3/s)	Simulated Discharge (m^3/s)	Difference (%)
Kemijoki (Isohaara)	404	413	2.2
Oulujoki (Pyhäkoski)	151	141	−6.6
Kokemäenjoki (Harjavalta)	107	111	3.7
Kymijoki (Anjala)	136	150	10
Vuoksi (Imatra)	361	331	−8.3

A comparison of the simulated discharges and water levels using the weather from the reference drought period and current regulations and watershed arrangements and the simulated values for the period 1981–2010 are shown in Figure 4. The minimum discharges during the modeled drought were smallest in South-Eastern, Western, and Central Finland (Figure 4a) when compared to the average annual minimum discharge of the control period. In these areas, the minimum discharges were only 20–50% of the average annual minimum values, which are extremely low discharges for Finland. In Northern Lapland, the discharges were close to the average minimum values, and the drought was not particularly severe. Thus, the severity and the return period of the simulated drought depended on the location.

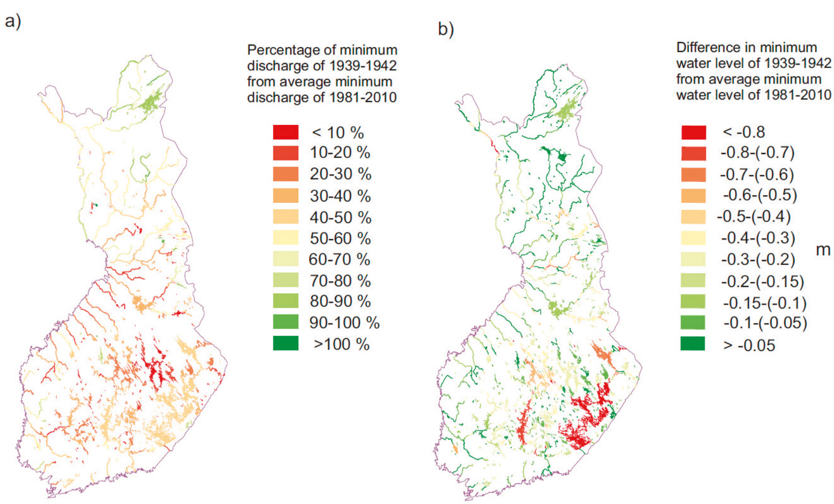

Figure 4. Minimum (**a**) discharge (%) and (**b**) water level (m) in Finland under the reference drought conditions compared to the average annual minimum of the control period 1981–2010.

The timing of the lowest water levels differed in different locations. In the largest lakes (with an area approximately above 100 km^2), the lowest water levels occurred only during the last year of the reference drought (corresponding to 1942), while in the small and medium-sized lakes the lowest water levels were in most cases at the end of the summer in the second or third year. In the largest lakes, the inflow remained low for an extended period, and even occasional periods with greater precipitation were not enough to significantly increase the inflow, while the smaller lakes responded much faster to precipitation in the smaller catchment areas. In many of the strongly regulated lakes, the lowest water levels usually occur during the winter and are more strongly affected by regulation rules used than by drought.

The water levels fell to the lowest, compared to the average annual low water levels, in the largest lakes with limited regulation. The lowest water levels were 50–90 cm below the average low water levels and occurred in Lake Saimaa (including lakes in the same lake complex with almost the same water level) in South-Eastern Finland, Lake Pielinen in Eastern Finland and Lake Päijänne in South-Central Finland (Figure 4b, for locations see Figure 1). In most of Finland, the water level difference compared to the average annual lowest water level was modest at only 10–30 cm, since many lakes have a natural lower water level bound below which the outflow becomes very small. In Lakes Saimaa, Päijänne, and Pielinen the outflow remains relatively large even with low water levels, and the length of the drought meant the water levels had time to fall very low. These lakes are all regulated, but the possibilities to decrease discharge are limited. For example, in Lake Saimaa (South-Eastern Finland) the outflow must be at least 300 m^3/s or related to the natural rating curve as stipulated by the agreement with Russia, where the Vuoksi river (outflow river of Lake Saimaa) flows [57]. On some other large lakes, such as Oulujärvi, the water level remained near normal levels due to more efficient regulation possibilities, but the outflow was 50–70% smaller than the average annual minimum values.

3.1.2. Groundwater

Groundwater tables were simulated for three selected groundwater stations in different parts of Finland (Figure 5). The groundwater tables also decreased to very low levels during the reference drought period. The lowest water levels occurred mostly during the two last years of the reference drought period, but in small groundwater formations the water tables already dropped to very low levels during the autumn of the first year of drought. The minimum levels for many stations were lower than during the shorter drought period of 2002–2003, but the differences were relatively small. The simulated drought period affected the station situated in Central Finland (Figure 5b) more than that in South-Western Finland. This result implies that Central Finland may be especially vulnerable to severe drought periods than earlier studies [56,58] have predicted. This phenomenon was also seen during the drought of 2018, when the all-time lowest groundwater table levels were measured in Central Finland in small and shallow aquifers [59].

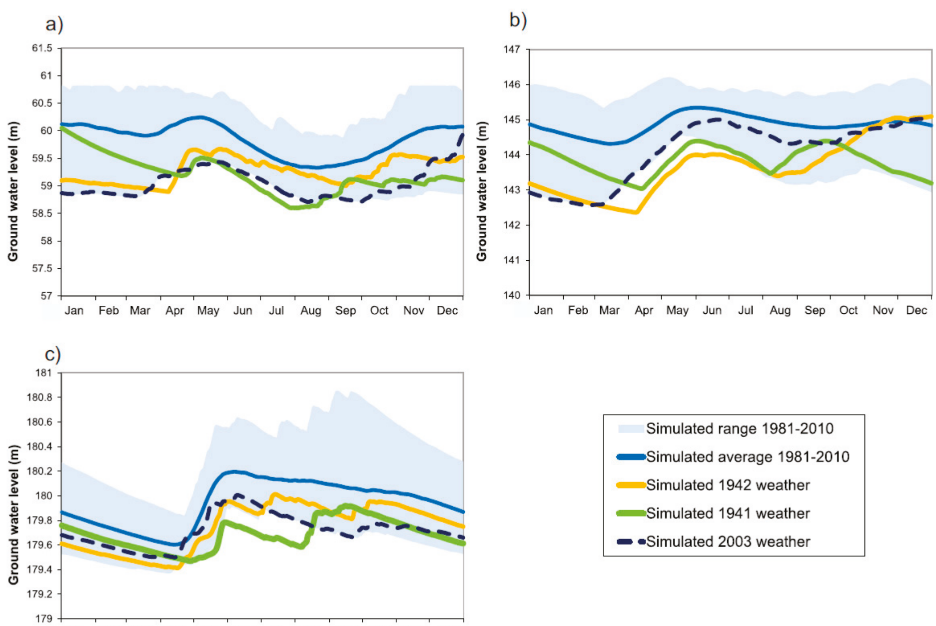

Figure 5. Simulated groundwater tables for 1981–2010 and during the reference drought with weather conditions from 1941 and 1942 at selected groundwater stations: (**a**) Perniö (South-Western Finland), (**b**) Akonjoki (Central Finland), (**c**) Sodankylä (Northern Finland).

3.2. Climate Change Impact on Discharge and Water Levels

In Finland, climate change is predicted to increase the average precipitation, leading to mostly larger average discharges [16,39]. Generally, the increase in average discharge will be larger in Northern Finland, where the increase in precipitation was also larger and the lake percentage was smaller. Besides the precipitation, the evapotranspiration will also increase, and therefore the increase in discharge will be smaller than the increase in precipitation [15,39]. Lake evaporation in particular, which is not limited by the availability of water, will increase with rising temperatures.

The climate change impacts were first assessed for a more common drought event, namely the minimum discharges and water levels for the control period 1981–2010 modified with climate scenarios for 2040–2069. The return period of the minimum discharges and water levels of the control period was approximately 20–40 years. The results show that climate change affects the minimum discharges differently than the average discharges. The minimum monthly average discharges (Table 3) and minimum daily discharges (Figure 6) in 2040–2069 mainly decreased compared to the control period. The average discharges increased (Table 3), except in the driest climate scenarios. The decrease in minimum discharges was due to the changes in the timing of the discharges. With warmer temperatures there will be less snow accumulation during winter and earlier spring floods caused by snowmelt. During summer, evaporation combined with evapotranspiration is generally higher than precipitation and the discharge and storage commonly decrease. This was also the case for the future scenarios, since the projected increase in precipitation was smaller in summer than during winter, and the evaporation increased with warmer temperatures. With an earlier spring and longer summer, as well as a longer growth period and more evapotranspiration, the minimum discharge during late summer and early autumn (typically August or September) will be lower in 2040–2069 than during the control period. In Southern and Central Finland, all the modeled climate scenarios projected decreases in the minimum discharges, while in Northern Finland five scenarios projected decreases, but one scenario, with the largest precipitation increase, projected a notable increase.

Table 3. Average annual and minimum monthly discharge in the control period and with different climate scenarios in 2040–2069 and during the reference drought.

	Time Period	Average Annual Discharge (m^3/s)	Change of Average Annual Discharge (%)	Minimum Monthly Discharge (m^3/s)	Change of Minimum Monthly Discharge (%)
	Southern and Central Finland *				
Control period	1981–2010	1810		592	
Climate scenarios for the period 2040–2069 with control period	Average RCP2.6	1820	0.3	491	−17
	Average RCP4.5	1830	1.4	487	−18
	Average RCP8.5	1870	3.2	476	−20
	Warm and wet	1980	9.5	465	−21
	Warm and dry	1800	−0.5	449	−24
	Cold and wet	1820	0.4	489	−17
	Cold and dry	1690	−6.7	462	−22
Reference drought	1939–1942	946		533	
Climate scenarios for the period 2040–2069 with reference drought	Average RCP2.6	964	1.9	491	−7.8
	Average RCP4.5	980	3.6	487	−8.6
	Average RCP8.5	1010	6.9	476	−11
	Warm and wet	1110	17	465	−13
	Warm and dry	941	−0.5	449	−16
	Cold and wet	923	−2.4	489	−8.2
	Cold and dry	895	−5.4	462	−13

Table 3. *Cont.*

	Time Period	Average Annual Discharge (m^3/s)	Change of Average Annual Discharge (%)	Minimum Monthly Discharge (m^3/s)	Change of Minimum Monthly Discharge (%)
	Northern Finland *				
Control period	1981–2010	1810		592	
Climate scenarios for the period 2040–2069 with the control period	Average RCP2.6	2270	4.8	803	0.5
	Average RCP4.5	2290	6.0	775	−3.0
	Average RCP8.5	2390	10	688	−14
	Warm and wet	2370	9.7	726	−9.2
	Warm and dry	2210	2.3	676	−15
	Cold and wet	2380	10	841	5.2
	Cold and dry	2000	−7.5	628	−21
Reference drought	1939–1942	1510		815	
Climate scenarios for the period 2040–2069 with the reference drought	Average RCP2.6	1590	5.0	803	−1.4
	Average RCP4.5	1600	6.1	775	−4.8
	Average RCP8.5	1680	11	688	−16
	Warm and wet	1680	11	726	−11
	Warm and dry	1510	−0.2	676	−17
	Cold and wet	1700	12	841	3.2
	Cold and dry	1380	−8.5	628	−23

* Southern and Central Finland approximately south of the city of Oulu (latitude 65 °N), Northern Finland north of Oulu (including River Oulujoki).

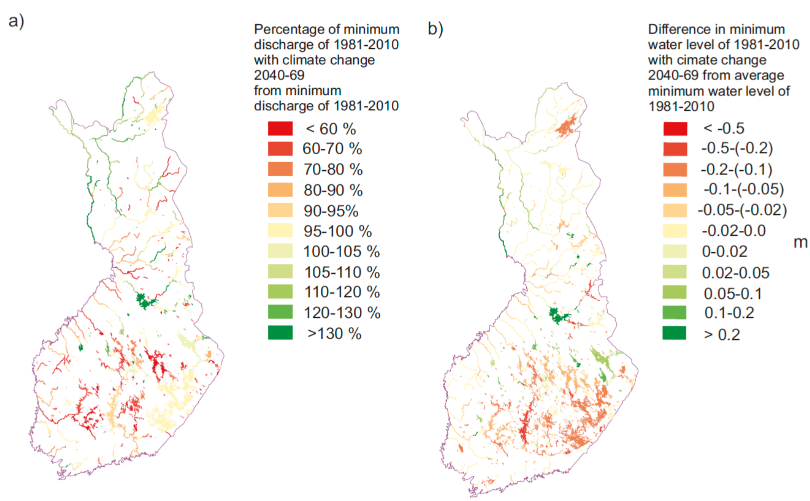

Figure 6. Climate change impact on droughts during the control period (1981–2010). Changes in minimum (**a**) discharges, and (**b**) water levels when climate change scenarios for 2040–2069 (average representative concentration pathways (RCP) 4.5 scenario) are compared to the period 1981–2010.

The minimum discharges during the reference drought also mainly decreased with the climate scenarios for 2040–2069 (Table 3, Figure 7a). On average in Southern and Central Finland, the projected range of decreases in the minimum discharge was between 8 and 16%, while in Northern Finland the changes range from a 3% increase to a 17% decrease (Table 3). For different rivers and lake outlets, the decreases were mostly between 5 and 40% with the average RCP 4.5 scenario (Figure 7a). In addition, the water levels mainly decreased, with modest 5–20 cm decreases on most lakes and rivers (Figure 7b). In places where climate change increased the discharge and water levels, the timing of the minimum discharge and water level was mostly during winter, due to either the northerly location or lake regulation. The increase is caused by the increased melting of snow during winter due to increased temperatures.

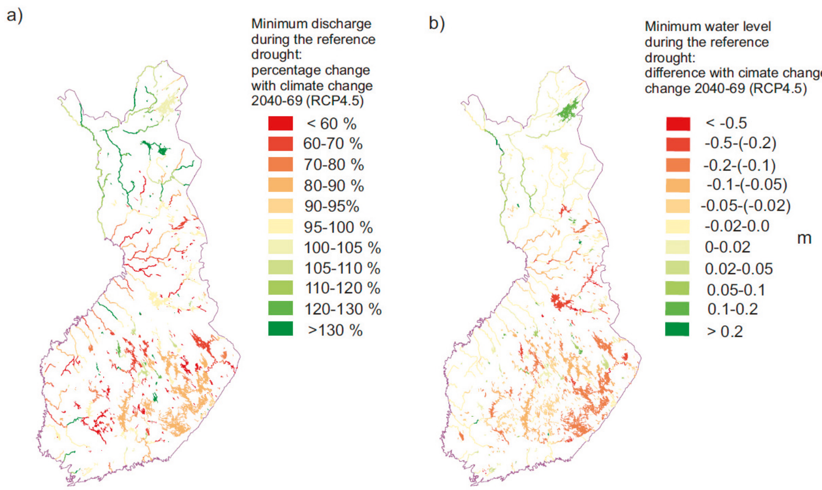

Figure 7. Climate change impacts on the reference drought period conditions. Changes in minimum (**a**) discharges, and (**b**) water levels when the climate change signal for 2040–2069 (average RCP 4.5 scenario) was added to the weather during the reference drought.

The range of changes under the different climate scenarios remains large, which demonstrates the large uncertainties involved in future climate change (Table 3). The differences between the scenarios, and especially between the different RCPs, will become even larger by the end of the century. For Southern and Central Finland, however, the climate signal is robust, producing decreases in all the simulated scenarios.

Figure 8 shows the modeled development of the total lake storage (for lakes over 1 km^2) and soil and groundwater storage for Finland during the reference drought (conditions of 1939–1942) compared to the period 1981–2010. For one and a half years, the storage levels of the reference drought were lower than the minimum values for the summer of the third year of drought in 1981–2010 (corresponding summer 1941). Climate change (the average RCP 4.5 scenario) will further decrease the storage levels during the latter part of the reference drought.

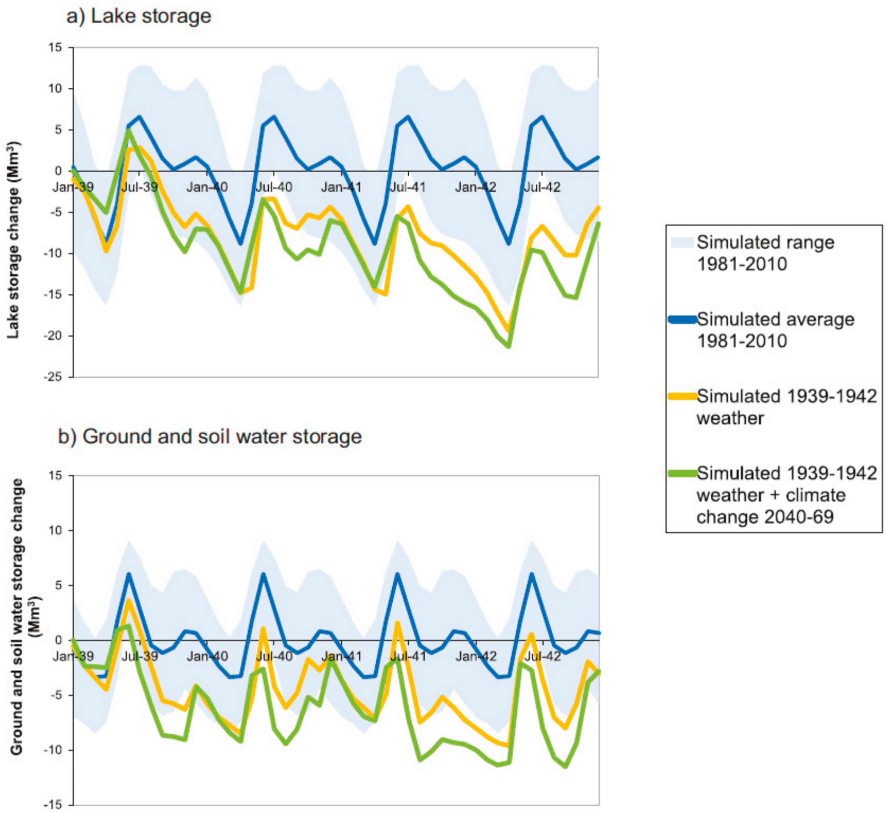

Figure 8. Modeled (**a**) lake storage and (**b**) ground and soil water storage for the average and normal range of changes in 1981–2010 and changes during the reference drought. Lake storage includes all of the largest lakes in Finland with a surface area of over 1 km^2.

3.3. Impact of Severe Drought on Selected Water-Related Sectors

3.3.1. Hydropower

The reference drought period would result in a severe decrease in hydropower generation of approximately 42% in Finland. The average discharges and annual hydropower production during normal years and during the analyzed drought period are presented in Table 4. Jääskeläinen et al. [13] carried out an analysis of the impact of severe drought on energy security in Finland under different scenarios, and concluded that a severe drought affecting only Finland would not cause large problems for power adequacy during the peak demand period in January. However, if the drought were large-scale and simultaneously affected Norway and Sweden, as was the case in 1939–1942 and 2002–2003 [8], the impact on Finnish energy security could be much larger due to the decreased availability of electricity imports.

Table 4. Simulated hydropower production in Finland for the control period 1981–2001 and for the reference drought and climate change impact for 2040–2069 (with the average RCP 4.5 scenario).

Period	Average Discharge (m^3/s) of Major Hydropower Plants [1,2]	Annual Production (TW) of Major Hydropower Plants [1]
Simulated control period 1981–2010	202	12.0
Simulated reference drought—third year (1941 weather)	112	6.8
Simulated reference drought—fourth year (1942 weather)	106	6.5
Climate change 2040–2069	217	12.9
Simulated climate change with control period	217	12.9
Simulated reference drought—third year (1941 weather)	113	6.8
Simulated reference drought—fourth year (1942 weather)	107	6.6

[1.] All hydropower plants in Finland with a capacity over 10 MW, ~92% of total capacity. [2] Without spillage.

A severe drought will have several noteworthy socio-economic impacts on the energy sector. First, a drought will evidently decrease the production volumes of hydropower plants, as depicted in Table 4. Due to the inelastic nature of electricity demand in the Nordic countries, a reduction in the supply of low marginal priced power production will increase the average electricity wholesale price. The spot price has the potential to increase nearly a hundredfold compared to the current price level before the price cap, as the system approaches generation inadequacy. Moreover, the abundant and flexible hydropower capacity in the Nordic countries decreases electricity price volatility, as hydropower is well suited for balancing the market. Therefore, a drought would most likely increase consumer electricity prices and result in economic losses for industry and households [60]. Estimations of the value of the lost load in the case of generation inadequacy range between 5000–20,000 euros per MWh, i.e., much higher than the price cap in the wholesale market [61].

With regard to the supply-side, the issue is more ambiguous. Power producers typically set their supply bids according to the short-term marginal costs of production in a liberalized energy market such as that in the Nordic countries. However, the marginal costs of hydropower production are practically non-existent, and hydropower can be easily stored in many cases. Hydro reservoirs are especially significant in Norway and Sweden, with storage capacities of approximately 85 TWh and 34 TWh, respectively [62]. Hydropower producers hence aim to maximize the value of their hydro reservoirs by selling the electricity when it yields the highest revenues. Despite losing up to half of the production volume during a severe drought compared to a good hydrological year, the revenue might not decrease. Summer 2018 was a good example of electricity prices soaring in the Nordic countries during a dry summer, and the average spot prices almost doubled compared to the previous years. It should be noted, however, that in addition to the drought, there were also other factors affecting the price, such as the high emissions allowance prices. Nevertheless, as droughts that are much less severe than our reference drought already increase the electricity wholesale price significantly, a prolonged severe drought could have far more drastic implications. The economic implications for a hydropower plant owner are very case specific and are affected by issues such as whether the plant is run-of-river or dammed, and how the drought affects the discharges in the river in question. Overall, the majority of the cost of the drought would hence likely fall on energy consumers, rather than on hydropower generators.

3.3.2. Groundwater and Water Supply

Declining groundwater tables cause problems during droughts for many municipalities and households that are dependent on groundwater. Water availability issues affect private shallow dug wells and water supply plants using small glaciofluvial formations first, but prolonged severe drought would also decrease water tables below normal levels in larger aquifers and drilled wells using water from the bedrock.

We can use information from recent, less severe droughts to help estimate the possible impact of drought on the water supply. During the drought of 2018, some water supply companies set voluntary water use limitations, and some private wells were reported to have dried up in the most-affected areas. During the drought of 2002–2003 the situation was more severe, and approximately 15% of water supply companies had problems with water availability. In some areas, groundwater tables were up to five meters below the long-term annual average. The situation was especially alarming in North Karelia and in the western parts of Finland, and the estimated direct costs caused by the drought for water supply were approximately 5–10 million euro [8,63]

Since our reference drought period was significantly longer than the drought in 2002–2003, it would likely cause more problems, and greater damage and economic losses. More water transfers would be needed, and water availability even in large groundwater formations would decline. At the same time, however, Finnish society has taken some practical steps since 2002–2003 to increase drought resilience. Urbanization and larger agricultural units have decreased the number of households and livestock not connected to a municipal water supply, and connections between separate municipal supply systems have been added. Both of these measures enhance the possibilities for more coordinated adaptation measures. However, an important measure that should be implemented to save water in most of Finland's pipelines is renewing aged pipelines as leakage rates grow. Overall, large water supply companies are typically well-prepared for different disturbances and have both preparedness plans and climate change adaptation plans [63]. Despite this, Finland also has many small water supply companies with very limited resources for preparedness, adaptation and even maintenance, making them particularly prone to the impact of drought [64]. Small water supply companies that rely on groundwater have relatively short observation records, and are not prepared for a severe drought similar to our reference drought.

Ahopelto et al. [24] assessed water availability during a severe drought using the Water Depletion Index (WDI), concluding that water stress would be particularly likely in South-Western Finland. This is an area with few lakes and small catchments, but a relatively dense population and large withdrawals due to industry and agriculture. Some individual catchment areas in Southern and Western Finland would also be likely to suffer from water stress during such a drought [24]. These are the areas in which more studies and adaptation are needed.

Water quality would also be likely to suffer as a result of the drought. The most common quality problems are caused by decreased oxygen content, which leads to a reducing environment and the dissolution of iron and manganese into groundwater. The drought could impact groundwater flows and change water flow directions, as a result, for example, pollutants in contaminated land areas may start flowing towards to water intake areas [63]. In rural areas, approximately 10,000 households and 1400 farms suffered from both quantity and quality problems during the drought of 2002–2003 [65].

3.3.3. Other Impacts of a Severe Drought

Besides the impact on water supply and hydropower, a severe drought would also have many other impacts on society and the economy, as well as on nature. Such impacts are, however, difficult to assess and their detailed analysis is thus beyond the scope of this paper. In the following, we therefore merely discuss some general examples of the impact of a severe drought on other water-related sectors.

Navigation in inland waters and the recreational use of lakes and rivers would most likely be significantly affected during a severe drought; particularly large lakes where water levels fall the most. This would cause damage to logistics and tourism especially. The potential degradation of water quality would further hinder recreational use and water supply. Toxic blue-green algae blooms are common in Finland, and they could become more frequent during dry summers, especially if the temperatures are also high (as is often case in summer if a high pressure area is located over Finland). The oxygen content of water would also be likely to diminish, potentially causing fish deaths. The summer of 2018 saw uncommonly large algal blooms and the death of some fish and mussels [66]. Other environmental impacts could also be significant.

Agriculture and forestry would potentially suffer significant drought damage due to the varied impact of limited water availability. Recent droughts provide some guidance on possible impacts. For example, the drought of 2018 caused a large impact on agriculture, with 14–57% lower yields for most cereals [67]. Forestry is an important sector in Finland and would suffer from an increased number of wildfires, forest pest insects, and diseases. Suffering caused to saplings and decreased tree growth has an economic impact [68]. These complex impacts on agriculture and forestry merit their own in-depth studies.

4. Discussion

4.1. Methodological and Climate Change-Related Findings

We analyzed the impact of drought in Finland using a past, real drought period as a reference drought. The main advantage of this approach is that it is relatively easy to model and it can also be perceived as a more realistic option by stakeholders than an artificially simulated drought. However, there are also disadvantages of using an observed drought, related mainly to the fact that the modeled drought is not of similar severity throughout the country. The simulated reference drought of 1939–1942, for example, was not severe in Northern Finland. However, in this case this did not cause a large problem, as Northern Finland is not particularly vulnerable to droughts. Every drought period is different, and the period of 1939–1942 is only one example of a drought event. Modeling several different types of drought could provide insights to different types of responses and the climate change impact of different droughts in different regions.

In terms of climate change analysis, comparing our results with previous studies carried out with continental scale models [22,23,69] shows both similarities and differences. Our studies showed a decrease in minimum discharges by 2040–2069, for all the climate scenarios in Southern and Central Finland and most of the scenarios in Northern Finland. According to Forzieri et al. [22] the drought risk will decrease in the whole of Finland, while our results show an increase at least in Southern and Central Finland. The study by Roudier et al. [23], in turn, showed a decrease in drought frequency in Northern Finland and mainly no change in Southern Finland. The study by Lehner et al. [69] indicated that 100-year-droughts have become less frequent in most of Northern Europe, but some areas in Finland show more frequent droughts. The different findings of these studies can be explained by the different climate scenarios and the different assessment and modeling methods used, as well as differences in the variables in question (deficit volume, minimum discharge, daily/monthly values). Large scale models often do not include all the available local information used in national scale models, such as lake regulation schemes or lake evaporation. For example, Forzieri et al. [22] indicated that snow amounts will increase due to increased precipitation, while our results as well as those from several other studies [39,70–72] predict decreased snow amounts and an earlier spring due to warmer temperatures in many parts of the Nordic countries. Smaller snow amounts and earlier spring floods have also been observed in recent years [21,73,74]. Earlier and smaller spring snowmelt volumes affect the minimum discharges substantially, especially in the more southern parts of the Nordic region.

It is also important to note that the climate of Finland has already changed from our reference drought period. The reference period 1939–1942 was colder and snowier than the last 30 years, as the climate of Finland has already become warmer due to climate change. The estimated increase from the 1940s to 2010s was over one degree Celsius [75], and winters as cold and snowy as those in the 1940s have thus become rarer. For this reason, the simulation using weather from 1939–1942, but adding the climate scenarios of 2010–2039 (from 1981–2010), were actually closer to today's climate.

We estimated the impact of climate change using data from only one severe drought event for the years 1981–2010 using the delta change method. However, it would also be important to know how the likelihood of severe droughts will change due to climate change. According to the delta change method, average monthly changes are used to modify the reference period climate, and possible changes in variability between years is not included. These changes in variability are of course very relevant to changes in the likelihood of severe droughts. However, the evaluation of changes in the likelihood of severe drought is not simple, as the processes leading to prolonged periods with little precipitation are complicated and not well represented by current climate models [76,77]. Changes in dry spells have been evaluated [17], but these studies concentrate on time periods considerably shorter than those that are critical in large watersheds. Changes in average droughts and the timing of minimum discharge can provide some ideas for change in a severe drought, but extremes may change differently than averages. The changes in extremes should be taken into account in future studies on the impacts of climate change on severe droughts in Finland.

Modeling water resources during a drought, as was carried out in this study, involves several uncertainties. The meteorological observations during the modeled drought are sparse and the hydrological model structure and parameterization cause uncertainty. Evapotranspiration and snow models in WSFS are still under development. In addition, assessing the possible impact of drought contains many uncertainties. Drought also has several direct and indirect societal and environmental impacts that are difficult to evaluate, and more studies are therefore needed to fully understand the diversity of impacts that drought has on different sectors.

4.2. Policy Implications

Our analysis examined the impact that severe drought could have on Finland's water resources and, consequently, on key water-related sectors. While our analysis focused on hydropower and (ground) water supply, Ahopelto et al. [24] studied other water-related sectors, such water availability for industry. While Finland, in general, has natural resilience towards drought thanks to its abundant water resources, a severe drought similar to our reference drought would have significant impacts on energy production (particularly if the drought also affected Sweden and Norway) [13], as well as on food security.

Despite this, the current water management strategies in Finland focus on floods, with very limited consideration of drought. The National Climate Change Adaptation Plan for Finland [78] also includes only few remarks on droughts, while the European Union has carried out a more comprehensive review related to European drought policies [79]. Knowledge of droughts and their consequences is a prerequisite of establishing appropriate drought management plans [19], and preparing in advance is the best way to mitigate the impact of drought. This study together with the results of Ahopelto et al. [24] provide information on the most vulnerable areas, impacts on different sectors, and future changes necessary for planning more detailed studies and adaptation measures. Ways to prepare and adapt to droughts include institutional development, livelihood and economic diversification, insurance and other market tools, monitoring and data collection, as well as early warning and alert systems [5]. The good news is that many such measures seem compatible with general climate change adaptation and preparedness measures, providing potential for synergies. At the same time, due to its specific nature, drought also requires some specific measures and ways of working, and these could and should be looked at in more detail together with the key actors.

One practical way forward would be to include drought in selected regional preparedness exercises, which are regularly organized in different parts of Finland, in order to enhance cooperation and increase knowledge related to different risks and threats [80,81]. The first such exercise focusing on droughts is to be held in South-Western Finland in April 2019, and it aims to highlight vulnerabilities related to drought, thus improving the preparedness and resilience of society. Other concrete measures include drought management plans, e.g., included in the River Basin Management Plans (RBMP), for the areas most vulnerable to drought. In the first and second round of RBMPs, Finland did not prepare any drought management plans. In their recommendations for the second RBMPs, the EU Commission urged Finland to reconsider preparing drought management plans on the grounds of the prevalence of local and sub-basin drought spells [82]. These plans should include estimations of the costs of drought, the impact of climate change and adaptation possibilities.

Drought should be taken into account when water, food and energy security are assessed. There are practical ways to improve drought resilience in key water-related sectors. In the energy sector this could mean, for example, maintaining and creating viable alternatives to hydropower. Establishing more connections between different power grids is another way to cope with the possible reduced availability of hydropower generation. In the water supply sector, resilience could be improved by building more connection pipelines between water supply utilities and having more alternative aquifers for water supply [63]. In areas where groundwater reservoirs are naturally scarce, looking into alternative methods, such as the artificial recharge of groundwater or the use of surface water as backup water should be assessed [56]. The condition of water supply pipelines should be improved, and the leakage percentage should be reduced. At the individual household level, shallow wells can be deepened or replaced by drilled wells. It would also be valuable to study Finnish and EU law from the viewpoint of drought preparation and management in more detail.

5. Conclusions

Our results showed that a severe drought would have a significant impact on water resources and cause damage to the water supply in Finland. Drought would also have negative implications for hydropower production and agriculture, which emphasises the importance of looking at drought not only as a risk to water security, but also to energy security and food security. As such, drought can be seen as one risk multiplier for the emerging water–energy–food security nexus approach (e.g., [83–85])

Water resources and water withdrawals are not equally distributed throughout the entire country, making some regions much more prone to seasonal drought risks [24]. However, the national averages used in most water availability studies hide this spatial and temporal variability, and local scale assessments with local knowledge are therefore needed to complement this overall picture. The simulated discharges during the reference drought were the smallest in Southern and Central Finland. For the water levels, the impact of a drought would be most severe in Central and South-Eastern Finland, with the lowest water levels in the largest lakes with no regulation or only limited regulation possibilities. In addition, the impact on navigation, recreational use and tourism would be considerable.

We also analyzed how climate change would affect droughts and minimum discharges in Finland. Climate change is projected to increase precipitation in Finland, but according to our results, the minimum discharges still decreased, especially in Southern and Central Finland. Due to an increase in temperature and longer summers, the likelihood of a drought during summer and early autumn will, according to our results, increase, but this depends on the climate scenario, weather patterns and changes in evapotranspiration. According to the current climate model results, severe drought will still remain a rare occurrence in Finland, but in the areas already most vulnerable to droughts, climate change may worsen the situation.

Finland is a highly developed society with a long traditions of water resource management and preparedness. However, drought resilience could be further improved with actions at different scales. On a practical level, more water transmission connections can be built, and possibilities for alternative water sources developed for both water supply and agriculture. At the policy level, regional drought management plans should be prepared. To ensure policy coherence and the wise allocation of resources, such plans should link to existing policies, including the EU's River Basin Management Plans and Finland's advanced flood management and climate change adaptation plans. For the same reason, the drought management plans should focus only on the regions that are most prone to drought. These regions should also be the focus areas for regional drought-related preparedness exercises. In terms of increased information and knowledge, the risk of drought can be decreased by estimating the impact of drought in advance to identify the most critical sectors and areas, and then to prepare the necessary, cost-effective adaptive actions. Overall, our study showed that drought can negatively affect water security, as well as the related fields of energy security and food security, even in a water-abundant country such as Finland.

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Can There be Water Scarcity with Abundance of Water? Analyzing Water Stress during a Severe Drought in Finland

Lauri Ahopelto [1,2,*], Noora Veijalainen [1], Joseph H. A. Guillaume [2], Marko Keskinen [2] and Olli Varis [2]

1 Finnish Environment Institute, Latokartanonkaari 11, 00790 Helsinki, Finland; noora.veijalainen@ymparisto.fi (N.V.); mika.marttunen@ymparisto.fi (M.M.)

2 Water & Development Research Group, Aalto University, 02015 Espoo, Finland; joseph.guillaume@aalto.fi (J.H.A.G.); marko.keskinen@aalto.fi (M.K.); olli.varis@aalto.fi (O.V.)

* Correspondence: lauri.ahopelto@aalto.fi; Tel.: +358-505-344-400

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Abstract: Severe droughts can affect water security even in countries with ample water resources. In addition, droughts are estimated to become more frequent in several regions due to changing climate. Drought affects many socio-economic sectors (e.g., agriculture, water supply, and industry), as it did in 2018 in Finland. Understanding the basin-wide picture is crucial in drought management planning. To identify vulnerable and water stressed areas in Finland, a water use-to-availability analysis was executed with a reference drought. Water stress was analyzed with the Water Depletion Index WDI. The analysis was executed using national water permits and databases. To represent a severe but realistic drought event, we modelled discharges and runoffs from the worst drought of the last century in Finland (1939–1942). The potential for performing similar analyses in data scarce contexts was also tested using estimates from global models as a screening tool. The results show that the South and Southwest of Finland would have problems with water availability during a severe drought. The most vulnerable areas would benefit from drought mitigation measures and management plans. These measures could be incorporated into the EU River Basin Management Plans.

Keywords: water depletion index; global water models; consumptive water use; water stress; water security; water scarcity; Finland

1. Introduction

We investigate whether water availability would be limited for agriculture, industry, and water supply during a severe drought in Finland, which is famous for its ample water resources. Possible drought impacts, policy, and mitigation measures for water security, food security, society, and the environment (including water quality) are discussed. The analysis contributes to the discussion about water scarcity. Water scarcity is a man-made problem resulting from insufficient water availability to meet the demands of water users. Physical water scarcity is typically distinguished from economic scarcity, where the former counts water availability in terms of every drop available within a region, whereas the latter explicitly assesses whether the socio-economic system is able to mobilize that water for use. Physical water scarcity is itself a multi-facetted issue, including water shortage (population-driven scarcity, i.e., low water availability per person) and water stress (demand-driven scarcity, i.e., high water use divided by water availability) [1]. Drought, on the other, is a natural phenomenon, which reduces available water resources for months or years. Our analysis focuses on water stress during a severe prolonged drought.

Drought affects local and national water security. Water security is an emerging and increasingly dominant concept in both research and policy-making [2–5]. While its definitions are numerous, the key is that water security emphasizes the importance of water simultaneously for local and national security and sustainability, including the societal resilience to environmental impacts and water-borne diseases [6]. For this analysis we use the definition by UN-water [6], which notes the importance of water-related disasters, e.g., droughts. The linkages between water, food, and energy security have recently been the subject of intensive research, both globally as well as in Finland, most prominently under the so-called nexus paradigm [7–10]. Additionally, Sustainable Development Goal 6 (SDG6) is very much linked to water security. Thus, by increasing water security, one promotes the SDG6 targets also. However, there are some gaps and limitations raised related to the indices and implementation of SDG6 [11,12].

Many nations globally and in Europe strive to assess and mitigate drought risks [13]. In contrast to many other European countries, Finland does not have national or local drought mitigation plans [14]. Finland, with 187,888 lakes, is a country with plentiful fresh water resources. This is probably why drought in Finland has gained less attention. However, drought can affect the water security of the country via many sectors directly and indirectly. While severe inter-annual droughts can cause significant damage in Finland [15,16], drought risk mitigation has gained little attention thus far. In addition, climate change might increase the frequency and severity of droughts in some parts of Scandinavia, especially during summer [17], yet water use during drought has not been analyzed comprehensively on a basin level in Finland. The only recent larger drought study was carried out in 2004 [15], focusing on the impacts of the drought in 2002–2003. The impacts during the drought in 2018 were even greater [18] and the government agreed on an €86.5 million aid package for the agriculture sector, though without a comprehensive study of the impacts. Water supply companies and large water intensive industries have individual risk plans that usually include water shortages, but a basin wide, multi-sectoral view of drought impacts and water usage during drought is missing. However, a basin level analysis is crucial for the comprehension of drought related water security risks and implementation of mitigation measures [19].

Several different water availability and water stress indices exist [20–22]. Most indices use global estimations for consumptive water use (withdrawals subtracted with returned waters) or just withdrawals with annual or monthly time-steps [23]. Water use-to-resource threshold ratios have also been used, though the correct levels are debatable and case specific [20,22,24,25]. Despite some challenges with these indices, they tend to be useful in indicating possible problem areas that might require more detailed studies [26].

To indicate possible problem areas in Finland, we developed a method for the diagnosis of water stress to key water use sectors at the basin and sub-basin scale. The method involves comparing consumptive water use to water availability during a reference drought with the Water Depletion Index (WDI) [24]. The method also identifies basins and sectors that use large amounts of water, and reflects on how the results affect water security nationwide. In addition, a comparison between local statistical data and open-source globally modeled data is conducted and the differences are scrutinized to evaluate the potential for applying the method in data scarce contexts.

2. Materials and Methods

We assess drought vulnerability and water availability in Finland during a severe drought with the Water Depletion Index (WDI) [24]. Severe drought is used as a reference drought during which consumptive water use is compared against water availability at the sub-basin level. The index was calculated with statistical national water use data and compared with estimates from several global models from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) [27]. The steps of the analysis are briefly presented in Figure 1. This section introduces the study area followed by methods and data. Lastly, the comparison between local datasets and globally modelled data is explained.

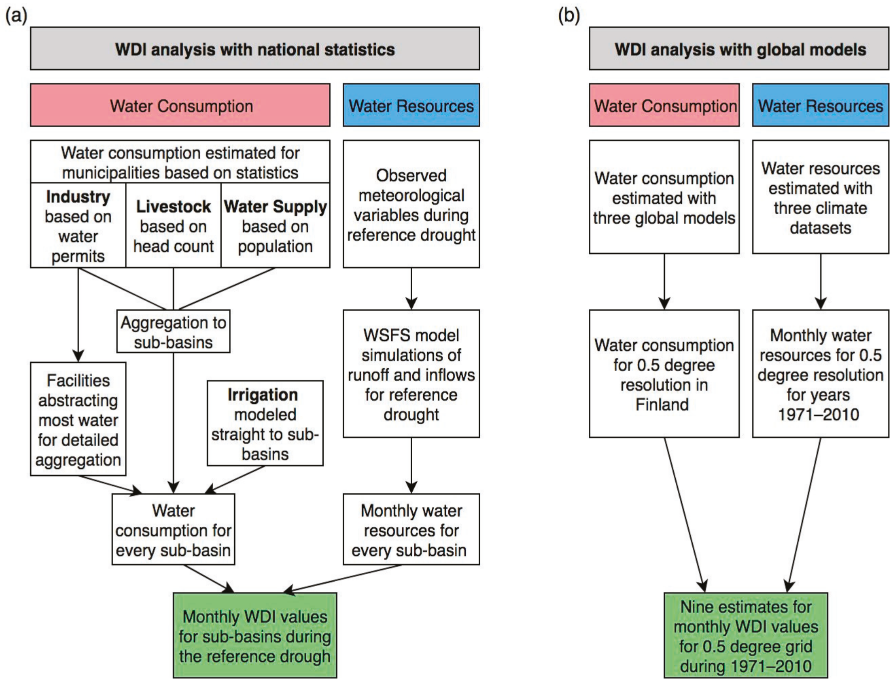

Figure 1. Steps of the analysis for (**a**) WDI (Water Depletion Index) analysis with national statistics and (**b**) WDI analysis with global models.

2.1. Study Area: Finland

Finland has ample water resources. Due to its northerly location next to the Baltic Sea, the climate is cold and humid, with moderate precipitation (450–700 mm annually) and evaporation (200–450 mm annually) (see Figure 2). The country has four distinct seasons, but no dry season. Large amounts of lakes and forest areas decrease the hydrological variability [28]. Long-term meteorological droughts are rare, due to the prevailing moist westerly winds. In addition, periods of no precipitation are relatively short. Thus, a drought in Finland does not mean that there is no precipitation; it just rains noticeably less than average.

The majority of the lakes are situated in the inner parts of the country, whereas the population is concentrated in the coastal areas in the south and southwest, where the basins and rivers are smaller. Most small basins have only a few lakes, making them hydrologically more variable than the large basins with large lakes, thus increasing the vulnerability to droughts. The amount of lakes and lake-percentage (ratio of lake area to total basin area) varies substantially between basins (from 0.03% to 20%). Finland's lakes are numerous but shallow by character, with an average depth of less than 7 meters. One third of the lake area (more than 330 lakes) and most of the large lakes are regulated with dams at the outlet [29]. The main purposes of regulation are hydropower production and flood protection. Droughts are not usually explicitly considered in the regulation permits, but dams could provide help to drought management by regulating water levels and minimum flows. Finland's groundwaters are local and shallow due to glacial erosion in the last ice age, thus increasing the vulnerability to drought [30]. Soils and fields in South and Southwest of Finland are former clayish seafloor, and particularly vulnerable to drought [31].

Finland is geographically a large country (338,424 km^2) with a population of 5.5 million. Industry is the largest water user (66%) followed by domestic water use (22%). Irrigation accounts roughly only for 1–3% of the total water use. Of the total freshwater use, 41% is surface water, 42% is groundwater, and 17% is artificial groundwater [32]. Population is concentrated in South and Southwest Finland, and thus land and water use are more intensive in these areas due to more water utilities, agriculture, and industry. The drainage of fields, forests, wetlands, and peatlands has also intensified the drought effect by decreasing the water retention capability, and has worsened the water quality of lakes and rivers.

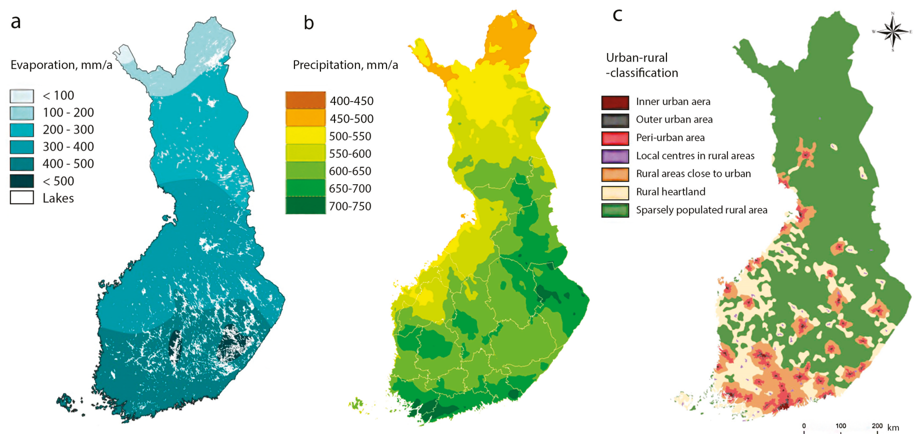

Figure 2. (**a**) Average annual evaporation sum in 1951–1980 (mm) (adapted from [33]), (**b**) average annual uncorrected precipitation sum in 1981–2010 [34], and (**c**) urban-rural areas [35] of Finland.

2.2. Water Depletion Index

Most water use-to-resource indices were designed for long-term water scarcity analyses on a national or basin scale (i.e., to find structural water overuse issues). The Water Depletion Index (WDI) developed by Brauman et al. in 2015 [24] was chosen for this study because it is one of the newest indices, created to assess also seasonal and dry-year water depletion at the sub-basin scale. The formula for WDI is as follows:

$$WDI = consumptive\ water\ use/(inflows + runoff\ generated\ within\ the\ sub\text{-}basin)$$

In this study, WDI was calculated at monthly temporal resolution for consumptive water use [22,23,36] on a sub-basin level. Basin and sub-basin scales are relevant for mitigation plans if they are incorporated in the River Basin Management Plans (RMBPs), as mandated by EU [19]. WDI uses consumptive water use instead of withdrawals, since Perry [37] suggested that using only withdrawals would overstate shortages.

Inflows and runoff were modelled using The Finnish Watershed Simulation and Forecasting System (WSFS) [38,39] developed by the Finnish Environment Institute. Groundwater recharges were taken into account in the modelled values (see Section 2.4). Desalination and non-renewable groundwater use are minuscule in Finland, and thus not accounted for in this analysis.

It is important to notice that water scarcity is complex and partly a socially constructed phenomenon. As has been noted by many scholars [40–43], water scarcity can be analyzed from different perspectives, ranging from hydrological assessments focusing on water quantities to economic, social, and political analyses considering institutional arrangements, interests, and politics related to the scarcity. This also means that technical understandings of water scarcity can hide the real causes of scarcity, leading to inefficient or even incorrect actions [40]. Thus, in some situations water scarcity can be used as a means to justify certain agendas, interests, or discourses [42,44,45]. In Finland, "the land of a thousand lakes" [46], the dominant narratives related to water typically evolve around the abundance of water, making the promotion of measures related to drought and water stress in Finland more challenging.

Thresholds for water scarcity indices are a constant debate [25,26]. For screening purposes, this study adopts the same thresholds as Brauman et al. [24]. This is sufficient to identify possible water-stressed areas or other vulnerable areas for deeper analyses. Brauman et al. [24] used a 75% threshold to define a "depleted" sub-basin. Other often-used thresholds for scarcity are 20% for moderate scarcity and 40% for severe water scarcity [26].

These water scarcity thresholds implicitly include a provision for environmental flows, but are not tailored to local circumstances. Drought causes stress to ecosystems and deteriorates water quality. Estimating environmental flows can, therefore, be useful when estimating the drought impact to the environment. Finnish rivers have generally stable flows, due to the large number of lakes and steady precipitation (no dry seasons or monsoons), but snow accumulation and melting brings considerable fluctuation to the rivers' flow regime. Many rivers are in a relatively natural condition, although only a few are completely undammed, unregulated, or undredged. These characteristics lead to higher environmental flow requirements than average [26,47,48]. Nature can normally adapt to short droughts, but longer drought episodes can be damaging [49,50]—especially in Finland, where no annual dry-season occurs, and the nature is not accustomed to drought. Humans may worsen the impact by not cutting down water use to adapt to drought conditions, regardless of the needs of the environment. Therefore, this analysis should not be taken to provide a comprehensive analysis of drought impacts on the environment.

Similarly, the thresholds can be assumed to implicitly include a provision for the need to dilute pollutants or salts to acceptable levels (as considered by "grey" water footprints [51]). Finland has many industries that have large water withdrawal but relatively low water consumption, including the paper and pulp industry, mining industry, and aquaculture. Thus, they might affect water quality during drought more than quantity. Heat waves during dry summer also create algal blooms that affect recreational use, and sometimes water withdrawal. Water quality is usually the reason a water user needs a permit in Finland, and the permitting and governance systems have been designed more from a quality than quantity perspective. Mining, aquaculture, and industries generally withdraw substantial amounts of water but consume only a little. They might have considerable effects on the ecological status of the water bodies into which they discharge the process waters. During drought, water bodies are in a more fragile state than usual. In addition, water quality in aquifers and lakes deteriorate [52,53]. On the other hand, nutrient washout from agriculture is usually smaller due to less precipitation and erosion. While water quality is important for water users, these phenomena are not explicitly investigated here.

This analysis focuses on blue water (i.e., lakes, rivers, and aquifers). For agriculture, only impacts on irrigation are therefore considered, and not impacts on rainfed agriculture (relying on green water). While potentially significant, these impacts are outside the scope of this analysis. Irrigation is of special interest as it provides protection from drought, but a severe drought would drain some smaller water sources that irrigators would use, potentially accentuating the impacts experienced.

2.3. Data: Water Use

Finland's water use and hydrology differs from the global averages, most notably due to the country's northern location and (usually) snowy winters. Thus, global estimations do not necessarily give the best result in Finland [36]. Water management and related monitoring is generally of high standard and quality, providing actual data on intensive water users via water use permits. Nevertheless, even with good data sources, a study of sub-national scale includes assumptions and generalizations.

Selecting an appropriate unit of analysis is important, as it can have a major effect on the results [54]. The unit of analysis in this study is a river basin. The larger river basins (area over 1000 km^2) were further divided into sub-basins based on the Finnish catchment division system [55].

We analyzed all 74 main basins and 949 sub-basin areas (avg. area 351 km^2) of the country. The water use data is generally available at annual timescale resolution. However, looking at water availability annually gives an insufficient picture [26,56]. Finland has four distinct seasons with specific hydrological features. The growing season is short and irrigation is used mostly in June and July. Temporal downscaling of each sector is outlined below.

The water use data was mostly available at municipal resolution. There are 295 municipalities in mainland Finland. They vary greatly in size (6 km^2 to 17,334 km^2) and population (734 to 642,000). After estimating water use for every municipality, it was aggregated to the 949 sub-basins and the main basins. The water use was divided into sub-basins on the areal extent ratio that the municipality had on each catchment with GIS software. However, to make the aggregation more accurate, irrigation (see next chapter) and all water permits that exceeded 1Mm^3 withdrawals from freshwater annually were analyzed in more detail and the exact sub-basin of water use was used instead of adding it to the municipal value. The criterion was met with 91 water permits out of 565. The 91 permits account for 88% of all industrial freshwater withdrawal volumes that have water permits. The consumptive water uses for the sub-basin are available as Supplementary Materials.

2.3.1. Agriculture

Agricultural water use in this study includes two categories: livestock and irrigation. The water use estimates of livestock were based on the reported headcounts of livestock by the Natural Resources Institute Finland (LUKE) [57,58]. Only a small percentage of the fields are irrigated regularly in Finland (1–2% or ~8000 ha) [59], since it is not generally profitable. Despite the small percentage, the irrigated fields and greenhouses generate approximately half of the market value of the whole plant production [31]. However, the true value of irrigation might become visible only during droughts. For example, in England and Wales, the net economic benefit of irrigation in a dry year was estimated at £665 million [60]. Irrigation has been in decline in Finland since 1995 after Finland joined the EU. The EU agricultural subsidies focus on area instead of crop yield, making irrigation less profitable. This has, in part, led to the decline of irrigation schemes in Finland, making the agricultural sector less resilient to drought.

No reliable records are available on water abstractions for irrigation in Finland. As there was no data, we estimated the irrigation with an unpublished model that was built on an existing VEMALA model [61] developed by the Finnish Environment Institute. The irrigation water use was modelled with hydrology similar to the dry year of 1941, but with today's land use and crops. The irrigation model uses soil moisture to assess the need for irrigation. When soil moisture decreases below a threshold, a specific amount of water is irrigated. Both the threshold of soil moisture and the amount of water irrigated is a crop specific parameter estimated based on irrigation guidelines [31,62]. We assumed that during a severe drought, all farmers with irrigation equipment (101,900 ha in 2013 [59]) would irrigate. For the purpose of the depletion index, we estimated potential water use rather than actual use. Hence, irrigation was not limited by water availability. The annual irrigation amount was divided to months as follows: May 15%, June 35%, July 35%, and August 15%.

2.3.2. Industry

We used water permits from the national VAHTI-database to estimate industrial water use, dividing it into cooling water use, paper and pulp industry, aquaculture, and other industrial water use. A permit is needed in Finland if groundwater abstraction is larger than 250 m^3 per day. In addition, water supply utilities and large-scale facilities need a permit for surface and groundwater abstraction. Water abstractions have to be reported annually (Water act 2011, 3§3). The amount of water use without water permits (abstracting less than 250 m^3 per day) is not recorded, but some estimates have been made for the total water use per sector [32]. Water use was divided equally across months, in absence of evidence otherwise.

2.3.3. Public Water Supply

Water use of the public water supply was based on municipality populations. Water use per capita has been estimated at 204 liters per day per person. The estimate is based on information provided by the water supply companies (VEETI-database). Of the 204 liters, inhabitants use approximately 130 liters, and the remaining 74 liters derive from network leakages and water use by companies and industry, who buy water from the water supply companies. Approximately 90% of the population get their water from water supply companies and the remaining 10% have their own wells. There are roughly 0.5 million wells in Finland providing water to permanent residents (50%), but also to hundreds of thousands of summer cottages (50%). Many wells would run dry during a severe drought, so we estimated potential water use, similarly to irrigation, assuming that water use was not limited by the drought.

The two largest water transfer schemes were also taken into account. The Päijänne tunnel brings water to the Helsinki region (100 Mm^3 annually) and Virttaankangas aquifer recharge project brings water to the Turku region (23 Mm^3 annually). There are also other smaller water transfers, like emergency water transfer pipes between water supply companies, but we excluded them due to lack of data. Water use for public water supply and water transfer schemes was also divided equally across months.

2.3.4. Returned Water

As WDI analysis is based on consumptive water use, the returned water (i.e., the proportion of water returned back to the ecosystems) has to be accounted for. However, the returned water in Finland is not reported in any way and there are no studies on the matter either, so estimated values have to be used. The analysis used the following return flow percentages, which were derived from the WaterGAP model [57] and USGS (United States Geological Survey) reports [63,64]: domestic 83%, industry 78%, and cooling water 97% (thermoelectric cooling in Finland is once-through cooling). Livestock return water percentage was estimated to be 78% [57,58]. Irrigation was modelled with theoretical optimal irrigation water need, creating no return flows. Domestic and industrial water users close to the sea return their waters straight to the sea, thus municipalities with coastline had no returned waters from domestic and industry sectors. The largest inland fish-farming facilities are all "run-through" facilities in Finland and have only a small consumptive effect. Thus, the 15 facilities with annual water withdrawal over 1 Mm^3 were estimated to have a 97% return rate. Hydropower was assumed not to consume or withdraw water.

2.4. Data: Reference Drought

This study uses the most severe drought period of the last century in Finland, the drought of 1939–1942, as a reference drought. The actual drought lasted for 3.5 years, starting in May 1939 and ending in November 1942, yet to understand seasonal variation, we extend the analysis to the full calendar years 1939–1942. The return period of this hydrological drought was estimated to be once in 100–150 years for most of Finland [65], and it is modelled and described in more detail by Veijalainen et al. [66]. The observed temperature and precipitation were used to simulate the runoff and discharges of 1939–1942 using the WSFS model, but with the current regulation rules and dams in the catchments. This enables the estimation of impacts during a severe but realistic drought situation.

During the period of 1939–1942, winters were cold and snow amounts were reasonably large, despite the drought. Since climate change has already increased the temperatures in Finland over 2 degrees [67], these kinds of cold winters have become rarer. According to the results of Veijalainen et al. [66], however, climate change would not significantly change the 1939–1942 drought severity. Winters would become somewhat wetter and summers drier, but the general water availability would change only modestly. Snow amounts were, therefore, not altered.

Inflows and runoff values for sub-basins were modelled with the Finnish Environment Institute's WSFS model [38,39]. WSFS is a hydrological model used in Finland for national operational hydrological and flood forecasting and for research purposes [68]. The reference drought water resources were simulated for the full 4 years period of 1939–1942. The model calculates daily values from which mean monthly discharge and runoff for every sub-basin is calculated. The WSFS includes a conceptual three-layer soil model, where the lowest storage represents groundwater storage and the middle storage soil water and the variations in these storages are calculated. The surface water storages (i.e., lakes and rivers) are taken into account in the model. However, only lakes with area larger than 1 km^2 are included (see Supplementary Materials for a diagram of the model modules).

2.5. WDI Analysis with Global Models

Many water use-to-availability analyses use globally modelled data (e.g., Brauman et al. [24] and Kummu et al. [1]). For comparison with the national statistical water stress analysis, the authors did a similar analysis with global datasets. This was carried out to test whether the global data produce similar results than the more detailed national water permit-based data, and to assess if global data with 0.5 degree resolution (approximately 25 $\times$ 50 km or 1250 km^2 in Finland) could be used for sub-national water availability analyses, at least as a screening tool.

To test the above-mentioned questions, the WDI was calculated with data extracted from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2a [69]). ISIMIP2a is a historical validation experiment, in which historical climate and socio-economic datasets are used to evaluate the performance of the models from 1971 to2010. While this does not cover the reference drought years 1939–1942, it provides the most reliable benchmark for the purpose of comparison. The climate datasets are based on reanalysis of observations, and therefore, in principle, are more reliable than using a climate model. ISIMIP2a includes four climate datasets. We used Princeton, GSWP3, and WFDEI, leaving out WATCH as it only covers the period 1971–2001.

The three global water models used were PCR-GLOBWB, H08, and WaterGAP2. These are the only three models currently available that estimate domestic and industrial water use in addition to irrigation. PCR-GLOBWB and WaterGAP2 additionally estimate livestock water use. Estimates of irrigation water use are typically obtained using climate forcing, land use data, and crop models. Estimates of other water uses are typically obtained by downscaling country-scale statistics. A variety of assumptions are used, often including water use intensities, technological changes over time, and local data, e.g., population, GDP, and livestock populations. Most of the data was obtained at the monthly scale as separate variables from the ISIMIP website. WaterGAP2 water use data was downloaded as a single file containing the sum of industrial, domestic, manufacturing, electricity, and livestock water use. Industrial water use for PCR-GLOBWB was obtained directly from IIASA (International Institute for Applied Systems Analysis), and the livestock water use for H08 model runs was taken from PCR-GLOBWB. The full list of files used is available in the Supplementary Materials.

Inflows and runoffs were calculated similarly to the analysis based on national statistics as the sum of monthly inflows and local runoff. Inflows and runoffs, however, were calculated on 30 arcmin grid cells, which is the smallest spatial unit provided in ISIMIPa. Large water transfer schemes are not incorporated. Routing between cells is included within the models using the DDM30 Drainage Direction Map [70], and some large dams are accounted for. Water consumption estimates were taken from the year 2010. For each cell and each combination of climate dataset and water model (i.e., 9 estimates), we extracted the maximum WDI values over time in order to capture the most severe conditions within 1971–2010.

3. Results

3.1. WDI Results with National Statistics

The core of the analysis consists of the Water Depletion Index (WDI) results. Figure 3 presents the percentage of the Finnish population living in water-stressed areas during a severe drought with three different WDI-thresholds (see below). The WDI is calculated with monthly water consumption from the year 2015 during the reference drought. As can be seen from Figure 3, the population living in sub-basins experiencing drought has a clear seasonal variation. The scarcest month is during the seventh month of the third year, when 11 sub-basins, or 5% (~275,000 people) of population, are above WDI-75%. According to Brauman [24], these basins would be depleted, meaning that usable water is limited in these months. A further 41 sub-basins, or 10% of the population, are above WDI-20%, indicating that another 275,000 people might experience water stress. WDI-20% should be chosen as a threshold when some difficulties start to appear in accessing water (including potential water management, water quality, or environmental impacts [1]). WDI-40% should be chosen as a threshold when some difficulties can be expected and WDI-75% when the sub-basin can be seen as depleted. However, as discussed earlier, the thresholds are exemplary, and should not be treated as absolutes. In 9 sub-basins, the WDI goes occasionally above 100%. While data errors cannot be ruled out (e.g., in consumption, return flows), this can also occur due to unaccounted water storages and water transfers, which shift water availability, and therefore stress, across time and space. More importantly, it includes areas where potential irrigation water use and groundwater extractions may exceed available water, and would therefore need to be curtailed. Therefore, these are important sub-basins for further work to focus on.

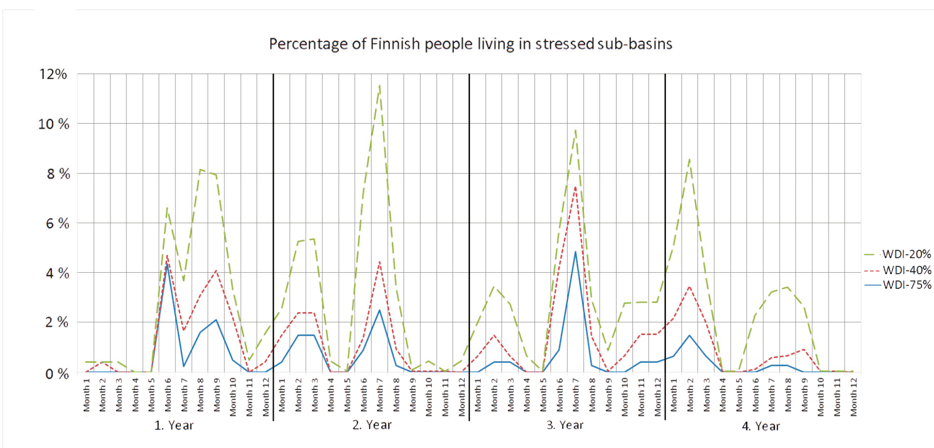

Figure 3. Percentage of Finnish population living in sub-basins that are above three Water Depletion Index (WDI)-thresholds (20%, 40%, and 75%) during the reference drought event.

The majority of basins exhibiting potential water stress problems are located in the South and Southwest of Finland (Figure 4). These basins are mostly small and have few lakes, but also have relatively large amounts of population, farmland, irrigation, and industry. On the other hand, the most water intensive industry is mostly located outside these areas along the large basins, where water is available even during a severe drought. It is notable that the Helsinki region shows relatively low WDI values: this is due to the Päijänne tunnel water transfer. In addition, while many small coastal basins show high WDI values, their public water supply may, in reality, be sourced from neighboring larger basins. In addition, some sub-basins on large lakes, like Päijänne and Saimaa, show elevated WDI values, but when investigating the lakes as whole, water availability is sufficient to avoid water stress.

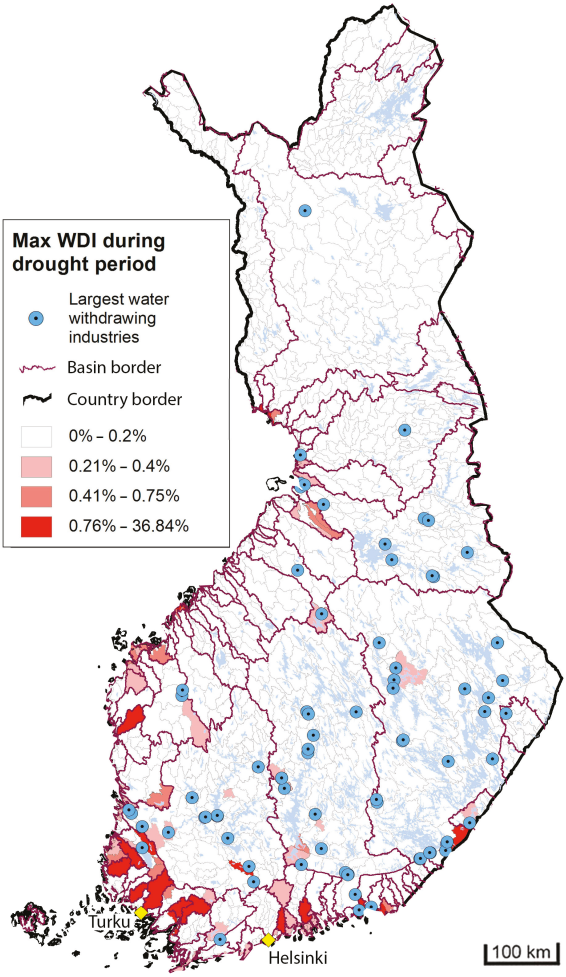

Figure 4. Maximum monthly WDI values during the reference drought period and locations for largest water withdrawing industries.

Figure 4 also shows where the largest industrial and fish-farming units are located. One hundred units that abstract the most freshwater are shown in the figure. The largest units are mostly located in the large basins and near large water bodies or rivers, as expected. The largest water abstractors are the paper and pulp industry, energy production, aquaculture, and the chemical industry. The largest water withdrawals are usually cooling water, with most of the water returning.

Figure 5 shows how the modelled total storage capacity of lakes and reservoirs decreases during the reference drought. The model includes lakes larger than 1 km^2. The storage was at a normal level at the beginning of the drought. The figure shows that the spring floods did not fill the lakes to the previous year's level. The storage is lowest in March of the fourth year. When comparing this to the March of the first year, a difference of over 9000 Mm^3 can be observed. This is almost ten-fold the annual water consumption. Diminished water storage means that there are less options to mitigate drought impacts with regulation and irrigation. The figure does not include groundwater storage, but typically, groundwater storage follows the surface water storage with a short delay. Lower groundwater levels lead to more difficulties, with water users relying on groundwater.

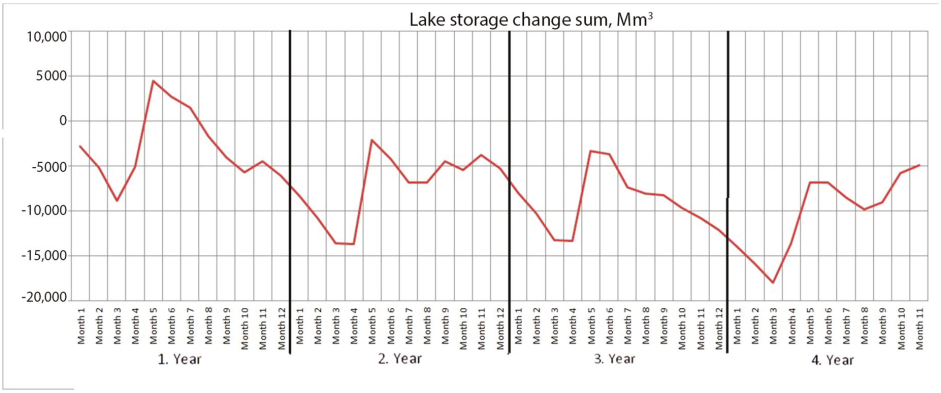

Figure 5. Cumulative change of the lake storage during the reference drought.

3.2. WDI Results with Global Models

Results using estimates from global models should be seen as a screening tool to identify areas that are potentially depleted rather than being directly comparable to national data. The 30 arc minute resolution is quite coarse, and there is substantial uncertainty across model estimates. Using 3 climate datasets for period 1971–2010 and 3 models, the analysis yields 9 different estimates. The number of estimates with WDI values above 20% is shown in Figure 6. Similarly to Figure 2, the global estimates also highlight southern coastal regions. Some cells are outside the land borders—they should be interpreted as coastal areas, as this is due to the limitations of the coarse raster representation. Water depletion is, however, also suggested in inland areas, especially in the north. This turns out to only be due to a single model (PCR-GLOBWB, see Supplement). The utility of global models is further discussed in Section 4.2.

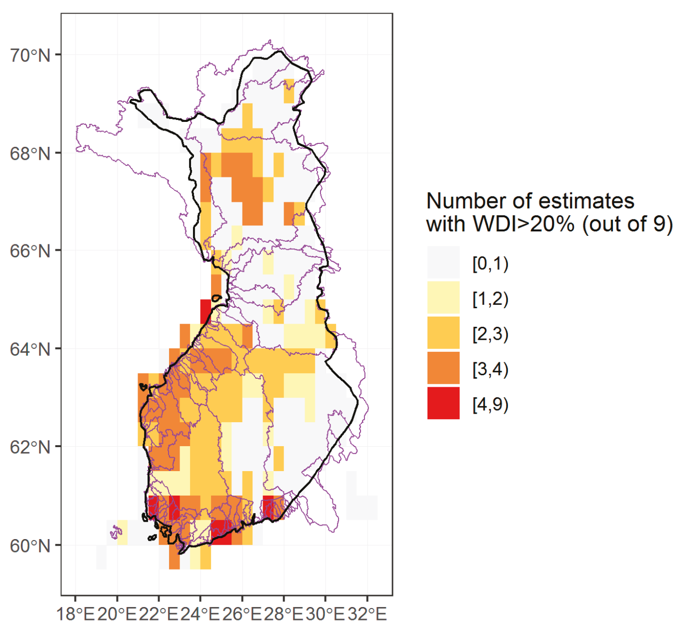

Figure 6. Water Depletion according to global models: Number of estimates reporting WDI > 20%, using 3 climate datasets and 3 global models (9 estimates) for the period 1971–2010.

4. Discussion

The findings of this study have been divided into three parts: context-specific, methodological, and policy-relevant findings. A fourth part then presents the limitations and ways forward.

4.1. Context-Specific Findings: South and Southwest Finland Most Vulnerable to Drought

In this study, drought vulnerability was analyzed by estimating consumptive water use during a severe drought in Finland. The main impacts from severe drought in Finland would come in two ways: through combined impacts from reduced water availability for food security, and through specific impacts for selected water-intensive water users, such as industries and water supply companies. While the analysis indicates that most areas in Finland would have enough water, areas in South and Southwest Finland would have difficulty securing sufficient water availability for all sectors, such that prioritization of sectors would be needed to minimize impacts.

In terms of economic implications, the drought impacts for pulp and paper industry would be particularly critical, as they use remarkable amounts of water and are important for the Finnish economy. However, the pulp and paper factories are generally well protected against drought due to their efficient water use and locations next to large water bodies (partly due to the fact that the timber was historically transported via lakes and rivers). Also, thermo-electric facilities are adjacent to large water bodies, protecting them relatively well from drought.

Drought would have implications also for water supply. After the 2002–2003 drought, some emergency water transfer pipes have been built between supply companies, increasing their resilience and providing alternative options for raw water. This is likely to mitigate some of the water stress predicted in this analysis. Potentially the largest impact for water supply would be through private wells, as many of them would run dry, similarly to the droughts in 2002–2003 [15] and 2018 [71]. Deteriorated water quality would also become a problem for water supply. These issues could be further investigated in the sub-basins identified in this study.

4.2. Methodological Findings: WDI Useful for Drought Analysis, Global Analysis has Limitations

This study indicates that the Water Depletion Index (WDI) is a useful indicator for analyzing the drought vulnerability for the following two reasons. First, WDI clearly states the biophysical fraction of water use from human activities. It is simple, yet precise. Secondly, it can be used with different time-steps and resolutions for drought analyses or water scarcity analyses. It is a good screening tool for sustainable water governance and water resource management.

The WDI also has some limitations that need to be addressed when using WDI and communicating its results. As WDI value does not explicitly account for environmental flows or thresholds and the sustainability of water use is not directly visible from WDI values, some additional information is always needed. For example, definitive identification of impacts would require case-specific rather than generic thresholds. In addition, with a relatively short time scale (a month), the water consumption can exceed the availability during drought, resulting in sub-basins with WDI values over 100%. Such sub-basins are prime candidates for further investigation, as this can occur for a variety of reasons, including if discharge is close to zero (dams are closed), runoff is low (as often happens during drought), or water demand cannot be met and would need to be limited by de facto or regulatory restrictions in consumption.

Interesting context-specific and methodological findings emerge also when comparing the study results with global model analysis. The global analysis seems to highlight the same areas as the local analysis, thus providing corroboration. Such global analysis is useful for providing a general overview and it can highlight areas that are likely to have water stress. Due to its coarse scale, however, it should not be used to rule areas out. At the same time, our studies also indicated some key challenges in the global model results. The considerable differences between the climate models highlight the importance of using multiple global models for screening analyses. Further investigation would be needed to understand why the PCR-GLOBWB model's estimates differ from the others. If we consider only regions where 4 or more (out of 9) estimates agree, there are in fact fewer regions that appear depleted than reported by the local analysis. While model inaccuracies are likely at play, this is also expected for two other reasons. Firstly, the cell size is larger than the sub-basin size in many coastal basins. This means that water availability is aggregated over larger areas, resulting in lower WDI values. Secondly, the climate datasets used here only start in 1971. The worst-case water availability is, therefore, not as extreme as in 1939–1942.

It should also be noted that global analysis doesn't consider water transfer schemes. This can be seen in the Helsinki region, which is highlighted in the global model analysis, but not as clearly as in the local statistical analysis. The reason for the difference is the Päijänne tunnel water transfer scheme, which provides all the raw water to the Helsinki metropolitan area from lake Päijänne via a 120 km tunnel. Water transfer schemes are globally common and an important part of water supply, especially during drought. Hence, they should be better incorporated in both global and local water availability analyses. Obtaining data on actual water access and water supply networks is a common problem in global analyses, which has led to issues related to the modifiable areal unit problem [54]. In general, this is dealt with by careful selection of the unit of analysis, e.g., Food Production Unit [72], but this study demonstrates that the ability to adequately capture small basins and associated water transfers is crucial in otherwise water abundant settings.

4.3. Policy-Relevant Findings: Establishing Drought Management Plans

Finland has relatively well-established policies and plans related to water management and climate change adaptation [73], and Finland's water security is globally at a high level [74]. However, as drought has not conventionally been considered a significant threat in Finland, both climate change adaptation actions and preparedness exercises have focused on floods. There are currently no specific Drought Management Plans (DMPs) in place. The findings of this study suggest that such plans would be useful to improve water security, at least in the most vulnerable areas in South and Southwest Finland. These plans should include, for example, guidance on communications and responsibilities, water use limitations guidelines, co-operative irrigation schemes, preparedness exercises, and other mitigation measures. Good drought mitigation practices can minimize the damage to societies and the environment considerably, e.g., by sustaining minimum flows and water levels with regulation dams. Currently, regulation permits in Finland do not mention droughts and there is usually no guidance for drought-related dam regulation.

The long-term drought mitigation measures would be logical and efficient to implement in the EU Water Framework Directive's River Basin Management Plans (RBMPs) [13,19]. In RBMPs, the water quality aspects of drought should also be taken into account. The DMPs could be drafted only to areas vulnerable to drought, as was done with Finland's flood risk management plans [75]. The areas highlighted in this study provide the first step forward when choosing the areas for the DMPs. Short-term mitigation measures, i.e., preparedness plans and water use limitations, could be implemented at the municipal level, where needed. With the RBMPs and the EU's drought management plan guidance, it would possibly make multinational co-operative drought management easier between EU countries.

4.4. Limitations and Ways Forward

Water scarcity and water stress are multifaceted concepts, and therefore they can be looked at from a variety of viewpoints and analyzed with a number of different approaches [40,41]. This article has focused on a quantitative drought analysis, meaning that we did not look at much broader economic, social, or political aspects related to water scarcity. However, the mitigation measures responding to the drought are equally multifaceted, and would thus require also addressing key economic, social, and political aspects and interests.

A basin level drought analysis can serve practitioners and river basin managers in improving water security and drought resilience, yet more local knowledge and research is required before actions can be taken. For example, interviews and detailed local studies should be made to learn more about the local vulnerabilities and water use practices, as well as their linkages and trends. Additionally, multinational drought management would require more research.

The uncertainties of this water use-to-resource analysis are multiple. For larger global comparison and analysis, the thresholds are understandable, but for smaller cases like Finland, relative thresholds could make more sense when trying to find possible vulnerable areas. In addition, returned waters bear substantial uncertainties, because there are no records of them even in Finland. The WaterGAP3 values were mostly used in this study, but stricter values might be justified for the small time-step (month) and small spatial extent (sub-basin), as Schrerer et al. [36] suggested.

The ability of the hydrological model to simulate the discharges during extreme drought is also uncertain. The observation data from 1939–1942 is rather sparse and may contain biases. Lakes and reservoirs were taken into account in the model calculations, but their role in an actual drought situation may be underestimated. In addition, groundwater storages are included in the model as aggregated average values for the sub-basin. In many places, groundwater storages are crucial in carrying both nature and societies over the drought period [26,76] and efforts to enhance resilience would benefit from better knowledge of them. Some uncertainty also arises from the irrigation model, which is new and needs further validation.

5. Conclusions

Finland, despite being among the countries with the most abundant freshwater resources, has areas that are vulnerable to drought. The most vulnerable areas are in the South and Southwest parts of the country. Drought management and drought resilience are, therefore, important when assessing national and regional water security and its linkages (for example to food security).

The Water Depletion Index (WDI) provides useful and easily interpretable information for decision-makers. It can provide knowledge for private entities, such as industry and farmers, but foremost it is useful to public entities and river basin managers to plan their water resource management actions. The WDI should, however, be used only as a screening tool, given that stress thresholds used are generic, environmental flow requirements and water quality impacts are only implicitly considered, and results are dependent on accurate estimates of water consumption, availability, storage, and transfer. Areas identified as water-depleted are prime candidates for further, more detailed investigation. To complement our national water stress analysis, we carried out similar analysis with global datasets. The current status of global models means that they provide an even coarser screening tool for drought analysis, and their actual value is likely to depend on local conditions. They have been effectively used at the scale of countries or large river basins, but are of limited use for sub-national drought analysis, especially for small basins.

Finland has an advanced water resource management system, and it has created flood risk management plans for every significant flood risk area. The first step in the process was to choose the significant flood risk areas. Our findings indicate that a similar process should be carried out with drought, and this analysis provides a good starting point for identifying the areas requiring Drought Management Plans (DMPs) to enhance their water security. A good place to implement such plans could be the River Basin Management Plans (RBMPs) within the EU Water Framework Directive.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/6/1548/s1, Excel sheet for maximum WDI value for every sub-basin; Shape-file for sub-basins; CSV of files used from ISIMIP project for global analysis; Total water use in 2010 for each individual global model; Worst case monthly WDI calculations for each individual model for period 1971–2010; Model modules of the WSFS model.

Author Contributions: The authors have contributed to the article accordingly: Conceptualization, L.A. and N.V.; methodology, L.A., N.V., and J.H.A.G. (global models); software, L.A., N.V., and J.H.A.G. (global models); formal analysis, L.A., N.V., and J.H.A.G. (global models); investigation, L.A.; resources, L.A., N.V., and J.H.A.G.; data curation, L.A., N.V., and J.H.A.G.; writing—original draft preparation, L.A.; writing—review and editing, all; visualization, L.A. and J.H.A.G.; supervision, M.K., M.M., and O.V.; project administration, L.A. and M.M.; funding acquisition, M.M., M.K., and O.V.

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Northern Warning Lights: Ambiguities of Environmental Security in Finland and Sweden

Emma Hakala [1,2,*], Ville Lähde [2], Antti Majava [2], Tero Toivanen [2], Tere Vadén [2], Paavo Järvensivu [2] and Jussi T. Eronen [2,3,*]

1 Global Security Programme, Finnish Institute of International Affairs, 00101 Helsinki, Finland
2 BIOS Research Unit, 00170 Helsinki, Finland; ville.lahde@bios.fi (V.L.); antti.majava@bios.fi (A.M.); tero.toivanen@bios.fi (T.T.); tere.vaden@bios.fi (T.V.); paavo.jarvensivu@bios.fi (P.J.)
3 Ecosystems and Environment Research Programme & Helsinki Institute of Sustainability Science (HELSUS), Faculty of Biological and Environmental Sciences, University of Helsinki, 00014 Helsinki, Finland
* Correspondence: emma.hakala@fiia.fi (E.H.); jussi.t.eronen@helsinki.fi (J.T.E.)

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Abstract: As the literature on environmental security has evolved and widened, knowledge of the full range of potential consequences of environmental change for different societies remains scattered. This article contributes to a more comprehensive approach to the implications of environmental change by providing a three-level framework of the security impacts. In particular, it will address gaps in knowledge by pointing out the relevance of geopolitical and structural factors behind environmental security impacts. The article will focus on the cases of two countries, Finland and Sweden—both seen as stable, high-income democracies that are well equipped to adapt to climate risks. Yet even under these conditions, preparedness to threat-prevention will not follow without a recognition of the full range of risks, including ones that are linked to socio-economic and geopolitical factors. On the basis of the Finnish and Swedish cases, the article proposes an analytical framework of three categories of environmental security impacts: local, geopolitical and structural.

Keywords: environmental security; security impacts; societal transformation; resilience

1. Introduction

During recent years, the perceived magnitude and severity of different kinds of environmental threats have been on the rise. For example the World Economic Forum annual survey [1] shows that there has been a clear shift from economic to environmental threats between 2009 and 2019. As the severity of environmental problems that the world is facing is increasingly understood, the risks that they pose to societies also become more apparent. Although the impacts endured in different parts of the world will vary considerably, no region will be fully spared from the consequences [2–4]. Environmental security literature has aimed to explore the interactions between environmental change and society in various geographic and societal contexts [5–7].

Analyses tend to focus on regions where environmental impacts are manifest concretely. These tend to also be regions where changes are acutely felt due to their severity, the fragility of local communities or a combination of both [3]. Studies have examined direct security links caused by the interactions between the environment, access to natural resources and threatened livelihoods [8]. These are especially apparent in post-conflict or high conflict risk areas [9,10]. Meanwhile, impacts that are less local and more geopolitical tend to be neglected [11]. In addition, less attention has so far been paid to the security impacts of the society-wide transformations that will be necessary to both mitigate climate change and to adapt to it [12,13]. Key sectors like energy, food production and transportation should already be adjusting to a changing environment while also being restructured to be sustainable in the long run [14–16]. Moreover, these impacts concern industrialized and developing countries alike and therefore need to be analyzed on a case-by-case basis but in a global context.

Our focus here is on two countries, Finland and Sweden. As Nordic countries, they are exposed to relatively severe climate induced risks, as the impacts of climate change are more profound in the Northern latitudes than the global average [17–19]. On the other hand, as stable, high-income democracies they are considered to be well equipped to adapt to new conditions and therefore not highly vulnerable to the risks [20]. These two reasons make Finland and Sweden excellent case studies to analyse the security implications of environmental change in the context of "stable Western democracies" which should be equipped to deal with the consequences.

We distinguish between two steps that are necessary for preparedness to threat-prevention to follow: the full range of risks needs to adequately be recognised, and deliberate policy measures need to be taken to address them. In this article, we focus on the recognition of risks, which in most cases will need to precede policy-making. Therefore, we identify cases where an explicit link has been made between environment and security and point out linkages that appear to be missing from these analyses. An examination of the decision-making and policy-context is beyond the scope of this paper, but we are developing another manuscript on that theme. While there are several analyses in the literature that consider what environmental security could ideally entail [21–23], we turn to look at what are the issues countries, as security actors, have already recognised. On the basis of our analysis we point out aspects that are, in light of theoretical research, missing from their analyses and that should be taken into account in order to provide grounds for sound policy-making.

The Nordic countries therefore constitute an interesting case where the ability to prepare and adapt to climate change depends more on the level of analysis than on technical capacity alone. In addition, they provide a perspective beyond the direct ecological risks of environmental change, emphasising instead the security impacts associated with the societal transformation required to mitigate and adapt to it. The discussion of two countries instead of only one makes it possible to make comparisons and to identify differences caused by the approaches chosen by the two countries.

The paper will proceed by first giving a brief overview of current environmental security literature, pointing out gaps concerning societal transformations. This will yield the basis of our categorization of environmental security impacts into local, geopolitical and structural ones. Then, we consider the Nordic country cases, outlining the major environmental security threats they are facing and that they recognise in their current strategic assessments. In particular, we focus on the gap in preparedness concerning the adaptation to a world with zero CO_2 emissions. Finally, the paper will conclude by proposing a new, comprehensive framework for more effectively taking environmental security impacts into account.

2. Theoretical Approaches to Environmental Security

As a theoretical concept, environmental security is by no means a neglected topic. Starting with the rise of the wider approach to security at the end of the Cold War, the literature has ranged from environmental causes of conflict [24–26] to the threats of pollution to human health [3]. Due in part to the variety of topics it covers, however, the discussion often runs into ambiguities and inconsistencies with regard to specific impacts on society.

Environmental security literature has traditionally been divided between two major strands, one focusing on conflict and the other on human security. What a majority of the research suggests, however, is that environmental security usually is closely linked to societal and political factors and is virtually impossible to reduce to straightforward causal relations. Conflicts, for instance, do not stem from one environmental cause, but may occur when environmental factors are combined with other ones, such as governance [21,27], population growth [28], health [29], migration [30] or excessive resource extraction [31,32]. Human security, on the other hand, considers environmental threats to be linked to various other factors that increase vulnerability, such as deteriorating health, welfare, livelihoods or equality [3,23,33,34].

The indirect character of many environmental security impacts makes their prediction and management all the more difficult. Knowledge about environmental changes has to be combined with knowledge on socio-economic and political developments that are difficult to predict as such, resulting in prognoses so complex and uncertain that their information-value suffers considerably. Moreover, direct impacts that are experienced locally in one place may be felt indirectly elsewhere as a result of geopolitical linkages [35]. If environmental security is able to render these complex connections visible, it can offer a means to examine and potentially resolve environmental problems in a way that takes their cross-sectoral implications into account.

Yet the idea of environmental security as an overarching framework for multi-faceted analysis counters theoretical views that consider it an inherently reductive concept. According to Deudney [36], Aradau [37] and Bettini [38], among others, the linkage to security may lead to the use of force and to politics of emergency. This echoes the securitisation framework first introduced by Buzan, Waever and de Wilde [39], who argue that the introduction of new issues into the security sector will often have the effect of moving them beyond normal democratic discourse. Others, however, question whether this always is the logic emerging from securitisation. Trombetta [40] argues that appeals to security in the environmental sector have yielded new kinds of measures and helped to involve a wider group of actors. For Oels [41], efforts to securitise climate change have given rise to new risk management mechanisms that have had the effect of 'climatising' security rather than vice versa.

In fact, it would make sense to acknowledge the security consequences of environmental change well in advance in order to address them through democratic processes as long as they are still in effect. According to Dalby [42], this is becoming more urgent as climate change advances. Policy-making needs to understand and foresee the deep social, political and economic roots of environmental changes and try to affect them before they erupt as crises, rather than seeing crises as externally caused events. Furthermore, this capacity for foresight will have to be built up simultaneously with a vast societal change necessary to mitigate climate change.

Yet current literature does not adequately take into account the societal challenge of climate change. Some studies have pointed out the potential security consequences of climate change mitigation [43] and adaptation [44,45], but are for the most part limited to direct impacts in local contexts. They also focus on the Global South, where such efforts have been carried out through development cooperation projects [46]. This tendency may help to maintain the false impression that countries in the North will easily be able to deal with the repercussions of climate change that they face [47]. In a more global context, the security impact of mitigation has primarily been discussed with regard to climate geoengineering, which could potentially have significant consequences on ecosystems and societies [48–50]. However, policy discussion about its actual utilisation has so far remained marginal [51].

The focus on direct impacts and specific one-off mitigation actions runs the risk of neglecting the extent to which climate change and its prevention will influence production patterns, politics and societies as a whole [14,15]. This has been noted by Dalby [11], who argues that geophysical factors will increasingly have a role at the core of geopolitics. In terms of policy planning, the attention will therefore have to shift from a traditional focus on military power to issues like energy, food systems and infrastructure. In particular, Dalby highlights the need to acknowledge the economic foundations of environmental problems and a necessity to reconsider current production patterns. Environmental problems tend to transcend territorial state borders, and cannot be defended against with the use of force. They call for coordination, anticipation and foresight rather than a reaction to a threat that has already occurred. In other words, a transformation in geophysical and societal factors will require a corresponding transformation in our thinking about security and its governance [11].

The approaches linking environment to the human security approach offer some pathways to transformative thinking. Through a recognition of the economic, social, institutional, political, cultural, and technological factors, it allows for analyses that set environmental change into its context [52]. As such, it creates an interface between these fields, bringing in actors outside traditional formulations of security and encouraging interactions between them [53]. As proposed above by Trombetta [40] and Oels [41], it may therefore have a democratising impact on security discourse, as it disperses power from political elites to the wider society. Such an approach has the potential to encourage participatory processes of decision-making, which help to avoid resorting to the kind of extreme measures, such as geoengineering, that Dalby warns against [54]. However, policy discussion about such consequences still remains marginal, as Corry has pointed out [51].

New kinds of security thinking may already be overdue if they aim to reinforce democratic procedures rather than to erode them. As the consequences of climate change become more acute and its prevention more urgent, the potential for the use of force or restrictive measures increases. One of the scholars behind the original securitisation framework, Jaap de Wilde, has observed that the structures of society can either be changed voluntarily and in an orderly manner, or violently and randomly through environmental crises [55]. As long as countries do not adequately take these impacts into account, they are unlikely to fully engage in implementing policies to address them. The key question therefore is how environmental security can be implemented into policy in a measured and premeditated way.

Previous literature shows that environmental security cannot be construed through a single, uniform perspective—on the contrary, it requires a way of recognising the diversity of environmental impacts. This also suggests that analytical tools for environmental security have to be developed and adapted to the needs of individual cases,—although they must also be understood in the context of the wider environmental security discourse. The following section will consider the cases of Finland and Sweden and aim to come up with an analytical framework to examine different kinds of environmental security impacts from the point of view of individual countries.

3. Materials and Methods

The previous sections suggest that it is possible to discern at least three kinds of environmental security consequences that have not all been recognised to an equal extent. Local impacts, such as the physical impacts of storms or floods, are starting to be acknowledged in both theory and policy-making. There also is an increasing understanding of impacts where environmental change is combined with geopolitical factors, although these are more difficult to predict and prepare for in terms of policy. Meanwhile, the impacts of mitigating and adapting to environmental change are still inadequately addressed in the literature and largely neglected in policy-making.

The present study will address the shortcomings of environmental security analysis through the cases of Finland and Sweden. It will examine the environmental security impacts currently taken into account in the strategic planning of the two countries, while also identifing consequences that are not yet adequately recognised. The aim is to formulate a comprehensive picture of the kinds of impacts that Finland and Sweden are facing, but also to consider the strategic relevance given at state-level to the security impacts of environmental change. Our main focus, therefore, stems from the need to understand the extent to which traditional security and foreign policy analysis has been able to change and incorporate new risks associated with a changing environment. Rather than aim to identify every aspect of environmental change that could have relevance for security, we instead direct our discussion to instances where environmental issues have already been noted in security analyses in Finland and Sweden.

Our perspective also determines our data selection. In order to examine the recognition of environmental impacts in strategic analysis, we look at major state-commissioned research papers and policy documents that have a key role in determining decision-making or significant influence on policy discussion. Due to our focus on decision-making concerning security, we have only looked at assessments that explicitly make the link between security and environment. While we do not argue that no other assessments of environmental impacts or climate mitigation measures exist, these do not take into account the areas of security and foreign policy, which are central to our approach. Based on our survey and focus, the main documents which are analysed here are: Sweden facing climate change—threats and opportunities (2007) [56], Klimatförändringarnas konsekvenser för samhällsskydd och beredskap—En översikt (The consequences of climate change for the security of the society and preparedness, Sweden 2012) [57], Risker, konsekvenser och sårbarhet för samhället av förändrat klimat—en kunskapsöversikt (Risks, consequences and vulnerability to the society from a changed climate—An overview of capacity) (2012) [58], *Klimatförändringarnas indirekta effekter och deras betydelse för Sverige* (2014) [59], Crossborder effects of climate change in Finland (2016) [60] and Weather and Climate Risks in Finland—National Assessment (2018) [61]. In addition, some regional and sectoral assessments [62–67] have been examined to gain a more extensive idea of the risks that have been taken into account and that may also be used to inform policy-making.

To guide our analysis, we rely on the observations made above regarding different kinds of consequences that environmental change may have. It will therefore look at environmental security at three levels: local, geopolitical and structural. *Local impacts* are caused by environmental factors, such as extreme weather, and directed at individuals and the society. In other words, they include impacts on human wellbeing both directly or through critical functions of the society. *Geopolitical impacts* occur as environmental changes are combined with political and international factors. Finally, *structural impacts* are caused by the societal transformations that need to be carried out in order to mitigate and adapt to environmental change itself. The assumption here is that structural changes in the economic and political systems will be required to achieve sustainable and secure societies.

For each category of impacts, our analysis proceeds as follows. First, we examine whether the existing assessments take the category into account overall. Second, we look more closely at the kinds of impacts that are recognised and the consequences they are expected to have. Third, on the basis of our analysis of environmental security theory, we aim to identify gaps in the current recognition of impacts.

The focus of this paper is particularly on the two latter kinds of impacts, which tend to be neglected more than local ones. However, rather than predetermining exact characteristics for the categories, the country cases are used to trace potential impacts. The aim is to give substantial examples of environmental security impacts that often remain vague in policy discussion.

As mentioned above, Finland and Sweden are interesting from the point of view of understanding environmental security impacts in the context of countries that are considered to have low vulnerability [68,69] and high capacity to adapt to climate change [70]. This interpretation, however, neglects the less immediate geopolitical impacts as well as societal transformations that cause structural impacts. The cases of Finland and Sweden thus offer grounds for exploring environmental security more comprehensively than merely in terms of immediate and local impacts. Therefore, they also illustrate the need for a more systematic framework for analysing environmental security in order to gauge the full range of impacts.

4. Results: Environmental Security Impacts in Finland and Sweden

4.1. Local Impacts on Environmental Security in Finland and Sweden

Both Finland and Sweden have commissioned research projects to assess local impacts of climate change on the security of their societies. In Sweden, the main document on climate impacts, entitled "Sweden facing climate change—threats and opportunities", analyses the consequences for various sectors of the society, from transportation to communications, energy and health [56]. The original assessment dates back to 2007, but both the main document and its various attachments have since been updated. In addition to the national level, it also evaluates impacts for individual municipalities or regions [58]. Other authorities, such as the Swedish Civil Contingencies Agency, have produced similar assessments on sectoral impacts [57]. Both Finland and Sweden are also required to assess 'vulnerability, risks and climate change impacts' for their National Communications to the UN Framework Convention on Climate Change (UNFCCC) [62,63]. However, for both countries this section in the report is brief and does not add anything beyond the data in the assessments mentioned above.

In Finland, sectoral impacts have been included directly in a recent assessment of climate impacts. It presents a fairly detailed analysis that also aims to take into account the influence of different future scenarios, although also pointing out the impossibility of covering all potential impacts and interactions [61]. A similar report has previously been prepared on the measures to promote the management of climate risks [64]. Local actors, like the city of Helsinki, have also produced their own assessments [65]. In addition, there are more sectoral assessments, such as a report by the Finnish Climate Change Panel on the expected impacts of climate change on forests, which constitute a crucial economic asset for the country [67].

In both countries, temperatures will rise more than the global average [61]. The change will be more severe in the winter and in northern areas. Finland and Sweden will also experience increased precipitation, potential flooding and other changes in water systems. Overall, weather patterns will become more variable and unpredictable. Both countries will also be affected by rising sea levels and decreased ice cover of the Baltic Sea [56,61].

Both Finnish and Swedish assessments raise the following local impacts on different sectors [56,61]:

- traffic and communications;
- water management;
- health;
- forestry, agriculture, fishery;
- built infrastructure;
- energy sector.

Both Finnish and Swedish analyses point out that the expected impacts rarely pose direct risks to people's lives. They do point out, however, that severe consequences in different sectors are directed to the security of the society. Heat waves, for instance, are expected to have health effects and a rise in average temperature may increase the occurrence of various transferable diseases. Extreme weather, such as storms and heavy precipitation, may threaten energy supply and distribution. Transportation infrastructure and housing are also at risk of floods, storms and other unexpected weather events [57,61].

Based on the research reports, the kinds of local impacts expected for Finland and Sweden can be contained in such a way that they will not necessarily cause significant damage to society. This, however, requires planning and preventive actions. The fact that the research reports and risk assessments have been state-commissioned and publicly funded suggests a degree of recognition of the relevance of environmental security impacts even in the Nordic context. Especially in the Finnish case, the assessments also provide practical insight to the concrete consequences of environmental impacts and suggest ways to manage them.

However, recognition alone does not amount to action. Practical policy measures are required to achieve any kind of preparedness to deal with environmental security impacts. The current presence and implementation of policies for local environmental security impacts in Finland and Sweden is explored in another article written by us [71]. On the basis of the analysis here, it can be argued that an adequate level of knowledge exists in both countries to form the groundwork for policy.

4.2. Geopolitical Impacts on Environmental Security in Finland and Sweden

As the geopolitical impacts of environmental change can be quite wide-ranging, their assessment may often be limited to sector-based analyses. In Finland, however, a recent study was commissioned to explore the 'crossborder effects of climate change' [60]. Meanwhile, in Sweden, one of the updated attachments to the assessment of the impacts of climate change also considers geopolitical impacts. The report calls these 'indirect' impacts, but the discussion is strongly on the geopolitical level. However, the report is careful to point out that it is intended as a brief overview rather than as a comprehensive assessment [59]. In the Swedish case, therefore, an overview of the geopolitical impacts appears to be missing.

On the other hand, a report by the Swedish Environmental Institute presenting a Transnational Climate Impacts Index proposes indicators for country-level exposure to transnational impacts of climate change and thereby provides an analytical framework to guide adaptation efforts. Its scope is global and by no means aimed at examining the Swedish situation in particular [35]. Meanwhile, the Mistra Geopolitics project attempts to examine the geopolitical implications of climate change both globally and from the point of view of Sweden and has devised scenarios to take into account the geopolitical interactions, but at the time of writing it has not published reports on the specific impacts in Sweden [72,73]. For Finland, similar geopolitical research with potential strategic impacts on decision-making does not exist.

In its introduction, the Finnish assessment points out 'chains of events' as a central feature of the transboundary or geopolitical analysis of environmental change. This underlines the indirect connection between local impacts that take place elsewhere and their consequences that are felt elsewhere through geopolitical, economic or other linkages [60]. The Swedish report refers to the same process as 'indirect, cross-border and long-distance effects' [59]. Both assessments therefore emphasise that the countries are in many ways linked to and even dependent on global resource flows and international frameworks, which considerably increases their vulnerability to disruptions in these systems.

The Finnish and Swedish assessments give an outline of potential indirect impacts—also in the Swedish case, as the countries are similar enough in terms of political and structural factors. The reports lists the following issues among those that may have adverse impacts on security [59,60]:

- resources and critical production: price instability, food security, problems in access and supply, damage to infrastructure for trade, passive approach to climate change based on an inadequate risk perception;
- energy: price instability, problems in access and supply, damage to energy infrastructure, rising reinsurance payments;
- international transport: risks associated with new transport routes, damage to transport infrastructure;
- business and finance: uncertainty in global markets, rising reinsurance payments, disruptions in data networks, damaged assets;
- population: unexpected migration flows
- health: new disease risks due to food, population movements and new species;
- biodiversity: risks caused by invasive species e.g. to agriculture and forestry;
- foreign policy: increasing global uncertainty, conflicts, increasing regulation;
- development cooperation: deterioration of the achievement of development goals, increased need for humanitarian relief resources, increased propensity for conflict.

Both reports acknowledge that the intensity of indirect impacts strongly depends on the severity of climate change, but also the development of world economy [59,60]. According to the Finnish assessment, climate change may change competitive advantages between the countries, which will influence the dynamics of global trade. It does not, however, clarify what these changes are in more detail. It may also have physical impacts on critical infrastructure, such as ports and distribution networks, which could cause disruptions on trade routes. This is significant for Finland, where the value of international trade was about 30% of GDP in 2013 and is expected to grow in the coming decades [60].

Yet according to the Finnish assessment, the impacts of climate change on Finnish industry, for instance, will remain small, as most of the source countries of Finnish imports are in Europe, rather than in areas where climate impacts are more significant. Forest industry, which is an important sector for Finland, is noted as a sector that might suffer as over 50% of Finnish forestry production is located in areas of the Global South where production is likely to go down [60]. With regard to energy production, the Finnish report is more ambiguous. While the common Nordic energy market Nord

Pool is described as highly secure and adaptive, climate change might still increase variability and disruptions. Similarly, crucial oil and gas imports from Russia could suffer from interruptions.

The above estimations, however, seem to neglect the full impacts of global warming on the world economy. 2 °C of global warming has been estimated to lead to severe economic losses [74], which in turn is likely to cause at least some degree of global recession. Due to the global connectivity that the assessment also recognises, it is not clear that Finland will be protected from economic and geopolitical impacts, regardless of the geographic range of its trade partners.

The blind spots of the Finnish assessment are perhaps best illustrated by the case of the Arctic region. The report does note that extreme weather events will become more common in the Arctic region, causing risks and requiring new safety measures for transportation. Overwhelmingly, however, it presents climate change as an opportunity for Finnish Arctic policy due to new transportation routes and access to natural resources made available by the melting of the ice sheet [60]. The analysis appears to entirely overlook the global risks presented by the increasingly severe impact of climate change in the Arctic [75]. Moreover, the increased activity and interest in the Arctic has been argued to increase geopolitical risks, including for Finland [76].

The cross-border impacts become perhaps the most evident in the discussion of health and migration. According to the assessment, the 'number and frequency of pathogens may increase in imported foodstuffs' and new diseases will enter Finland also as a result of travel and population movements [60]. In addition, the report notes that climate change may increase global migration. It refers to the 'refugee situation of 2015' which suggests that some of the migration may also be directed to Finland.

Meanwhile, the Swedish report quite extensively acknowledges the global chains of geopolitical and economic impacts. In keeping with its own premises, however, it does not provide a full sectoral analysis, and is more ambiguous on the details of impacts. It notes, for instance, that as Sweden is in many ways integrated into the global energy market, it will also be influenced by its increased instability. The report also notes the risk of an intensified politicisation of energy, which could weaken Swedish energy security [59]. Likewise, the report points out that climate change may have significant consequences on Swedish food security due to global disruptions in production, but notes that the specific form of these impacts have so far not been studied.

The Swedish report points out migration as one of the priority sectors influenced by climate change. It argues that changes in living conditions around the world, as well as potentially rising risk of conflicts will force people to migrate, and some of this movement is likely to be directed towards Sweden. This may put a strain on Swedish social security services and increase pressure on facilitating integration into the society [59]. The Swedish assessment dates back to 2014, so unlike the Finnish one it does not refer to the refugee situation during 2015.

Both reports propose actions for taking geopolitical impacts into account in policy-making. The Finnish one calls for increased cross-sectoral and international coordination, but also suggest that it is possible to develop individual actions in various sectors to address specific impacts. In addition, the report emphasizes the need for a better understanding of the causal chains behind geopolitical impacts, particularly in a global context [60]. The Swedish report mainly calls for further, more comprehensive analysis and assessment to guide policy-making. However, it also recognises the need for cross-sectoral coordination. In addition, it suggests analysing the policies and strategic work carried out in other countries on the linkages of environment and security, pointing out the potential to learn from work that has already been done [59].

The recommendations correlate with the observation made above that there is a lack of recognition of the consequences that geopolitical changes may have on Finland and Sweden, whether in the Arctic, in neighbouring countries or in a wider international context. In other words, both the Finnish and Swedish assessments seem to be correct in pointing out that further research is needed. However, emerging knowledge on the geopolitics of environmental change will only be effective if it is utilised in policy-making. The extent to which this is the case in Finland and Sweden is discussed in another article written by us [71].

4.3. Structural Impacts on Environmental Security in Finland and Sweden

While the previous sections have focused on the consequences of environmental change itself, the final one discusses the impacts of the measures taken in order to either mitigate it or adapt to it. Even in global terms, the territory is relatively uncharted, but implications especially in the field of energy transition are beginning to be acknowledged [77]. The impacts associated with energy transition are also included in a Hongkong and Shanghai Banking Corporation (HSBC) study tracing the climate vulnerability of countries around the world. Although Finland and Sweden are the two least vulnerable countries in terms of their overall score, they both rank higher in the energy transition section: Finland is 47 and Sweden 56 out of 67 countries, where the first position indicates highest vulnerability [69]. The scores suggest that it may indeed be the structural transitions that pose the highest relative risks to countries like Finland and Sweden.

The Finnish climate impact assessment takes some note of the consequences of adaptation and mitigation on the energy sector. It points out that vast changes will be needed in order to cut greenhouse gas emissions by the required 80%–95% by 2050, and that Finnish development is highly dependent on global changes. However, on the basis of the National Energy and Climate Strategy for 2030, Finland is expected to become more energy independent [78] which would curb the risk of transboundary or geopolitical impacts. Another publicly commissioned study that examines energy transition from the point of view of Finland-Russia relations concludes that the increasing independence will make Finland less susceptible to Russian influence in the energy sector. On the other hand, Finnish dependence on Russian nuclear power is simultaneously increasing, which in turn may hold back the development of renewable energy production in Finland [79].

In Sweden, the geopolitical consequences of energy transition have been under even less scrutiny than in Finland. These are not mentioned in the main document on climate risks, which primarily focuses on local impacts [56]. The analysis of indirect impacts suggests that the Swedish energy sector will undergo changes as the overall European energy market and production balance develop, although it does not explicitly argue this would be due to policies for the mitigation of climate change. It does point out that interest in and demand for Swedish hydropower production may increase [59]. The Swedish Energy Agency has published a study on the transition to a sustainable energy system, but the challenges observed are limited to barriers such as lack of financing [66]. This document suggests that at least at the official level, energy transition appears to be perceived primarily as an opportunity for Sweden.

Moreover, the assessments in both Finland and Sweden are based on a limited perspective in which future changes are expected almost exclusively within the energy sector. The Finnish assessment does note that climate change may give rise to protectionism, although it is not explicitly stated whether this would be due to the policies to mitigate climate change or climate impacts as such [60]. In addition, the assessment points out that the increasing importance of carbon sinks in global climate negotiations might have significant consequences for Finnish forestry. However, it does not clarify what the effects would be like, apart from concluding that demand for Finnish wood could rise as a result of an increasing interest in sustainable forestry and wood-based products [60]. In other words, it does not take into account the possibility that international mitigation policies, such as EU regulations, would require increasing carbon sinks in forests. This would require Finland to reduce wood harvesting, potentially leaving forests as stranded assets for the forestry industry.

Although the Finnish and Swedish assessments attempt to consider environmental change in an interaction with some socio-economic and climate-related factors, they do so within a relatively static economic and societal system. In other words, they expect full the mitigation of climate change and full energy transition to accommodate to the prevailing conditions of the society. Yet, as the theory presented in Section 2 shows, the measures required to prevent environmental change from reaching a critical threshold have to take place at a systemic level incorporating changes in behavior, governance and economics [16]. It has been argued that the present economic model based on constant growth is fundamentally irreconcilable with rapid cuts in emissions, and effective decarbonisation therefore necessitates a transition of the entire system [80]. Such radical changes, especially when combined with the urgency of taking action, will inevitably produce new opportunities and threats as well as winners and losers both domestically and globally. This may lead to societal instability and shifts in geopolitical relations, thereby creating new security issues. In particular, the transition poses a challenge to democratic decision-making, which needs to be able to rapidly come up with efficient climate policies while also ensuring that they are socially just and acceptable to various groups of the society.

By neglecting the structural impacts apart from some aspects of the energy transition, Finnish and Swedish analyses end up discounting a crucial dimension of the security consequences of environmental change. Assessments based on an analysis of separate sectors will not be able to produce a comprehensive picture of the changes ahead. Although precise predictions are impossible to come by due to the difficulty of factoring in simultaneous changes in different fields, further research can still help to widen our understanding of the dynamics involved. This is also a precondition to providing any insight on the adaptation impacts to aid policymaking.

5. Discussion

The analysis in the previous sections shows that the three-level classification helps to go beyond the usual focus on direct environmental security impacts and to get a more comprehensive perspective. It shows that even for relatively resilient countries like Finland and Sweden, environmental change creates various security issues. In addition, it confirms the expectation that while the level of recognition is good on local impacts and emerging on geopolitical impacts, structural impacts are to a large extent neglected in research and risk assessments.

Table 1 provides a framework for analysing environmental security impacts. Different impacts can be overlapping and simultaneous, and they are related in many ways. Yet the division into three categories makes it possible to see the different dynamics behind them. Local impacts are often possible to anticipate as an interaction of cause and effect, although they might still end up having wide and cross-sectoral consequences. Geopolitical impacts, on the other hand, usually have a crossborder aspect and require an understanding of complex linkages between countries and sectors. Meanwhile, structural impacts are analytically challenging as they for the most part refer to changes that have not yet been implemented.

Table 1. Framework of environmental security impacts.

Local Impacts			
Possible impacts	*Geographic scope*	*Time frame*	*Scale*
Storms, floods, droughts, heat waves and other extreme weather events	Local, regional	Short to long term	Sectoral, cross-sectoral
Geopolitical Impacts			
Possible impacts	*Geographic scope*	*Time frame*	*Scale*
Conflict, migration, food shortages, disruptions in energy production, disruptions in resource flows	Regional, global	Short to long term	Cross-sectoral
Structural Impacts			
Possible impacts	*Geographic scope*	*Time frame*	*Scale*
Systemic shock in energy production patterns, failure of economic production system, erosion of democratic governance	Local, regional, global	Long term	System-level

An understanding of both the different dynamics of the impacts but also the inter-linkages between them can help to come up with ways to address them. For one thing, it shows that environmental security requires both domestic and international approaches. Local impacts may in some cases be possible to address purely through national policies, but geopolitical and structural impacts require an international perspective and foreign policy engagement. Moreover, environmental security at all levels seems to benefit from international cooperation and coordination.

In addition, our analysis suggests that there still is an acute need to go further explore the consequences of adapting to and mitigating environmental change. The current low level of recognition of the structural impacts makes it virtually impossible to produce ways to address them. Although some aspects are starting to be noted especially concerning changes in the energy sector, this will not suffice to perceive the full scale of the transition. Therefore, structural impacts in particular require coordination across sectors.

6. Conclusions

We argue that while local security impacts in the Nordic countries are relatively limited, it still is imperative to have an understanding of environmental security in the comprehensive sense. There are multiple geopolitical impacts and tipping points in the global system that will influence the Nordic countries as well. Although it is, at present, difficult to accurately predict the patterns that these factors will lead to, this should not be a reason for not taking them into account. On the contrary, it should prompt further inquiry.

What all environmental security impacts have in common is that while they undeniably influence the security of the society and individuals, they cannot be understood strictly as a matter of security policy in the narrow sense. They call for taking into account the security impacts of environmental change through risk assessments and preparedness while also integrating political, economic and societal perspectives. In other words, environmental security needs to be to some extent inclusive, thereby setting it in contrast with traditional formulations of security as a restricted sector, as discussed in Section 2 above. Yet this is not to argue that the entire security sector should be opened up. Our suggestion is to start interactions between security and various other sectors in the environmental case. This echoes the previously presented points by scholars like Trombetta [40] and Oels [41], suggesting that the security sector also needs to adopt new modes of action in the face of new threats.

The previous points become particularly compelling as environmental security discourse moves beyond the recognition of local impacts to acknowledging those associated with structural changes in the society. The transformations in energy and economics take place at a systemic level, and are highly unlikely to take place in an orderly manner without governance. The question is how to implement adequately effective and fast changes through the relatively slow democratic process. Yet at the same time, democratic governance is invaluable as a way to ensure that the transformations are equal and just. While it does not in itself work as a definite guarantee against discontent or instability, democracy provides the means to deal with them through open, participatory processes. In this context, the environmental security approach should aim to support decision-making by providing anticipatory insight into the society-wide and geopolitical implications of the transformation.

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A Lot of Talk, But Little Action—The Blind Spots of Nordic Environmental Security Policy

Emma Hakala [1,2,*], Ville Lähde [2], Antti Majava [2], Tero Toivanen [2], Tere Vadén [2], Paavo Järvensivu [2] and Jussi T. Eronen [2,3,*]

1 Global Security Programme, Finnish Institute of International Affairs, 00101 Helsinki, Finland
2 BIOS Research Unit, 00170 Helsinki, Finland; ville.lahde@bios.fi (V.L.); antti.majava@bios.fi (A.M.); tero.toivanen@bios.fi (T.T.); tere.vaden@bios.fi (T.V.); paavo.jarvensivu@bios.fi (P.J.)
3 Ecosystems and Environment Research Programme & Helsinki Institute of Sustainability Science (HELSUS), Faculty of Biological and Environmental Sciences, University of Helsinki, 00014 Helsinki, Finland
* Correspondence: emma.hakala@fiia.fi (E.H.); jussi.t.eronen@helsinki.fi (J.T.E.)

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Abstract: Despite an increasing recognition that environmental change may have implications for security, there only are few policies to address the issue. This article will look at environmental security policies in Finland and Sweden and propose ways to develop more effective measures. It relies on a three-level framework that aims to enable the identification of environmental security impacts by categorising them into local, geopolitical and structural ones. The article will examine present environmental security strategies and policies in Finland and Sweden, consider their efficacy for addressing various kinds of impacts and point out approaches that are currently missing. Based on the discussion, it argues that a comprehensive policy approach is needed to tackle environmental security impacts. This requires closer coordination and interchange between sectors as well as strategic intent. In addition, further research is needed on the structural impacts of mitigating and adapting to environmental change.

Keywords: environmental security; environmental policy; societal transformation; resilience

1. Introduction

In recent years, environmental issues have become an increasingly established part of security and foreign policy discourse [1–3]. Climate change, in particular, features in the speeches of politicians and military officers alike as one of the major global security threats that require urgent action [4–6]. Yet the discussion has not resulted in a great deal of concrete measures and its bearing upon national polices considerably varies from one country or organisation to another [7,8]. From our perspective, the value of environmental security as a concept for policy practice has not gained the place or momentum it deserves.

Most of the impact and concrete discussion on environmental security has focused on climate induced conflicts [9,10] and their linkages to questions such as water and food [11,12]. Other major topics have been climate impacts on critical infrastructure [13], national security [14] and increased violence [15]. These themes have played to the hands of the hard security community, giving armies and security forces the central role and initiative in the policy discourse on environmental security.

Based on our categorisation of three different kinds of security impacts of environmental change, presented in another article [16], we argue that environmental security should in fact involve a broad range of sectors. In our view, the consequences of ecological change and the efforts to mitigate and adapt to it are experienced throughout society, so environmental security policy also needs to be shaped by various actors. Leaving the issue only to the hard security community is less likely to produce outcomes that take into account all fields of governance affected.

Our aim in this article is to examine how different kinds of environmental security impacts—local, geopolitical and structural—have been taken into account in actual real-life policy-making. Rather than merely suggesting which issues environmental security policy should address, here we concentrate on instances where security and foreign policy explicitly has made a linkage to environmental change. In addition to reviewing the evidence, we also point out the elements that are missing from current environmental security policy. We then discuss possible reasons why environment and security have not been linked and why the field has remained a marginal one.

In the next section, we outline the present state of policies on environmental security. We focus on the role environmental security has been traditionally given, overview the topics briefly and go on to discuss how its present role makes it subordinate to traditional geopolitical and security analysis. We use the Nordic countries Finland and Sweden as examples to illustrate how the security impacts of environmental change are currently incorporated into security and foreign policy. Relying on our three-level framework of environmental security impacts [16], we illustrate what is missing from current policy and how the inclusion of the neglected parts can help policy-making on environmental security.

2. Turning Environmental Security into Policy

Current research suggests that despite some examples of acknowledgement at a high political level, environmental security has not been turned into policy in a systematic way [7,8,17]. Governance on the topic has been fragmented among a number of institutions and lacks common conceptualisations and responses [7,18]. This may be partly explained by the theoretical literature, which covers an extensive scope but lacks a degree of coherence, making it difficult to pinpoint specific policies. We describe the theoretical approaches in more detail in a companion article [16].

As an intrinsically transboundary issue, environmental security questions fit particularly into the work of inter-governmental bodies, although no single actor has taken the lead on the issue. The UN Security Council (UNSC) has held both formal and informal discussions on environmental issues, especially emphasising the role of climate change [19,20] and natural resources [21] in conflicts. The acknowledgement has been regarded as an important signal of approval for the linkage of environment and security [22], but the UNSC has also been criticised for not taking a strong enough stance or coming up with concrete actions [23].

Some UN agencies have brought environmental security into their practical work. The UN Development Programme (UNDP) integrates the environment into its human security approach, emphasising its interconnections with other aspects of sustainable development [24]. Meanwhile, the UN Environment Programme (UNEP) has a unit for conflicts and disasters and has created concrete practices, such as post-conflict environmental assessments and early-warning systems [25]. In this sense, the work of the UN touches on both the human security and conflict approaches to environmental security, but these have not evolved into any systematic policy.

The EU has included climate change and environmental degradation in its Global Strategy from 2016, pointing out that these ‘exacerbate potential conflict’ [26]. It puts this strategic commitment into practice by incorporating climate security into its work on natural disasters and conflict-prevention, focusing on early-warning systems. Yet the EU has also been said to lack a systematic approach to the topic, which makes it more difficult to come up with effective, coherent measures [27].

At the state-level, responses are even more scattered. According to Brzoska’s [8] comparison of the inclusion of climate change in national security and defence strategies of several countries, climate or environmental issues are often mentioned as an emerging or even a potentially significant threat, but concrete responses are rarely proposed. The United Kingdom is an exception as it has drafted measures for the defence forces to take climate change into account. Meanwhile, in the United States, the military and other actors from the traditional security sector have had a major role in promoting discussion about climate security and ways to address it in practise. Their focus has been on ensuring the effectiveness of defence forces in conditions of environmental change, which often leads to an emphasis on national security [28].

Some countries see environmental security as an issue of their global engagement. Germany has considered the security implications of climate change for its development cooperation [29], and also considerably contributed to the discussion on climate security at the UNSC since its non-permanent membership in 2011 [30]. Sweden, on the other hand, raised climate security high on the agenda for its membership in the UNSC, working with researchers and practitioners to find effective ways to address it through the UN system [31]. So far, however, these efforts have not produced any kind of high profile consensus on environmental security actions [32].

The lack of implementation cannot be fully put down to an inability to come up with concrete proposals for environmental security responses. Research-based analyses have suggested new practices, such as targeted risk assessments, monitoring, early-warning systems and setting up new organisational structures [1,23,27]. They also point out the need to integrate environmental security into existing policies and institutions across sectors. Cross-sectoral coordination and information-sharing are seen as necessary to reach a level of institutionalisation that enables environmental security approaches to actually be implemented [1,27].

Overall, the environmental security policies adopted so far have a focus on the interconnections between environment and conflict or, to a lesser degree, human security. In light of our analysis of the security impacts of environmental change [16], they therefore have potential to address local and geopolitical impacts, although no overarching approach has emerged to ensure coherence or coordination. Meanwhile, current policies almost entirely neglect the security consequences of mitigating environmental change and adapting to it. We argue that this category, which we call the structural impacts, is increasingly important as climate change and the policies to counter it advance. This aspect also highlights the need to understand the extensive, cross-sectoral implications of environmental security.

3. Materials and Methods

This analysis looks at environmental security policies in the case of two countries, Finland and Sweden. Often seen as 'green' countries within the EU [33], they are well placed to take environmental changes into account in policy planning. With regard to environmental security, however, neither country has been able to comprehensively recognise the full range of impacts [16]. This is likely to be reflected in policy-making as well.

Our aim is to give an overview of existing policies, and identify gaps in the current policy framework. In particular, we look at the extent to which environmental issues are taken into account in security and foreign policy, but also whether these have been implemented more practically into policy-making. Our focus is to understand the extent to which traditional security and foreign policy has been able to change and incorporate new risks associated with a changing environment. Therefore, rather than aim to identify every aspect of environmental change that could have relevance for security, we instead focus our discussion on instances where environmental issues have already been noted in security and foreign policy in Finland and Sweden.

Our focus affects our selection of materials for analysis. In order to examine the policy-relevance of environmental security, it has been necessary to focus on the key strategy and policy documents that set the foundations for the security policies of the two countries. In addition, as we are interested in policy-making that concerns security, we have only looked at strategies and policy documents that are explicitly linked to the security sector. On the basis of relevance, we have therefore focused on the following documents: Finnish Government Report on Finnish Foreign and Security Policy (2016) [34], Finnish Security Strategy for Society (2017) [35], Finnish Internal Security Strategy (2017) [36], Finnish National Risk Assessment (2018) [37], Sweden's Defence Policy 2016 to 2020 (2015) [38], A summary of risk areas and scenario analyses for the Swedish National Risk and Capability Assessment (2016) [39], and Swedish National Security Strategy (2017) [40]. In addition, in order to trace the implementation of the policies, we have looked at reports and documents produced by a number of state agencies [41–46], particularly ones focusing on civil preparedness and emergencies.

The analysis builds upon our observations in a companion paper [16], which looks at the extent to which environmental security impacts have been recognised in strategic assessments in Finland and Sweden. In our view, this kind of country-specific knowledge base on the security impacts of environmental change is necessary for relevant policies to emerge. In order to help identify the environmental security impacts, the companion article also provides a framework for grouping environmental security impacts into three categories: Local, geopolitical and structural impacts. The framework is shown in Table 1.

Table 1. Environmental security impacts.

Local Impacts			
Possible impacts	*Geographic scope*	*Time frame*	*Scale*
Storms, floods, droughts, heat waves and other extreme weather events	Local, regional	Short to long term	Sectoral, cross-sectoral
Geopolitical Impacts			
Possible impacts	*Geographic scope*	*Time frame*	*Scale*
Conflict, migration, food shortages, disruptions in energy production, disruptions in resource flows	Regional, global	Short to long term	Cross-sectoral
Structural Impacts			
Possible impacts	*Geographic scope*	*Time frame*	*Scale*
Systemic shock in energy production patterns, failure of economic production system, erosion of democratic governance	Local, regional, global	Long term	System-level

Based on our analysis of Finland and Sweden, local impacts are currently recognised extensively in official state-commissioned assessments, and a knowledge base exists on the potential consequences on humans and the society. Geopolitical impacts have been recognised to some extent but there is very little analysis and a low level of understanding of the interactions through which they emerge. Meanwhile, structural impacts have largely been neglected. The extent of the societal transformations needed to mitigate climate change is generally not taken into account as a factor influencing security. In other words, beyond local impacts, there are significant gaps in environmental security knowledge in both Finland and Sweden.

In this article, we utilise the results presented above to structure our analysis. For each category of impacts, we look at the issues that have been raised as potential concerns in the assessment reports, and examine whether these have been addressed in policy documents. Through this discussion, we trace the extent to which strategic analysis has been turned into policy so far. Furthermore, we examine whether any of the issues we have found to be neglected in the assessments are in any way included in the policies.

The framework shows that due to the diversity of impacts, environmental security policy cannot be based on a single, uniform policy. The actions needed to address storm damage and systemic change in energy production, for instance, are very different. Yet it is necessary to also acknowledge that the impacts are inter-connected and sometimes overlapping. Environmental security can provide this overarching approach, implemented through a variety of policies.

4. Results: Environmental Security Policies in Finland and Sweden

4.1. Policies for Local Environmental Security Impacts in Finland and Sweden

In the Finnish and Swedish assessments of local environmental security impacts, it has been pointed out that changes like increased precipitation, potential flooding, as well as rising sea levels and temperatures will have various kinds of consequences on the society. In particular, affected sectors include transportation; water management; health; forestry, agriculture and fishery; built infrastructure and energy [16].

Both Finnish and Swedish security strategies take note of such local impacts, but there are differences between their approaches. The main Finnish policy document focuses almost entirely on impacts that originate outside Finland [34], as does the strategy for internal security [36]. Instead, Finland deals with local impacts in its Security Strategy for Society [35], which outlines the implementation of security policy at the local and societal level. Likewise, local environmental impacts are included in the latest National Risk Assessment [37]. In the Swedish Security strategy, on the other hand, climate change is listed among the main threats facing the country, pointing out that it "impacts security in Sweden both directly and indirectly" [40]. The description of direct impacts correlates approximately with local impacts in our framework, as they refer to concrete impacts, like flooding and heavy rain, and their consequences to critical services maintaining the society. Meanwhile, Swedish defence policy only mentions climate in terms of the need of the Swedish forces to be able to operate in local conditions [38].

For Finland, the Security Strategy for Society particularly points out environmental accidents, such as oil spills at sea [35]. However, it also includes a section on the "[d]etection and monitoring of changes taking place in the environment, adapting to the changes and combating the threats arising from them". It points out that "environmental threats may cause significant property and environmental damage", although it does not explain in more detail what the threats could be like.

The Swedish strategy document points out that "[a] change in climate has implications for many key services in society", such as "physical planning, buildings, communications and transport infrastructure, technical supply systems and, of course, agriculture, hunting and fishing". In particular, it emphasises the risk of flooding in various areas of the country [40]. In addition, the analysis made for the National Risk and Capability Assessment takes into account local environmental impacts and notes that climate change is likely to aggravate them. As concrete impacts it also especially mentions flooding, as well as heat waves [39].

Both countries explicate some policy measures to tackle environmental or climate impacts. The Finnish security strategy for the society relies entirely on environmental monitoring and goes on to assign responsibilities for it between several authorities, namely environmental and municipal ones, that also coordinate their work among one another [35]. Meanwhile, the Swedish strategy calls for "reducing vulnerabilities and leveraging opportunities", for example, by developing a strategy to strengthen and coordinate climate adaptation [40].

Both countries have also developed mechanisms for managing local environmental impacts, concentrating on regional and municipal authorities. Finland, for instance, has a natural disaster warning system LUOVA (Luonnononnettomuuksien varoitusjärjestelmä), which works as an information channel between relevant authorities [41]. In Sweden, activities on environmental risks are coordinated through a Working group for environmental accidents [42] and a Network for climate adaptation [43].

Yet despite the existence of such administrative structures, implementation is held back at the level of individual organisations. According to a recent study on the management of climate impacts, most municipalities in Finland do not follow climate risks systematically. They are hindered mainly by a lack of resources, but municipal actors also find it difficult to fit climate-related knowledge into local decision-making processes [44]. Similarly, inadequate resources and coordination hinder Swedish municipalities from applying effective climate adaptation measures [47].

Overall, there is a clear strategic engagement on local environmental impacts in both Finland and Sweden, and some measures have been taken to address them in policy. These also, to some extent, build upon the recognition of local impacts in strategic assessments, as many of the same issues are mentioned also at the policy level. The status of the recognition of impacts and policy responses is depicted in Table 2 below.

Table 2. Policy framework for local environmental security impacts in Finland and Sweden.

	Impacts Recognised in Assessments	Impacts Recognised in Policies/Strategies	Policy Measures Adopted
Finland	Precipitation, flooding, temperature rise, disruptions in transportation, water management, health, forestry, agriculture and fishery, infrastructure, energy	Environmental accidents, environmental change	Natural disaster warning system; cross-sectoral coordination
Sweden	Precipitation, flooding, heat waves, disruptions in transportation, water management, health, areal livelihoods, infrastructure, energy	Flooding, sea level rise, heat waves	Working group for environmental accidents; Network for climate adaptation

The framework for environmental security policy thus exists, but its implementation is still primarily left to individual actors that are often restricted by a lack of resources and leverage. This also suggests a deeper predicament about environmental security policy: Due to its cross-sectoral character, its implementation ultimately relies on the coordination of individual actors in a range of different fields, often in addition to their actual work. Coordination, support and especially additional resources are therefore necessary to at least pave the way for the applicability of environmental security.

4.2. Policies for Geopolitical Environmental Security Impacts in Finland and Sweden

Finland and Sweden have to some extent assessed geopolitical environmental security impacts, with similar results. Finland has highlighted impacts on economic production, energy, transport, business and finance, migration, health, biodiversity and development cooperation. In the Swedish case, particular focus has been given to migration, livelihoods, food security, transport and energy. The potential dynamics of these changes are not explicated in more detail, however, and the impacts are expected to remain relatively small. In our analysis, we argue that the assessments may have neglected the full scope of consequences that a 1.5 or 2 °C rise in average temperature would have [16].

The Finnish foreign and security policy paper mentions environmental threats and climate change among rising global risks that require international responses. Sustainable development, specifically in terms of the UN Agenda 2030, is considered as a key “set of goals for dealing with many global threats and challenges”, also including the impacts of climate change. Climate policy is also mentioned as one of the components of dealing with the “root causes of migration”. In addition, it is mentioned as a central topic in Arctic cooperation [34]. Similar goals are echoed in the strategy for internal security, which lists the ‘crisis of sustainability’ among the global megatrends that influence Finland. It particularly points out climate-related migration and the pressures that this can cause to Europe [36].

Apart from international cooperation and sustainable development policy, however, the Finnish security policy does not suggest clear measures to address geopolitical environmental impacts [34]. According to the internal security strategy, the influence of ecological change will not be significant during the planning period (which is not explicitly stated, but its objectives are to be achieved by 2025), but it points out that solutions for sustainable development are necessary. In particular, it stresses that Europe should prepare for increased migration, but does not clarify the measures that should be taken to this effect [36].

The Swedish Security Strategy argues that geopolitical impacts of climate change threaten Sweden as much as local ones [40]. It points out several global consequences, specifically the increased risk of conflict, poverty and lack of food or water. It also notes that the combination of these factors may result “in people being forced to flee”. However, it does not clarify how exactly these influence Sweden. Yet in terms of measures to be taken, the Swedish strategy strongly emphasises the role of international cooperation. Similarly to Finland, it mentions the Agenda 2030 but also notes that “Sweden will continue its efforts to ensure that climate and security are high on the agenda in international organisations, particularly the UN and the EU". In addition, it suggests that strengthened "cooperation between development assistance and humanitarian aid could enable the risks and consequences of natural disasters to be reduced."

With regard to international cooperation on environmental security, Sweden has followed through substantially, especially when it comes to climate change. The link between climate and security featured prominently on the programme of its rotating membership in the UN Security Council [48], and the country chaired a debate on climate-related security risks in the UNSC in July 2018 [49]. Climate security was described as a priority for the government that held office from 2014 to 2019 [48]. Accordingly, Sweden has supported research on climate security, for example, by establishing the Stockholm Climate Security Hub, which promotes policy-making on climate security by producing up-to-date knowledge on climate risks and their prevention. In more concrete terms, the initiative has proposed creating "an institutional home" for climate security within the UN framework to coordinate and advance exchange of information on the topic [50].

Finland, on the other hand, has not put such an international emphasis on the issue [51]. The environment has been linked to security policy as a part of Finnish peace-building activities especially during the 2000s, as the country significantly contributed to funding international bodies such as the Environment and Security Initiative as well as the work of UNEP on conflicts and disasters [52]. This work, however, does not tie into a more comprehensive discussion of the security impacts of environmental change.

Instead, Finland relies heavily on its policy of security of supply, which aims to ensure the continuity of the functions or the society, such as economy, national defence and livelihoods, during major crises. As the security of supply perspective has increasingly come to emphasise inter-dependency and Finnish reliance on global resource flows [53], it seems ideal for integrating an assessment of the geopolitical impacts of environmental change. In fact, the recently updated security of supply scenarios, leading up to 2030, quite comprehensively take into account the consequences of both severe and moderate environmental change [45].

So far, however, this perspective has not featured prominently in policy-making on security of supply. The latest Government decision on the objectives of security of supply from 2018, for instance, only remarks that climate change mitigation and adaptation are taken into account unless the security of supply requires otherwise [46]. This formulation suggests that climate change is considered as something that can be taken into account if it suits other objectives, not as a critical factor of its own. In this sense, the gap between risk recognition and policy implementation is even wider on geopolitical impacts than local ones, as risk assessments do exist, but the policy framework is still largely missing.

Sweden, on the other hand, does not have a similar supply security approach. The country has instead chosen to consider geopolitical environmental security impacts as a matter of global responsibility. Certainly, the international approach is by no means inconsistent with national interest, as it may contribute to preventing environmental risks at the global scale. It can be argued that Sweden aims to address the root causes of environmental security impacts, whereas the Finnish model is more attuned to treating the symptoms. From the point of view of comprehensive environmental security policy, the two approaches should be implemented simultaneously.

Table 3 outlines the policy frameworks on geopolitical environmental security impacts for Finland and Sweden. It shows that the impacts pointed out in strategic assessments have only partially been included into foreign and security policies. In terms of implementation, there is a clear difference between Finland and Sweden. While Finland does not have specific measures either at the domestic or international level to address any of the impacts mentioned in the policy documents, Sweden has actively engaged in or initiated policy-making internationally. However, even in the Swedish case an explicit link seems to be missing between the potential impacts for Sweden and international diplomatic initiatives. It can be argued that there still is a need for more detailed analysis of geopolitical impacts and the measures to address them from a national point of view.

Table 3. Policy framework for geopolitical environmental security impacts in Finland and Sweden.

	Impacts Recognised in Assessments	Impacts Recognised in Policies/Strategies	Policy Measures Adopted
Finland	Economic production, energy, transport, migration, health, biodiversity, development cooperation	Sustainable development, migration, the Arctic region, security of supply	Potential for inclusion in security of supply policy (domestic); partially included in peace-building (international)
Sweden	Migration, livelihoods, food security, transport, energy	Global risks of conflict, poverty, lack of food or water, migration	Engagement at UN Security Council, Climate Security Hub, Proposal for an institutional home for climate security at the UN

4.3. Policies for Structural Environmental Security Impacts in Finland and Sweden

Our analysis in another article shows that the structural impacts of environmental change is the category that has been recognised the least in Finnish and Swedish research and risk assessments [16]. The mitigation and adaptation to climate change appear to generally not be considered as the kind of policy imperatives that would have consequences of their own. Both countries do mention that the restructuring of the energy sector will have some influence on their security and foreign policy. However, they both appear to emphasise potential positive impacts—Finland in terms of increasing energy independence and Sweden with regard to opportunities for renewable energy production.

Finnish security strategy documents only mention mitigation as a way to prevent the worst consequences of climate change and adaptation as a necessity to diminish its impacts. They do not go further into discussing the scope of the measures that are needed or their potential impacts on society [34]. Meanwhile, the Finnish security of supply scenarios do factor in consequences of both strict and negligent climate mitigation policies and show how these may contribute to different outcomes [45]. The analysis does not go very deep into detail or take into account a particularly wide range of factors, but it indicates a recognition of the dynamics of environmental security impacts.

In practice, however, the appearance of climate policy in the scenarios has limited relevance. The issue is not reflected in any way in the Government decision on security of supply, which has been updated after the publication of the scenarios [46]. Likewise, it has not been picked up in the most recent National Risk Assessment. The document does point out that climate policies create insecurity on finance markets, causing new risks on holdings like oil reserves and real estate [37]. However, the strictly economic focus ends up neglecting the full scale of societal and geopolitical impacts that climate policy may have.

Similarly to the case in Finland, Swedish security strategies make no mention of security impacts of mitigation or adaptation [40]. In addition, Sweden has so far not explicitly integrated the impacts of adaptation impacts into its international climate security policies [38,48]. To some extent, this is consistent with the Swedish agenda, which prioritises efforts to address geopolitical effects like livelihoods, migration and conflict in the global context of international organisations. This focus may have outweighed a more domestically oriented perspective, where the impacts of climate mitigation and adaptation to Sweden might have been more apparent. However, it is also symptomatic of the way in which the international discussion on environmental security continues to largely overlook the structural impacts.

Beyond the energy sector, structural environmental security impacts are not even mentioned. The impacts of mitigation and adaptation policies on food or water security or natural resource use are not included as issues of security and foreign policy. Importantly, however, this is not to claim that Finland or Sweden would not have considered food, agriculture, water and other issues in their climate adaptation policies. Our argument is that the links are not made explicit between these issues and security policy, thereby neglecting their potential influence on it.

The policy framework of structural environmental security impacts in Finland and Sweden is depicted in Table 4. It shows that the entire category of impacts still primarily remains outside policy-making. This can, to a great extent, be explained by the lack of recognition and knowledge of the structural dynamics even at the level of research and assessment.

Table 4. Policy framework for structural environmental security impacts in Finland and Sweden.

	Impacts Recognised in Assessments	Impacts Recognised in Policies/Strategies	Policy Measures Adopted
Finland	Energy security	Climate change mitigation and adaptation	None
Sweden	Energy security	Climate change mitigation and adaptation	None

With fairly ambitious environmental policies overall and a relatively low vulnerability to local impacts, Finland and Sweden would seem to have both an interest and the resources for identifying other kinds of environmental impacts. The lack of policies for structural impacts in these countries can therefore be seen as indicative of a wider shortcoming in policy-making in global terms. An international-level discussion about the consequences of effective climate policy is yet to be had. At least so far, it does not seem as if either Finland or Sweden were likely to initiate it.

5. Discussion

Our analysis shows that the policy framework on environmental security in both Finland and Sweden remains fragmentary. In particular, there is no evidence of a comprehensive approach that would allow the recognition of environmental security impacts on multiple sectors and levels. As Table 5 suggests, both countries have some policies in place while others are entirely missing. However, there also are significant differences between their approaches.

Table 5. Policy framework for environmental security in Finland and Sweden.

	Policy Framework in Place		
	Local	*Geopolitical*	*Structural*
Finland	Extensive	Weak	None
Sweden	Extensive	Average	None

Both Finland and Sweden have an extensive set of policies and tools for countering local environmental security impacts. This is consistent with the findings of our companion article [16], which shows that several assessments have been carried out that give a fairly comprehensive background knowledge of the local impacts. However, our analysis in this article shows that there are still problems in the implementation of the policies, as this is often left to individual actors without additional resources.

The biggest differences between the countries are revealed with regard to geopolitical impacts. Sweden has an ambitious international policy especially on climate security and has gained a position as one of the leading countries maintaining the topic at the UN Security Council. However, the entirely international perspective may end up underestimating potential geopolitical impacts on Sweden itself. Finland, on the other hand, has not taken an active role in the international environmental security discussion. Its security of supply policy would provide a convenient model for integrating environmental issues into a national security policy, but so far this opportunity has only been used to a very limited extent.

Both Finland and Sweden are on equally uncharted territory when it comes to policies for structural impacts. This is by no means exceptional in global terms, as the ramifications of decarbonisation are only starting to be understood even in research. The Finnish and Swedish cases suggest that in practice, the recognition of the structural impacts of climate policy is virtually non-existent.

However, structural impacts are becoming increasingly essential to address also in policy as climate change advances and the actions to mitigate it will need to expand. For instance, the planned ban on coal in energy use by 2029 in Finland, would initiate a structural change in the energy sector, both in terms of electricity and heat provisioning. The National Emergency Supply Agency as well as several energy producers have in their official statements on the proposed legislation pointed out that the change would have effects on security of supply that should be better taken into account in the legislation [54]. The structural perspective to environmental security thus emphasises the role of climate policy as a fundamental part of both global and domestic policy-making. It also helps to point out that the changes following from this shift will be of such a scale that they will also influence security and geopolitics.

The issue of structural impacts is also connected to the lack of a comprehensive approach to environmental security. The analysis shows that both Finland and Sweden treat different kinds of environmental security impacts separately and with policies that are detached from one another. Although it is clear that local and geopolitical impacts, for instance, require different responses, they still share the similar underlying root causes that are linked to environmental change. It is necessary to perceive the range of different but interconnected impacts in order to understand the extent of their potential consequences on the society and to come up with policies that can adequately address them.

6. Conclusions

In our analysis, we have shown that there are considerable gaps in the capacities of Finnish and Swedish security and foreign policies to address environmental security impacts. This particularly concerns geopolitical and structural impacts. We further argue that a comprehensive policy approach on environmental security is necessary to thoroughly take into account the kind of complex and multi-sectoral impacts that may result from environmental change.

On the basis of these observations, we make the following recommendations for policy-making.

- **Further inter-disciplinary research is needed on the geopolitical and structural environmental security impacts.** The current level of knowledge is inadequate to guide well-grounded policy-making. In addition to the kind of country-specific assessments already carried out in Finland and Sweden, there is still a need for basic research to develop methodologies to understand the security consequences of global power relations and resource flows or of adaptation and mitigation. Inter-disciplinarity, also between natural and social sciences, should be encouraged in order to consider the geopolitical and structural impacts of different IPCC scenarios, for instance.
- **Coordination and exchange of information between researchers and policy-makers on environmental security issues**. Our analysis has shown that in the case of all environmental security impacts, policy implementation often remains inadequate. A closer interchange between researchers and policy-makers or practitioners can help to raise awareness on the potential consequences and the need for effective policy responses. For researchers, on the other hand, it gives access to invaluable information and insight from the practitioners.
- **Integration of environmental change and its mitigation into risk assessments and scenario-building on various sectors**. It is becoming increasingly clear that both environmental changes and actions to mitigate and adapt to them will be significant. Therefore, any risk assessments or future scenario work has to reflect this and take them into account as factors. This also concerns sectors like foreign policy and security that are not traditionally considered to be linked to the environment.
- **Establishment of a comprehensive environmental security approach through a strategy or action plan**. Due to the multi-sectoral character of environmental security impacts as well as the relative novelty of the concept itself, it is necessary to spell out its implications to the various

actors involved. A strategy or action plan will be useful here as a point of reference to direct and coordinate work across sectors.

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A Framework for Assessing Water Security and the Water–Energy–Food Nexus—The Case of Finland

Mika Marttunen [1,*], Jyri Mustajoki [1], Suvi Sojamo [2], Lauri Ahopelto [1,2] and Marko Keskinen [2]

1 Finnish Environment Institute, Latokartanonkaari 11, FI-00790 Helsinki, Finland; jyri.mustajoki@ymparisto.fi (J.M.); lauri.ahopelto@aalto.fi (L.A.)

2 Water & Development Research Group, Department of Built Environment, Aalto University, Tietotie 1E, FI-00076 Aalto, Finland; suvi.sojamo@aalto.fi (S.S.); marko.keskinen@aalto.fi (M.K.)

* Correspondence: mika.marttunen@ymparisto.fi, Tel.: +358-295-251411

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Abstract: Water security demands guaranteeing economic, social and environmental sustainability and simultaneously addressing the diversity of risks and threats related to water. Various frameworks have been suggested to support water security assessment. They are typically based on indexes enabling national comparisons; these may, however, oversimplify complex and often contested water issues. We developed a structured and systemic way to assess water security and its future trends via a participatory process. The framework establishes a criteria hierarchy for water security, consisting of four main themes: the state of the water environment; human health and well-being; the sustainability of livelihoods; and the stability, functions and responsibility of society. The framework further enables the analysis of relationships between the water security criteria as well as between water, energy and food security. The framework was applied to a national water security assessment of Finland in 2018 and 2030. Our experience indicates that using the framework collaboratively with stakeholders provides a meaningful way to improve understanding and to facilitate discussion about the state of water security and the actions needed for its improvement.

Keywords: water security; water, energy and food nexus; indexes; assessment framework; qualitative assessment

1. Introduction

Water security is described as the overall aim for water resources management by a growing number of actors and organisations [1–4]. However, it does not have one all-encompassing definition and its meaning has varied in different contexts and over time. While water security was mostly used to describe specific human security concerns or to set general visions in the 1990s to early 2000s [5], more recently it has been increasingly used to make explicit the actual goals to be achieved with better water resources management [6]. Those goals can be contested and are open to debate between different stakeholders, but water security as a concept has provided a frame for their negotiation [7,8]. Furthermore, it has provided the means to link water to other sectors and their "securities," most importantly to energy security and food security under the concept of the water–energy–food security nexus [9–12].

Today, water security is most commonly understood through four key dimensions, as presented by Hoekstra et al. [6]: economic welfare, social equity, long-term sustainability and water-related risks. Water security thus aims simultaneously to guarantee the three pillars of sustainability (economic, social and environmental) and to address the diversity of risks and threats related to water. This "dual aim" is also recognised by UN-Water, who define water security as "the capacity of a population to safeguard sustainable access to adequate quantities and of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" [3]. Ultimately, water security is thus also linked to the broader foundations of societal security.

Several frameworks have been suggested to support water security assessments and policy making at different levels from local watersheds to national and global scales (e.g., [13–15]). On the one hand, they share similarities with comprehensive nexus [16–18] and water governance assessments (e.g., [19,20]). On the other hand, they build on more quantitative risk and resilience assessment methodologies that utilise water availability, vulnerability and sustainability indexes [7,21,22]. The latter enable illustrative comparisons and trend analyses with comparatively little effort but have been criticised for simplifying complex and often contested water issues and neglecting their social and political aspects (e.g., [7,22–24]). Accordingly, water security as a concept can be both broadened and deepened and its practical applicability improved by combining quantitative and qualitative assessments, considering water security through various alternative aspects and dimensions and engaging different actors and stakeholders, i.e., the end-users in the assessment processes themselves [25–27].

This study builds on these recent recommendations and presents a new assessment framework. The framework is tested in a national water security assessment of Finland. We cover two crucial dimensions to water security that to our knowledge have not been addressed to date. First, even though the importance of considering the linkages between water uses, freshwater ecosystems as well as other sectors is increasingly emphasised (e.g., [9,10,24]), there are currently no studies that assess the internal linkages between the different water security criteria as well as the relations between water, energy and food security. Second, there appears to be no studies combining the systematic assessment of the current and future state of water security taking into account local and global development trends and trajectories.

Existing water security assessment frameworks and indexes have typically focused on such national-level assessments that enable the comparison of water security between different countries and identify issues that require development (e.g., [28,29]). However, the central issues of water security can vary substantially between countries. For example, from policy-making and management perspectives, the common water availability and access indexes and indicators are typically more useful in developing regions that suffer from water scarcity than in water-rich and highly-developed countries. In Finland, a high-quality water infrastructure has been built in recent decades, but its condition is degrading [30]. Therefore, commonly used indicators that measure the coverage of water infrastructure are less useful than an indicator that measures the repair debt of water infrastructure. Thus, our framework aims to capture national and context-specific characteristics.

Water security in Finland is regarded to be at a very high level and Finland is ranked among the top countries in various water security assessments (see, e.g., the water poverty index, [31]; global water security index (GWSI) [28]). In addition, the characteristics of nature and water systems in Finland differ from many other countries. Therefore, urgent management actions can also be very different from other countries. Although the framework is customised to Finnish conditions, it can be modified to be applicable in other countries or regions as well. In addition, the ideas on how to present and visualise the results can be adopted in various types of indicator frameworks.

The paper is structured as follows. In Section 2, we review the existing water security frameworks and indicators and the challenges in their use. Section 3 presents our water security assessment framework and Section 4 the findings from its application in the Finnish water security field. In Section 5, we discuss the strengths, challenges and future development needs related to the application of the framework. Section 6 concludes the paper.

2. Water Security Frameworks, Indicators and Challenges

A large number of frameworks and indexes have been developed to assess the sustainability of water management from local to global scale (see the reviews of 95 indicators by Vollmer et al. [21] and 170 indicators by Pires et al. [22]). These indexes enable within-basin comparisons over time or via scenarios and comparisons across basins or countries. Examples of global frameworks are human water security threat maps [32] and global water security indexes [28]. Frameworks that have national or state-wide scope encompass analyses of water security in China [33,34] and Alaska [35]. Vollmer et al. [21,24] developed a freshwater health index and applied it in one Asian river basin, whereas Jensen and Wu [36] developed urban water security indicators (UWSI) and piloted them in Hong Kong and Singapore. In addition to studies with different spatial scales, there are studies that focus on a specific sector, such as agricultural water use [37]. In the majority of earlier water security and sustainability assessments, the target area was located in Africa and Asia, and over the last few years studies have particularly focused on China (e.g., [24,34,36,38]).

The dimensions in the developed frameworks and indexes vary enormously. Chaves and Alipaz [39] proposed the watershed sustainability index (WSI) that incorporates hydrology, environment, life, and policy; each having the parameters of pressure, state, and response. Gain et al. [28] go beyond earlier water scarcity analyses, and use spatial multi-criteria analysis to assess water security in terms of availability, accessibility to services, safety and quality, and management. Sun et al. [33] divide factors affecting sustainable water use into five sub-categories and their key variables: economy, population, water supply and demand (different sub-variables for water supply and demand), land resources, and water pollution and management (quantity of wastewater effluent, sewage treatment capacity, treatment rate of sewage).

Frameworks, indices and indicators can play an important role in various tasks. They can, for example:

- be used as diagnosing tools to identify threats to water security (e.g., [32]),
- be used as management tools giving direction to managerial policy, the allocation of resources and to measure the effectiveness of interventions [31,36,40]
- stimulate policy actions [36],
- improve opportunities for making judgements about the effectiveness of government policy [31]
- provide decision support for better formulation of regional water resources planning [34],
- be powerful tools for stakeholder engagement and communication, and allow policy-makers to communicate policy achievements to the public [36], and
- be important tools for the operationalisation of integrated water resources management [24] and sustainable development goals [41,42].

Despite the fact that many useful indicators and indexes have been developed to assess the sustainability of water management, their use in policy-making is not common [43,44]. There are many challenges in the operationalisation of indicators and indexes that can explain their limited use. Methodological challenges relate to the selection, banding and aggregation of indicators, and consideration of stakeholder participation [38]. The large range of contexts have led to numerous indicators and indexes, which makes the selection of those that are relevant, analytically sound, and measurable difficult [45,46]. Damkjaer and Taylor [47] state that, due to their simplicity, indicators are not meaningful for practical purposes; for instance, intra- and inter-annual variations are typically not considered when measuring water scarcity. Operationalisation can be complicated due to the vague and contested content of the concepts or the overly broad scope (geographical or content) of the analysis [36].

The water, energy and food security nexus (WEF nexus) provides a complementary approach to water security and its linkages to energy and food (e.g., [9–11,48]). The nexus approach can be considered both an analytical framework and a governance approach, with the latter promoting policy coherence and collaboration between different sectors [11]. When used as an analytical framework, the nexus aims to identify synergies and trade-offs within the subsystems that constitute the overall water–energy–food security nexus system (e.g., [10,49–51]). Many literature reviews have been realised during the last few years covering concepts and methodologies related to the WEF nexus (e.g., [11,51–55]). It is interesting to note that according to these reviews, the use of WEF nexus methods to systematically evaluate water, energy and food interlinkages has been limited [53], and an empirical WEF nexus research has not yet validated claims that nexus approaches can improve resource management and governance outcomes [54].

3. Assessment Framework

The process of applying our proposed framework is presented in Figure 1. The first phase (framing) includes the identification of the problem and its elements (step 1 in Figure 1), and defining the assessment criteria and structuring them into a hierarchical form (step 3). This phase also includes the identification of the stakeholders (step 2) whose involvement in the development process is considered important, and the determination of end-users of the information produced by the assessment. The second phase is the actual assessment, where each criterion is assessed in terms of various dimensions (steps 4–7). In the last phase, analysis, the status of the water security is obtained on the basis of the overall view of the assessment (step 8) and future conclusions are made (step 9).

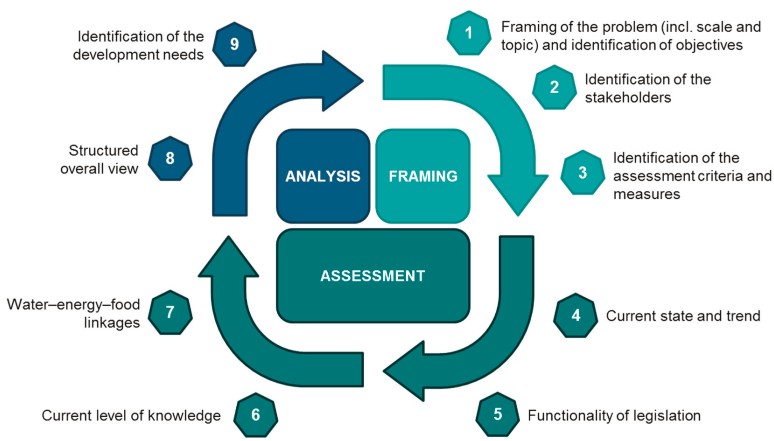

Figure 1. The steps of the water security assessment process.

Development of the framework was a combination of extensive research by the authors and other researchers in the Winland research project (2016–2019), looking at future energy, food and water security in Finland, and consultation and co-creation with key stakeholders. The research included, for example, analysis of strategy documents from different ministries (Ministry of Environment, Ministry of Agriculture and Forestry, Ministry of Foreign Affairs), a literature review of 32 international papers dealing with indicators, frameworks, metrics and indexes for measuring water security and sustainable water use, and the identification of 25 drivers that may affect water security of Finland (12 of them were selected for the analysis).

The research findings were discussed with stakeholders at regular intervals in workshops and interviews. Altogether four stakeholder workshops were organised, of which the first two dealt with identification of drivers and assessment criteria for water security and development of a criteria hierarchy for water security (explained in Section 3.1). The hierarchy was further developed in the third workshop, before which the participants, who came from ministries, research institutes and national security organisations, were also able to comment on the content and structure of the hierarchy in a web survey (e.g., whether there is a need to add or remove criteria or to change their names). The hierarchy was modified on the basis of the comments received. In order to get feedback from the potential end-users on the assessment framework and its application opportunities, we carried out six high-level interviews: four directors from the Finnish Environment Institute (SYKE) and two officials with lengthy experience in national and international water management tasks from ministries. After the interviews, a fourth workshop focusing on the actual assessment of Finnish water security was arranged, and the participants were still able to comment on the hierarchy in the workshop after which the framework was finalised.

We also developed an Excel tool to support the operationalisation of the framework. The tool consists of different sheets, including a sheet for defining the criteria structure and separate sheets for each of the assessment dimensions. In addition, there is another separate sheet for summarising the results, and various others for visualising the results of the analysis, for example, with the possibility to create an individual assessment card for each criterion (see Appendix A, Figure A1).

3.1. The Criteria Hierarchy for the Assessment

Water security is a broad concept covering all water-related sectors, and taking all the different issues into account separately would make the analysis too complex. Our main aim in the development of the criteria hierarchy was to find a balance between the comprehensiveness and practicality of the analysis. Therefore, we decided to use an approach where most criteria were defined so that they consisted of several issues. For instance, sustainable use of natural resources includes mining, forestry, fishery and peat extraction. The development process was iterative, and modifications to the hierarchy were made after the workshops and the interviews. Additions to the hierarchy typically also required some restructuring or rewording of the existing criteria.

As water security has differing meanings for different actors, it is critically important to agree on its key criteria at first. The final criteria hierarchy used in this study consists of 18 criteria classified under four main criteria: 1) State of the water environment; 2) Human health and well-being; 3) Sustainability of livelihoods; and 4) Stability, functions and responsibility of society (Figure 2, see descriptions of the criteria in Table A1, Appendix B). The assessment was demarcated to cover the Finnish water security field.

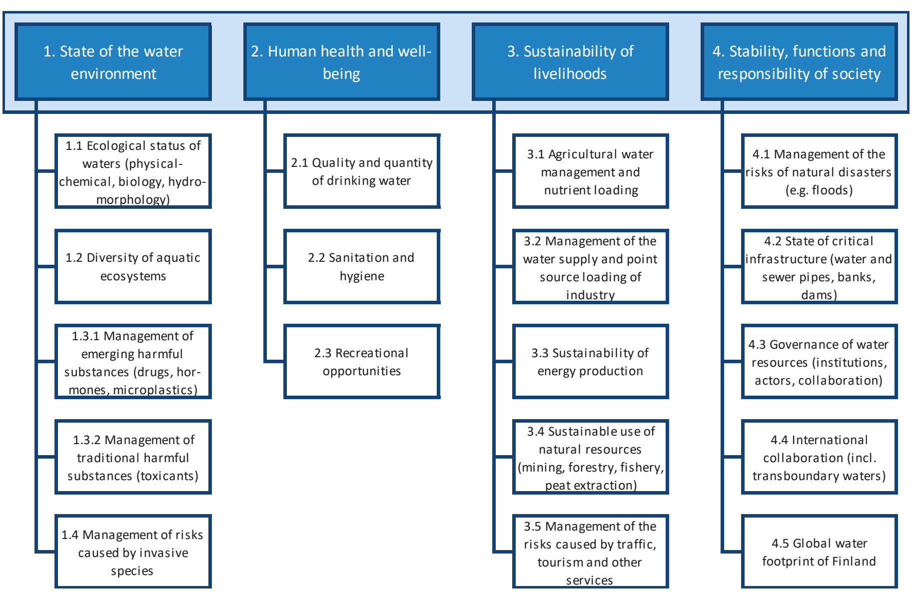

Figure 2. The criteria hierarchy used in the water security framework.

As mentioned, the hierarchy evolved somewhat during the process. For example, at first the framing seemed to be unambiguous, but there were still lively discussions on how to deal with the impacts related to global water security. The harmful substances were initially considered as one criterion, but this was divided into two parts as its assessment as one entity was difficult; traditional harmful substances (e.g., heavy metals) are a decreasing environmental problem in Finland, whereas new harmful substances (e.g., drugs, hormones, microplastics) are an emerging problem. At first the management of the environmental risks of traffic (e.g., oil and chemical accidents in roads, railways and waterways) was only implicitly considered under the other criteria, but it was finally included as an explicit element of the framework, also including tourism and other services.

3.2. Assessment Dimensions

The aim of the assessment is to identify the issues that are currently managed (reasonably) well, as well as the issues that have to be improved to achieve good status or to prevent the deterioration of their current status in the near future. Thus, we did not calculate an aggregated assessment index for overall water security like Gain et al. [28], but instead assessed each water security criterion separately.

The process of setting suitable dimensions for assessing each criterion was also iterative, in a similar way to the development of the criteria hierarchy. The challenge here was also to get a set of meaningful and relevant assessment dimensions that are able to capture central aspects related to water security. The current state of the criterion and its future trend were selected as natural starting points for the assessment. The current level of knowledge and functionality of legislation (i.e., how up-to-date the legislation is and how flexible it is to changing circumstances) were included in the set of assessment dimensions, as a lack of knowledge and outdated legislation are both clear signals that further actions are needed. The linkages between the criteria as well as the linkages to energy and food security were also included, as one of our objectives was to improve the understanding of the complex relationships between the water, energy and food security nexus.

Figure 3 provides a summary of the assessment dimensions and outcomes of the assessment. The dimensions and especially their assessment scales are partly case-dependent; therefore, they are explained in more detail in Section 4 along with the Finnish water security case.

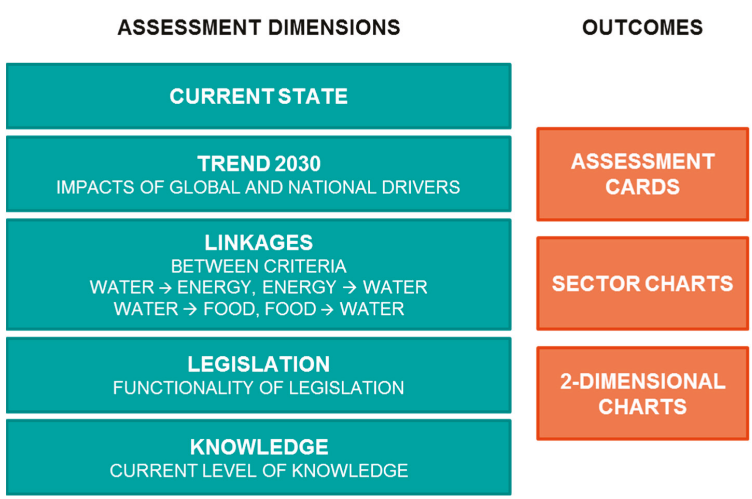

Figure 3. Summary of the assessment dimensions and outcomes of the assessment.

The assessment was based on expert judgments informed by various indicators and research reports. We did not, however, create any numerical scales for the indicators to describe their current state. Instead, we used a five-point generic Likert scale complemented with qualitative description for the assessment. The reason for this was that we wanted to make explicit the justification for the state estimates of each criterion. For this purpose, single indicators would have narrowed the analysis too much (e.g., [47]). Furthermore, the use of numerical scales would also have required an expert assessment of its endpoints, and their choice would also have been partly subjective.

3.3. Presenting the Results

A visual, illustrative presentation of the results is one of the key factors when discussing the assessment results with stakeholders and decision-makers, and it was therefore one of the main reasons for developing the Excel tool for the assessment. Appendix A provides examples of various visualisations in the Excel tool. For the overall comparison of different criteria, the tool provides a summary table, which includes results from all assessments in a plus/minus form. The matrix is also coloured according to the assessment scales, which makes it easy to see which criteria perform the best and which are the worst in each of the dimensions. The tool presents matrix information as a collection of sector graphs for each criterion. This kind of visualisation makes it easier to grasp the overall performance of each criterion at a glance, as all the assessments of each criterion are collected in a compact circle instead of showing them as a single line in the matrix.

For analysing a single criterion in a more detailed way, the tool automatically creates an assessment card (i.e., a score card) for each criterion (Appendix A, Figure A1). In that card, all the information regarding a single criterion is offered in a structured form. The card also includes qualitative descriptions of the assessments, which are omitted from the summary tables. At the end of the card, there is a summary of the information and the sector presentation of the assessment values.

4. Assessing Finnish Water Security with the Framework

4.1. Application Process

Utilising the available indicator data (see Appendix B, Table A2), related assessments and data collected in the first three workshops, preliminary estimates for the criteria on the various assessment dimensions were first made by the authors. These estimates were then presented to experts from different sectors. For instance, estimates of the natural disaster management were commented on by a person who works on flood risk management issues. The preliminary estimates were discussed in four interviews with water management experts at SYKE and two in the associated ministries (see also Section 3).

4.2. Assessment of the Current State and Trend, Level of Knowledge and Functionality of Legislation

The results regarding the state, legislation and knowledge of water security criteria are presented in Table 1. Besides the estimates presented in Table 1, the qualitative explanation behind each estimate was included to elaborate on the reasoning behind the estimate. Our analysis highlighted that there are several water security issues in Finland that need more attention. For example, the loading of nutrients and solid substances from agriculture and the use of natural resources (forestry, peat extraction) are currently at quite high levels, and actions are needed to improve the situation, especially if the targets of the EU Water Framework Directive (WFD) [56] are to be reached. The quality of the drinking water is currently very good, but the constantly increasing repair debt of the water infrastructure is expected to have a negative effect on the situation in the future (e.g., [30]). There are also various harmful substances (drugs, hormones, microplastics) that are an emerging problem (e.g., [57]). In addition, there is not much knowledge about their impact chains and long-term effects, and therefore this is a topic that needs further research.

Table 1. Assessment of the criteria for Finnish water security.

Water Security Assessment	State: Current State	State: Trend 2030 (State Change)	Legislation Functiona- Lity of Legislation	Knowledge State of Knowledge
1. State of the water environment				
1.1 Ecological status of water (physical-chemical, biology, hydro-morphology)	-	-	-	-
1.2 Diversity of aquatic ecosystems	- -	-	-	+
1.3.1 Management of emerging harmful substances (drugs, hormones, microplastics)	- -	-	-	- -
1.3.2 Management of traditional harmful substances (toxicants)	-	-	o	+
1.4 Management of risks caused by invasive species	-	-	-	-
2. Human health and well-being				
2.1 Quality and quantity of drinking water	+	- -	o	o
2.2 Sanitation and hygiene	+	-	o	o
2.3 Recreational opportunities	+	-	o	-
3. Sustainability of livelihoods				
3.1 Agricultural water management and nutrient loading	- -	-	-	-
3.2 Management of the water supply and point source loading of industry	-	-	-	+
3.3 Sustainability of energy production	-	o	-	o
3.4 Sustainable use of natural resources (mining, forestry, fishery, peat extraction)	- -	-	-	+
3.5 Management of the risks caused by traffic, tourism and other services	o	-	+	-
4. Stability, functions and responsibility of society				
4.1 Management of the risks of natural disasters (e.g., floods)	o	-	o	o
4.2 State of the critical infrastructure (water and sewer pipes, banks, dams)	o	-	-	-
4.3 Governance of water resources (institutions, actors, collaboration)	o	-	o	o
4.4 International collaboration (including transboundary waters)	+	+	o	o
4.5 Global water footprint of Finland	-	+	o	o
Scales for the assessment dimensions				
Current state				
+ +	Current state excellent or exceeds the target level			
+	Current state predominantly good or at the target level			
o	Current state is ok or close to the target level			
-	Current state is satisfactory or worse than the target level			
- -	Current state is weak or considerably below the target level			
Trend 2030 (State change)				
+ +	State is expected to improve significantly by 2030			
+	State is expected to improve somewhat by 2030			
o	State is expected to remain same as now in 2030			
-	State is expected to weaken somewhat by 2030			
- -	State is expected to weaken significantly by 2030			
Functionality of legislation				
+ +	Legislation works well, is flexible and makes it possible to make justified decisions also in changing conditions			
+	Legislation works well in current conditions			
o	Legislation works quite well, but needs some updating			
-	Legislation is partly outdated and needs updating			
- -	Legislation is outdated and greatly needs updating			
State of knowledge				
+ +	The level of understanding is very good, enabling the choice and implementation of the cost-effective measures			
+	The level of understanding is good, and there is little need for additional research			
o	The level of understanding is moderate, but new research can help to identify cost-efficient measures			
-	The level of understanding is quite poor and more research is needed to understand the system and find cost-effective measures			
- -	The level of understanding is poor and much more research is needed to understand the system and find cost-effective measures			

In the assessment of the current state, the main challenge was to decide on the good or acceptable state (baseline) of each criterion. With some criteria, generally approved goals or measures exist that were used in the assessment. For example, the WFD provides a classification system according to which the ecological state of the water can be assessed. To support the assessment, we collected a list of existing indicators related to each criterion (Appendix B, Table A2). However, with most of the criteria, the assessment had to be made qualitatively as an expert judgement. The assessment of the current state was made using the five-point Likert scale, with a range from "*Current state is weak or considerably* *below the target level*" to "*Current state is excellent or exceeds the target level*". With regard to some criteria, a precise target level exists. For the ecological status of water, the target level is good ecological status according to the Water Framework Directive. For some other criteria (e.g., sustainability of energy production), target levels were more vague and the assessment was based on experts' views about the prevailing situation compared to an ideal situation. The baseline level of the assessment is "*The state is OK or close to the target level*".

It was decided that the time span for the trend analysis should run until 2030. While this is the target year for UN SDGs, it is only a tentative date, which is far enough in the future so that the trends that can be observed today might have more prominent impacts (positive or negative) on the state of the criteria. However, one should note that the trend up to 2030 is just an estimate and should not be considered literally as a representation of the future. For the systematic assessment of the trends, we created a list of global and national drivers that have previously been identified that will potentially affect water security in the near future. The global drivers included in the framework were:

- Climate change
- Population growth
- Globalisation (transfer of people and goods)
- Digitalisation
- Development of science and technology
- Increase in the use of harmful substances and chemicals

Similarly, the nationally important drivers or trends included into the framework were:

- Urbanisation
- Ageing of population
- Low investment rate to the renewal of water infrastructure
- Deterioration of the drainage systems of agricultural fields
- Intensification and centralisation of agriculture
- Diminishing water expertise in environmental administration

Each driver's impact on each criterion was assessed using a five-point scale ranging from "*Significant negative impact*" to "*Significant positive impact*" (i.e., a noticeably or measurably large amount). After the driver/trend-specific assessment, the overall impact of the different types of drivers on each criterion was assessed holistically using a five-point scale ranging from "*State is expected to weaken significantly by 2030*" to "*State is expected to improve significantly by 2030*".

Five-point scales were used for current level of knowledge and functionality of legislation. In terms of the level of knowledge, the scale was based on how much knowledge there is for making informed decisions regarding the necessary measures, and how much further research is needed. The end points of the scale are "*The level of understanding is poor and much more research is needed to understand the system and to find cost-effective measures*" and "*The level of understanding is very good, enabling the choice and implementation of the cost-effective measures*". For the assessment of the functionality of legislation, the focus was on how up-to-date the existing legislation is, and whether there is a need to renew it. The end points of the scale are "*Legislation is outdated and there is a great need to update it*" and "*Legislation works well, is flexible and makes it possible to make justified decisions in changing conditions*".

The tool provides the possibility to create two-dimensional tables, in which the performances of the criteria can be classified simultaneously according to any two assessment dimensions. One can, for example, set the current state to the x-axis and the trend to the y-axis (Figure 4). Then, the most critical criteria requiring urgent actions are those in the lower-left corner, where the current state is poor ("*Current state is poor or considerably worse than the target level*") and the trend is alarming ("*State is expected to weaken significantly by 2030*"). Those criteria where the current state is good but the trend is alarming (lower-right corner) might require special attention, as the good current state may give a false feeling of satisfaction that things will be OK in the future, even if this is not necessarily the case.

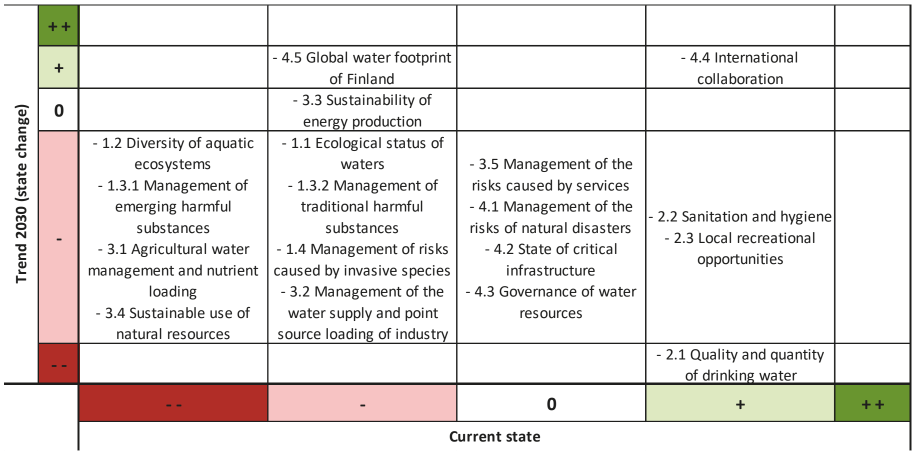

Figure 4. A two-dimensional chart for identifying the criteria that need the most attention. Note that the width and height of each column is adapted to the amount of text.

4.3. Linkages between the Water Security Criteria

To support the identification of the linkages between the water security criteria, the Excel tool provides a cross tabulation matrix of them (Figure 5). The aim is to point out that the systemic nature of water security also requires the analysis of interrelationships between the criteria. In practice, the impact can either be positive or negative. A positive relationship means that the positive movement of a criterion in a row leads to a positive movement of a criterion in a column, and, correspondingly, a negative movement in a row leads to a negative movement in a column. In a negative relationship, the impacts are the other way around. For example, improvement in the ecological status of water improves the diversity of aquatic ecosystems as the living conditions for salmonids that prefer oligotrophic conditions improve.

When considering the internal linkages between the criteria, ecological status, diversity of aquatic ecosystems, quality and quantity of drinking water and recreational opportunities are the criteria that are most affected by the other criteria. The governance of water resources has the widest range of positive relationships as it affects all other water security criteria. International collaboration, such as within the EU, can also affect water security in several ways: (i) it can lead to new directives to protect water or limit emissions, (ii) it can lead to joint projects that aim to improve the status of water (e.g., the Baltic Sea), and (iii) research funding from the EU plays an important role in many restoration and rehabilitation projects. The possible deterioration of ecological status may either restrict human activities and industry or cause stricter emission permits. Flood risk management includes measures such as dredging, building flood banks and regulating lakes and rivers, which can have negative environmental impacts.

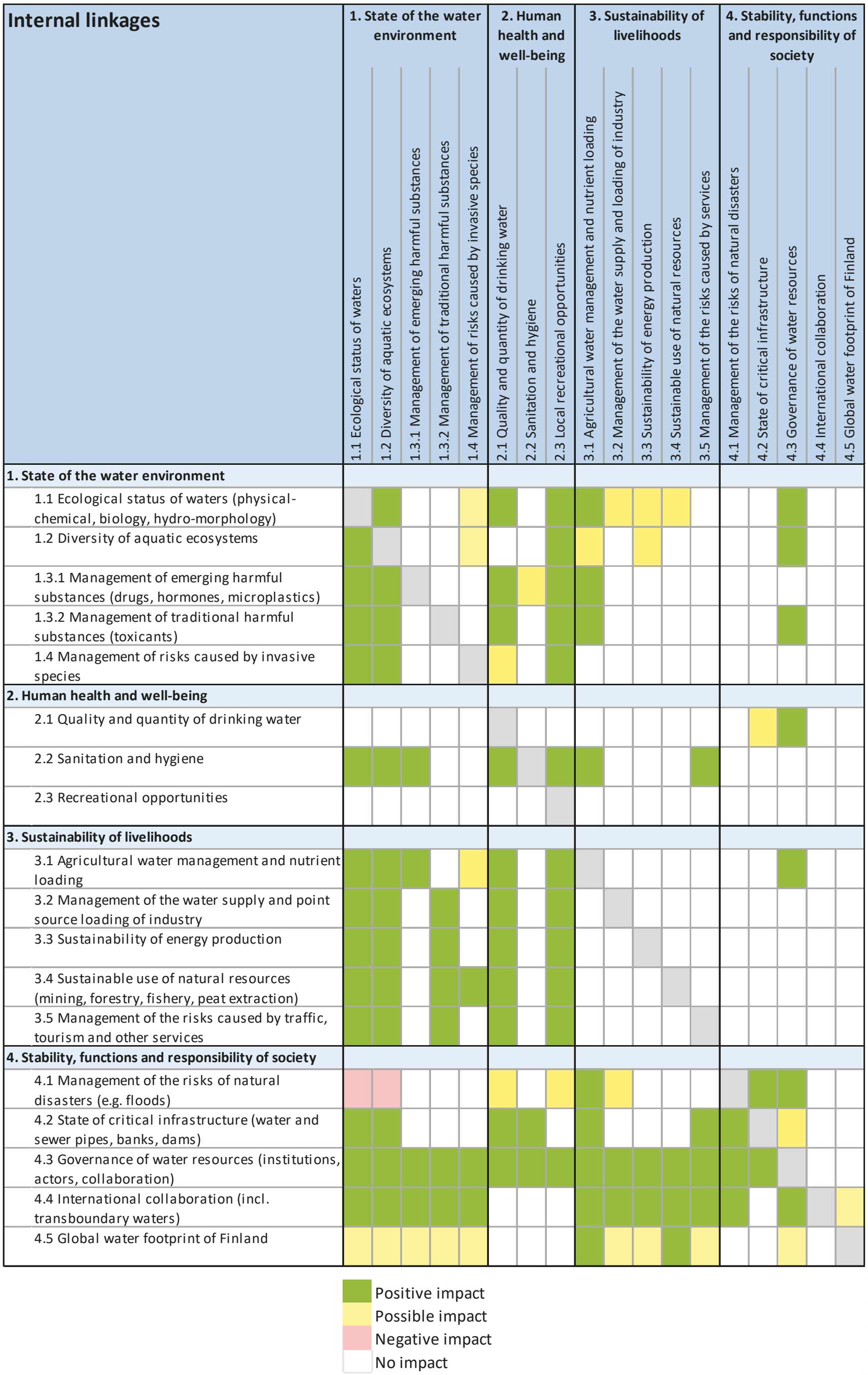

Figure 5. Internal linkages between the 18 assessment criteria.

4.4. Linkages between Water Security Criteria and Food and Energy Security

The assessment of linkages in the water–energy–food security nexus was bi-directional so that for each water security criterion, we identified whether it has an impact on food/energy security, and also whether food/energy security has an impact on this particular water security criterion. In practice, the impact can either be positive or negative, but we did not take a stance on the direction of the linkage. The reason was that in many cases there can be linkages in both directions, as energy and food security are such broad areas. For example, an improved state of water can improve food security through improved water quality, but on the other hand this can also reduce food security through actions that are required for farming to improve water quality. In our case, it was most important to identify that this link exists, but its direction was not that important, as both directions increase the significance of the criterion. Thus, in the assessment of linkages, we applied scale "*No or weak linkage*", "*Positive or negative linkage*", or "*Significant positive or negative linkage*".

It is noteworthy that we analysed the linkages between each water security criterion and energy security and food security systematically. For example, for energy security, all types of energy sources were covered (e.g., hydro power, nuclear power, wind power, coal, natural gas, peat), which, of course, complicated the assessment as there were several issues that had to be borne in mind simultaneously, and because the linkages to different energy sources are not identical. In terms of the linkages between food/energy security and the rather specific criteria of water security in particular, it was sometimes hard to concretise the actual impact, which further supported the use of a non-directional scale. Therefore, we instructed experts to narrow down the perspective and, for example, with regard to the energy-water nexus, consider only the amount of energy production instead of energy security in general, which is a broad concept.

The linkages between water and energy security (Table 2) stem mainly from the conflict of interest between hydropower production and the ecological criteria in harnessed and regulated watercourses. On the other hand, the watercourse regulation developed for hydropower production can play an important role, for example, in flood prevention. However, all these issues have been under debate in Finland for several decades and therefore have a central role in the governance of water resources. In terms of the linkages between water and food security, the obvious ones are those between farming and the status of the water (ecological status and biodiversity). This link can be noted both in the livelihood criterion and the environmental criterion. This issue is also related to the governance of water resources.

Table 2. Linkages between water and food/energy security.

Water Security Assessment	Linkages with Energy		Linkages with Food	
	Water→ Energy	Energy→ Water	Water→ Food	Food→ Water
1. State of the water environment				
1.1 Ecological status of water (physical-chemical, biology, hydro-morphology)	* *	* *	*	* *
1.2 Diversity of aquatic ecosystems	* *	* *	o	* *
1.3.1 Management of emerging harmful substances (drugs, hormones, microplastics)	o	o	*	*
1.3.2 Management of traditional harmful substances (toxicants)	o	*	*	*
1.4 Management of risks caused by invasive species	o	*	*	o
2. Human health and well-being				
2.1 Quality and quantity of drinking water	o	o	*	*
2.2 Sanitation and hygiene	o	o	*	o
2.3 Recreational opportunities	*	*	o	* *
3. Sustainability of livelihoods				
3.1 Agricultural water management (water supply, consumption, drainage) and nutrient loading	o	*	* *	* *
3.2 Management of the water supply and point source loading of industry	o	o	*	*
3.3 Sustainability of energy production	* *	* *	*	*
3.4 Sustainable use of natural resources (mining, forestry, fishery, peat extraction)	*	* *	*	o
3.5 Management of the risks caused by traffic, tourism and other services	o	*	o	*

Table 2. *Cont.*

Water Security Assessment	Linkages with Energy		Linkages with Food	
	Water→ Energy	Energy→ Water	Water→ Food	Food→ Water
4. Stability, functions and responsibility of society				
4.1 Management of the risks of natural disasters (e.g., floods)	*	* *	o	o
4.2 State of critical infrastructure (water and sewer pipes, banks, dams)	o	* *	*	o
4.3 Governance of water resources (institutions, actors, collaboration)	*	* *	*	* *
4.4 International collaboration (including transboundary waters)	* *	* *	o	o
4.5 Global water footprint of Finland	*	*	*	o
Scale				
* * Significant positive or negative linkage				
* Positive or negative linkage				
o No or weak linkage				

5. Discussion

5.1. Methodological Discussion: Pros and Cons of the Assessment Framework

The application of our framework can support water security assessment in several ways. It helps to concretise the abstract water security concept, and provides a systematic and visual way to discuss different aspects of water security. Use of the broad definition of water security also enables us to cover issues that are less frequently examined, such as stability, functions and responsibility of society, and functionality of legislation. A comprehensive understanding of water-related issues and their relative importance is vital for rational decision-making. To support this, the tool combines the knowledge of experts from various fields into a coherent overall picture. In public debate, less important issues sometimes get lots of attention, whereas much more important issues are ignored. In this respect, the framework assists in highlighting issues that should be focused on. The framework also includes a way to link water security with food and energy security, thus promoting the nexus approach. A systemic and comprehensive approach can be useful in foresight and risk management processes by providing a structuring framework for discussions and assessment.

This was the first time a water security assessment framework was developed and an assessment conducted in Finland. Therefore, it is not surprising that deciding on the water security criteria, assessment dimensions and the scales of the criteria was a rather difficult and iterative process. A central question was the trade-off between the compactness and the level of detail of the analysis. In the final framework, the criteria are large entities (e.g., different types of industries/use of natural resources have been combined) to facilitate the implementation of the analysis and to reduce the workload. This had a side effect, as setting an overall estimate for the combined criteria was sometimes difficult because various sectors may have advanced differently or may have diverging impacts regarding a water security criterion. One challenge was to ensure that the estimates assigned by several experts were coherent with each other. Different experts may interpret the qualitative scales in different ways, which may undermine the comparability of the results of the various criteria. To avoid that, we recommend that experts are interviewed personally, as it allows for a reduction of the risk of misunderstandings and provides the opportunity to ask about further arguments. Furthermore, the interpretation of the results was challenging due to the general nature of some criteria. However, as our aim was to get a picture of the overall water security situation in Finland, a certain generality in the assessment was considered acceptable. In the forthcoming cases, it is important to judge on a case-by-case basis if there is a need to split a combined criterion into sub-criteria.

Compared to many other recently developed water security frameworks (e.g., [28,34,35]), our approach is more comprehensive (including, e.g., the water–energy–food nexus and governance), more visual, and involves stakeholders more intensively. It is also more qualitative and subjective (expert judgements are used for example in the overall assessment of the state of criteria consisting of several issues), which also enables the inclusion of non-measurable issues in the assessment. On the other hand, this brings a certain kind of vagueness to the estimates and thus may reduce the credibility of the assessment from the perspective of external actors. Due to subjectivity, it is likely that various experts may have differing opinions about the issues. However, one aim of the framework is to identify the issues of disagreement, for which the subjective assessment can act as a catalyst for discussion.

There are examples of using multi-criteria decision analysis (MCDA) to aggregate various water security criteria (e.g., [28,58]). We also discussed whether the application of MCDA would be useful in our case, but decided not to aggregate the criteria. First, our analysis is semi-quantitative and thus calculating a numerical index would have given a false impression of the accuracy of the analysis. Second, there is an obvious risk of double counting as there are several criteria that are closely linked to each other. For instance, all categories of DPSIR diagram (Drivers, Pressures, States, Impacts, Responses) are covered by the criteria of the framework. Third, we considered it easier for stakeholders to follow our analysis if we draw conclusions from the criterion-based analysis rather than from a more aggregated analysis.

5.2. Discussion of Water Security in Finland

Finland has been regarded as a model country for water supply. Currently, about 90% of Finnish households are connected to centralised water supply networks, about 85% of the inhabitants are linked to the sewerage and centralised wastewater treatment, and the rest have decentralised and personal systems [30,59]. However, the infrastructure is ageing and there are estimates that the current investments for water supply repair and replacement are 0.5–1% of the capital value of the networks (120 million euros) when the required level should be at least 2–3% (320 million euros). Ageing or poorly maintained distribution systems can cause the quality of piped drinking water to deteriorate below acceptable levels and cause serious health risks. The state of water supply networks affects the state assessment of two water security criteria (2.1 Quality and quantity of drinking water and 4.2 State of critical infrastructure) and is an issue that should be at the heart of water management and resource allocation in the near future.

Another infrastructure-related issue of central importance is Agricultural water management and nutrient loading (Criterion 3.1). As the role of state in co-funding main drainage investments has decreased and the profitability of agriculture has been poor for a long time, the investments in agricultural drainage infrastructure have not been at an adequate level. Inadequate drainage can reduce crops, make it more difficult for machinery to move in the fields and increase nutrient loads. There is also a lack of knowledge about the state of the main drainage systems as the last national investigation was performed at the beginning of 1990 [60]; therefore, this topic should be a research priority.

Sustainable use of natural resources is a widely accepted goal that applies to different ministries in Finland. However, whether economic, social and environmental objectives have been balanced well enough has been a topic of continuous debate. As forestry is one of the pillars of the economy in Finland, intensive forest management, including the ditching of peatlands, is practiced throughout the country, except in northernmost Lapland. Forest felling is also expected to increase to meet the envisioned national bioeconomy targets, which is causing growing conflict between economic and environmental objectives [61]. There is also a widespread concern about the increased activities of international mining companies. There have been shortcomings in the assessment and management of the impacts of mining water, both on the part of authorities and the mining operators. The responsibilities and guarantees of mining companies regarding incident terms of prevention and preparedness, remediation and post-closure care remain inadequate [62].

Climate change is the most dominant driver, as it has negative impacts on several water security criteria, most notably on the state of the water environment. Climate change will directly affect lake ecosystems through higher temperatures and changes in the hydrological cycle [63]. As a result, nutrient and organic matter runoff to water courses is expected to increase, which in part increases the risk of eutrophication. In addition, higher summer temperatures may cause changes in the flora and fauna in lakes and rivers. The distribution of salmonid fish species, which favour cool water, may move north, for example. Climate change also increases the potential for harmful invasive species to spread.

The analysis of legislation revealed that, out of the 18 water security criteria assessed for legislation, nine of them were partially outdated (Table 1), so the need to update the regulations is moderately high. Regarding the nexuses, four water security criteria were estimated to be significantly linked to energy production. For example, improving the Diversity of Aquatic ecosystem requires an increase in environmental flows in many rivers, which cause losses to hydro power production. On the other hand, energy production was estimated to have a significant link to eight water security criteria.

The assessment highlights the development needs for policy-makers by providing a structured and detailed understanding of the state of water security in Finland.

5.3. Limitations and Ways Forward

We emphasise that the aim of our analysis is to provide one viewpoint for the Finnish water security discussion, and that there is uncertainty and subjectivity in the estimates. They are not designed to be an "ultimate truth". Thus, the estimates can and should be contested. Actually, an important objective of the framework is to identify the issues in which there are disagreements between stakeholders. Thus, pinpointing the estimates that are not in line with someone's personal view is one way to promote and direct discussion regarding water security. The assessment conducted with the Excel tool is available for feedback on the internet, and suggestions for adjusting the assessments are welcome.

Our nexus analysis was qualitative and was done at a very general national level, and should therefore be seen as indicative only. We assume that realising the analysis in a much more limited geographical area, e.g., a watershed, could produce more concrete and more applicable results. Further practical testing of the approach would also provide additional information about which water security criteria and dimensions the assessment should address, as all the dimensions of the framework may not be relevant in every case.

It should be noted that the assessment is scaled to Finnish conditions, with the aim of identifying critical issues and development needs. On a global scale, water-related challenges in Finland are relatively minor compared to those in many other countries. For instance, Finland has been ranked one of the top countries in the world with regard to water security several times (e.g., [28,31]). Therefore, if the ranges of the scales were set up to cover all the countries in the world, they would not have been discriminating enough for our purposes.

Defining a more comprehensive set of indicators would make the assessment more objective and transparent. The challenge is that a large number of metrics are needed, as metrics typically describe only a small part of the content of one criterion.

If the development of the framework was laborious and demanding, its use may be too. As the framework aims to be comprehensive, it covers a wide variety of environmental, socioeconomic and institutional criteria. There are very few experts who have expertise in all of these criteria, and therefore the application of the framework should be realised in a group consisting of representatives from different fields. Thus, the analysis could be updated from time to time to find out whether the results are still valid and how the state of the various criteria has developed, as well as whether any new issues or threats have emerged that should be given particular attention in water policy-making and management.

6. Conclusions

In this paper, we have presented a comprehensive framework and an Excel tool to assess water security in Finland. We have described the elements of the framework and the main results of analysis utilising it, as well as the challenges we faced during the development process.

Compared to the majority of earlier frameworks developed for water security or sustainability assessments, ours is more comprehensive, less quantitative, more visual and more subjective. The framework helps us to compare different dimensions of water security, facilitate discussion among stakeholders, and identify central research and development needs through a process that is less biased. The framework developed responds to the need for systemic approaches in foresight and risk management.

Applying the framework in a collaborative way with different stakeholders provides a structured yet laborious way to increase managers' and policy-makers' understanding about the different elements of water security, as well as its state and interconnections. In addition to national analyses, the framework can also be applied in more limited and specific analyses, such as regional or river basin-level assessments, or more detailed assessments of specific sectors (e.g., agricultural water management and loading, energy production). The analysis suggests that at least the following topics should be priorities in water management and research in Finland: the improvement of ecological status and biodiversity of aquatic ecosystems; understanding of the risks related to emerging harmful substances; adequate investment in water supply networks and agricultural drainage systems; and climate change adaptation and mitigation.

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Appendix A Screen Captures from the Excel Software

Water security assessment - Assessment card for a single criterion

Crite-rion	1. State of the water environment 1.1 Ecological status of waters (physical-chemical, biology, hydro-morphology)

State assessment			
	Current state:	-	Current state is satisfactory or worse than the target level
	Trend 2030:	-	State is expected to weaken somewhat by year 2030
	Reasoning: The target level of WFD has not been reached in many watercourses: 35 % of the river length, 15 % of lake area and 75 % of the coastal sea area are still in worsta than good condidtion. Climate change is expected to increase the nutrient and solid loads, which consequently increses eutrophication and darkening of the waters, which makes is more difficult to reach the goos state. Of the fish, arctic charr, whitefish and trout require cold water, but pike perch benefits from eutrophication and warming.		

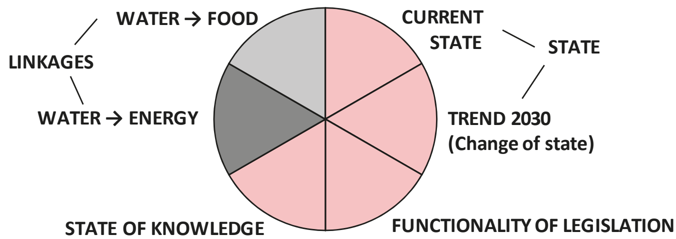
Linkages to food and energy security	Linkages		Reasoning:
	Water → Energy	* *	Improving the state of important migratory fish requires concessions from the hydro power companies (e.g. large enough streams, more ecological regulation practices). On the other hand, hydro power is an important factor in the energy mixture by providing means to store energy to reservoirs. Peat extraction is not allowed in the areas, where achieving the good state of waters is jeopardized.
	Energy → Water	* *	Peat extraction and hydro power production has an impact to the biota and migratory fishes of rivers and lakes. Condennsation water of nuclear and fossil power plants cause local warming on watercourses that has an impact to the biota and fishes. Sulphur and nitrogen dioksides cause acidifying fallout to the lakes, although nowadays removal of these particles from the emissions is very efficient.
	Water → Food	*	Increasing the quality of surface and ground water has positive impact to agriculture (irrigation water) and to the quality of the water used in food production. The quality of the water has an impact to shares of the different fish species and consequently to the amount of fish catches.
	Food → Water	* *	The loading from farming and fish farming has a negative impact to the ecologial state of the waters. Irrigation and other water intake can affect to the amount of waters in small water courses. Watercoures regulation is ofter carried out on the basis of the needs of farming (e.g. lowering the water levels during spring time).

Legislation			
	Functionality:	-	Legislation is partly outdated and there is a need for updating it
	Reasoning: The state targets of the water framework directive has not been fully reached. The consideration of permissions and the relationships between state of the waters and controlling them are not clear in the legislation. Means of legislation to reduce scattered loading are restricted.		

Figure A1. *Cont.*

Crite-rion	1. State of the water environment 1.1 Ecological status of waters (physical-chemical, biology, hydro-morphology)

Summary



The target level of WFD has not been reached and climate change is expected to worsen the situation. There is need for research especially on understanding the cause-effect chains of the issues having an impact to the state. New methods have been developed (e.g. gypsum, nutrient calcium), which can be used for reducing loading of the farming. The state is strongly linked with both energy and food security, which increases the significance of the criterion. The consideration of permissions and the relationships between state of the waters and controlling them are not clear in the legislation, and means of legislation to reduce scattered loading are restricted.

General interpretation of the colors

Very good	Significant positive or negative linkage
Good	Positive or negative linkage
Ok	No or weak linkage
Less than ok	
Poor	

Figure A1. Example of an assessment card for a single criterion (ecological status of water).

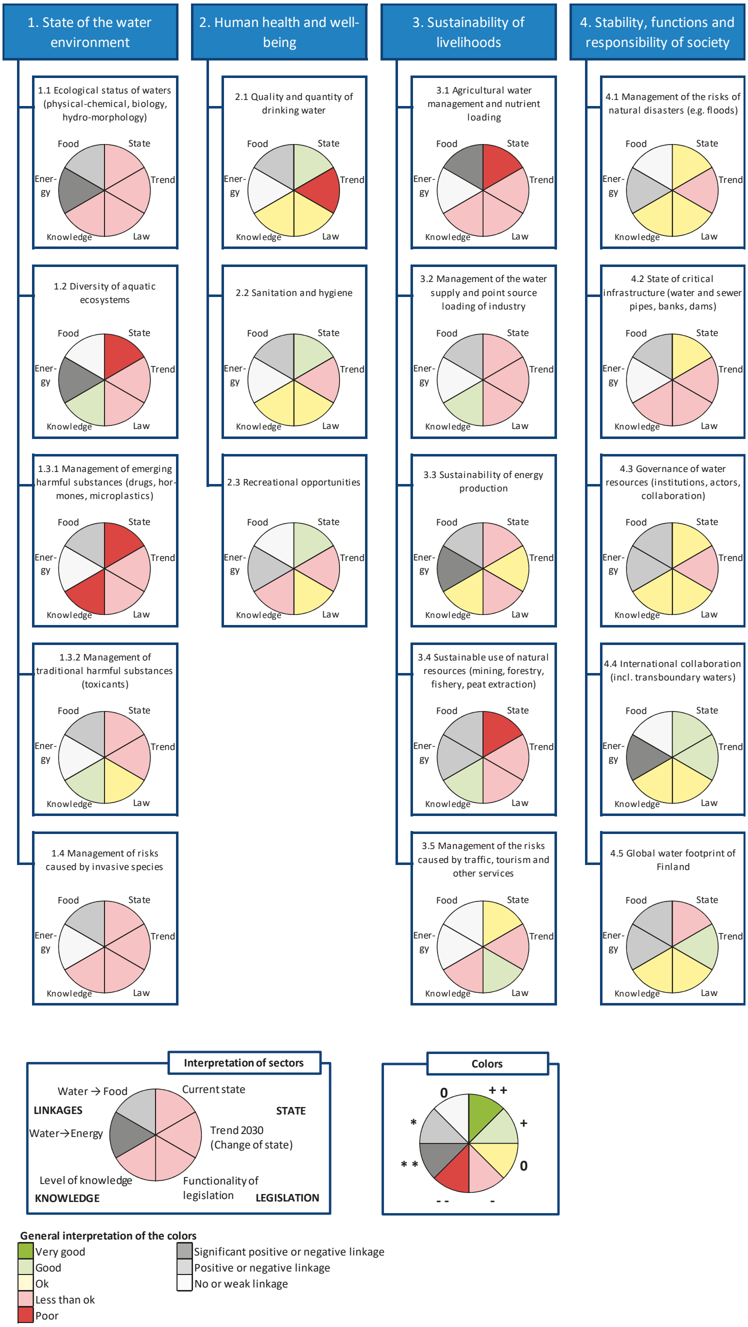


Figure A2. Sector charts for the criteria.

Appendix B Detailed Information about the Water Security Criteria

Table A1. Descriptions of the water security criteria.

Criteria	Description
1. State of the aquatic environment	
1.1. Ecological status (physicochemical, biology, hydro-morphology)	Describes the physicochemical, biological and hydro-morphological status of surface water ecosystems using the ecological classification system of Water Framework Directive (WFD).
1.2. Diversity of aquatic ecosystems	This criterion describes diversity and surface water that are not included in the ecological classification system of WFD; e.g., small water bodies (wells and springs), water bodies created by the uplift of land. In addition, endangered species are included, e.g., land-locked salmon, lake and sea trout, Saimaa ringed seal.
1.3. Management of harmful substances in the water courses (toxicants, drugs, hormones, microplastics)	Includes both "old" and "well-known" harmful substances, like heavy metals, DDT, dioxin and new emerging chemicals (e.g., pesticides, pharmaceuticals and personal care products, fragrances, plasticisers, hormones, flame retardants, nanoparticles, perfluoroalkyl compounds, chlorinated paraffins) and plastic pollution. Both surface and groundwater are included; 33 priority substances that are known to be harmful or dangerous at EU level and included in the ecological classification are not considered here to avoid overlap.
1.4. Management of risks caused by invasive species	An invasive species is a species that is not native to a specific location (an introduced species), and that has a tendency to spread to a degree believed to cause damage to the environment, human economy or human health.
2. Human health and well-being	
2.1. Quality and quantity of drinking water	The quality and quantity of household water is estimated on the basis of average water quality and availability. In addition, the assessment takes into account individual events (water crises) that weaken quality/quantity and their frequency.
2.2. Sanitation	Sanitation is assessed on the basis of how well the treatment of municipal waste water is handled on average. In addition, the assessment takes into account the possible individual events (water crises) that reduce wastewater treatment and their frequency.
2.3. Recreational opportunities	Recreational values are evaluated on the basis of the value added by the aquatic environment for recreation. Includes swimming and fishing opportunities, but also the landscape and cultural values of the aquatic environment. Increase in water turbidity, disadvantages caused by eutrophication (e.g., massive/toxic algae blooms) and decrease in the public access to water bodies (e.g., construction of shoreline) diminish recreational opportunities.
3. Sustainability of livelihoods and industry	
3.1. Agricultural water management and nutrient loading	Good conditions of the fields, soil (e.g., amount of humus), drainage and irrigation systems, influence considerably on the crop and nutrient loading to the water bodies. In addition, the use of fertilisers, status of water protection measures in fields and farms are assessed (e.g., protection zones, wetlands, two-stage channels, sludge treatment).
3.2. Water supply and point-source loading of industry	Quantity and quality of water used by industry and treatment of wastewater discharges from the plants. Includes, e.g., pulp and paper industry, chemical industry, ore enrichment plants.
3.3. Energy production (hydro power, nuclear, peat extraction, wind power)	The assessment includes, in particular, the sustainability of hydropower and peat extraction (peat is an important source of energy in Finland; peat extraction area has varied annually between ca. 40,000 and 60,000 ha) but also impacts of cooling water of nuclear power plants as well as other power plants.
3.4. Sustainable use of natural resources (forestry, mining, fishery)	The management, production and harvesting of natural resources, such as forests (felling, drainage of forest areas), aquaculture and ore extraction.
3.5. Management of the risks caused by traffic, tourism and other services	Includes transport (e.g., oil and chemical accidents in roads, railways and waterways), tourism and sales services (gas stations, etc.). For example, the accidents of oil tankers particularly in the Gulf of Finland and chemical accidents in land transport can cause significant impacts on aquatic ecosystems.
4. Stability, functions and responsibility of society	
4.1. Reduction of the natural disaster risks (floods, droughts)	Prevention, preparedness and response of natural risks; in particular flooding and drought.
4.2. State of critical infrastructure (water and sewer pipes, banks, dams)	Status of critical infrastructure as defined in the Social Security Strategy (2017), incl. water supply infrastructure, banks and dams.
4.3. Governance of water resources (institutions, actors, collaboration)	Water resources management covers organisations and stakeholders responsible for water as well as institutional frameworks that regulate the interaction between them (policy, strategies, laws).
4.4. International collaboration (including transboundary water management)	International cooperation in the water sector, incl. transboundary cooperation. It can be assessed in terms of its magnitude (share of boundary waters with existing agreements) or with the criteria of UNECE, Global Water Partnership, World Bank or Strategic Foresight Group.
4.5. Global water footprint of Finland	Impact of Finnish consumption, production and investment on water resources and water safety outside Finland. Measurements include: water footprint (see, e.g., https://wwf.fi/mediabank/2306.pdf), water risks (e.g., http://waterriskfilter.panda.org/) and commitment to water responsibility (see, for example, water liability https://commitment2050.com/browse-#commitments/details/59254488D4DF3C0D1C6027FA).

Table A2. Examples of research information and indicators used in the water security assessment.

Water Security Criteria	Examples of Indicators	Source
1. State of the water environment		
1.1. Ecological status of water	Ecological status of surface water	https://www.ymparisto.fi/en-US/Waters/State_of_the_surface_waters
1.2. Diversity of aquatic ecosystems	Threatened inland water species	https://www.biodiversity.fi/en/habitats/inland-waters/iw11-threatened-inland-water-species
1.3.1. Management of emerging harmful substances	Microplastics and drugs in wastewater	Talvitie, J. et al. 2015[1)]. Kankaanpää, A. et al. 2014[2)].
1.3.2. Management of traditional harmful substances	Loading of heavy metals from industry	https://www.biodiversity.fi/en/habitats/inland-waters/iw3-harmful-substances
1.4. Management of risks caused by invasive species	Alien inland species	https://www.biodiversity.fi/en/habitats/invasive-species/as2-alien-inland-water-species
2. Human health and well-being		
2.1. Quality and quantity of drinking water	SDG 6.1.1 Proportion of population using safely managed drinking water services	http://pxnet2.stat.fi/PXWeb/pxweb/en/SDG/ Gunnarsdottir, M. J. at al. 2017.[3)]
2.2. Sanitation and hygiene	SDG 6.3.1 Proportion of wastewater safely treated	http://pxnet2.stat.fi/PXWeb/pxweb/en/SDG/
2.3. Recreational opportunities	Proportion of bathing water sites with excellent water quality	http://ec.europa.eu/environment/water/water-bathing/index_en.html
3. Sustainability of livelihoods		
3.1. Agricultural water management and nutrient loading	Phosphorus load into inland water	https://www.biodiversity.fi/en/habitats/inland-waters/iw1-phosphorus
3.2. Management of the water supply and point source loading of industry	Nutrient discharges into surface water	https://www.ymparisto.fi/en-US/Maps_and_statistics/The_state_of_the_environment_indicators/Fresh_water_and_the_sea/Nutrient_discharges_from_industry_and_co%2828956%29
3.3. Sustainability of energy production	Coverage of regulation development projects	https://www.biodiversity.fi/en/habitats/inland-waters/iw15-regulation-development
3.4. Sustainable use of natural resources	Area used for peat production	https://www.biodiversity.fi/en/habitats/mires/mi3-peat-production
3.5. Management of the risks caused by traffic, tourism and other services	Maritime transport	https://www.biodiversity.fi/en/habitats/baltic-sea/bs4-maritime-transport
4. Stability, functions and responsibility of society		
4.1. Management of the risks of natural disasters	Flood damages and flood risk management	https://www.ymparisto.fi/en-US/Waters/Floods/Flood_risk_management/Flood_risk_management_planning
4.2. State of the critical infrastructure	SDG 6.a.1 Amount of water- and sanitation-related official development assistance, euros	http://pxnet2.stat.fi/PXWeb/pxweb/en/SDG/
4.3. Governance of water resources	General governance indicator	https://info.worldbank.org/governance/wgi
4.4. International collaboration	SDG 6.5.1 Degree of integrated water resources management implementation; SDG 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation, Water cooperation quotient	https://www.strategicforesight.com/publication_pdf/Water%20Cooperation%20Quotient%202017.pdf
4.5. Global water footprint of Finland	Sustainability of water footprint	https://waterfootprint.org/en/resources/waterstat/national-water-footprint-statistics/ https://waterfootprint.org/en/resources/waterstat/water-pollution-level-statistics/ https://waterfootprint.org/en/resources/waterstat/water-scarcity-statistics/

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From Top–Down Regulation to Bottom–Up Solutions: Reconfiguring Governance of Agricultural Nutrient Loading to Waters

Antti Belinskij [1,2,*], Antti Iho [3], Tiina Paloniitty [4,5] and Niko Soininen [1,4]

1 Law School, University of Eastern Finland, 80101 Joensuu, Finland; niko.soininen@helsinki.fi
2 Freshwater Centre, Finnish Environment Institute SYKE, 00790 Helsinki, Finland
3 Bioeconomy and Environment Unit, Natural Resources Institute Finland, 00790 Helsinki, Finland; antti.iho@luke.fi
4 Helsinki Institute of Sustainability Science (HELSUS) and Faculty of Law, University of Helsinki, 00170 Helsinki, Finland; tiina.paloniitty@helsinki.fi
5 Faculty of Law, University of Lapland, 96399 Rovaniemi, Finland
* Correspondence: antti.belinskij@uef.fi; Tel.: +358 46 920 9189

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Abstract: Animal agriculture is shifting toward larger farms and regional agglomerations in many countries. In step with this development, manure nutrients have started accumulating regionally, and are leading to increasing eutrophication problems. Nevertheless, the same trend may also prompt innovations in manure treatment. For example, Valio Ltd (the largest dairy processer in Finland) is planning a network of facilities that would remove water from manure, fraction the nutrients in it, and produce biogas from the excess methane. One of the main hurdles in developing this technology is that the current regulatory framework does not support a shift from diffuse loading, which is seen in the traditional application of manure on fields, to point-source loading; the regulations may even prevent such a change. This article analyzes a governance framework that addresses this dilemma in EU–Finland, and discusses how the governance described could curtail the nutrient loading of agriculture to waters. The approach is based on adaptive governance theory. We argue that traditional top–down regulation, which emphasizes food security, contains serious shortcomings when it comes to managing agricultural nutrient loading to waters, and that the current regulatory framework does not necessarily have the adaptive capacity to facilitate new, bottom–up solutions for manure treatment. Interestingly, the strict water quality requirements of the EU Water Framework Directive (2000/60/EC) open new windows of opportunity for such solutions, and thus for improving the overall sustainability of animal agriculture.

Keywords: adaptive governance; regulation; EU law; animal agriculture; nutrient loading; eutrophication; manure treatment; water protection; food security

1. Introduction

Eutrophication resulting from excessive loads of nitrogen and phosphorus to surface waters causes nuisance and economic damage to societies around the globe. For example, outbreaks of mass algal blooms have led to outright financial losses for communities that rely on lakes or rivers as sources of drinking water. Notable blooms have taken place, for instance, in the Baltic Sea, Lake Erie in North America, and Lake Taihu in China [1–4].

The main anthropogenic source of nutrient loading is food production. Crops are produced in large, open areas prone to stochastic weather events, leading to surface runoff and the subsurface leaching of nutrients. In Finland, as in many other countries, animal agriculture is shifting toward larger and more professional farms agglomerated in certain regions. This development is having an unintended consequence: manure nutrients have started accumulating in those regions, potentially leading to massive problems from nutrient loading [5,6].

When the eutrophication of surface waters became an environmental issue, regulatory machinery emerged to curtail nutrient loading. Current environmental laws, such as the European Union (EU) Industrial Emissions Directive (2010/75/EU), require industrial operators to obtain environmental permits for activities causing point-source pollution. The permits set limit values for nutrient loading that can be monitored with high accuracy and without excessive costs. Technical solutions and substantial investments in abatement technologies have followed apace. As a result, point-source loading has been reduced dramatically. In the Baltic Sea, the external loading of phosphorus—the main driver of blue green algae blooms—has decreased by more than 50% from its peak levels in the 1980s [7].

However, this success in reducing point-source loading has not been reflected in the water quality improvements in the Baltic at the scale desired [8]. Accordingly, any regulatory or technical innovations that would improve the utilization of manure nutrients, and thus reduce diffuse-source loading, would have considerable significance. The scale of the problem is substantial. In Finland, manure originating from production animals contains around 20,000 tons of phosphorus, which is about 75% of the phosphorus in the total biomass of the country. Currently, the field application of manure and the uptake of crops are principal mechanisms abating nutrients.

Interestingly, the same emergence of larger and regionally centred animal farms causing the nutrient problem might also provide solutions. Larger unit sizes and regional agglomeration provide economic returns to scale that may enable larger investments and energize timely innovations in collaborative networks, opening new windows of opportunity in manure treatment and its regulation [9,10]. In Finland, for example, Valio Ltd (the largest dairy processor in the country) plans to establish a network of manure treatment facilities that would produce biogas as well as fraction the nutrients in and remove the water from manure in an economically feasible way [11]. In examples from other countries, the Irish BHSL offers large-scale solutions for collecting energy and nutrients from poultry litter, while Perdue AgriRecycle operated a massive pelletizing facility on the Delmarwa Peninsula from 2001 to 2017 [12–14]. Such developments make it possible to sever the pernicious link between spatially agglomerating animal operations and regional nutrient loading. This in turn would drastically improve the overall sustainability of animal agriculture. In the long term, food security can only be based on environmentally sustainable food production [15,16].

Such a change in manure treatment would also alter its regulatory framework: a manure treatment facility is a point source of nutrients, which falls under stricter legal scrutiny than traditional field application, as it is a source of diffuse pollution. Regulation such as the EU Nitrates Directive (91/676/EEC) sets limits on field application, although the practice is largely governed through voluntary agri-environmental subsidy programs. By contrast, a manure treatment facility requires an environmental permit under the Finnish Environmental Protection Act (527/2014) and must fulfill, among other conditions, the water quality requirements of the EU Water Framework Directive (WFD 2000/60/EC). This shift in the applicable regulatory framework between diffuse and point-source operations creates a dilemma: while the environmental problems of intensive livestock production could be solved by converting diffuse into point-source loading, the current regulation does not support such a shift, and may even prevent it.

This article analyzes a governance framework that addresses the dilemma and discusses how the governance could curtail the nutrient loading of agriculture to waters. The approach is based on adaptive governance theory and seeks to reassess the relationship between the top–down regulation of and bottom–up solutions to the problem. We analyze how the EU–Finnish regulatory framework has managed agricultural nutrient loading, whether it facilitates emergent grassroots solutions to manure treatment and whether there are new windows of opportunity for such solutions. We use an investment plan by Valio Ltd as a real-world example to concretize our approach. The core question of the article is whether the EU–Finnish legal framework has the adaptive capacity necessary to facilitate what is an emergent shift toward sustainable food production through bottom–up solutions. Methodologically, our article builds on legal analysis, the case study approach, and literature reviews on adaptive governance and agricultural manure management.

We conclude that traditional top–down regulation contains serious shortcomings when it comes to managing the complex environmental problem of agricultural nutrient loading to waters. Moreover, we argue that the current regulatory framework does not necessarily have the adaptive capacity to facilitate new, bottom–up solutions for manure treatment. Then again, the strict water quality requirements of the WFD open up new windows of opportunity for such solutions. Thus, finding the right balance between the nutrient abatement objectives and the regulation of adaptive bottom–up solutions is crucial to solving the nutrient loading problem. The regulatory framework should have the capacity to take into account the overall impact of manure treatment and agricultural nutrient loading to surface waters, groundwater, and the Baltic Sea, not only the point-source pollution that treatment facilities cause.

The section to follow presents adaptive governance, which forms the theoretical framework of the article. Section 3 proceeds to analyze traditional top–down legal regulations of farming activities, while Section 4 discusses emergent bottom–up solutions to manure treatment from a technical and legal perspective. The last section contains discussion and conclusions on the shortcomings of the current governance framework and how it could be improved.

2. Adaptive Governance as a Theoretical Framework

Common pool resources, such as water, are notoriously complicated to manage and govern sustainably. As Hardin famously illustrated, they attract short-sighted behavior that often leads to a collapse of the resource and ecosystem services it provides [17]. Moreover, the management of common pool resources is riddled with complexity and uncertainty [18,19]. For a number of years, the principal challenge for environmental governance has been to determine what kind of policy mix would best address complex environmental challenges such as the overuse of natural resources, climate change, disruption of nutrient cycles, and eutrophication [20]. Whereas Hardin's approach was to tackle the externalities problem with the privatization of common pool resources, or to regulate them with substantive laws, complex problems compounded by uncertainties often require a more potent solution. Both direct regulation and markets suffer from critical deficiencies in their failing to pay enough attention to emergent behavior and self-organization when seeking effective solutions to complex environmental problems [21–23].

Adaptive governance theories have emerged to address this shortcoming [24–26]. Adaptive governance has been defined as "a range of interactions between actors, networks, organizations, and institutions emerging in pursuit of a desired state for social-ecological systems" [27]. One typical feature of adaptive governance is that it facilitates institutional designs that encourage experimentation and learning among public managers and private operators [23,24,28]. In this regard, it bears a close family resemblance to collaborative governance and new governance theories, which embrace emergent behavior, collaboration between public and private actors, and learning as prominent features of environmental governance [23,27,29,30]. The links between adaptive governance and transformative governance are also evident [28].

Collaborative processes that bring together public and private stakeholders to solve environmental problems at the level where they emerge are typical examples of adaptive governance. In the Finnish context, an illustrative case is Iijoki's otva, which is a project with processes bringing together stakeholders to discuss new management approaches to social–ecological uncertainties and trade-offs between hydropower interests and the recovery of migratory fish stocks [31]. Such examples of adaptive governance have drawn especially strong research interest in the North American context [32].

With the inclusion of legal scholars, the research on adaptive governance has focused increasingly on studying the role of law in facilitating emergent grassroots behavior in managing social–ecological problems [32]. Top–down regulation has been remarkably effective in solving simple environmental problems, such as point-source pollution, in countries with the requisite political will and institutional capacity [33]. Despite its impressive track record, the role of such regulation (law) in adaptive governance is mixed. On the one hand, emergent solutions to complex environmental problems require laws as a source of authority and a means to resolve disputes [34]. On the other, strict top–down laws regulating substantive solutions to environmental problems are commonly criticized for creating barriers to bottom–up experimentation and learning, although these would be crucial for reaching the desired social–ecological states [23]. Adaptivity is a characteristic of emergent grassroots developments, and cannot be imposed by regulation without risking major shortcoming in governance. Law needs adaptive capacity—that is, room for the private and public stakeholders to experiment with novel technologies and management approaches in dealing with complex problems, one being agricultural nutrient runoff. Law can do no more than facilitate adaptive governance [27].

The pursuit of a desired social–ecological state through grassroots behavior is contingent on two critical factors: whether the social system (law included) is prepared to facilitate such behavior, and whether there is a window of opportunity for such behavior. The windows come in many shapes and sizes, ranging from natural disasters to policy shifts, technological developments, and litigation [24,26,35]. The governance of nutrient pollution in EU–Finland currently has at least three such windows available to it: the first is the strict water quality requirements of the EU Water Framework Directive (legal window), the second is a societal shift to large-scale farming units (societal window), and the third is the development of centralized manure treatment technology (technological window). The core aim of the article is to determine whether the relevant social systems in general, and the law in particular, are prepared to make use of these opportunities.

The reason why emergent behavior is best equipped to navigate complex problems and seize opportunities is illustrated in Figure 1 below:

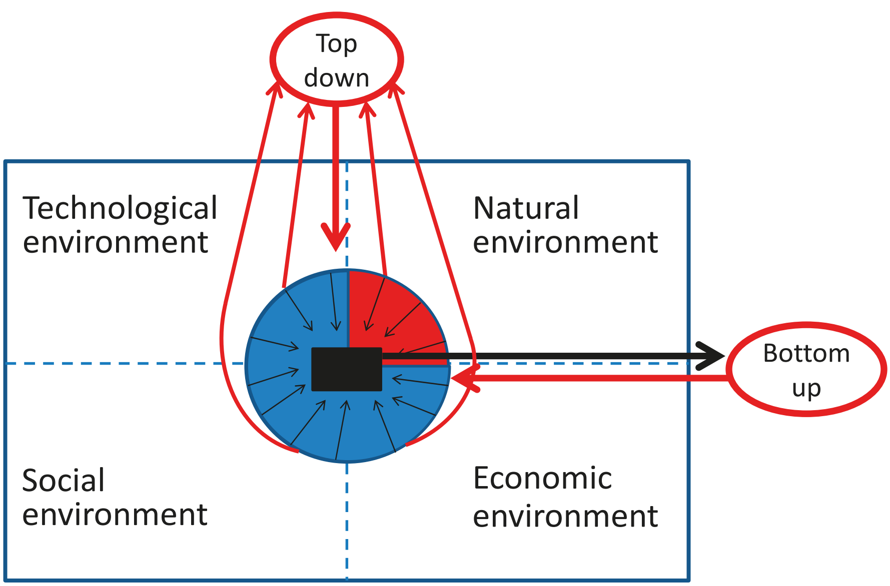

Figure 1. Top–down and bottom–up approaches. A bottom–up approach uses the regulated operator's own, continuously updated information on its interface with the operating environment. With a top–down approach, the regulator must gather the information. The faster the environment changes, and the more dimensions the operational environment has, the harder it is for the regulator to update information, and the higher the potential gains from a bottom–up approach.

An operator such as a company or a farmer (black box in the middle of the figure) is influenced by different operating environments (thin black arrows). Since information on these environments is crucial for its economic performance, the operator always possesses the latest and best available information. In addition, the operator influences these environments through its own activities (circle around black box); the sector of the circle corresponding to the natural environment is colored red to denote the negative externalities associated with that environment.

Given the option (or mandate) to do so, an operator can identify the most innovative ways to mitigate the environmental externalities (thick black arrow in the figure) by using information on the environments. The regulator could facilitate such a bottom–up approach by enacting adaptive regulation that sets clear environmental targets, but allows operators leeway in choosing the best bottom–up means to meet those targets. However, the traditional top–down approach imposes substantive solutions, does not allow the operator such leeway, and forces the regulator to collect the information (thin red arrows) and enact detailed regulation (thick red arrow). The more complex and frequently changing the operational environment and the regulated industry are, the harder it is for the regulator to keep the information base for top–down regulation updated.

Since Dietz et al. coined the term "adaptive governance" in 2003 [24], there has been an almost exponential growth in theoretical scholarship in the field [27]. Not surprisingly, the main focus of the research is shifting toward empirical and practical examples [27]. In this article, we draw inspiration from adaptive governance theory and apply it in a context that is somewhat different to the collaborative governance examples in the literature. In the context of managing agricultural runoff, we study the role of law in supporting or hindering corporate front-runners in transformative technology. The theory does not offer a method, but a normative perspective in answering what kind of environmental governance is likely to be effective in responding to complex problems such as agricultural nutrient runoff.

3. Top–Down Governance of Agricultural Diffuse Nutrient Loading

Where environmental law in general has developed apace, the effective centralized governance of diffuse nutrient loading to waters has remained an elusive goal. This dilemma is not due to lack of effort: the past few decades have seen the EU adopt a multifaceted approach in trying to address the issue. In what follows, we focus on three of the principal top–down instruments in EU–Finland: the EU common agricultural policy (CAP), the Nitrates Directive, and the Water Framework Directive.

3.1. Economic Incentives

The EU common agricultural policy is the most cost-intensive instrument designed to check agricultural nutrient loading to waters. It is a financial tool that has witnessed a rise in environmental concerns during its existence. The CAP has three key concerns, each of which affects the shape the policy ultimately takes:

1. Trade
2. Food supply and security, and
3. The environment.

The current CAP (2014–2020) is largely characterized by flexibility and a multitude of voluntary measures [36]. While the flexibility can work toward pro-environmentalist objectives, it also makes the environmental aspects less binding and more case-specific [37]. It has even been pondered whether a greater regional or local focus might be more efficient for the purpose, promoting solutions tailored to the regions involved and paying full attention to their priorities and needs.

The most recent CAP reform was envisaged as a profound transformation toward 'greening the CAP' by making the instrument more environmentally friendly. However, at the end of the day, productivist discourse emphasizing farmers' income and food security figured more significantly in the reform than, for example, the further abatement of agricultural nutrient loading [38]. Nevertheless, the CAP includes a mandatory component of environmental considerations in the direct payments, resulting in mechanisms such as crop diversification, the maintenance of permanent grassland, and ecological focus areas. "Mandatory" means that a Member State cannot opt out of implementing the component: the funding allocated for it is 30% of each Member State's national ceiling for direct payments [39]. Most of the environmental mechanisms of the CAP are subject to the individual Member State's discretion [36].

The binding references from the CAP to the Water Framework Directive were removed in the EU parliamentary process [40]. Thus, the CAP was decoupled from the WFD, and its ambitious water quality objectives, counteracting both the CAP's environmentality and the ability of the WFD to achieve its aims [41,42]. Bearing in mind that environmental considerations did not come up in CAP discussions until the 1990s [43], the progress of environmental concerns in the CAP has nevertheless been clear and resolute.

From the perspective of adaptive governance, the reflections on the CAP's development draw an interesting picture. The CAP has developed toward environmentality—albeit with no clear nutrient abatement objectives—yet has also been moving toward flexibility, regionality, and tailoring policy to specific needs. All in all, the discussion surrounding the CAP emphasizes a move toward the regional or even local level as a way forward in controlling agricultural nutrient loading.

It is also worth reflecting on whether the CAP has made the most out of the window of opportunity for greening it during the most recent reform. The development of the CAP has been a constant battle between varying and also conflicting interests and their objectives, and even though environmental concerns have gained impetus, their role in the current version of the CAP is not as central as was expected [37,41]. The current CAP encompasses flexibility that favors adaptive governance, but at the same time, its environmental objectives are not clear and well-defined.

3.2. Pollution Prevention

A second key regulatory instrument addressing agricultural nutrient loading to waters is the Nitrates Directive. It dates back to the 1990s, and represents the first generation of environmental regulation designed to prevent pollution from entering the environment [43,44]. The regulatory logic in the directive is straightforward, and captures the physical and realistic aspects of the nutrient-loading dilemma.

The directive requires Member States to set the dates on which manure can be spread on fields, the aim being to balance the runoff of nutrients into nearby waters with the needs of optimal growth. The directive encourages regional tailoring of the policy by requiring Member States to designate parts of their areas as nitrate-vulnerable zones, which are subject to stricter regulations. Finland has designated the entire country as such a zone, effectively rendering moot the option of tailoring policy regionally on the basis of the intensity of animal agriculture. Member States must monitor and report the implementation of the directive and its results (Nitrates Directive, Art. 1, 2 (k) and 3–6). Thus, even though the Nitrates Directive's primary approach is not that modern, it includes some adaptive components.

The Nitrates Directive operates with process standards (manure distribution restrictions) and specification standards (regulation on nitrate-vulnerable zones). In order to employ more advanced performance standards—familiar from regulation on point-source pollution—the regulator ought to know the amount of pollution emitted from the property [44,45]. Thus, the incompatibility between agricultural nutrient loading regulation and more developed environmental performance standards is partly explained by the difficulty of establishing trajectories in the case of diffuse pollution. The issue boils down to the question of adequate information: the ability to pinpoint exact emission sources and establish trajectories is the key difference between point- and diffuse-source pollution. In the case of the latter, it is difficult to establish the robust and site-specific scientific findings required to warrant regulation [46].

The EU Industrial Emissions Directive, implemented in Finland through the Environmental Protection Act, regulates sources of point-source pollution and utilizes environmental permits to meet its targets. In order to be granted an environmental permit for an animal farm, the applicant must have enough land on which to spread the manure produced by the farm. The land may be either owned by the applicant or its use agreed upon with neighboring farms. A specific acreage is designated for each animal type, representing the area needed for manure [47]. However, the permit does not specify the application rates per hectare; it merely guarantees that the farm has enough field acreage at its disposal. Here, the link between manure distribution and water pollution is broken: authorities establish the amount of available land, but the scrutiny is not extended to the amount of water pollution that the manure causes.

3.3. Water Quality Requirements

The CAP and the Nitrates Directive illustrate the basic challenge of regulating agricultural nutrient loading: the environmental issue is significant, but due to trajectories that are difficult to establish, legally binding regulation is difficult to justify. By contrast, the EU Water Framework Directive (WFD) is site-specific and sets clear water quality objectives for each water body. In principle, the WFD draws upon adaptive management theory and seeks to employ ecological knowledge to its fullest, accepting a holistic understanding of ecosystems and taking an integrated approach toward activities affecting them, agricultural nutrient loading included [48–50].

In the WFD, waters are categorized as water bodies and river basins. Member States are obliged to evaluate and assess the quality of water bodies. Then, the evaluations are incorporated in river basin management plans, which include classifications of environmental programs and measures adopted to achieve the environmental objectives [51]. The environmental objectives of the directive require that no water bodies may deteriorate in quality, and that they should attain good ecological status (WFD, Art. 4 (1) and Annex V).

Since the directive was adopted, there has been a running debate on whether it imposes substantive requirements on Member States in addition to procedural obligations. This issue was settled in the Weser ruling (C-461/13), in which the Court of Justice of the European Union (CJEU) ruled that the environmental objectives of the WFD are binding when authorizing individual undertakings [52,53]. However, since activities causing agricultural nutrient loading—for example, land cultivation—do not need authorization, they do not face administrative scrutiny, and their acceptability is never considered in the light of the environmental requirements of the WFD. Thus, while the Water Framework Directive is a prime example of regional water management in the EU, the lack of administrative oversight undermines its ambition of controlling agricultural nutrient loading.

Having analyzed the challenges of the top–down governance of agricultural diffuse nutrient loading in this section, we go on to discuss whether the structural changes in agriculture and developing manure treatment technologies might provide answers to 'the top–down or bottom–up' dilemma. We shift the perspective from diffuse- to point-source pollution, and analyze how the regulatory framework of EU–Finland facilitates or hinders emerging bottom–up solutions.

4. (Mal)adaptive Facilitation of Bottom–Up Solutions to Nutrient Loading

4.1. Structural Changes in Agriculture as a Source of and Solution to Manure Management Problem

Animals had multiple roles in traditional agriculture. Since inputs of food production and food itself were scarce, no resources were wasted. Pigs, for instance, transformed household waste into edible form (meat). Bovine animals provided milk and meat, but also transformed grass into nutrient-containing manure, which was used as crop fertilizer. Spatially, animals thus concentrated much-needed nutrients from forests and pasture lands onto crop fields, which were closer to farm centers.

As specialization within agriculture took hold, animal numbers per production unit increased. This development continues. Larger farms are more likely to grow than smaller ones, and smaller ones are more likely to cease production. As a result, average animal numbers per facility are on the increase [54,55].

The logic of how nutrients flow through the production system has not changed, but the increase in scale has turned spatial scarcity into potentially harmful nutrient abundance. Moreover, today, nutrients in animal feed and forage might be imported from other parts of the world. Some of the nutrients in feed are transmitted to end products, and thus eventually to food-processing facilities and wastewater treatment plants. However, the largest share of nutrients is being found in the excrement of production animals. On the largest farms, the quantities of manure have long since exceeded the amounts economically sensible for fertilizing crops in the fields close to production facilities. As a result, nutrients accumulate in the soil and eventually leach into the surrounding environment, causing water quality problems. Throughout the developed countries, the eutrophication of surface waters is ever more closely linked to concentrated animal production [56–58].

Technically and economically, two impediments prevent the efficient utilization of manure nutrients. The first is the above-mentioned excessive quantity of manure nutrients in a given location. As it contains a great deal of water, manure is too heavy to be hauled long distances without economic losses. Excessive manure will stay within a particular radius of the source farm as a surplus [58,59]. The second impediment is the mismatch between the ratio of nitrogen and phosphorus that crops need, and the ratio in manure. Phosphorus occurs in excess in essentially all manure types and for most crops. As manure is mostly applied based on crops' nitrogen needs, phosphorus will be applied excessively, even in areas where nitrogen input and output are in balance [59–63].

Figure 2 below illustrates conceptually how the gradual increase in unit size influences nutrient surpluses:

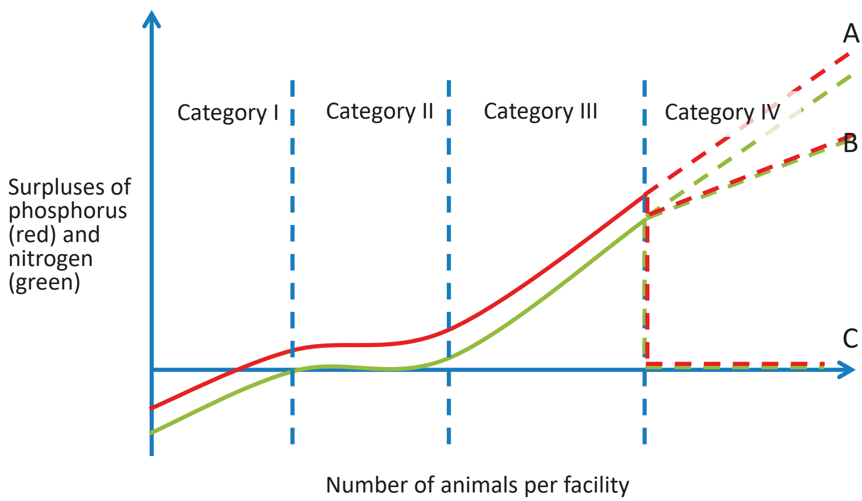

Figure 2. Influence of unit size on nutrient surpluses.

The horizontal axis denotes the number of production animals in a representative facility. Nutrient surpluses are depicted on the vertical axis, the red curve denoting phosphorus and the green curve denoting nitrogen. Nutrient surpluses change with the number of production animals. We identify the following four categories in this development:

Category I: Nutrient deficiency. There are only a few animals per farm, and the manure nutrients they generate are not sufficient to satisfy crops' agronomic needs. Manure is utilized extensively; there is even a market for (almost) untreated manure. While crop production is reduced by the lack of nutrients, soils may start accumulating phosphorus in the fields closest to the farm center. Historically, all farms operated in this category. Even today, many developing countries suffer from nutrient deficiency [64].

Category II: Stabilized production. Farming is economically sustainable, and the number of animals does not increase above that at which the quantity of manure would become excessive. Within the economically critical radius, farms are able to acquire land as they grow. That is, all manure generated at the farm center is hauled to and applied on the farm's own fields in accordance with the nitrogen requirements of crops. Phosphorus is applied somewhat excessively because of the different phosphorus–nitrogen ratio in crops and in manure.

Category III: Manure dumping. Economic returns to scale have gradually increased the unit size. The quantity of manure generated in the regions of intensive animal agriculture is so high that, on the one hand, manure cannot be applied according to crops' needs, and on the other, excessive costs prevent the haulage of manure across different regions. Hence, nutrient surpluses of both nitrogen and phosphorus increase in step with increasing animal numbers [59,60].

Category IV: Technological breakthrough to the decoupled world. Economic returns to scale, spatial agglomeration, and vertical integration trigger technological innovations in manure management. Paths A, B, and C in Figure 2 depict alternative scenarios. Path A is the business-as-usual scenario, where surpluses continue to increase with farm size. Path B depicts a combination of separation technology that decreases the weight of manure and an innovation in feed management that decreases the phosphorus content of manure. Path C denotes full decoupling, where the weight of the manure is reduced to a level permitting long-distance hauling, and the main nutrients are fractioned. Fractioning makes it possible to apply both nutrients exactly according to crops' needs. Path C describes a situation in which manure nutrients become almost perfect substitutes for mineral fertilizers.

Development from Category I to Category III is taking place throughout the world. As there are currently no drivers in the markets that would mitigate the accumulation of manure nutrients, entering Category IV seems like the only viable option to regain sustainable animal production.

To sum up, there is an urgent need to decouple nutrient surpluses from intensifying animal agriculture—that is, to move into Category IV (C), following Path C in Figure 2. As described in the introduction, the firms operating in the industry are developing the necessary technologies for that purpose. In the following, we analyze whether water protection regulation is encouraging or hindering the implementation and further development of such technologies. Using the example of Valio Ltd's planned manure treatment facility, we illustrate the regulatory stumbling blocks in moving from Category III to full decoupling, as depicted by Path C in Category IV.

4.2. Regulatory Incentives for and Stumbling Blocks to Manure Treatment Facilities

Valio's facility, to be built in Nivala, a municipality in Northern Ostrobothnia, offers a case showing how nutrient surpluses and intensifying animal agriculture could be decoupled in many regions. The plant will treat manure collected from nearby dairy farms and produce fertilizers and biofuel from it. The facility has been designed to treat a maximum of 19,500 tons of sludge manure, and will produce 2400 tons of solid fraction (phosphorus), 3500 tons of liquid fraction (nitrogen and potassium), and 650,000 m^3 of biogas per year. The solid fraction will be refined into phosphorus fertilizer fractions, and the biogas will be refined into traffic fuel [65].

The municipality granted Valio an environmental permit for the facility in spring 2018 based on the Finnish Environmental Protection Act [62], but Valio retracted its permit after a few months to make changes in the plans [65,66]. Valio has reapplied for an environmental permit, and the permitting process has begun.

The facility will cause point-source pollution in the form wastewater, air, and noise emissions [64]. From a legal perspective, the wastewater emissions pose the biggest challenge. The facility will produce a maximum of 12,000 m^3 wastewater per year. Even after treatment, the wastewater will contain ammonium nitrogen (maximum 20 mg/L) and nitrogen (maximum 20 mg/L) [64].

While diffuse pollution from agricultural fields is loosely regulated (see Section 3), point-source pollution from a manure treatment facility must meet the strict legal requirements of the Water Framework Directive and other legislation in EU–Finland. In a significant development, in 2015, the Court of Justice of the European Union (CJEU) issued a ruling—the Weser (C-461/13) ruling cited above—providing an interpretation of the environmental objectives of the WFD. The court first declared that unless a derogation is granted, the Member States must refuse authorization for an individual project where it may cause a deterioration of the status of a body of surface water or where it jeopardizes the attainment of good status. Second, it stated that there is deterioration of the status as soon as the status of at least one of the quality elements falls by one class, even if there is no fall in classification of the body of surface water as a whole.

Following the ruling, if the nutrient emissions of a manure treatment facility jeopardize the achievement of the environmental objectives of the WFD (non-deterioration and good status), the first option is to minimize the emissions. Additionally, the Finnish Environmental Protection Act requires the use of the best available technology (BAT). However, even if the facility fulfills the BAT requirements, the emissions may still jeopardize the strict environmental objectives of the WFD, in which case achieving the objectives could require technically unfeasible or disproportionately expensive wastewater treatment measures. We do not have enough knowledge as yet on Valio's planned facility to assess the feasibility of taking measures that go beyond the BAT requirements.

The second option under the directive is to offset emissions by taking compensatory measures in the receiving water body or in its drainage basin. In Valio's case, diffuse loading to the recipient water body may decrease substantially when manure is treated in the facility and not spread on the nearby fields. However, the Finnish environmental permit system does not recognize nutrient offsetting. The Environmental Protection Act aims to prevent and control pollution, not to manage the combined effects of different activities through offsetting. While diffuse pollution to the receiving water body may decrease substantially with the construction of the facility, such positive overall impacts cannot be considered in environmental permitting [67].

The third option is to apply the derogation regime of the WFD. Article 4(7) provides a possibility to derogate from the environmental objectives due to new activities, but it can be applied to nutrient pollution only in cases where the status of the receiving water body (or, in light of the Weser ruling, one of its quality elements) deteriorates from high to good. In addition, a derogation requires that the modifications to a water body are to be made for reasons of overriding public interest, and that there are no significantly better environmental options to reach the objectives of the activity [68]. Thus, the possibilities to derogate from the environmental objectives of the WFD in the case of the planned manure treatment facility are rather limited.

All in all, while the WFD opens a window of opportunity for new manure treatment technologies by requiring EU Member States to achieve good environmental status for surface waters, it also poses legal challenges. Even where the net impact of a biofacility on the quality of water bodies would be positive, the directive does not allow (unless a derogation is granted) local point-source emissions that would jeopardize the environmental objectives for a single water body. What is more, the permit system of the Finnish Environmental Protection Act, which is largely based on the EU Industrial Emissions Directive, fails to consider the combined effects of nutrient loading on a river-basin scale, for instance.

5. Discussion and Conclusions

The management of agricultural nutrient loading is changing in Finland due to new opportunities to treat manure and produce fractioned fertilizers and biofuel from it. While this article has not assessed the environmental impacts of such developments from a scientific perspective, it is clear that new technologies provide a promising opportunity to abate agricultural nutrient loading to inland, coastal, and marine waters in regions where intensive animal agriculture causes nutrient surpluses. However, the challenge is whether the regulatory framework can adapt to the change from diffuse- to point-source pollution and support emerging bottom–up solutions such as Valio Ltd's manure treatment facility.

The current top–down regulatory framework in EU–Finland has serious shortcomings when faced with the task of managing the complex environmental problem of agricultural nutrient loading to waters. The regulation on the field application of manure is loose and ill-coordinated with the environmental permit system. It places greater emphasis on food security and farmers' income than the abatement of nutrient loading. One part of the problem is that the agricultural sector consists of numerous operators, whose combined environmental impact is clear but whose individual emissions are difficult to verify.

New opportunities to manage agricultural nutrient loading through bottom–up solutions have emerged with the structural change in agriculture, new manure treatment technologies, and the strict requirements of the EU Water Framework Directive. However, the current regulatory framework has only limited adaptive capacity, making it ineffective in facilitating these solutions. Moreover, while the WFD may open a window of opportunity for bottom–up solutions, this is likely a narrow one, given that the instrument's focus is on single water bodies. For example, if the emissions of a manure treatment facility cause the status of a water body's quality element to deteriorate—that is, the ratio of one of the quality elements falls below the level for the current class—the facility cannot be granted a permit without a derogation, even if it has positive combined effects on waters.

Finding the right balance between the nutrient abatement objectives and the regulation of adaptive bottom–up solutions is of the utmost importance in solving the nutrient-loading problem. It is a challenging task that relates to the regional scale of the problem. In addition to considering the local-scale environmental impacts of a manure treatment facility, the regulatory framework should be able to take into account the overall effects of such a facility on nutrient loading at the national and river basin levels. This improvement would require adjustments in the regulatory framework of EU–Finland.

The economic viability of manure treatment facilities depends on three aspects closely linked to the regulatory framework: operation costs, sources of raw materials, and markets for products. The operation costs depend partly on the pollution prevention requirements; pollution control must be based on the best available technology, which takes the economic costs into account. Access to raw materials could be enhanced through animal farm permits that require—or at least allow—manure to be treated instead of being spread on fields. Regulation could also advance markets for products by, for example, advancing biogas use in public transport and requiring the use of organic fertilizers in addition to chemical ones.

Finally, the new manure treatment technologies open up possibilities to combine food security with environmentally sustainable food production. While the aim is that "all people, at all times have physical, social and economic access to sufficient, safe and nutritious food" [69], there is also an urgent need to reduce the environmental impact of food production. These technologies also provide a timely reminder of the water–energy–food nexus approach [70,71]. The treatment of manure is required for protecting waters from the impacts of food production. The end product is a combination of fertilizers and biogas, the latter being used for energy. Thus, the new, bottom–up solutions can greatly advance water, energy, and food security, and effectively combat eutrophication and harmful human-induced climate change.

From a theoretical perspective, our article illustrates that adaptive governance theory has much to give also in contexts that expand on, or even deviate from, narrowly defined collaborative governance arrangements. The development of Valio's centralized manure treatment technology is a good example demonstrating how law can fail in its ecological goals by imposing ill-advised limitations on the grassroots implementation of ecologically sustainable technology.

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