CAN FARMERS MEET ALL THE SOCIETAL DEMANDS WITH THE AVAILABLE NATURAL RESOURCES?

KRISTINE VALUJEVA

Propositions

1. Not every field has an equal right to be cultivated.
   (this thesis)
2. Cooperation and understanding of desired outcomes between actors form the basis for sustainability.
   (this thesis)
3. The impact of the EU Green Deal may diverge amongst Member States, despite its common objectives.
4. In research experiencing is as important as reporting.
5. Knowing how to search and whom to ask is a skill in itself.
6. Working with stakeholders problems and solutions in science is like combining flavours, structures, and textures in baking.

Propositions belonging to the thesis, entitled

Can farmers meet all the societal demands with the available natural resources?

Kristine Valujeva
Wageningen, 21 March 2023

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Kristine Valujeva

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Can farmers meet all the societal demands with the available natural resources?

Kristine Valujeva

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For my grandmother,
smallholder farmer with a big heart

♥

TABLE OF CONTENTS

Chapter 1

General introduction

1. CHANGING ENVIRONMENT

When I was a little girl, I was asked at school what the world would be like after 100 years. I remember drawing a globe, painting it blue, drawing small brown patches of land, and writing under the picture, "*in 100 years there will be only water, very little land*". I'm not sure where I learned this, because global concerns were never discussed in my family. Now after many years my answer is becoming more and more important as we experience changes in the landscape, both as a result of economic activities and naturally. We have deforested areas, drained wetlands and plowed meadows for agricultural production. Climate change causes further biodiversity disturbances and mortality, changes in the hydrological cycle and threatens natural resources and the resilience of ecosystems. Climate change also causes irreversible changes to the landscape, and can have significant impacts on human health, safety and economic stability. As a result, we experience flash floods, when the monthly norm falls in a short period of time, or long periods of drought which negatively affect yield if there is no irrigation system in place. Flora and fauna gradually change, and in addition to typical wild plants and animals, other species arrive for which the temperate climate was not previously suitable.

When we grow up in one place or live in the same residence for many years, we get used to the landscape that we see around. The landscape becomes predictable, and we have the impression that next year, or in five or ten years, that it will still be the same. Residents of temperate regions see wetlands, coastal dunes, grasslands, agricultural fields, forests, lakes and rivers around them. Interaction between nature and humans in the long-term has created a mosaic-like landscape with different proportions of forests and agriculture in the landscape. The proportions between these land uses differ between countries, for example, 11% of land is under forestry in Ireland whereas in Finland forestry occupies 66% of land use (Eurostat, 2021).

Economic activities in temperate regions have mostly been based on agricultural and forestry production. Agriculture in temperate regions has changed not only as a result of political changes, during which farms of a few hectares were transformed into collective farms and later back to land privatization and the revival of private farms, but also as a result of agricultural industrialization and technological development. Technological development has made it possible to create very large farms that manage several thousand hectares. However, it has also led to the gradual disappearance of small farms and the abandonment of rural areas. There is an ongoing competition between farmers for productive agricultural land, which results in annually rising land prices and makes it very difficult for young farmers to start farming from scratch.

2. THE CHALLENGES OF TODAY AND TOMORROW

Within the EU, different countries have followed different trajectories in agricultural development, the echoes of which are still present in land management decisions today. Agriculture in Western Europe was driven by the Common Agricultural Policy (CAP) with the original aim to increase productivity, ensure availability of food at reasonable prices and provide fair living standards for farmers, but that led to an increase in environmental externalities (Schulte et al., 2019). In Eastern Europe, economic and agricultural activities dramatically decreased after 1990 in response to geopolitical changes. There, land abandonment occurred and new free market-oriented agriculture emerged, resulting in bimodal distributions of farming. Most of the farms are very small or medium sized while the number of large farms is significantly lower, but these large farms manage the majority of the land area (i.e. Kreišmane et al., (2018); Van Vliet et al., (2015)).

Nowadays, society expects more from the land. Society also expects the land to deliver ecosystem services, but the demand for ecosystem services varies between scales and stakeholders. Soil and land management in particular are affected by discrepancies between the scale of supply vs. demand for ecosystem services (Schulte et al., 2015a). For instance, policy makers seek to preserve biodiversity and to increase carbon sequestration at the national scale, while farmers are more interested in increasing yields and soil fertility at the local scale. Agricultural and environmental stakeholders prioritize ecosystem services differently depending on values, knowledge and experience. Ureta et al. (2020) concluded that residents living further away from water bodies with insufficient water quality prioritize other ecosystem services. In order to preserve the values that are important to the wide range of stakeholders, it is necessary to focus on multi-functionality as a shared goal in addition to seeking local land use solutions (Hölting et al., 2020). This challenge requires meeting multiple policy targets at national levels, while solutions and diverging societal expectations may be found at local and regional scales.

3. SUSTAINABLE LAND MANAGEMENT

Sustainable land management has been defined as "*a knowledge-based procedure that helps to integrate land, water, biodiversity, and environmental management to meet rising food and fibre demands while sustaining ecosystem services and livelihoods*" (World Bank, 2006). The main premise for sustainable land management is to maintain the ability of soil to provide a wide variety of ecosystem services. Poor land use practices degrade soils which are crucial for providing food, fibre and further essential goods for humans to achieve socio-economic and climate policy objectives. Understanding the capacity of soils to provide ecosystem services and ensure sustainable land management is a key factor for achieving all the demands that society expects from soils and the land (Mueller et al., 2010; Schulte et al., 2014).

Soils are multifunctional but have a different capacity to deliver on each of soil function. For example, some soils are better at providing food and feed, while other soils are better at providing carbon sequestration. This in turn determines what kind of land use would be most appropriate for that soil and therefore for society to gain the expected benefit from the land. In this context, the Functional Land Management (FLM) framework was developed by Schulte et al., (2014) with the aim to optimise rather the maximise the supply of soil functions to meet agronomic and environmental demands, namely primary productivity, water purification and regulation, carbon sequestration and regulation, the provision of habitats for biodiversity and the provision and cycling of nutrients. The European Research Project LANDMARK (LAND Management: Assessment, Research, Knowledge Base), funded by the European Union's Horizon 2020 research and innovation programme, described each soil function and developed definitions used in the FLM framework (LANDMARK, n.d.):

1) Primary productivity is a capacity of soils to produce plant biomass for human use, providing food, feed, fibre and fuel within natural or managed ecosystem boundaries;
2) Water purification and regulation is a capacity of a soil to remove harmful compounds from the water that it holds and to receive, store and conduct water for subsequent use and the prevention of both prolonged droughts and flooding and erosion;
3) Climate regulation and carbon sequestration is a capacity of a soil to reduce the negative impact of increased greenhouse gas (i.e., CO_2, CH_4, and N_2O) emissions on climate;
4) Soil biodiversity and habitat provisioning is a multitude of soil organisms and processes, interacting in an ecosystem, making up a significant part of the soil's natural capital, providing society with a wide range of cultural services and unknown services;
5) Provision and cycling of nutrients is a capacity of a soil to receive nutrients in the form of by-products, to provide nutrients from intrinsic resources or to support the

acquisition of nutrients from air or water, and to effectively carry over these nutrients into harvested crops.

Determining the suitability of a specific soil type for a land use is the first step towards achieving a balance between demand and supply of soil functions. Synergies do exist between soil functions, but when the maximisation of one soil function happens, trade-offs may occur when other soil functions are negatively affected (Schulte et al., 2019). For instance, the intensification of agricultural production is one way to quickly and efficiently meet the demand for primary productivity, but such actions may also reduce the ability of the land to meet biodiversity and climate regulation demands (de Vries et al., 2013; Tuck et al., 2014). Optimisation of individual functions can lead to state where all needs have been taken into consideration. Policies are required for the careful management of our soils and land at local levels in order to meet the demand for all the various socio-economic and climate policy requirements at national scales. The inclusion of soil multi-functionality and targeted incentives for sustainable land management in policy development ensures sustainability in the long-term.

4. THE CASES OF IRELAND AND LATVIA

Ensuring long-term sustainability in land management is highly dependent on local soil characteristics and its best-suited land management approach. Ireland and Latvia represent the Western-most and Eastern-most extremes of the temperate climate region in the EU (Figure 1). There are differences in climate between the two countries, as Ireland has a temperate oceanic climate and Latvia has a temperate continental climate (Kottek et al., 2006). Climatic differences have determined that in Ireland grassland and livestock production play the main role in the economy, while in Latvia it is crop production and forestry.

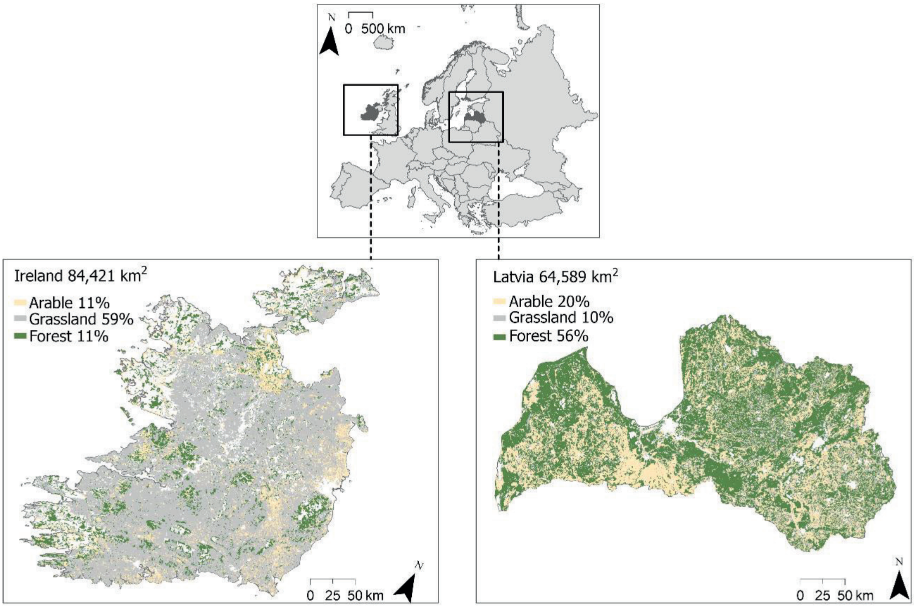

Figure 1. The locations of the study areas.

4.1. FARM DEMOGRAPHICS

Agriculture in temperate region is highly productive, and is important source of income for rural residents. In the last twenty years, the population globally has migrated from rural regions to cities in search of better livelihoods. For the development of rural areas, it is crucial to improve infrastructure, provide the necessary services for residents within close range, and promote the desire of young people to stay in and/or to move to rural areas. Approximately 137,500 family farms are located in Ireland, of which 50% are small farms and 12% are large farms, with an average size of 32.4 ha per holding (CSO, 2016). The number of agricultural holdings in Latvia is smaller (69,933), but the majority of farmers have small and medium-sized holdings (97.1%) managing 54.8% of the total agricultural land, while large holdings are managing 45.2% of the total agricultural area (CSB, 2018).

4.2. MANAGING SOILS FOR CLIMATE MITIGATION

Despite these differences in land use and farm demography, the challenges in land management caused by soil properties are similar in both countries, as both mineral and organic soils are cultivated for agricultural production. In both countries precipitation exceeds evaporation, which necessitates the removal of excess water and the construction of artificial drainage systems. In Ireland 44% of all agricultural land is artificially drained and in Latvia 70% (Helmane, 2020; Paul et al., 2018). The drainage of mineral soils decreases the groundwater level and changes the soil moisture regime, but it does not significantly affect the greenhouse gas (GHG) balance from mineral soil. The IPCC guidelines also do not require to report GHG emissions from drained mineral soils (IPCC, 2019).

Depending on land use and management, organic soils can serve as a carbon sink and also create enormous emissions when drained (Roßkopf et al., 2015). The area of managed organic soils is 339,370 ha in Ireland and 159,6300 ha in Latvia (NIR IE, 2022; NIR LV, 2022). In 2020, the agricultural sector accounted for 31.3% of total GHG emissions in Ireland and 18.7% in Latvia (EEA, 2021). GHG emissions from the management of organic soils also contributes a significant share of total GHG emissions from the agricultural sector, as CO_2, N_2O and CH_4 emission factors for drained organic soils in grassland and cropland ranges from 3.6 to 7.9 tonnes CO_2-C ha^{-1} yr^{-1}, 8.2 to 13 kg N_2O-N ha^{-1} yr^{-1}, and 0 to 39 kg CH_4 ha^{-1} yr^{-1} (IPCC, 2014).

4.3. MEETING MULTIPLE SOCIO-ECONOMIC AND ENVIRONMENTAL OBJECTIVES

Considering the aforementioned challenges, Ireland and Latvia are contemporary and highly relevant case studies for the global challenge to increase bio-based production, decrease GHG emissions, improve carbon sequestration and water quality and preserve biodiversity simultaneously, due to the availability of bio-resources. Both Ireland and Latvia have the potential to increase bio-based production, but two issues arise. Firstly, it is restricted by Paris Agreement where the EU has set the GHG emission reduction targets in 2030 to -30% for Ireland and -6% for Latvia (EU, 2018). Secondly, the possible expansion of bio-based production is limited by the Birds Directive, which protects all wild bird species and their most important habitats throughout the EU; the Habitats Directive, which aims to promote the conservation of biodiversity while taking into account economic, social, cultural and regional requirements; and the EU Biodiversity Strategy for 2030 (EC, 2020a), which is the latest strategy at the EU level with aims to protect and significantly improve the quality of biodiversity in the EU. Thirdly, the intensification of bio-based production is restricted by the Nitrates Directive (EC, 1991), which limits nitrates of agricultural origin in water in order to achieve the aim of the Water Framework Directive, which is good chemical and ecological status of all water bodies in the EU (EC, 2000).

This, in turn, complicates the achievement of socio-economic targets. Following the EU's abolition of the milk quota in 2015, Irish farmers had the opportunity to increase their production without market constrains for the first time over 30 years. In Latvia, the Bioeconomy Strategy has set targets to 1) increase added value from traditional bioeconomy sectors, namely agriculture and forestry, from EUR 2.33 billion in 2016 to EUR 3.8 billion in 2030; 2) to increase the value of exported goods from EUR 4.26 billion in 2016 to at least EUR 9 billion in 2030; and 3) to ensure that employment is provided for 128,000 inhabitants (LIBRA2030, 2017).

4.4. MEETING MULTIPLE OBJECTIVES: EXISTING RESEARCH

Assessments of ecosystem services provided by land resources are very complex, as the evaluation of the land-based ecosystem services provided depends on the scientific field represented by the researcher, the researcher's understanding of the definitions and the available data (Bouma, 2014; Calzolari et al., 2016; Haygarth and Ritz, 2009). On the other hand, the demand for land-based ecosystem services is created by society, state policy planning documents and international agreements. Assessment of land-based ecosystem services requires the involvement of a diverse team of scientists, as soil resources are heterogeneous, and yields within a single farm can differ greatly due to different on-site variables, micro-topography and soil heterogeneity. The FLM approach was developed to provide a framework for the assessment of the land-based ecosystem services provided by farmland and the demand for those resources. The framework was first applied to land management in Ireland with the aim to meet clearly defined objectives of agricultural growth and the environment (Coyle et al., 2016; O'Sullivan et al., 2015; Schulte et al., 2014, 2015a). From 2015 until 2020 the FLM framework was further developed within the European Research Project LANDMARK where the project aimed to manage the competing societal demands on land in Europe. LANDMARK was a pan-European multi-actor consortium of 22 leading academic and applied research institutes, chambers of agriculture and policy makers from 14 EU countries and Switzerland, China and Brazil (https://cordis.europa.eu/project/id/635201).

Building on the FLM concept as developed in Ireland and in the LANDMARK project, the Latvian project "Evaluation of the land use optimization opportunities within the Latvian climate policy framework" ran from June 2016 until June 2018. The project was funded by the Latvian State Forest and explored the scope to expand forestry, considering agricultural needs and requirements for carbon sequestration and biodiversity in Latvia. The findings of this project allowed for the determination of the socio-economic impact of scenarios for the supply of different soil functions. Within the project, available land use, land management, and soil data were collected from the Rural Support Service, the State Forest Service, the State Land Service, the Latvian State Forest, the Central Statistical Bureau, the Agricultural Data Centre, the Ministry of Agriculture and the Ministry of Environmental Protection and Regional Development. One of the findings from the project was the distribution of agricultural land in Latvia: 2,349,498 ha of land was formally classified as agricultural land, but in practice about 11% of agricultural lands were abandoned. More than 50% of total area in Latvia was covered by forests, and other land uses including water bodies, peatlands, and urban areas occupied less than 1 million hectares. 1,965,157 ha were maintained in good agricultural condition and approximately 85% of that area was used for commercial agricultural production and was registered for support payments, namely the Single Farm Payment.

4.5. KNOWLEDGE GAP

We expect many ecosystem services from land resources, but not all soil and land-use combinations can provide all of these ecosystem services simultaneously. While the LANDMARK project and the Latvian project provided the frameworks for assessing the supply and demand for multiple soil functions, the socio-economic and policy mechanisms to match supply and demand remained elusive. This knowledge gap marked the starting point of my PhD:

1) How can we meet national obligations while acknowledging, and leveraging, local and regional variation in the supply of soil functions?
2) How can land managers be incentivised most effectively to maximise synergies and minimise trade-offs between soil functions, to meet multiple societal demands?

5. OBJECTIVES AND RESEARCH QUESTIONS

The dual aims of this PhD study were to further develop the FLM methodology for implementation and to provide the knowledge base for stakeholders to jointly optimise land use and land management to meet competing expectations on land, which include the intensification of food production, the preservation of natural habitat and the mitigation of climate change.

To achieve the dual aims of this PhD study the following research questions were posed:

1) How to maximise the synergies and minimise the trade-offs of land use and land management in line with local demands? (Chapter 2)
2) How to evaluate the performance of landscape through FLM, and to what extent does the supply of soil functions meet the demand? (Chapter 3)
3) How can regional differences in both the supply and the demand of soil functions be utilised and harnessed to deliver on national objectives? (Chapter 4)
4) What are the main gaps facing implementation for agri-environmental stakeholders and how can these gaps can be bridged? (Chapter 5)
5) How can these methodologies be used to inform trajectories for sustainable land management? (Chapter 6)

6. THESIS OUTLINE AND METHODS

The outline of this thesis is shown in Figure 2. In this thesis FLM methodology is further developed through Irish and Latvian case studies. Primary productivity, carbon regulation and water purification were used for the Irish case study. The Latvian case study focuses on biodiversity instead of water purification because in 2018, the annual average nitrate concentration in surface water bodies did not exceed the limit of 11.3 mg nitrate-N per L as defined by the EU Nitrates Directive (LVĢMC, 2018).

The following methods were used to investigate how to increase food production in the Irish case study while achieving environmental objectives: 1) literature research for framing the supply and demand for primary productivity, carbon regulation and water purification; and 2) non-spatial modelling of land management to achieve both production and environmental targets at the same time.

To analyse and describe the differences in supply and demand of three soil functions in Latvia, namely primary productivity, carbon regulation, and biodiversity and how those differences can be implemented in policies to achieve socio-economic and climate targets simultaneously, three different methods were used: 1) literature research to describe indicators of soil functions and to develop a tabular index system for the evaluation of soil functions; 2) land use spatially-explicit modelling and application of management practices; and 3) semi-structured interviews with farmers.

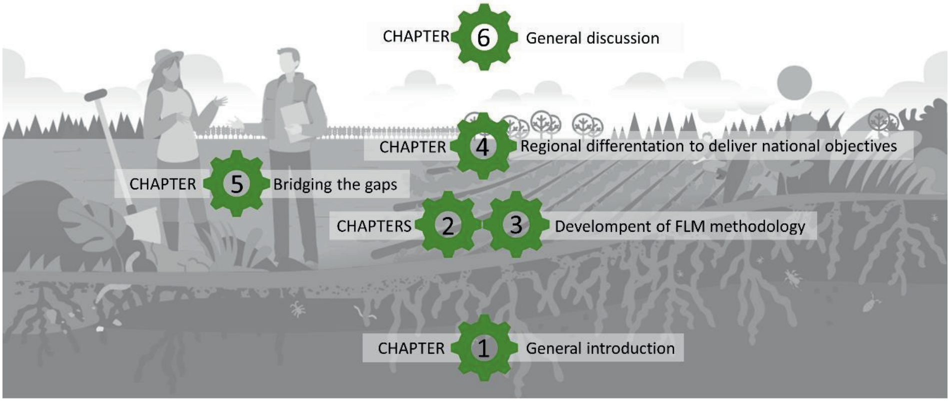

Figure 2. Schematic outline of the thesis.

Chapter 2 describes the Irish case study where FLM is deployed and evaluated to understand to what extent agronomic and environmental targets can be met simultaneously. This chapter investigates how land management can be used to increase food production and simultaneously meet environmental targets, such as the protection of water and the mitigation of greenhouse gas emissions.

In **Chapter 3** FLM is used for the Latvian case study to develop a national approach which shows regional differences in the capacity of three soil functions associated with land use and contrasting soil organic content (mineral vs. organic soil), namely primary productivity, carbon regulation and the provision of habitat for biodiversity. Demand for each soil function is framed by national policies and international commitments.

In **Chapter 4** the extent to which regional differences in the supply of soil functions can be leveraged to meet multiple national objectives has been assessed. To do so, a quantitative national model for land use optimisation and application of management practices in Latvia has been developed. This chapter focuses on the role of reintegrating abandoned agricultural land into land management decisions and shows to what extent the synergies and trade-offs between three soil functions differ per region.

Chapter 5 further identifies how different synergies and trade-offs in different regions can be communicated to the farmers to help them to optimise their land management. Using social network analysis, an analysis of the Agricultural Knowledge and Information System (AKIS) in Latvia has been done to investigate knowledge exchange about primary productivity, carbon regulation and biodiversity.

In the **General Discussion** chapter, outcomes and implications of the thesis as a whole are discussed. A combination of knowledge of soil functions and implementation via policies increases the likelihood that multiple targets will be achieved. Knowledge and information exchange between different stakeholders is an important factor in finding solutions for national objectives at local and regional levels. The importance of links between farmers and other stakeholders to provide knowledge-based land management is emphasised. Inconsistency of policy planning documents and possible trajectories towards sustainable land management are also discussed.

Chapter 2

The challenge of managing soil functions at multiple scales: an optimisation study of the synergistic and antagonistic trade-offs between soil functions in Ireland

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ABSTRACT

Recent forecasts show a need to increase agricultural production globally by 60% from 2005 to 2050, in order to meet a rising demand from a growing population. This poses challenges for scientists and policymakers to formulate solutions on how to increase food production and simultaneously meet environmental targets such as the conservation and protection of water, the conservation of biodiversity, and the mitigation of greenhouse gas emissions. As soil and land are subject to growing pressure to meet both agronomic and environmental targets, there is an urgent need to understand to what extent these diverging targets can be met simultaneously. Previously, the concept of Functional Land Management (FLM) was developed as a framework for managing the multifunctionality of land. In this paper, we deploy and evaluate the concept of FLM, using a real case-study of Irish agriculture. We investigate a number of scenarios, encompassing combinations of intensification, expansion and land drainage, for managing three soil functions, namely primary productivity, water purification and carbon sequestration. We use proxy-indicators (milk production, nitrate concentrations and area of new afforestation) to quantify the 'supply' of these three soil functions, and identify the relevant policy targets to frame the 'demand' for these soil functions.

Specifically, this paper assesses how soil management and land use management interact in meeting these multiple targets simultaneously, by employing a non-spatial land use model for livestock production in Ireland that assesses the supply of soil functions for contrasting soil drainage and land use categories. Our results show that, in principle, it is possible to manage these three soil functions to meet both agronomic and environmental objectives, but as we add more soil functions, the management requirements become increasingly complex. In theory, an expansion scenario could meet all of the objectives simultaneously. However, this scenario is highly unlikely to materialise due to farm fragmentation, low land mobility rates and the challenging afforestation rates required for achieving the greenhouse gas reduction targets. In the absence of targeted policy interventions, an unmanaged combination of scenarios is more likely to emerge. The challenge for policy formation on future land use is how to move from an unmanaged combination scenario towards a managed combination scenario, in which the soil functions are purposefully managed to meet current and future agronomic and environmental targets, through a targeted combination of intensification, expansion and land drainage. Such purposeful management requires that the supply of each soil function is managed at the spatial scale at which the corresponding demand manifests itself. This spatial scale may differ between the soil functions, and may range from farm scale to national scale. Finally, our research identifies the need for future research to also consider and address the misalignment of temporal scales between the supply and demand of soil functions.

Keywords: Functional Land Management, Greenhouse gas, Livestock, Optimisation, Sustainable intensification, Water quality

1. INTRODUCTION

Recent forecasts indicate that world population will grow by 2.5 billion from 2015 to 2050 (PRB, 2015). By that time, agriculture production globally must have increased by 60% from 2005 levels (WWDR, 2015). This poses challenges for scientists and policymakers to derive solutions on how to increase food production and at the same time meet environmental targets such as water protection, conservation of biodiversity or climate change mitigation. For example, the European Union (EU) Water Framework Directive (2000/60/EC) provides a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater (EC, 2000). It requires Member States (MS) to establish river basin districts and an associated management plan for each river basin. It supersedes the Nitrates directive (91/676/EEC) which was developed to reduce water pollution caused by nitrates from agricultural sources (EU, 2010). Similarly, in 2011 the EU adopted its EU Biodiversity Strategy to 2020 to halt the loss of biodiversity and ecosystem services by 2020 (EU, 2015a). In relation to mitigating climate change, in 2007, the EU committed to reducing greenhouse gas (GHG) emissions in the year 2020 by 20% compared to 1990 levels, increasing renewable energy use by 20%, and to improving energy efficiency by 20% (EU, 2014), as part of the "EU Energy and Climate Package 2020". This policy will be replaced by the new "EU Climate and Energy framework 2030" for the period between 2020 and 2030 (EU, 2015b), which proposes to reduce GHG emissions by 2030 by 40% compared to 1990, and to increase renewable energy use and energy savings by at least 27% compared with the business-as-usual scenario (EU, 2015b).

The growing societal pressures on the soil resource prompted the European Commission (EC) to publish the EU Thematic Strategy for Soil Protection in 2006, which set a common EU framework for action to preserve, protect and restore soil by implementing actions customised to local situations (EC, 2006). This strategy considers the different functions that the soil can perform, and also the main threats to soil quality. Soil based ecosystem services, also known as soil functions, have previously been described in a number of studies including Bouma and Droogers (2007); Calzolari et al. (2016); Haygarth and Ritz (2009). In the Netherlands, Bouma and Droogers (2007) proposed a six-step procedure for a water management unit using existing soil data related to the soil topics of soil functions, threats and quality. Haygarth and Ritz (2009) proposed 18 ecosystem services that are critical for soil and land use in the United Kingdom. Also, a methodological framework of eight soil functions has been developed by Calzolari et al. (2016).

In many countries, the diverging policies put pressure on land and soil to meet both agronomic and environmental targets, necessitating a better understanding as to how and to what extent these targets can be achieved simultaneously. In response, Schulte et al. (2014) developed the concept of Functional Land Management (FLM) as a framework for optimising the delivery of five soil functions, specifically for agricultural land use:

1. Primary productivity;
2. Water purification and regulation;
3. Carbon sequestration and regulation;
4. Provision of habitat for biodiversity;
5. Nutrient cycling and provision.

Within the FLM framework the supply of these soil functions is dependent upon land use and soil type while demand is framed as policy drivers. Accordingly, challenges to sustainability will vary spatially across locations. To meet the challenge of intensifying agriculture sustainably, FLM seeks to match the supply of soil functions with demand (Schulte et al., 2014).

The FLM framework is underpinned by the multifunctionality of soils: which is that all soils perform all of these five functions simultaneously, but some parts of the land perform some functions better than others (O'Sullivan et al., 2015; Schulte et al., 2014). Central to the FLM framework is that land

and soil management is aimed at optimising, rather than maximising, the supply of each of the soil functions. While maximising would seek to achieve the highest total delivery of soil functions, optimising gives priority to meeting demands at the spatial and temporal scales required by policy objectives (Schulte et al., 2015a).

Coyle et al. (2016) elaborated on the FLM framework, by relating the delivery of multiple functions to land use and soil properties, using the Atlantic pedo-climatic zone of Europe as their geographical region of interest. They showed that in this region, the delivery of soil functions is mainly determined by soil drainage properties and that augmentation of one soil function is likely to result in the alteration of other soil functions (see also O'Sullivan et al. (2015b)).

Furthermore, Schulte et al. (2015) explored how the demand for different soil functions operates at different scales. For example, the demand for water purification manifests itself at a local scale, whereas the demand for carbon sequestration exists at national scale. The authors conclude that this has implications for the management of the supply for soil functions, namely: soil management for water quality at local scale, and land use management for climate mitigation at national scale.

So far, the FLM framework, and the exploration of trade-offs and synergies between the various soil functions have been largely conceptual, with the exception of the study by O'Sullivan et al. (2015b) into the trade-offs between primary productivity and carbon sequestration. In this current paper, we used empirical data to explore scenarios for FLM, aimed at meeting multiple agronomic and environmental policy objectives. Using Ireland as a case study, we assessed how soil management and land use management interact in meeting multiple targets simultaneously. For simplicity, we limited our analysis to the three functions primary productivity, water purification and carbon sequestration. Two of these soil functions are part of the set investigated by Calzolari et al. (2016).

2. MATERIALS AND METHODS

3. CASE STUDY

For our case study, we used Ireland as a national example of the challenges facing the agricultural sector in relation to meeting both agronomic and environmental targets. Dairy and livestock production play a central role in Irish agriculture: 80% of agricultural land is grassland (Teagasc, 2015), and most of the herbage is grazed in situ, with the remainder harvested as silage that is fed during the relatively short housing seasons (2–5 months), during which it may be supplemented with various amounts of concentrates (Schulte et al., 2014). Food Harvest 2020 represents the industry strategy, supported by the Irish government, to increase national milk production between 2010 and 2020 by 50%. The abolition of the milk quota in Europe in 2015 gives Irish farmers for the first time in over 30 years the opportunity to increase their production without being constrained by quota. Food Harvest 2020 has now been followed by the Food Wise 2025 strategy which foresees a further rising of ambitions, however without defining further volume targets for production. Both strategies aim to keep volume outputs of other agricultural sectors stable while increasing export values. Following a Strategic Environmental Assessment (SEA) (EU, 2001), the preferred pathway for implementation is the 'Sustainable Growth' scenario, in which the increase in dairy output is achieved through sustainable intensification, that is without significant increases in pressures on the environment.

In this paper, we assess various permutations for the Sustainable Growth scenario, with a view to optimising the delivery of three soil functions, namely: primary productivity, water purification and carbon sequestration, to meet the societal demands as framed by legislation and national policy objectives.

3.2. PROXY-INDICATORS

The demand for soil functions is framed by the agri-environmental policy framework. Based on the original work of Schulte et al. (2014) the following are the proxy-indicators defined for the current research:

1. Primary productivity: for the first soil function we identify increased milk production as the most pertinent proxy-indicator. The demand for this soil function is framed within the national Food Harvest 2020 policy documents that seeks to increased dairy production volume by 50% by 2020 (DAFM, 2015).
2. Water purification: for this soil function we selected the nitrates concentration in groundwater recharge as the (partial) proxy-indicator. The demand for this function is defined by the Nitrates Directive that indicates that groundwater nitrates-N (NO_3-N) concentrations must not exceed 11.3 mg per litre (EC, 1991).
3. Carbon sequestration: for this soil function we adopt the annual planting rate of new afforestation as the proxy-indicator (DAFM, 2015). Ireland has been allocated an emissions reduction target of 20% (EU, 2014). The EU Climate and Energy Framework 2030, currently under review, expands on this ambition and proposes and EU-wide emissions reduction target for the non-emissions trading sector (non-ETS) of 30% compared to 2005 (EU, 2015b).

In relation to the third proxy-indicator above, the European target has not yet been transposed into national targets for individual MS, but is likely to result in a target for Ireland in excess of the current 20% reduction. Assuming the Irish government chooses to implement the reduction targets equally through all sectors not covered by the European Emissions trading System and in the absence of certainty, we adopted a nominal and realistic reduction target of 25% for Irish agriculture. Previously, (Schulte et al., 2012a, 2012b) showed that the predominance of ruminants in Ireland's agricultural sector means that it is very difficult to reduce sectoral GHG emissions under a Food Harvest 2020 growth scenario: at best, GHG emissions may be kept constant while growing milk output and any further reductions will require offsetting in the form of carbon sequestration. In a subsequent study (Schulte et al., 2013) identified new afforestation as the most promising pathway to increased carbon sequestration under Ireland's current land use and pedo-climatic conditions. Therefore, in our scenario assessments, carbon offsetting is achieved entirely through afforestation.

3.3. OPTIMISATION SETS

Having defined the soil functions of interest and the proxy-indicators for demand, we subsequently formulated three optimisation sets:

1. In our first set, we assessed options for land and soil management aimed at meeting the target for increased primary productivity only;
2. In our second set, we assessed options to meet targets for both primary productivity and water purification and;
3. In our third set, we assessed options to meet the targets for all three soil functions, namely primary productivity, water purification and carbon sequestration.

These optimisation sets were designed to allow the challenge of managing multiple functions simultaneously to be demonstrated. In turn, this will inform better understanding of the synergistic and antagonistic trade-offs between the three soil functions under examination and how the options for optimisation are altered as additional targets are added to the optimisation sets. Finally, this will determine to what extent the achievement of current policy demand drivers can realistically be achieved.

3.4. OPTIMISATION SCENARIOS

We explored the impacts of land use and soil properties on the delivery of the three soil functions of interest, informed by the land use x natural drainage class matrix developed by (Coyle et al., 2016) and deployed by Schulte et al. (2015). This framework is based upon an extensive literature review that considers the delivery of soil functions in the Atlantic pedo-climatic zone. This study identified soil drainage class as a dominant driver in relation to the delivery of soil functions for this particular climate zone. In this regard, Schulte et al. (2015) identified three options to manage, and hence optimise, soil functions in the Atlantic pedo-climatic zone:

1. Soil management aimed at augmenting a selective soil function (e.g. primary productivity) without compromising other functions (e.g. water purification, biodiversity). Examples include the introduction of nutrient or grazing management plans;
2. Land Use Change: the capacity of soils to supply the five soil functions is in first instance governed by land use. As a result, the local supply of soil functions may change following a change in land use. For example, a change from extensive grassland (typically associated with drystock production systems) to intensive grassland commonly found in dairy production systems is likely to result in increased primary productivity, but a concomitant decrease in the potential for water purification and biodiversity (Coyle et al., 2016).
3. Soil Drainage: additionally, the capacity of soils to supply the five functions is regulated by soil properties. In Atlantic Climates, the most important properties are those relating soil water dynamics (Coyle et al., 2016). These properties can be integrated and categorised by ascribing natural drainage classes to soils (see Section 2.5). The installation of arterial drainage systems changes the drainage class of a soil either from ‘poor’ to ‘moderate’, or from ‘moderate’ to ‘well’. This has a major impact on the supply and composition of the suite of soil functions. Typically, soil drainage allows for increased primary productivity, but at the expense of the potential for carbon sequestration (O’Sullivan et al., 2015).

Based on these pathways for managing soil functions, we investigated five scenarios aimed at meeting the demand for soil functions, for each of the aforementioned optimisation sets. These scenarios include a baseline scenario, each of the three pathways, and a combination scenario:

1. Baseline – this scenario represents current livestock production for Ireland.
2. Intensification – this scenario is based on soil management delivering higher productivity per hectare achieved by increasing the animal stocking rates and farm inputs on dairy farms.
3. Expansion – this scenario is based on land use change, namely an expansion of the dairy production platform into lands hitherto used for drystock production. This scenario is a reflection of current developments on dairy farms that were previously constrained by quota. In this scenario, the expansion of the area devoted to dairy farming is associated with an intensification (increased stocking rates and N usage) of the drystock farming systems, as the total number of drystock animals is assumed to remain constant, in line with the objectives of the Food Harvest 2020 and Food Wise 2025 policies.
4. Drainage – in this scenario, the productivity of land is increased, not by an increase in inputs, but rather by alteration of the static soil properties relating to drainage. Improved drainage results in higher grass growth, improved trafficability and improved grass utilisation (Schulte et al., 2012a, 2012b). Drainage is commonly associated with an increase in fertiliser N usage to support this increased productivity (Hanrahan et al., 2013), denitrification rates and hence nitrous oxide emissions are commonly lower as a result of the reduced anaerobicity (Jahangir et al., 2012).Conversely, nitrate concentrations in drainage water may be increased (Schulte et al., 2006) and the oxygenation of the soil may induce emissions of carbon dioxide (Burchill et al., 2014; Necpálová et al., 2014).

5. Combination – this scenario represents a combination of the intensification, expansion and drainage scenarios.

3.5. MODELLING FRAMEWORK

We simulated national livestock production in Ireland by dividing the grassland area into a matrix of land use classes and soil drainage classes. Soil drainage classes are based upon the Irish Soil Information System (SIS) launched in 2014 that classified Irish soils at a scale of 1:250,000 (Creamer et al., 2014). Within the Irish soil classification system, Soil Subgroups are defined upon diagnostic criteria, such as gleying or stagnic properties (Table 1). Diagnostic features were then used to define natural drainage classes for Irish soils and to develop the indicative soil drainage map of Ireland, described by (Schulte et al., 2015b). This allowed the soils to be clustered based upon natural drainage class here, following the matrix developed by Coyle et al. (2016). For land use, we focussed exclusively on grasslands. Irish agriculture is dominated by grassland, which comprises approximately 80% of the agricultural land in Ireland (Teagasc, 2015). Within this, we delineate our area of interest into modelling 'bins' dedicated to 'dairy' and for 'drystock' as representative of the main farming systems on these grasslands (Fig. 1). The total number of cattle in Ireland is ~6.4 million, including ~1.2 million dairy cows (CSO, 2015). The remaining drystock comprises of suckler cows, male and female cattle (ages less than two years), bulls and beef in-calf heifers (CSO, 2015). Due to the physiological strain on the animals producing milk, dairy farming is characterised by a higher feed demand and N excretion per head as compared to drystock farming (Shalloo et al., 2004). In addition, for the third Optimisation Set, we considered a third land use type, namely new afforestation, planted on grassland.

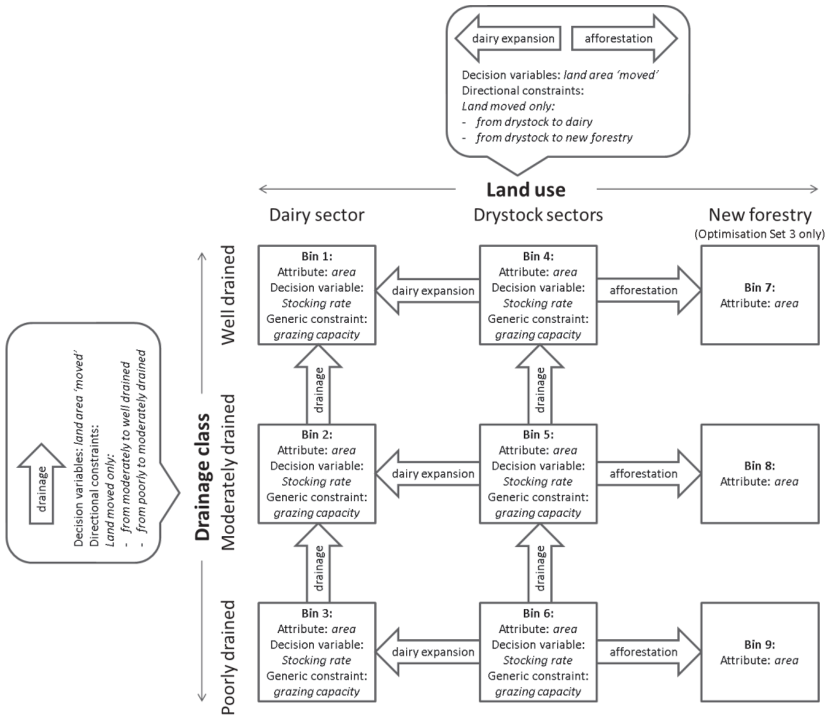

Figure 1. Modelling framework: visualisation of modelling bins, consisting of combinations of land use and soil drainage classes, as well as decision variables and generic and directional constraints.

3.6. DATA SETS

All optimisation scenarios (in all optimisation sets) used the baseline scenario as the starting conditions to in itialise the optimisation process. Using existing data (see Table 1) we established a baseline scenario for dairy production in Ireland before the abolition of the milk quota.

Table 1 Land area datasets

Managed grassland	LPIS "Permanent Pasture" data by DAFM which show farm outlines of all land held by farmers who have applied for support payments from the EU. Maps are updated annually by Mallon Technology since 1995 (Mallon Technology, 2014). This category was refined based upon the TLC95 map produced using aerial photography and satellite imagery (Fealy et al., 2009).
Soil Information System (SIS)	The Irish Soil Information System (SIS) has been prepared at a scale of 1:250,000 through the application of predictive mapping techniques in conjunction with traditional soil survey methods. The SIS was validated with a 2.5 year field survey including analysis of 11,000 auger bores (Creamer et al., 2014).
Drainage class	Drainage class based on the following diagnostic rules (Schulte et al., 2015b) was applied to Irish SIS at soil subgroup based on diagnostic features (Creamer et al., 2014): • Well: No mottling, no full argic/spodic horizon present • Imperfect: Mottling 40‑80 cm AND some organic matter accumulation and argic/spodic horizon present (at least a score of 1 in either category) • Poor: Mottling within 40 cm argic/spodic horizon causing stagnation

3.6.1. Land area

Our 'Managed grassland' category was derived by refining the Land Parcel Identification System (LPIS - used for administrative purposes by the Irish government Department of Agriculture, Food and the Marine) "Permanent Pasture" class through the application of a satellite image classification of land cover which classified 'Grassland' (Fealy et al., 2009). This overcame the challenge of mountain areas which are included in the LPIS "Permanent Pasture" class. Drainage classification was derived from the Irish Soils Information System 1:250,000 scale soils map (Creamer et al., 2014).

Using a geographical information system (GIS), the managed grassland class was intersected with drainage defined areas which enabled calculation of areas by class. In our scenario, dairy production occupies approximately 0.70 million hectares while 2.5 million hectares of grassland are used for drystock (Table 2).

3.6.2. Stocking rate

We derived livestock numbers from the census of Irish agriculture (CSO, 2012) which is conducted by the Irish national statistics body, the Central Statistics Office (CSO). CSO agricultural census data are available at an electoral division (ED) level in Ireland which corresponds to the Eurostat regional level LAU2 (Eurostat, 2015). The typical size of an ED is approximately 20 km^2. Again using GIS, we intersected the livestock numbers at ED level with the grass/drainage category spatial dataset. We subsequently calculated an indicative baseline stocking rate for each of the drainage classes, by regression of livestock numbers in each polygon against the grassland area of each polygon. We separated livestock numbers into 'dairy' and 'drystock', based on the dairy stocking rates reported in the Teagasc National Farm Survey (Hanrahan et al., 2013), with the remainder of the grassland areas devoted to drystock production.

The resulting stocking rates in the baseline scenario for dairy ranged from 2.04 Livestock Units (LU) per hectare for well and poorly drained soils to 1.29 LU per hectare on moderately drained soils, while the stocking rates for drystock ranged from 1.30 LU per hectare on well drained soils to 1.22 LU per hectare on moderately and poorly drained soils (Table 2). The counterintuitive finding that average dairy stocking rates on poorly-drained soils were not significantly different from those on well-drained soils may be explained by a higher internal variation within farm systems on poorly-drained soils, which include intensive systems that rely on large external inputs in the form of concentrates.

Table 2. Initialisation values for land area, stocking rates and grazing capacity for both dairy and drystock production systems, used for the baseline scenario in each optimisation set.

Drainage class	Land Area (ha)		Stocking rates (livestock units /ha)		Grazing capacity (livestock units /ha)	
	Dairy	Drystock	Dairy	Drystock	Dairy	Drystock,
Well	314,169	1,068,123	2.04	1.30	2.55	2.04
Moderately	205,954	700,209	1.29	1.22	2.57	2.00
Poorly	203,111	690,544	2.04	1.22	2.23	2.23

As a result, our model is based on six (for Optimisation sets 1 and 2) to nine (for Optimisation Set 3) modelling bins (Figure 1), for which we modelled changes in land area, stocking rate, nitrate concentration and GHG emissions.

3.6.3. Modelling of nitrate concentrations

For each of the modelling bins, we modelled nitrate concentrations of groundwater recharge as a function of nitrogen (N) surplus and net rainfall, for an 'average farm' within each bin. Nitrogen surplus was computed through a farm gate mass balance. The total nitrogen input data was calculated from N inputs in the form of fertiliser including the amount of N available in animal manure and N imported onto the farm in the form of concentrates.

We based fertiliser inputs on the national nutrient recommendations (Coulter and Lalor, 2008) which provide specific N recommendations for those parts of the farm that are (i) grazed only (ii) subjected to one cut of silage, followed by grazing and (iii) subjected to two cuts of silage. The proportions of these three areas depend on the grass sward type, stocking rate and animal type. The area defined for grazing only typically does not receive organic N in the form of slurry; this is instead applied to the two other areas. The amount of N available from slurry was calculated from livestock numbers, the length of the housing period and land area available for spreading. While this slurry represents an internal cycling of N within the farm boundaries, and is therefore not directly accounted for in the farm N balance, it does determine the quantity of fertiliser N that is recommended, following the national recommendations (Coulter and Lalor, 2008) and permitted at farm level under the Nitrates regulations.

The amount of concentrate intake for each livestock type, length of the grazing season, length of housing period and milk yield were derived separately for well drained and poorly drained soils, as described by Shalloo et al. (2004). For moderately drained soils, we interpolated the values for well and poorly drained soils.

We estimated the farm N surplus by subtracting N exports from N inputs. N exports were derived from stocking rate, productivity and milk and meat protein concentrations (Crosson et al., 2007; Shalloo et al., 2004) converted to N (Mariotti et al., 2008).

Part of the N surplus is lost to the atmosphere through denitrification or volatilisation of ammonia. Ammonia losses were calculated from animal housing and grazing periods according to the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines for National Greenhouse Gas Inventories (IPCC, 2009). Denitrification was computed as described in Schulte et al. (2014).

The annual quantity of nitrate produced was derived by mass balance. We converted this quantity to N concentrations using the typical annual net rainfall value of 500 mm, taken from Prado et al. (2006).

3.6.4. GHG emissions

We calculated greenhouse gas emissions for each bin, in accordance with the 2006 IPCC guidelines, using national emission factors taken from the National Inventory Report of Ireland (EPA, 2014). For the dairy and other livestock sectors we calculated nitrous oxide (N_2O) emissions from fertiliser use and methane (CH_4) emissions from enteric fermentation and manure management. Emissions associated with drainage were factored into the model based on the values found by O'Sullivan et al. (2015b).

In addition, for Optimisation Set 3, we calculated the offsetting potential of new afforestation, and the area of afforestation required to meet emission reduction targets, using the analysis of the "Carbon-Neutrality Report" (Schulte et al., 2013) with an indicative sequestration rate of 14.7 tonnes CO_2 equivalent per hectare per year for a 2050 timeframe.

3.7. OPTIMISATION

To optimise each of the scenarios, we used the Microsoft Office Excel 2010 add-in Solver. Solver is a built-in optimisation tool where users can develop a spreadsheet linear or non-linear optimisation model to find the optimal solution (Mason and Dunning, 2010). The optimisation of each set was controlled by defining the following parameters (Table 3):

- Objective function: in our case study the objective was to increase milk production by 50% (DAFF, 2010).
- Decision variables: these represent quantities that can be changed during the optimisation process in order to meet the objective function. In our case, the choice of variables depended on the scenario. For example, in our intensification scenario, the optimisation process was set to modify the values for the stocking rates for dairy on well, moderately and poorly drained soils.
- Constraints: these represent boundary conditions that the optimisation process must adhere to. Our constraints included generic, directional and specific constraints. Generic constraints included maximum stocking rates for well, moderately and poorly drained soils equating to the corresponding grazing capacities, as given in Lee and Diamond (1972). Feedlot systems with high stocking rates based on imported concentrate feeds were not considered. Directional constraints were applied to increases or decreases in the land areas of individual bins. For example, in the Drainage Scenario, soil properties can only change from moderately drained soils to well drained soils or from poorly drained soils to moderately drained soils. Other directional constraints included land use change from the drystock sector to the dairy sector, and from the drystock sector to farm forestry. Specific constraints were applied to individual optimisation sets: in Optimisation Sets 2 and 3 the nitrates concentrations were constrained to remain below the requirements of the Nitrates Directive (<11.3 mg l-1) (EC, 1991). Optimisation Set 3 included the additional constraint

for net GHG emissions (i.e. baseline emissions plus increase in emissions minus carbon offsetting through afforestation) to be reduced by 25% compared to the baseline emissions (2005). In line with the Marginal Abatement Cost Curve for Irish agriculture (Schulte et al., 2012a), we assumed that gross emissions can be reduced by 1.1 Mt of CO_2eq through technical abatement, with the remainder being offset through new afforestation (Schulte et al., 2013).

Table 3. Overview of the optimisation parameters (objective function, decision variables, and constraints) as applied to each of the five scenarios in each of the three optimisation sets.

	Optimisation set														
	Set 1 (primary productivity only)					**Set 2 (primary productivity + water purification)**					**Set 3 (primary productivity + water purification + carbon sequestration)**				
Optimisation parameters	baseline	intensification	expansion	drainage	combination	baseline	intensification	expansion	drainage	combination	baseline	intensification	expansion	drainage	combination
Objective function															
Increase milk production by 50%		X	X	X	X		X	X	X	X		X	X	X	X
Decision variables															
Increase stocking rate		X			X		X			X		X			X
Move land area from drystock to dairy			X		X			X		X			X		X
Move land area between drainage classes				X	X				X	X				X	X
Move land from drystock to forestry												X	X	X	X
Generic constraints															
Stocking rate <= grazing capacity of bin		X	X	X	X		X	X	X	X		X	X	X	X
Directional constraints															
Drainage: poor→moderate→well				X	X				X	X				X	X
Land use change: drystock→dairy			X		X			X		X			X		X
Land use change: drystock→forestry												X	X	X	X
Specific constraints															
NO_3-N <= 11.3 mg l^{-1}							X	X	X	X		X	X	X	X
GHG emissions: net reduction of 25%												X	X	X	X

4. RESULTS

Table 4 shows the results from all scenarios under all optimisation sets. Under the intensification scenarios, the stocking rates for dairy changed in all optimisation sets. Also, the stocking rates for drystock changed under Optimisation Set 3 due to changes in land area for drystock. Under the expansion scenarios, land area moves from land area for drystock to land area for dairy which is the reason for the change in stocking rates for drystock. Other changes in stocking rate for drystock can be attributed to land use change from drystock to forestry under Optimisation Set 3. Under the drainage scenarios, land area changes are due to the changes in land area between drainage classes, with the exception of Optimisation Set 3, where land area for drystock is also moved to forestry. The stocking rate for drystock changes in all optimisation sets because the number of drystock animals was assumed to remain constant.

Table 4. Optimisation results for each optimisation set (changes in red). Optimisation set 1 contained one objective only: to increase milk volume output by 50%. Optimisation Set 2 included the additional objective for water purification, to maintain NO_3-N concentrations below 11.3 mg l^{-1}, while Optimisation Set 3 included a further objective to reduce net GHG emissions from the agricultural sector by 25%. For a description of the various scenarios, see Table 3.

Objective		Optimisation Set 1					Optimisation Set 2							Optimisation Set 3									
		Primary productivity					Primary productivity, water purification							Primary productivity, water purification, C sequestration									
Scenario	Drainage class	increase in milk production, %	Stocking rate for diary, LU per ha	Stocking rate for drystock, LU per ha	Land area for diary, million ha	Land area for drystock, million ha	increase in milk production, %	max NO3 (dairy), mg per l	max NO3 (drystock), mg per l	Stocking rate for diary, LU per ha	Stocking rate for drystock, LU per ha	Land area for diary, million ha	Land area for drystock, million ha	increase in milk production, %	max NO3 (dairy), mg per l	max NO3 (drystock), mg per l	Stocking rate for diary, LU per ha	Stocking rate for drystock, LU per ha	Land area for diary, million ha	Land area for drystock, million ha	Emissions total, Mt CO_2 eq.	Emission offset required, Mt CO_2 eq.	Land use change to forestry, million ha
Baseline	well	0%	2.04	1.30	0.31	1.07	0%	10.8	9.4	2.04	1.30	0.31	1.07	0%	10.8	9.4	2.04	1.30	0.31	1.07	18.7	3.7	0.25
	mod		1.29	1.22	0.21	0.70		5.2	5.6	1.29	1.22	0.21	0.70		5.2	5.6	1.29	1.22	0.21	0.70			
	poor		2.04	1.22	0.20	0.69		3.4	2.7	2.04	1.22	0.20	0.69		3.4	2.7	2.04	1.22	0.20	0.69			
Intensification	well	35%	2.55	1.30	0.31	1.07	35%	11.0	9.4	2.55	1.30	0.31	1.07	35%	11.0	9.1	2.55	1.62	0.31	0.86	20.7	5.7	0.39
	mod		2.57	1.22	0.21	0.70		7.3	5.6	2.57	1.22	0.21	0.70		7.3	6.2	2.57	1.40	0.21	0.61			
	poor		2.23	1.22	0.20	0.69		2.9	2.7	2.23	1.22	0.20	0.69		2.9	3.0	2.23	1.40	0.20	0.60			
Expansion	well	50%	2.04	1.61	0.52	0.86	50%	10.8	9.2	2.04	1.61	0.52	0.86	50%	10.8	10.2	2.04	1.90	0.55	0.73	20.9	5.9	0.40
	mod		1.29	1.32	0.26	0.65		5.2	6.7	1.29	1.32	0.26	0.65		5.2	6.5	1.29	1.69	0.21	0.51			
	poor		2.04	1.38	0.28	0.61		3.4	3.1	2.04	1.38	0.28	0.61		3.4	3.0	2.04	1.69	0.29	0.50			
Drainage	well	13%	2.04	1.30	0.52	1.07	13%	10.8	9.4	2.04	1.30	0.52	1.07	13%	10.8	8.4	2.04	1.42	0.52	0.98	19.0	4.1	0.28
	mod		0.00	1.22	0	0.70		N/A	5.6	1.29	1.22	0	0.70		N/A	6.2	0.00	1.41	0.00	0.61			
	poor		2.04	1.22	0.20	0.69		3.4	2.7	2.04	1.22	0.20	0.69		3.4	3.0	2.04	1.41	0.20	0.60			
Combination	well	50%	2.55	1.30	0.32	1.07	50%	11.0	9.4	2.55	1.30	0.32	1.07	43%	9.5	8.1	2.35	1.46	0.31	0.95	20.3	5.4	0.32
	mod		2.57	1.24	0.22	0.69		7.3	5.5	2.57	1.24	0.22	0.69		6.4	6.6	1.37	1.97	0.36	0.43			
	poor		2.23	1.38	0.28	0.61		2.9	3.0	2.23	1.38	0.28	0.61		2.9	3.2	2.22	1.65	0.30	0.51			

In Optimisation Set 1, we assessed the pathways for achieving one objective only, namely to increase the supply of the function 'primary productivity' to meet the societal demand to increase dairy production volumes by 50% in Ireland. Of our four different scenarios (intensification, expansion, drainage and a combined scenario), this demand can only be met in the expansion and the combination scenarios (Figure 2). In these scenarios, the land area available to dairy is increased at the expense of land available to drystock, resulting in an increased stocking rate for drystock. By contrast, the demand for 50% more milk volume could not be met solely through intensification or drainage. In the intensification scenario; dairy stocking rates on all drainage classes reach carrying capacity, while in the drainage scenario, all moderately-drained land (which had the lowest dairy stocking rates) is converted to well-drained land, before the 150% milk volume target could be met. The combination scenario represents a combination of intensification, expansion and drainage scenarios. The higher milk production is due in part to higher stocking rates for well, moderately and poorly drained soils, similar to those under the intensification scenario, combined with dairy expansion onto land previously used for drystock production.

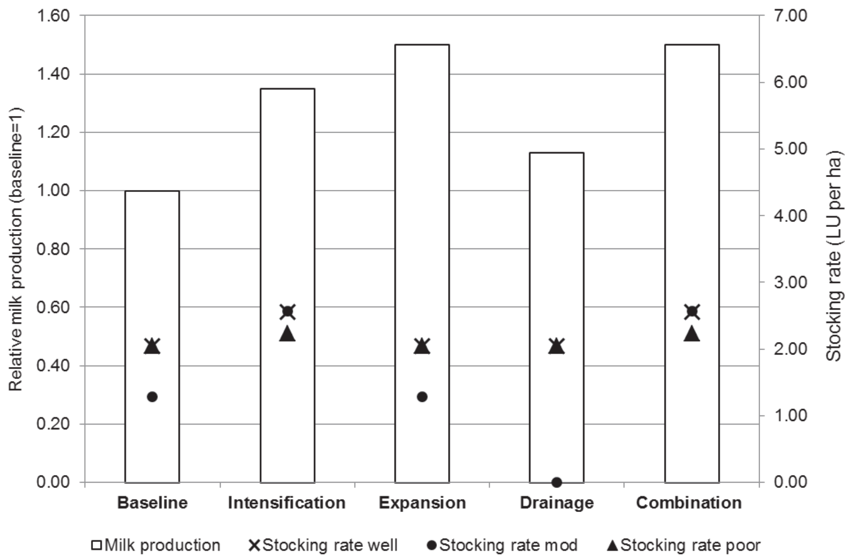

Figure 2. Outcomes of Optimisation Set 1 (Primary productivity): Relative changes (baseline scenario = 1) in milk volume production and associated stocking rates on poorly, moderately and well drained soils under the five scenarios shown. The Baseline Scenario represents the current situation in the bovine sector in Ireland.

In the second Optimisation Set, we assessed opportunities to increase two soil functions simultaneously: primary productivity and water purification. Similar to the first Optimisation Set, the productivity target was met only in the expansion and combination scenarios. However, Figure 3 and Table 4 show that in all scenarios of Optimisation Set 2, NO_3-N concentrations on well drained soils can be expected to approach the Maximum Allowable Concentrations (MAC) of 11.3 mg l^{-1}.

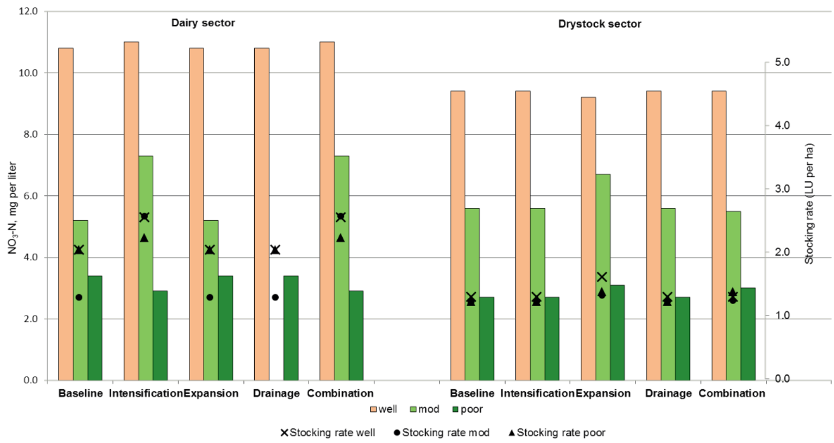

Figure 3. Outcomes of Optimisation Set 2 (Primary Productivity + Water Purification): Optimised stocking rates (symbols) and associate nitrate concentrations (bars) on well, moderately and poorly drained soils for the dairy sector (left) and the drystock sector (right) for the five scenarios.

In the third Optimisation Set, we also considered pathways to meet the demand for the soil function carbon sequestration, which limited the number of solutions in which the demands for primary productivity, water purification and climate mitigation were met fully simultaneously. While the carbon offsetting objective is met in all scenarios through increased afforestation, Figure 4 and Table 4 show that the primary productivity target is now only met in the expansion scenario. This scenario now requires a total new afforestation area of 400,000 hectares. While the combination scenario would also include the expansion scenario, it was characterised by a complex solution space with numerous local optima, in which the optimisation algorithms could not identify the global optimum in which all objectives were fully satisfied simultaneously. Instead, the combination scenario returned multiple 'local' optima that partially met the objectives, the best performing of which is shown in Figure 4.

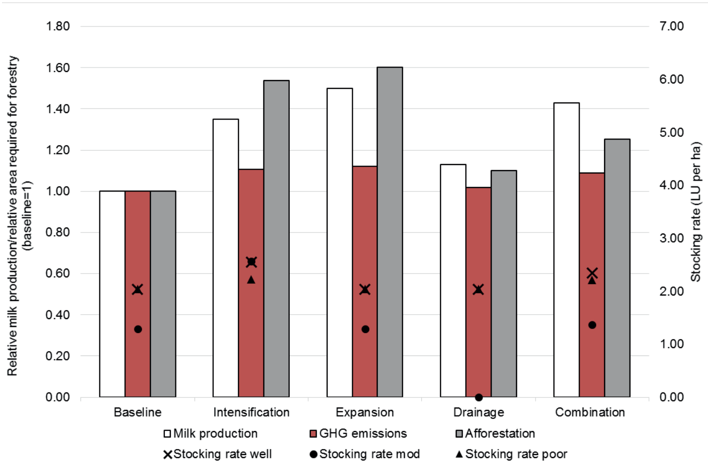

Figure 4. Outcomes of Optimisation Set 3 (inclusion of GHG reduction targets) Changes in milk production volume, sectoral greenhouse gas emissions and area of afforestation required to meet GHG reduction targets.

Figure 5 shows that, when the demands for primary productivity, water purification and carbon sequestration are consider simultaneously, each scenario is associated with complex synergistic and antagonistic trade-offs between the soil functions and as a result provides a different suite of functionality.

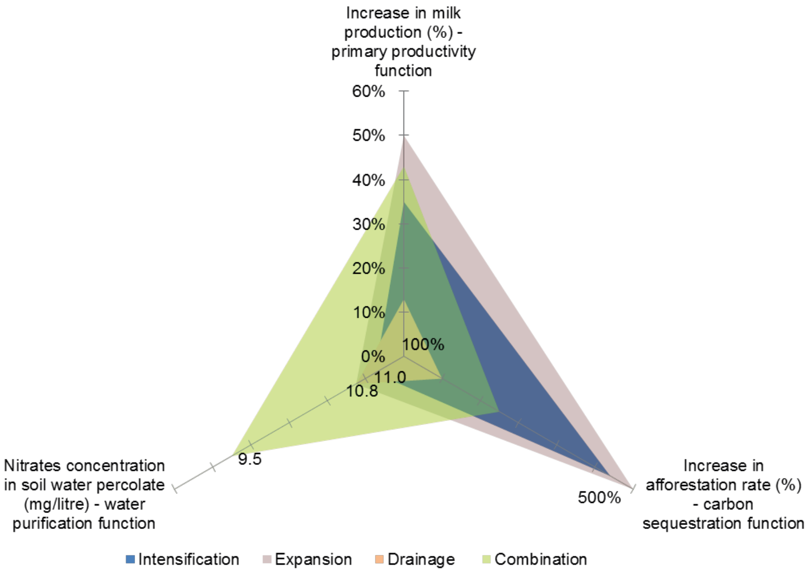

Figure 5. Illustration of the contrasting suites of soil functions (visualised using the proxies of milk production, nitrates concentration and afforestation rates), resulting from the different scenarios in Optimisation Set 3, which considers all three soil functions.

For example, the expansion scenario delivers on the target for primary productivity, but requires the highest rate of afforestation to offset sectoral GHG emissions. In addition, in this scenario, the supply of the water purification function barely matches demand, translating into nitrate-N concentrations close to the MAC. In contrast, the combination scenario requires a less dramatic increase in the rate of afforestation, and has 'spare capacity' for the water purification function. However, in this scenario the demand for increased primary productivity is not fully satisfied.

5. DISCUSSION

5.1. MODEL PERFORMANCE

Despite the relative simplicity of the optimisation model, modelled animal numbers, GHG emissions and nitrate concentrations closely aligned with previous empirical observations. For example, in the period 2007-2012, the average nitrate concentration in groundwater in Ireland was below 8.5 mg per litre at 96% of the monitoring sites (EPA, 2015). Our modelled GHG emissions in the baseline scenario of 18.7 Mt per annum closely matches the reported agricultural emissions in 2005 (the reference year for EU Climate and Energy framework 2030) at 18.9 Mt per annum.

Efforts were made to evaluate an alternative nitrogen mass balance model (Velthof et al., 2009) to compute nitrate concentrations were made, but this resulted in GHG emissions that were much higher, and nitrate concentrations that were much lower, than those reported in the Irish National Inventory Report (EPA, 2014). We traced the cause of this misalignment to the order of calculations in the Velthof et al. (2009) model, in which denitrification is the 'rest' fraction established from mass balance once ammonia and nitrate losses have been deducted. In our computation, we reversed the order of computations and derived nitrate losses as the 'rest fraction' once ammonia and denitrification were accounted for.

However, despite the realistic outputs of our model, we must bear in mind the purpose of the model is not to predict environmental impacts *per se*. Therefore, emissions and nitrate concentrations should not be interpreted as precise predictions. Instead the purpose of the model is to explore the trade-offs, both synergistic and antagonistic, between soil functions, and to illustrate the complexity of managing soil functions at multiple scales.

5.2. LIMITATIONS

Our research was subject to a number of limitations that must be borne in mind in the interpretation of results:

- For our function 'water purification' (Optimisation Sets 2 and 3) we only considered the ability of soils and the societal demand for soils to (partially) denitrify nitrates derived from farm N surpluses. The nitrates concentrations calculated in this paper are based on the average denitrification behaviour of well drained, moderately drained and poorly drained soils. Under local conditions, values will vary around this average. As the optimisation process moves the average nitrate concentrations in groundwater recharge closer to the legal limit for groundwater concentrations, the risk of exceeding this limit in some places increases. In addition, an important second aspect of water purification is the ability of soils to attain surplus phosphorus (P) and thus mitigate against freshwater eutrophication (see e.g. Coyle et al. (2016); Schulte et al. (2006)). Recent results from the Irish Agricultural Catchments Programme suggest that P dynamics may be of greater importance in maintaining surface water quality than nitrogen dynamics (Murphy et al., 2015). The inclusion of this into the FLM framework is the subject of on-going research, as part of the LANDMARK (LAND Management: Assessment, Research, Knowledge base) project (Creamer, 2014).
- Throughout this study, we focussed exclusively on three of the five soil functions: we did not consider the functions 'provision of a habitat for biodiversity' or 'nutrient cycling and provision' or other soil functions, which are described in Calzolari et al. (2016); Haygarth and Ritz (2009). Therefore, the results of this study must be interpreted with caution: the outcome of our Optimisation Set 3, where we consider all three soil functions, suggests that the expansion scenario is superior over the alternative scenarios. However, this outcome is likely to change when 'provision of biodiversity' is considered as a fourth objective: at national level, biodiversity is specifically at risk from conversion of (typically less intensive) drystock production to (more intensive) dairy production and from the intensification of drystock production resulting from this expansion of dairy production.
- In this study, we considered afforestation as the sole mechanism to offset GHG emission over and above the cost-effective abatement options for emission reductions assessed in the Marginal Abatement Cost Curve for Irish Agriculture (Schulte et al., 2012a). An alternative option for offsetting is the reduction of emissions from drained carbon rich soils trough reducing drainage depth or through rewetting of sites; the potential of this approach for Irish agriculture is explored in (Gutzler et al., n.d.). Other options include the production of biofuels and the displacement of fossil fuels, as described in the "Carbon-Neutrality Report" (Schulte et al., 2013), or the management and accounting of soil carbon sequestration as a function of land use and land management (Calzolari et al., 2016).

5.3. SCENARIOS FOR ONE, TWO AND THREE SOIL FUNCTIONS

Previous research (O'Sullivan et al., 2015; Schulte et al., 2014) illustrated how managing soil functions and land use is likely to result in trade-offs between production and the environment. In this paper, we managed, for the first time, to quantify these synergistic and antagonistic trade-offs. We showed that the number of trade-offs, and the complexity of their associated management, increase sharply as we increase the number of functions that we expect our land to deliver. In Optimisation Set 3, few management options remain to meet the specified targets for the three soil functions simultaneously.

All optimisation sets showed that the increase in primary productivity cannot be achieved through intensification or drainage scenarios alone: therefore, achieving the ambition of the Food Harvest 2020 and Food Wise 2025 Strategies will require a degree of expansion. In practice, the expansion scenario is hindered by the very low level of land mobility in Ireland. For cultural reasons, the level of land transfer by sale is minimal, with sale levels in 2011 equating to merely 0.3%. The difficulty to obtain farmland is exemplified by the problem faced by younger farmers in Ireland in finding farmland for sale (Bogue, 2013).

When we also consider the soil function water purification, then nitrate concentrations become of concern on well drained soils, where they may approach the MAC. Interestingly, this MAC is breached more or less when stocking rates exceed the carrying capacity of the land. In other words: in the grazing-based dairy systems that are prevalent in Ireland, both the primary productivity and water purification functions reach their maximum capacity at more or less the same stocking rate, implying that 'best practices in animal husbandry and grassland management' should largely suffice to maintain nitrate concentrations below the MAC.

In Optimisation Set 3, where we also consider the carbon sequestration and GHG mitigation function of land, the menu of management options is further reduced. The outcome of this optimisation suggests that the Expansion Scenario may allow for all three targets (primary production, water purification, carbon sequestration) to be met simultaneously (see Table 4). However, apart from the aforementioned concerns regarding biodiversity in the Expansion Scenario, we must appraise this outcome in the context of the current Irish Forestry Programme 2014-2020, which aims for the planting of approximately 43,000 ha over the five-year period to 2020 (DAFM, 2015), equating to just over 8,000 ha per annum. This is in sharp contrast with the requirements for afforestation in the expansion scenario, which amount to approximately 400,000 ha. As our model does not include a time dimension, our assessment does not specify the timeframe within which this planting has to be achieved. However, if we consider the time horizons of the current Food Wise 2025 Strategy and the EU Climate and Energy Framework for 2030, then it is reasonable to assume that the planting of the 400,000 hectares of new afforestation would have to be completed within a 15-year period, amounting to *c.* 27,000 hectares per annum, i.e. more than thrice the rate currently planned for.

In practice, the Combination Scenario is both more likely to materialise (as individual farmers are likely to choose different scenarios), and more pragmatic. However, this scenario, too, is not without caveats that must be taken into account. A Combination Scenario can be either 'managed' or 'unmanaged'. In an unmanaged scenario, the individual choices for intensification, expansion and drainage are not based on, nor optimised for, knowledge about soil type, soil properties, soil nutrient levels, or soil carbon contents. Figure 5 shows that this may inadvertently lead to expansion onto vulnerable soils or into high nature value grassland, or to drainage of high carbon soils. By contrast, in a managed scenario, these pathways are customised for the properties of individual fields, soils or catchments. For example, in the managed scenario in Figure 6 drainage is limited to low-carbon soils, thus minimising the environmental trade-offs (O'Sullivan et al., 2015), while expansion is limited to soils that have 'spare capacity' for water purification in the form of low nitrate concentrations (see Teagasc (2012)).

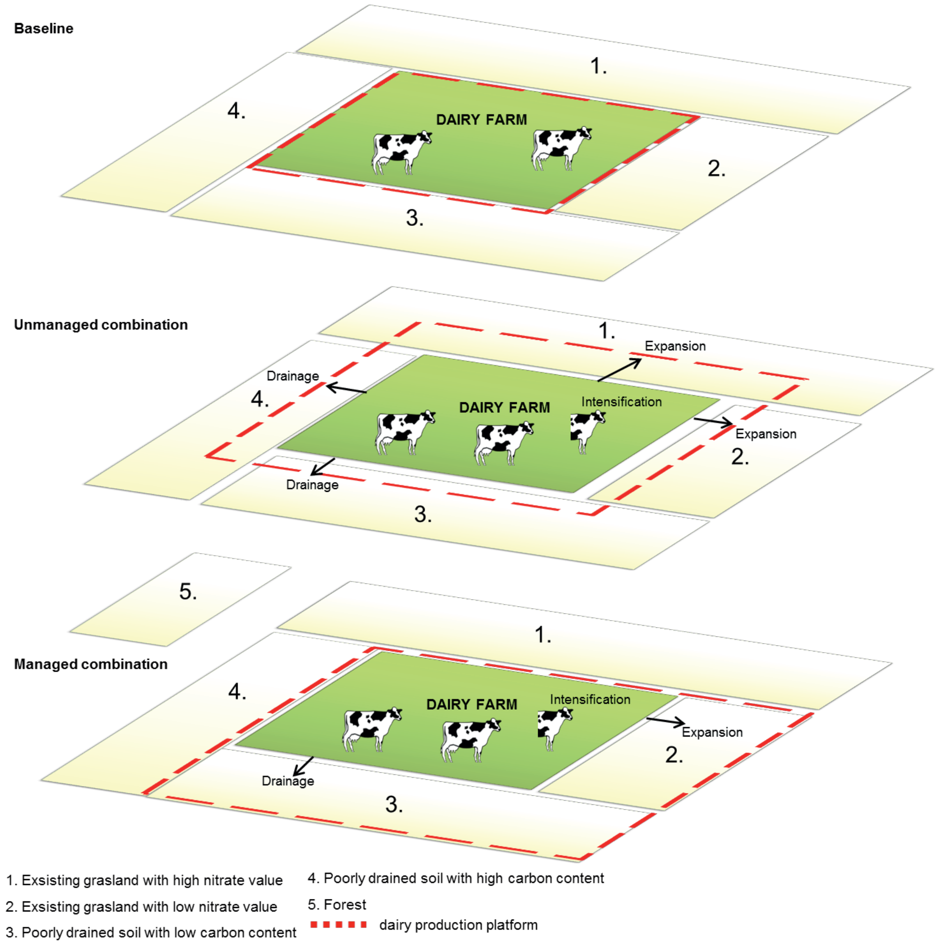

Figure 6. Visualisation of an unmanaged and managed Combination Scenario on a typical dairy farm.

5.4. SCALE

The 'managed combination scenario' presents a challenge with regard to the point of obligation. Put simply: who is responsible to ensure that the Combination Scenario amounts to a 'Managed Combination'? In a recent paper, (Schulte et al., 2015a) explored how the demands for different soil functions operate at very different spatial scales. In our study, this translates as follows: the demand for increased primary productivity, while specified at national level, also operates at farm level, as it is of economic interest to individual farmers to increase milk output following the abolition of EU milk quota. By contrast, the demand for carbon sequestration applies at national level and is primarily driven by societal concerns. Decisions at local (farm) level by thousands of individual farmers aimed at increasing output, will ultimately impact on the ambition required at national level to meet GHG reduction targets. For example, Figure 4 shows that the Expansion Scenario provides the most promising pathway for farmers, but this scenario is also associated with the most challenging demand for afforestation, which may prove to be unrealistic. This misalignment in the spatial scale of the supply and demand for soil functions has implications and challenges for management: there is a need to link management at national level and local level to ensure that the 'Combination Scenario' is proactively managed to account for soil properties.

Schulte et al. (2015)identified 15 existing governance instruments (i.e. market instruments and both mandatory and voluntary instruments) to manage soil functions from local to national level. They concluded that, rather than developing new policy tools, there may be merit in customising existing instruments to account for differences between soils and landscapes. The SQUARE (Soil QUality: Assessment & Research) project is currently collecting detailed data and information on soil structural quality and soil functional capacity in grassland and tillage systems across Ireland. When this functionality is linked to the new Soil Information System, this will result in high-resolution spatial data to support implementation of FLM.

5.5. REQUIREMENTS FOR FURTHER RESEARCH

In previous papers on FLM, we considered the spatial mismatch between the supply and demand for individual soil functions. This paper shows that there is a need to also consider the temporal mismatch between the supply and demand for soil functions, as exemplified by the temporal misalignment between the supply and demand for carbon sequestration to offset GHG emissions. Both the Food Harvest 2020 Strategy (DAFF, 2010) and the Food Wise 2025 Strategy (DAFM, 2015) anticipate rapid growth of the dairy sector up to 2020, in response to the abolition of the milk quote, after which production is expected to stabilise. This creates a demand for carbon offsetting through afforestation. However, while this demand may ultimately be met by new afforestation, the supply of this offsetting mechanism is likely to be asynchronous with, and lag years behind, this demand, resulting in a significant challenge to meet the GHG reduction targets over the shorter term to 2030. Furthermore, the major part of mitigation resulting from afforestation is due to the built up of biomass stock. Once this stock has been established, annual mitigation rates are reduced, while emissions from livestock farming are assumed to continue at similar levels. Therefore, afforestation at the described rates may be successful at offsetting GHG emissions in the medium term, but much higher afforestation rates would be needed in the long term. Effects at different time scales are also relevant in relation to soil processes, stocks and microbial communities following changes in nutrient input, stocking rate or soil moisture content. These temporal effects are still not fully understood but are likely to influence the investigated soil functions, especially the water purification function through changes in the denitrification rate.

Despite the complexity of soil processes, the sustainable management of soil functions requires the co-production and integration of knowledge and technologies that can span research scientists, policy-makers and land managers (Bouma et al., 2012). While compartmentalised research is essential for understanding tipping points, thresholds and drivers, the research has tended to be too compartmentalised (Abson et al., 2014) and reflects a lack of research integration and a lag in implementation (O'Farrell and Anderson, 2010). Here, we use the FLM as an integrative framework to frame our optimisation study, however, few other similar studies were found.

Further research is also required to consider the functions of biodiversity and nutrient cycling. As this will add further complexity to the optimisation procedure, this will necessitate more sophisticated optimisation tools, such as Bayesian Belief Networks. This is the topic of the current five year LANDMARK project, which aims to perform this optimisation at EU scale.

6. CONCLUSIONS

Functional Land Management seeks to optimise land use by accounting for different biophysical conditions and potentials of soils and by accounting for the fact that only some targets need to be met at the local scale while other targets are defined at the national scale. There are several options on how to achieve both production and environmental targets at the same time. Our paper showed that in principle, it is possible to meet production targets, water quality targets and climate change mitigation targets through optimised land management. The formal requirements for water quality target were fulfilled by almost reaching, but not exceeding the MAC. However, spatio-temporal variations in nitrate concentration may still give rise to local breaches of the MAC.

Afforestation is an effective mechanism to offset GHG emissions from livestock agriculture and meet a reduction target of 25%. However, both the planting of new forests, and the subsequent carbon sequestration in newly afforested areas are long term processes. For this reason, farm afforestation may not be sufficient to meet 2030 GHG reduction targets by 2030.

Because soil functions interact with each other, ambitious targets for one function may make it difficult to fully meet the targets for other functions. In our case study, we were able to reconcile the targets for primary productivity, water purification and carbon sequestration, but it is most likely that the inclusion of the remaining two soils functions, namely the provision of a home for biodiversity and nutrient cycling, or the inclusion of additional indicators per function, would result in additional limitations.

While on paper, the results indicate that an expansion scenario could meet all of the objectives investigated in the current study, in reality this scenario is highly unlikely to materialise. Key constraints identified in this regard relate to fragmentation of farms and low land mobility levels in Ireland and the afforestation rates required for achieving the objectives. What is more likely to occur in the absence of targeted policy interventions are unmanaged combinations. The challenge henceforth is how to move from an unmanaged combination scenario towards a managed combination scenario. At a policy level, target setting should consider the multifunctional demand on land and possible trade-offs between targets. This also needs to take into account the likelihood of unmanaged developments and may necessitate a reappraisal of targets. The FLM concept has the potential to optimise land use, but requires the implementation of policy tools to ensure that land use developments are managed in a way that converges towards the optimal scenario.

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Chapter 3

Assessment of soil functions: an example of meeting competing national and international obligations by harnessing regional differences

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ABSTRACT

The increased demand for bio based products worldwide provides an opportunity for Eastern European countries to increase their production in agriculture and forestry. At the same time, such economic development must be congruent with the European Union's long-term climate and biodiversity objectives. As a country that is rich in bioresources, the Latvian case study is highly relevant to many other countries—especially those in Central and Eastern Europe—and faces a choice of transition pathways to meet both economic and environmental objectives. In order to assess the trade-offs between investments in the bioeconomy and the achievement of climate and biodiversity objectives, we used the Functional Land Management framework for the quantification of the supply and demand for the primary productivity, carbon regulation and biodiversity functions. We related the supply of these three soil functions to combinations of land use and soil characteristics. The demand for the same functions were derived from European, national and regional policy objectives. Our results showed different spatial scales at which variation in demand and supply is manifested. High demand for biodiversity was associated with areas dominated by agricultural land at the local scale, while regional differences of unemployment rates and the target for GDP increases framed the demand for primary productivity. National demand for carbon regulation focused on areas dominated by forests on organic soils. We subsequently identified mismatches between the supply and demand for soil functions, and we selected spatial locations for specific land use changes and improvements in management practices to promote sustainable development of the bio-economy. Our results offer guidance to policy makers that will help them to form a national policy that will underpin management practices that are effective and tailored towards local climate conditions and national implementation pathways.

Keywords: agriculture, biodiversity, central and Eastern European countries, climate regulation, forestry, functional land management, primary productivity, soil functions

1. INTRODUCTION

The increasing demand for high-quality food and fibre and the simultaneous reduction in greenhouse gas emissions is a major global challenge. Our global resources determine social and economic development, and, as such, their sustainable management increases long-term benefits. Accordingly, the United Nations formulated 17 Sustainable Development Goals, aimed at ending poverty, protecting the planet, and ensuring peace and welfare (United Nations General Assembly, 2015). Additionally, an essential objective for human beings is the transformation towards net zero emissions by increasing the sequestration capacity of soils, and by changing the technologies and raw materials of commodity production.

In the context of combatting climate change, the Paris Agreement requires each Party to define its "commitment", and submit a national implementation plan for international peer-review (EU, 2018; UN, 2015). The European Union (EU) has set a target to cut its greenhouse gas (GHG) emission levels by 43% from the Emissions Trading System (ETS) sectors and 30% from the non-ETS sectors until 2030, compared to 2005 (EC, 2014). However, this overall target is distributed asymmetrically across Member States, depending on their economic development and the structure of their economy. The associated contemporary challenge for EU countries is to decouple emissions from production. Emission reductions are particularly challenging for the bio-economy (i.e. the agriculture and land use, land use change and forestry sectors). For instance, afforestation and wetland restoration reduce agricultural production while increasing carbon sequestration and storage, but may result in higher imports of food and feed (Eory et al., 2018).

3

Particularly challenging in operationalisation of land use and land management planning is the reconciliation of long-term national and regional policy objectives with the myriad of strategic and tactical farm management decisions that are made by thousands of individual land managers on a daily basis. Actors in land management typically have different and sometimes contradictory views (Dingkuhn et al., 2020; Pinillos et al., in press), which calls for an integrated approach in order to support knowledge-based decisions to link land use management at local scale and territorial planning at regional or national scale. There is a growing awareness of the need for better rural planning, protection of ecosystem services and innovative economic models to ensure environmental and socio-economic development (van Leeuwen et al., 2019). There is a growing awareness of the need for better rural planning, protection of ecosystem services and innovative economic models to ensure environmental and socio-economic development (van Leeuwen et al., 2019), and in this context, spatial information on ecosystem services or the benefits that people obtain from the ecosystems can support eligible land management decisions (de Groot et al., 2010).

Soil is the resource that underpins all of the functions that we expect from our land. It provides food, fibre, raw materials, and storage, transportation and filtration functions, as well as a platform for human activities, heritage, and a habitat and gene pool (EP, 2006). The capacity of soils to produce plant biomass is considered to be one of the most important soil functions, it is also associated to the growing demand for food security, energy and adaptation to climate change (Mueller et al., 2010). Also, the soil layers to 1 m depth can be either a significant sink or source of atmospheric carbon and play a major role in the global carbon budget, due to soil organic carbon degradation to inorganic forms (Taghizadeh-Toosi and Olesen, 2016). The Communication (COM(2006) 231) of the European Commission emphasizes the importance of soil functions; however, there is currently no overarching legislative proposal for protecting soils across the EU (EC, 2006).

In this context, soil management practices represent the operationalisation of land management practices (Schulte et al., 2015a), and this has been captured in a number of conceptual approaches to evaluate the supply of soil-based ecosystem services, e.g. Dominati et al., (2010); Calzolari et al., (2016); Greiner et al., (2017). These conceptual approaches for classifying, quantifying and estimating soil natural capital use soil properties as the main characteristic and can be used to determine the impact of soil properties, farming practices and soil management on the provision of ecosystem services. The soil-based multifunctional framework Functional Land Management (FLM), can subsequently be used to optimise the supply of soil functions (namely primary productivity, water purification and regulation, carbon sequestration and regulation, the provision of habitats for biodiversity, and the provision and cycling of nutrients) to simultaneously meet agronomic and environmental demands (Schulte et al., 2014). Based on a literature review, Coyle et al., (2016) expanded the FLM and developed conceptual models and soil matrices to visualise the interrelationships between land use, soil type and soil functions. The pedological, physical, chemical, and biological soil properties and land use determine the ability of soils to perform the aforementioned soil functions simultaneously. The FLM approach highlights spatial mismatches between the supply and demand, and can thus be used to identify priority areas for intervention (Schulte et al., 2015a). It can show synergies and trade-offs between the soil functions, allowing for the identification of interventions that maximise synergies where required (O'Sullivan et al., 2015). The European Research Project LANDMARK[1] used the FLM framework to develop tools for farmers and policy makers on the sustainable management of soils by optimising the supply of soil functions at the farm scale to provide an assessment of policies to ensure agronomic and environmental sustainability at the European scale. This current study contributes to further debates on the trade-offs between the supply of soil functions and the achievement of socio-economic and environmental objectives in two ways. First, as the original study by Coyle et al., (2016) was limited to the Atlantic climatic zone of Europe, which is dominated by grassland and livestock farming system; the current study of Latvia is chosen as a relevant Eastern European case study for quantifying the contribution of soil functions in the continental climate, which is characterised by a mosaic of cropping systems, mixed farming systems and forestry. Second, the mismatches between the demand and the supply of soil functions provides an opportunity to introduce land use changes and management practices that will ensure regional development.

The aim of our study is to identify regional opportunities for meeting national bioeconomic, climate mitigation, and biodiversity targets by assessing the spatial distribution of both the societal demands and the supply of soil functions in Latvia, as a function of land use and soil properties. The identification of the supply and the demand of soil functions spatially and the understanding of their mismatches and opportunities can provide entry points for regional land use changes and management practices to achieve national socio-economic objectives and international environmental commitments simultaneously.

2. MATERIALS AND METHODS

2.1. STUDY AREA

Latvia is a country in Baltic region located in north-eastern Europe (Figure 1) where bio-based industries play a pivotal role in the economy, and it is a contemporary and highly relevant national case study for territories where these global challenges collide.

The traditional bioeconomy sectors, i.e. agriculture, forestry, fisheries, food industry, and wood industry in Latvia is 9.2%, which is twice as high as the EU-27 average in 2017 (4.6% of total value added). Within the bioeconomy sector, the contribution of agriculture, forestry and fishing to the bioeconomy value added is 41% in the EU and 44% in Latvia (Eurostat, 2020a). A specific challenge for the sustainable development of the agriculture and forestry in Latvia, is that the expansion of the agricultural sector can cause an undesirable increase in GHG emissions and harm biodiversity, while the alternative of extending the scale of afforestation will not always give an immediate

[1] http://www.landmark2020.eu

contribution to economic development. Instead, expansion of the forestry area is considered a long-term investment into the economy. For instance, one of the most common and valuable tree species *Pinus sylvestris* has a rotation length of about 100 years (The Parliament of the Republic of Latvia, 2012). At the same time, the forestry sector offers significant benefits such as the local provision of habitats for biodiversity, the protection of soil from erosion, the safeguarding of water and air quality and the provision of forest-based food (including wild berries and mushrooms), fibre and recreational services. Therefore, whilst the expansion of the agricultural area can give an immediate short-term boost to the economy, the expansion of forestry contributes to the achievement of long-term climate targets. These trade-offs between the short- and long-term objectives, including increased biomass production, the use of bioenergy, and carbon sequestration and storage, play an important role in scenarios for climate change mitigation. For instance, it will be challenging to meet long term climate targets while avoiding food-fuel competition without an increase in the use of bioenergy (EM, 2018).

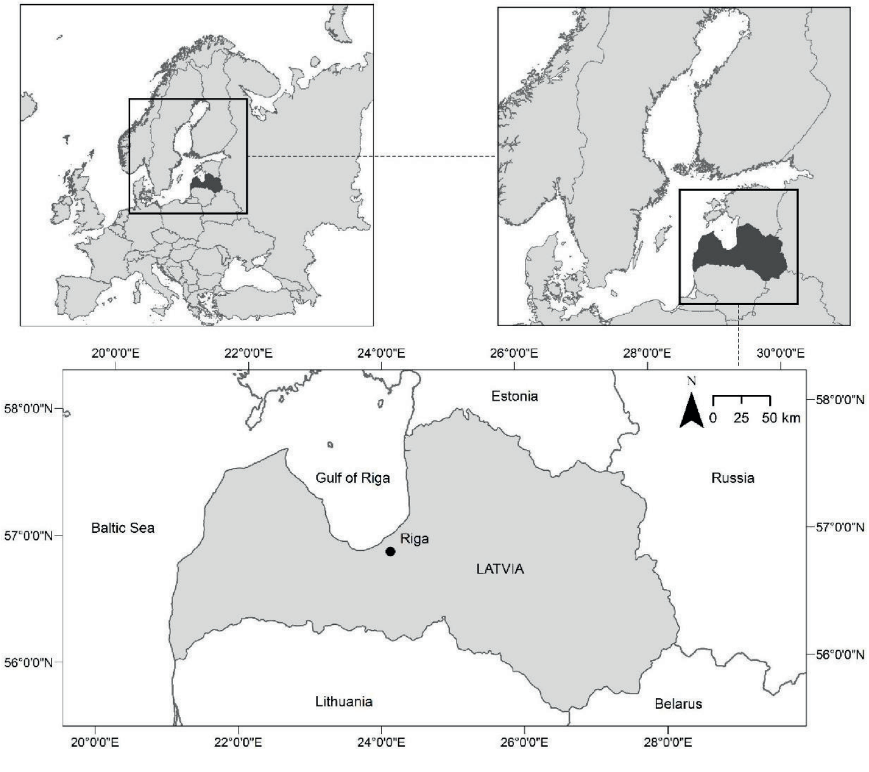

Figure 1. The location of the study area.

Another challenge that is specific to the Latvian case, and indeed to many Eastern European countries, is that its economic and agricultural activity decreased dramatically after 1990 in response to geopolitical events. As a result, agricultural activity, as well as associated GHG emissions were very low by the year 2005, which subsequently was chosen as the reference year for EU GHG policies, for reasons unrelated to the evolution of agriculture in Eastern Europe. By 2005, Latvia was slowly starting to recover its economic activities (Figure 2). Two possible way to increase production in the agricultural sector are: (1) re-using abandoned areas to expand the agricultural area or (2) producing high value-added bioproducts. As agricultural GHG emissions are coupled to agricultural activity, this means that it is very difficult for agriculture to reach its potential for primary productivity that it had previously, without breaching EU GHG emission targets that had their baseline set at 2005.

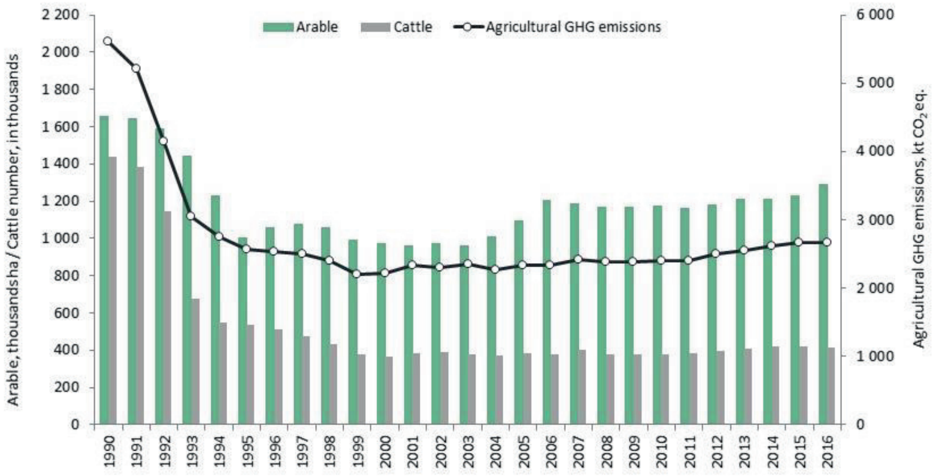

Figure 2. Area of tilled land (thousands of ha), number of cattle (thousands of heads) and annual GHG emissions (kt CO_2 equivalent) for Latvia (NIR, 2018).

The quest for solutions is further complicated by the fact that climate smart land management is not the only societal demand put on our land. We also expect it to provide habitats for biodiversity, as well as to deliver on nutrient cycling, water purification and carbon sequestration (Mueller et al., 2010; Schulte et al., 2014, 2019).

2.2. GENERIC RESEARCH APPROACH

We adapted the FLM framework and selected three out of five soil functions that are most relevant to the Latvian agro-environmental context: primary productivity, carbon regulation, and the provision of habitats for biodiversity (hereafter referred to simply as "biodiversity") (Step 1 at Figure 3). The two remaining soil functions that were included in the original FLM framework, i.e., water purification and the regulation and provision and cycling of nutrients, were not included in this research because of: (1) the lack of spatial data on manure at national scale and (2) the positive endorsement of good water quality in the surface water bodies in Latvia: in 2018, the annual average nitrate concentration in the surface water bodies did not exceed the limit of 11.3 mg nitrate-N per L as defined by the EU Nitrates Directive (LVĢMC, 2018).

The FLM framework is used to assess the supply of soil functions as a function of land use and soil class, where soil class is based on the local soil property that most predominantly defines the interactions between land-based production and the environment. For instance, in Ireland the dominant soil property is the natural drainage capacity of the soil (Coyle et al., 2016), while in the Philippines and Brazil it relates to topography (Dingkuhn et al., 2020; Pinillos et al., 2020). In Latvia, organic soils are important due to the fact that organic soils can be a carbon sink or emitter, depending on land use and management practices. On the one hand, agricultural production in 2016 from organic soils was only 3.7% of the total agricultural production in Latvia (Pilvere et al., 2017), but, on the other hand, organic soils play an important role in Latvia's national emission budget, because 50% of direct N_2O emissions originate from the management of organic soils (NIR, 2018). Therefore, for our study we chose the gradient from mineral to histic soils as the main soil property in Latvia.

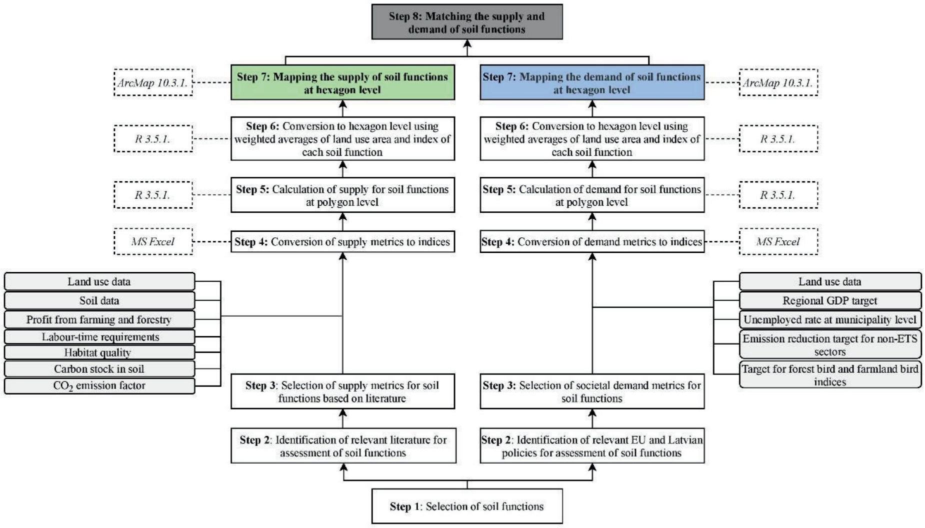

Figure 3. Diagram of methodological steps followed to map the supply and demand of selected soil functions.

An overview of the methodological steps, workflow, data used and data processing is summarized in Figure 3. We first identified the relevant literature and policy documents for assessment of soil functions (Step 2), then selected supply and demand indicators for each soil function (Step 3), converted the values of indicators to z scores similar to Schulte et al., (2015) to derive normalized weighting for each indicator, and applied the tabular index approach used by (Greiner et al., 2018) (Step 4). The description of data and databases used to indicate the values of indicators are provided in the next sections. Then we calculated supply and demand for each soil function at polygon level in R 3.5.1 (Step 5) and generated supply and demand maps at hexagon level in ArcMap 10.3.1. by using weighted averages of land use area and index of each soil function (Figure 4) (Step 6 and 7). Based on the balance between supply and demand for each of the functions, we aggregated the difference between supply and demand maps to identify opportunities and trade-offs between soil functions. (Step 8). The detailed descriptions of the selection process of indicators and the calculation of indices are provided in the next sections and in the Supplementary Material.

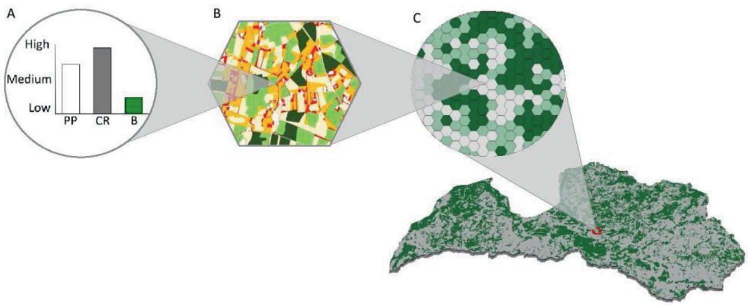

Figure 4. Hierarchy of data calculation and visualization levels: a) evaluation of supply – b) polygon (calculation) – c) hexagon (visualization).

2.3. LAND USE DATA

The total area of Latvia is 64,600 km^2, with forest land and agriculture occupying 52%[2] and 36%[3] of total area, respectively. We derived land use data for Latvia from the project, "Evaluation of the land use optimization opportunities within the Latvian climate policy framework" (funded by Joint Stock Company "Latvia's State Forests"), which has provided an in-depth socio-economic analysis of agricultural and forestry land in Latvia (Nipers, 2019). Within this project, a database was created using the following datasets:

- An agricultural spatial dataset at scale 1:5,000 from the Rural Support Service (RSS), the Ministry of Agriculture[4]. This dataset shows all agricultural land polygons with detailed information of the area, crop type, and farming system held by farmers who have applied for support payments from the EU.
- A forest spatial dataset at scale 1:10,000 from the State Forest Service (SFS), the Ministry of Agriculture[5]. The SFS is responsible for the implementation of forest policy in Latvia. Also, it provides quality control of forest inventory data, and maintains the State Forest Register. This dataset includes detailed forest information for each inventoried forest data polygon: forest type, age of forest stand, main species in forest stand, and restrictions in forest stand.
- A land use and land holder spatial dataset at scale 1:2,000 from the State Land Service (SLS), the Ministry of Justice[6]. The SLS operates the National Real Estate Cadastre information system, and the spatial dataset from this system includes information about property, holder, land area, land use, value, encumbrances, buildings and their elements. Land use distribution within one property is given as a percentage of the total area of property. The polygon data from SLS was intersected with agricultural dataset to determine the abandoned agricultural land by using ArcMap 10.3.1.
- The CORINE Land Cover data base[7] at scale 1:100,000 was converted from raster to polygon by using ArcMap 10.3.1., and then intersected with a forest dataset to identify spatially uninventoried forest polygons.
- A land reclamation map at scale 1:10,000 from the State Limited Liability Company "Ministry of Agriculture Real Estate"[8]. Data shows the drainage status of agricultural fields. The vector data from the land reclamation map was intersected with agricultural land polygons to find overlaps between drainage and agricultural fields to define "drained" or "not drained" status by using ArcMap 10.3.1.

The database consists of 4.4 million polygons for agricultural land use and 2.3 million polygons for forestry land use. The database is static and represents the situation in 2016. Due to the high data resolution and data processing and visualization capabilities, the territory of Latvia was subsequently divided into 68,408 hexagons of 100 ha each, as developed by Nipers, (2019).

Using the aforementioned database for this study, agricultural land was divided into arable (grain, oilseed, pulses (GOP), vegetables, perennial plantations, other crops), grassland, and abandoned agricultural land. Forest land was divided into managed and natural forests. Forests which forbid

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[2] https://www.vmd.gov.lv/lv/

[3] https://www.vzd.gov.lv/lv/

[4] http://www.lad.gov.lv/lv/

[5] http://www.vmd.gov.lv/lv/

[6] https://www.vzd.gov.lv/lv/

[7] http://map.lgia.gov.lv/

[8] https://www.melioracija.lv/

economic activities, main felling, or thinning activities were classified as natural forests. Forests without restrictions, or those in which clear felling or economic activities are forbidden only during the animal reproduction season were classified as managed forests. Depending on the main wood species, managed and natural forests were subsequently subdivided into managed coniferous, managed deciduous, natural coniferous, and natural deciduous forests (Figure 5).

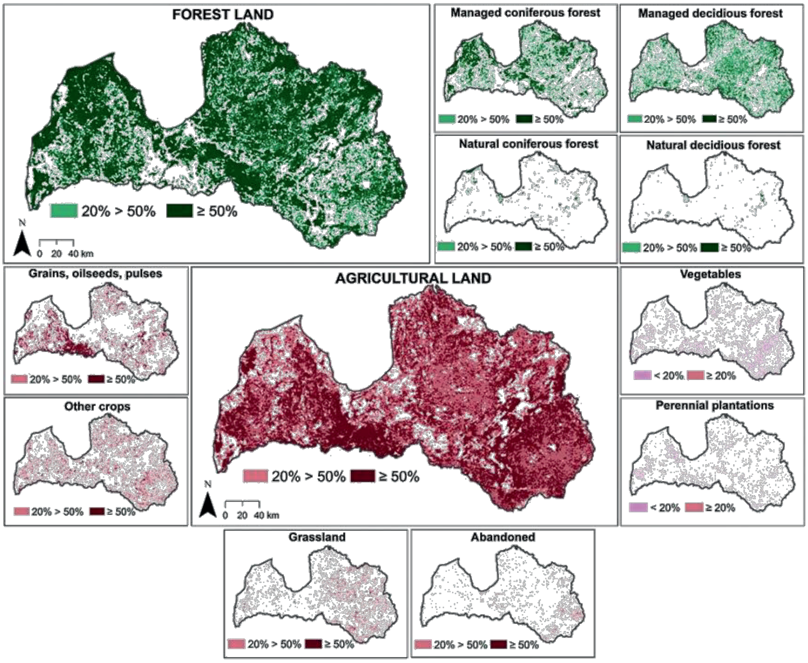

Figure 5. Indicative land use map of Latvia. The percentages indicate proportional land use. For example, where forest land exceeds 50%, it means that at least 50% of the hexagon area is forested (similar to O'Sullivan et al. (2015b) approach).

2.4. SOIL DATA

We utilized the agricultural soil data from digitized historical soil maps at the scale 1:10,000, based on soil mapping carried out from 60s to 80s, to add soil type to each agricultural land polygon. Currently, this is the main agricultural soil data source in Latvia[9]. Data about forest soils was extracted from the State Forest Service spatial dataset at scale 1:10,000 for each forest land polygon, considering the forest type and growth conditions as main factors to determine soil type in forest land. Soil data was used to create mineral, drained organic, and organic soil classes, in accordance with the Latvian Soil Classification and the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2015), with the depth of the organic layer as the main classification criterion. In the Latvian Soil Classification, the peat layer in organic soils ranges from 30 to 50 cm or more, corresponding to Fibric Histosols, Dystric Histic Gleysols, Hemic Histosols, Sapric Histosols and Histic Gleysols from the WRB. The mineral soil category included mineral and wet mineral soil types, which are found on artificially drained agricultural land (no organic layer) and naturally drained forest lands (organic layer less than 30 cm in depth). The drained organic category included artificially drained organic soils that is used for agricultural purposes (organic

[9] https://geolatvija.lv/geo/p/247

layer from 30 to 50 cm or more than 50 cm) and artificially drained mineral (organic layer smaller than 20 cm), as well as artificially drained organic soils (organic layer more than 20 cm) that are found in forest lands. Finally, the organic soil category included soil types found in naturally wet forests which have not been affected by artificial drainage (organic layer more than 30 cm). Natural bog areas and peat extraction fields were excluded from the study. Figure 6 illustrates where mineral, drained organic, and organic soils can be found in Latvia.

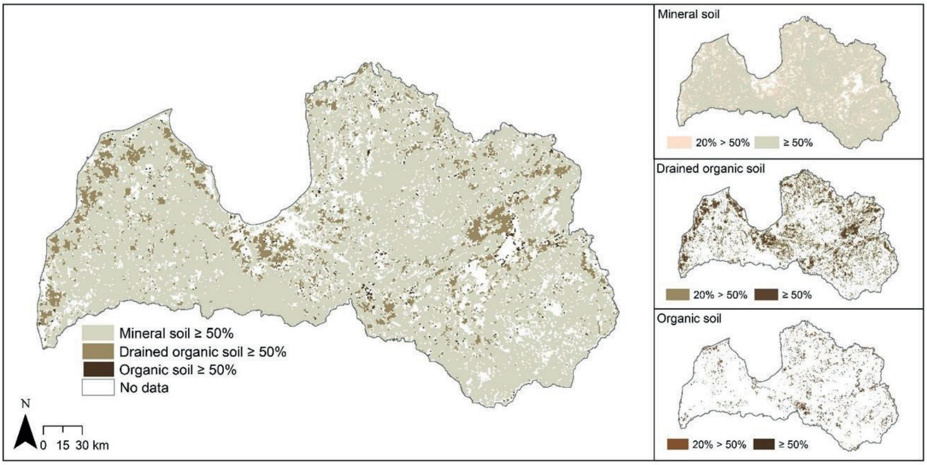

Figure 6. The distribution of mineral soils, drained organic soils and organic soils in Latvia. Percentages indicate the proportional areal extent of each soil class within hexagons.

2.5. DEMAND METRICS FOR SOIL FUNCTIONS

We built on the approach of the LANDMARK project, summarised in Schulte et al., (2019), in which the demands for soil functions (or "demands on land") were derived from European policy objectives, quantified in the context of national implementation. For quantification, Schulte et al. (2019) selected demand metrics that best, albeit partially, represented the aggregate societal demand for each of the functions.

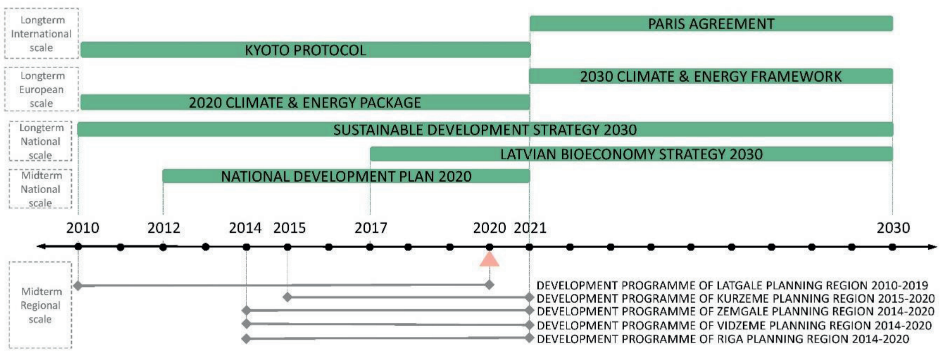

Figure 7. Summary of policies used for quantification of the demand.

We followed this approach with a similar assessment of EU and Latvian policies. We first identified the relevant policies (Figure 7) and then chose societal demand metrics for three soil functions in line with the following criteria: (1) Demand metrics must reflect the policy demands for each soil function; (2) Latvian datasets must be publicly available for each of the demand metrics; (3) Data are spatially available or could be integrated into available maps; (4) Demand metrics must allow for regional differences in Latvia to be manifested; (5) Demand metrics can be quantitatively linked to the indicators for the supply of soil functions in Latvia.

2.5.1. Demand for primary productivity

The global increase in the demand for bio-based products is allowing Latvia to once again meet its economic potential, following the radical decline in economic activities that followed the market changes in the 1990s. In response, the Latvian Bio-economy Strategy 2030 (which is being developed in line with the National Development Plan of Latvia for 2014–2020 and the Sustainable Development Strategy of Latvia until 2030) has defined two targets associated with the primary productivity function: (1) an increase in added value from the traditional bio-economy sectors, i.e. agriculture and forestry, from EUR 2.33 billion in 2016 to EUR 3.8 billion in 2030 and (2) the provision of employment for 128,000 inhabitants. Accounting for both targets in the bio-economy sectors, we framed the demand for primary productivity by combining regional GDP targets (e.g. Development Programme of Kurzeme Planning Region for 2015-2020; Development Programme of Zemgale Planning Region for 2014-2020; Development Programme of Vidzeme Planning Region for 2014-2020; Development Programme of Riga Planning Region for 2014-2020; Development Programme of Latgale Planning Region for 2014-2020;) and unemployment rates at municipal level[10]. The Latvia - Rural Development Programme (National) 2014-2020 emphasizes agriculture and forestry as key economic sectors in rural areas that provide jobs for local people, profit for rural businesses, and taxes. Therefore, we computed a bio-economic GDP target for each region as a function of the projected regional compound annual growth rate, the share of agriculture, forestry and fisheries in each regional GDP, and the national added value target of bioeconomic products, divided by the area of each region. Subsequently, we applied the tabular index approach used by Greiner et al. (2018), to create one indicator for primary productivity that combines these regional GDP targets with unemployment rates at municipality level (Supplementary Material, Table S1 and Table S2).

2.5.2. Demand for carbon regulation

The Paris Agreement is the most recent international agreement on mitigating climate change. The EU is participating as a single signatory, with its collective target asymmetrically divided between Member States as determined by their gross domestic products (GDP) per capita. The 2030 target for Latvia is a decrease in emissions for the non-ETS sectors by 6% compared to 2005, which has not yet been allocated across the various non-ETS sectors. For the period 2021-2030, each Member State can access credits from the land use sector through the so-called flexibility arrangement, subject to conditions such as the no-debit rule. This means that, for the first time in EU climate policy, carbon sequestration may be used to contribute to meeting the non-ETS target for emission reductions. The maximum level of flexibility for each Member State depends on share of emissions from agriculture; the proposed flexibility for Latvia equates to 3.6%[11] of non-ETS emissions.

2.5.3. Demand for biodiversity

The EU Biodiversity Strategy, the EU Birds Directive and the EU Habitat Directive are all aimed at preserving and restoring biodiversity at European level. Whilst these policies contain very few quantitative targets, bird species richness and abundance are two factors that are well monitored and studied around Europe and that can be used as generic indicators for biodiversity (Carrasco et

[10] https://raim.gov.lv/

[11] https://ec.europa.eu/clima/policies/effort/proposal_en

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al., 2018; Wuczyński, 2016). Therefore, similar to Schulte et al., (2019), the societal demand for biodiversity in Latvia is framed by the targets for forest bird and farmland bird indices in the National Development Plan of Latvia for 2014–2020. The forest bird index was 96.54 in 2017, with a 2020 target of 95 by 2020. Contrastingly, the 2017 farmland bird index stood at 87.87, with a target of 120 in 2030. Therefore, there is a higher societal pressure on agricultural land to augment its function as a habitat for biodiversity, and farmland bird index can be used as a demand metric for quantifying the demand for the biodiversity function.

2.6. SUPPLY METRICS FOR SOIL FUNCTIONS

We considered the gradient from mineral to histic soils and land use as the two main drivers of the supply of soil functions, namely primary productivity, carbon regulation and biodiversity, in Latvia. We also identified relevant supply metrics for three soil functions that were in line with the following criteria: (1) Supply metrics must reflect the present situation in Latvia for each soil function; (2) Latvian datasets must be publicly available for each of the supply metrics; (3) Data are spatially available or could be integrated into available maps; (4) Supply metrics must be capable of showing regional differences in Latvia; (5) Supply metrics can be quantitatively linked to the indicators for the demand of soil functions in Latvia.

2.6.1. Supply of primary productivity

Biomass production is determined by soil properties, climatic conditions, and management practices. Under optimal crop nutrient conditions, these interactions are mediated through the plant-available water dynamics of the soil. Lower crop yields are observed both when either the amount of available water in the soil is low or when the soil is subject to saturation (e.g. Bölenius et al., 2017; Coyle et al., 2016; Schulte et al., 2012). As a result, yields tend to be higher in mineral soils compared to organic soils. In Latvia, the average annual precipitation is 703 mm, which exceeds annual evaporation by 245 mm on average (LVĢMC, 2017). Transient waterlogging has a negative impact on crop yields, caused by limited root development and N loss due to denitrification and leaching (Jiang et al., 2008; Zhang et al., 2006). In forestry systems, too, tree growth is disturbed in areas with a high water table (Cedro and Lamentowicz, 2011; Frelechoux et al., 2000; Zalitis and Indriksons, 2009). As a result of a high water level and a lack of oxygen and nutrients, the decomposition of organic matter is inhibited and thus carbon rich soils are formed. As a result, opportunities for intensive agricultural or forestry activities are severely limited in the absence of artificial drainage.

The aforementioned factors impact on profits from farming and forestry, and the labour-time requirements. Therefore, we combined the indices of profit and employment, using the tabular index approach by Greiner et al., (2018) to derive one integrated societal supply metric for primary productivity (Supplementary Material Table S3 and Table S4). Calculations of profit and employment were taken from Nipers, (2019).

The economic component of the index is profit. The calculations for profit are similar for both agriculture and forestry, and ultimately computed as incomes from sold produce plus subsidies minus production costs (including amortisation). Subsidies are significant for Latvian farmers—especially for medium and small farmers whose livelihood depends on subsidies due to price fluctuations and unusual weather conditions. Subsidies for forestry were assumed to be zero. Unlike in agriculture, forestry investments are long-term and profits only occur during harvesting, which takes place 2-4 times during the rotation period of a stand (sometimes up to 100 years). In each forest stand, four different timber assortments may be produced during harvesting, each with a different price. Costs were computed as: the sum of stand regeneration and management costs after final felling, harvesting costs from final felling and thinning, administrative costs, and costs to maintain infrastructure (forest roads and drainage systems). Stand regeneration and management costs are expressed in per ha units and occur only after final felling, while harvesting costs are expressed as a product of total harvesting volume, and harvesting costs per 1 m3 volume and are occurring both in final felling and thinning. Administrative and infrastructure maintenance costs are assumed to be EUR 43.6 per ha for all of the forest stands, equating to the average value in 2017 that is provided by State Forest Service. Profit is calculated as euro per ha per year.

The social component of the index is employment. Employment was evaluated as a labour-time contribution which is expressed in working hours per ha. Working hours are calculated as a function of crop or forest type and farm size. For instance, wheat production on large farms requires 15 hours of labour per ha (Nipers, 2019).

2.6.2. Supply of carbon regulation

Soil organic carbon (SOC) is a key indicator for soil quality; it affects nutrient cycling, pesticide and water retention, and soil structure maintenance (Karlen et al., 1997; Mueller et al., 2010). Soil biota, including bacteria, fungi, plant roots and other soil organisms, regulate the decomposition process of residues in soil and carbon sequestration in aggregates (Blanco-Canqui and Lal, 2004). In this context, soils play a pivotal role in regulating global carbon fluxes. In Northern and Central European countries, the use of drained organic soils for agricultural purposes has contributed significantly to GHG emissions (Berglund, 2017). Therefore, reducing emissions from these areas is one of the main emission reduction measures that are available to the combined agricultural and land use, land use change and forestry (LULUCF) sectors.

Both the total carbon stock in soils and change thereof are important metrics in determining the capacity of a soil to contribute to carbon regulation. Therefore, for our evaluation of the climate regulation function, we combined soil carbon stock values from national studies with CO_2 emission factors for drained organic soils from the IPCC Wetlands Supplement 2013. The CO_2 emission factor was developed in line with the observation that in drained organic soils, CO_2 is emitted as long as soil is being drained or organic matter remains (Drösler et al., 2013). The values were combined to create one metric, again using the tabular index approach by Greiner et al., (2018) (Supplementary Material Table S5 and Table S6). Carbon stock values in agricultural land were obtained from a Latvian national study where organic carbon was evaluated in different soil types, including mineral and organic soil types, in cropland and grassland with no changes in land use for at least 20 years. In this study, data from 218 plots were used to calculate an average organic carbon stock for each soil and land use combination. In mineral soils, the organic carbon stock at 0-40 cm depth amounted to 83.9 ± 7.1 t ha^{-1} C and 89.4 ± 12.0 t ha^{-1} C for cropland and grassland soils, respectively, while in organic soils, these were higher at 122.0 ± 45.2 t ha^{-1} C in cropland and 208.2 ± 22.9 t ha^{-1} C in grassland (Bardule et al., 2017). The average carbon stock was 97.8 ± 14.7 t ha^{-1} C in afforested agricultural land (Lazdiņš et al., 2015) and 268.5 t ha^{-1} C in afforested organic soils (Lazdins et al., 2014). Carbon stock values for forest soils were obtained from the joint international demonstration project BioSoil. Data from 475 soil samples (that were collected from 95 monitoring plots at 0-40 cm depth across the country) were used to calculate carbon stock in forest soils. Carbon stocks ranged from 99.06 t ha^{-1} C in managed coniferous forests on mineral soil to 289.56 t ha^{-1} C in managed deciduous forests on organic soil.

2.6.3. Supply of biodiversity

The abundance of microbial communities in soil depends on soil pH, C:N ratio, and concentrations of calcium and aluminium cations (Thomson et al., 2015), and additionally interacts with soil management; for instance, less frequent tillage in grasslands results in higher biomass production in the root system and a higher soil food web diversity (Tsiafouli et al., 2015). High input agriculture, unsustainable forestry practices, and land use intensification lead to a decrease in biodiversity and ecosystem service delivery (de Ruiter and Brown, 2007; Sylvain and Wall, 2011; Wagg et al., 2014).

In addition, land use changes from permanent grassland and extensively managed land to annual crop rotations is the main cause of soil biodiversity loss because of the strong and consistent effect on the structure of soil food web (de Vries et al., 2013).

However, due to the lack of coherent national and EU census data, it is not possible to evaluate soil biodiversity by using genetic or species diversity; therefore, within this study, the biodiversity function is evaluated as the quality of habitats for birds at field level. Schulte et al., (2019) also concluded that farmland birds are the only available indicator for measuring the diversity and integrity of habitats at European scale. Ernst et al. (2017) found a strong relationship between farmland and woodland management status (managed versus abandoned) and bird species' richness and abundance in agriculture and forest dominated landscapes. Landscape diversity is a strong driver for the habitat quality for farmland and non-farmland birds, and refers to a mosaic of arable land, forest land and field margins with scrubs (Bretagnolle et al., 2019; Pedersen and Krøgli, 2017; Wuczyński, 2016; Zingg et al., 2018). Accordingly, we divided the landscape in Latvia into three types: heterogeneous landscapes, homogeneous arable (>70% of hexagon is arable) and homogeneous forest (>70% of hexagon is forest).

We derived indices for habitat quality from the relationships between habitat quality and land use intensity in the EU (Reidsma et al., 2006) with a maximum value of 10, which indicates a very good habitat quality with high potential for biodiversity, and a minimum value of 1, which indicates poor habitat quality. Land use intensity is characterized by discernment of organic and conventional farming systems. Intensification of agriculture decreases habitat quality with biodiversity scoring 34% higher in organic farming systems compared to conventional farming systems (Tuck et al., 2014). Therefore, arable fields in homogeneous landscapes with conventional farming practices were assigned index 1, whereas arable fields in homogenous landscape with organic farming practices were scored as 4. Higher habitat quality is attributed to fields located in heterogeneous landscapes. A reduction in land abandonment and the maintenance of landscape heterogeneity leads to improved farmland and non-farmland bird populations (Pedersen and Krøgli, 2017), and as such, the index for extensively managed grasslands in heterogeneous landscapes was ranked as 10 in line with Dickie et al. (2011) and Tsiafouli et al. (2015). Similar to agricultural land, there are no available data for evaluation of biodiversity in forest soils; therefore, biodiversity was evaluated as a habitat quality for birds depending on management intensity, forest stand age and dominant species (Supplementary Material Table S7, Table S8, Table S9, and Table S10).

3. RESULTS

3.1. DEMAND FOR SOIL FUNCTIONS

The demand maps for the three soil functions, namely primary productivity, carbon regulation and biodiversity, demonstrate the different spatial scales at which variation in demand is manifested; from the local scale (biodiversity) to regional scale (primary productivity) and national scale (carbon regulation).

A higher demand for primary productivity function is found in municipalities in which higher unemployment rates co-occur with higher targets for GDP growth (Figure 8). The south-eastern region has the highest demand of all regions in Latvia. In northern Latvia, and in the north central part of Latvia, the demand for primary productivity is lower, reflecting lower unemployment rates and more modest requirements for further economic growth.

Similar to Schulte et al., (2015) and Pinillos et al. (in press), the demand for carbon regulation is evenly spread at the national level, reflecting the absence of sector-specific targeting between the non-ETS sectors such as housing, agriculture, waste and transport (Figure 8). This inference was made because it is currently yet unknown which production sectors and land uses will be affected by the emission reduction target set by the Paris Agreement.

The demand for the augmentation of biodiversity is highest in areas dominated by agricultural land (Figure 8), most obviously in hexagons where agricultural land occupies more than 75% of the area. Demand is proportionally lower in hexagons dominated by other land uses in which the Bird Index is currently already meeting its 2030 targets.

3.2. SUPPLY OF SOIL FUNCTIONS

The right column in Figure 8 shows the spatial patterns of the supply of soil functions in relation to land use and soil organic carbon characteristics.

The supply of primary productivity is highest in managed agricultural land areas, specifically in the central part of Latvia and the western region. A medium supply can be found in forests on mineral and wet mineral and drained organic soils. Low and very low supplies are found in abandoned areas, as well as in natural forests and managed forests on organic soils (Figure 8).

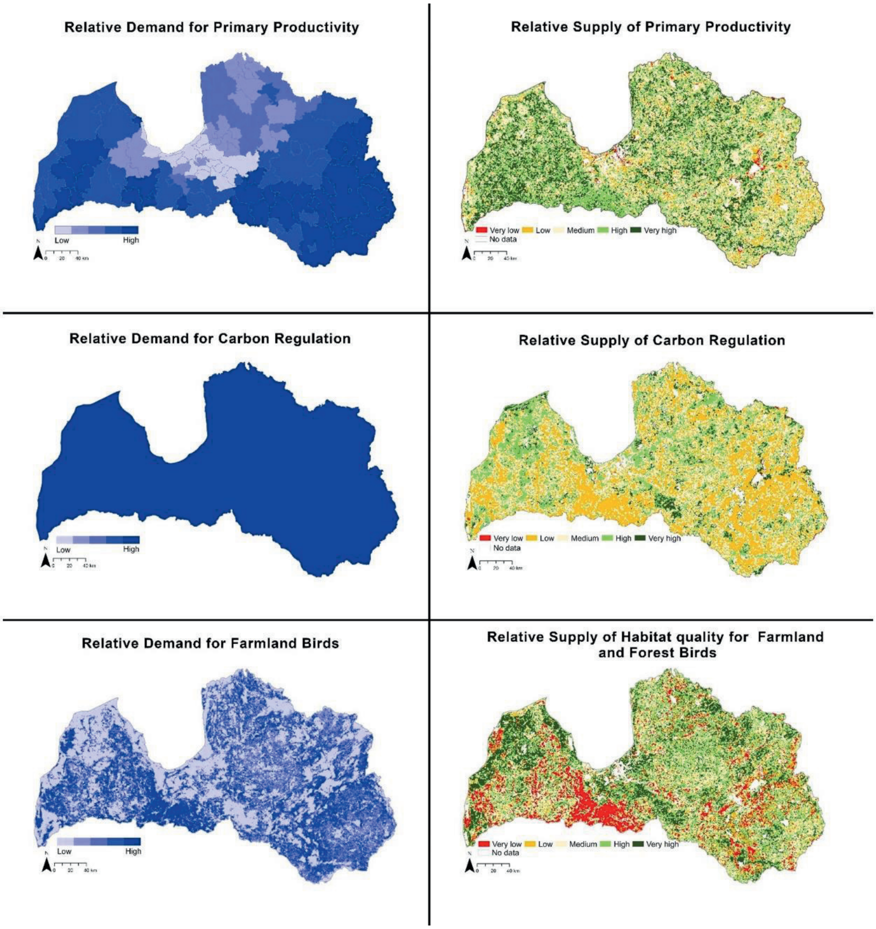

Figure 8. Indicative maps of the normalized demand (left column) and supply (right column) for the three soil functions, from top to down: primary productivity, carbon regulation and biodiversity.

The supply of the carbon regulation function ranges from low to very high across the country (Figure 8): the central parts of Latvia and the south-eastern region show lower supplies of the carbon regulation compared to other regions. The western part of Latvia shows a higher supply, while the north-eastern region shows a medium supply compared to other regions. Locations with a very high supply are located in the central part of the south-eastern region of Latvia, in the northern part of the western region, and in the centre of the north-eastern region.

Very low supplies of the biodiversity function are found in highly intensive agricultural land use areas located in homogeneous landscapes (e.g. the central part of Latvia), in natural forests with young and middle age stands and also in managed forests, in forest clearance areas, and middle age and seasoning age managed forests with white alder as the main tree species. In extensive grasslands, abandoned areas, and extensively managed areas located in heterogeneous landscapes, the supply of biodiversity function is high, and also in over-seasoned and maturity natural forest stands and in young and over-seasoned managed forest stands (Figure 8).

3.3. MATCHING SUPPLY AND DEMAND FOR SOIL FUNCTIONS

Based on the balance between supply and demand for each of the functions, we aggregated the difference between the supply and demand maps in Figure 8, into nine regions (Figure 9) that correspond to Pilvere (2015), who distinguished 14 regions to highlight the main territorial differences. Region 2 and 5 combines multiple regions from Pilvere (2015), because those areas show similarities in supply and demand of soil functions.

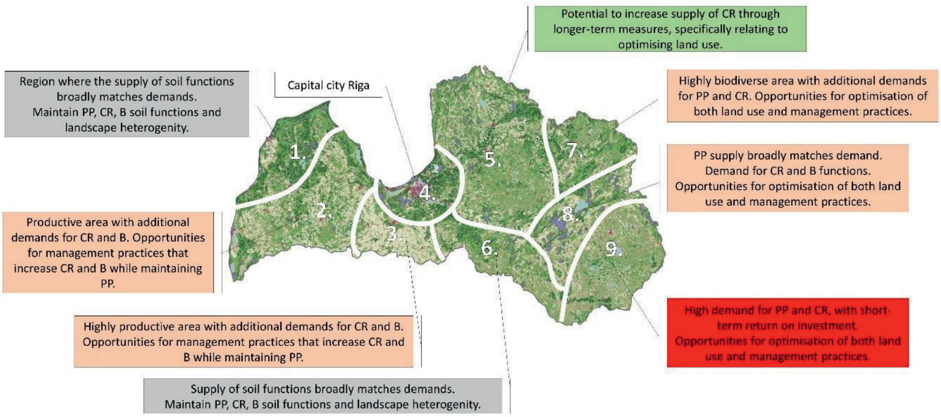

Figure 9. Indicative map showing geographical areas of relevance to soil functions and where application of land use changes or changes in management practices from Table 1 are applicable (PP – primary productivity, CR – carbon regulation; B – biodiversity).

Each region presented in Figure 9 has a specific balance between the supply and demand for the three soil functions, and hence a specific requirement for land use changes or improvements in management practices, with a view to matching the supply of soil functions with regional demands.

4. DISCUSSION

4.1. PATHWAYS TO MATCH SUPPLY AND DEMAND OF SOIL FUNCTIONS

Our results make explicit the discrepancies between the demand and supply of soil functions, the latter being determined by the gradient from mineral to histic soils as the main soil property and the land use. Our analysis has two implications for land managers and policy makers alike. Firstly, it underscores the notion that it may not only be difficult, but also not necessary nor desirable to try and maximise all soil functions everywhere; instead, the spatial variation in the demand and supply of soil functions calls for an optimisation, rather than maximisation, of soil functions. As part of a large-scale European monitoring exercise of the LANDMARK project, Zwetsloot et al. (2020) showed that it is virtually impossible for individual land managers to maximise all five soil functions simultaneously, as a result of trade-offs between the response of the soil functions to land management practices. However, the same date shows that it is feasible for most farmers to simultaneously optimise at least three soil functions on each farm, to meet functional and societal demands as defined by Schulte et al. (2019). Thus, a regional approach allows for a more realistic optimisation of soil functions, and can thus contribute to the successful operationalisation of policy ambitions. While the LANDMARK project (Schulte et al., 2019; Vrebos et al., 2020) recently demonstrated the need for a differentiated approach between EU Member States, our current study goes further and illustrates the need for sub-national differentiation of land management planning.

Secondly, there are two possible ways to such regional optimisation: targeted land use change and the introduction of management practices (Schulte et al., 2014): indeed, Dingkuhn et al. (2020) concluded that the combination of land use system and management strategies is necessary to reach sustainability in agricultural resource-use. This duality requires an integrated approach to land use planning and the targeted incentivisation of land management practices and therefore close cooperation between the stakeholders and the delivery of essential soil functions from the local to the landscape scale and at the national level. Such management of soil functions from farm to national scale to achieve current and future socio-economic and environmental goals is a key challenge for policy makers (Valujeva et al., 2016). One option is to provide targeted incentives to farmers to introduce new management practices or to improve existing management practices in order to jointly achieve national targets through knowledge transfer and financial resources.

In this context, the Latvian Bio-economy Strategy 2030 was developed to guide the development for the traditional bioeconomic sectors (LIBRA2030, 2017). This strategy must be taken into consideration in the development of future Latvian planning documents. Such planning documents for territorial development were developed several years ago and ideally should complement each other. However, in reality there is no clear measurable connection between targets in planning documents; as a result, they do not give a comprehensive vision of the desired direction for development of the bio-economy. Therefore, it is not possible to evaluate how short-term targets at regional scale improve long-term targets at national scale. For instance, each region in Latvia has specified targets that relate to our soil functions, such as GDP increase, the preservation of agricultural and forestry land use and even targeted declines in GHG emissions in some regions. However, thus far there has been no assessment of whether, and to what extent, these targets will contribute to the achievement of national targets or even international commitments. Here, we exemplify how purposeful regional differentiation in land management practices can be effective in meeting the demand for soil functions at regional level and thus deliver on aggregate commitments at national level.

4.2. IMPROVEMENTS IN THE SUPPLY OF SOIL FUNCTIONS

Changes in land use and land management practices that aim to selectively increase one of the soil functions are associated with the aforementioned trade-offs with the other soil functions. Here, we exemplify this with 17 management practices selected from the literature (referenced in Table 1) that are applicable for the temperate climate zone and that positively or neutrally affect the selected soil functions. In Table 1, we evaluate the percentage difference of supply of soil functions before and after the implementation of management practices, derived from these studies, illustrating the trade-offs between increasing primary productivity, promoting carbon sequestration and ensuring biodiversity, and accordingly, the need for close cooperation and knowledge transfer between land managers and policy makers to accomplish the desired changes. For example, extensification of grassland can increase the supply of the carbon regulation function due to increases in carbon stocks and a decrease in GHG emissions but at the expense of primary production, while intensification may result in the reverse trade-off. At the same time the maintenance or improvement of soil properties can also lead to higher primary productivity without a reduction in the supply of other soil functions (Bharali et al., 2017; Taghizadeh-Toosi and Olesen, 2016). For example, many studies have investigated the potential to increase the carbon stock in the agricultural landscape by creating a new biomass stock for the capture of CO_2 from the atmosphere (Fortier et al., 2015; Mäkiranta et al., 2007; Taghizadeh-Toosi and Olesen, 2016; Weslien et al., 2009). Carbon sequestration at farm level can be promoted by changes in farm management, such as high-precision management of resources, minimum or no tillage, and the diversification of crop types (de Ruiter and Brown, 2007; Nielsen et al., 2015). The impact on other functions, however, must be considered before instigating such changes.

Landscape diversity is the main factor for biodiversity (Bretagnolle et al., 2019; Pedersen and Krøgli, 2017; Wuczyński, 2016; Zingg et al., 2018) and even small changes in land use at the farm scale can decrease the provision of biodiversity at the landscape scale. One of the key changes that can improve the supply of the biodiversity function is extensive land management, for example through land use change from arable to grassland (Taghizadeh-Toosi and Olesen, 2016) or through the introduction of minimum or no-till management and diversification (Nielsen et al., 2015). This diversity of potential trade-offs and synergies necessitates the implementation of smart land management in accordance to medium-term and long-term targets.

Table 1. List of possible management practices (↑ - increase; ↓ - decrease; → - do not affect).

No.	Management practise	Primary productivity	Carbon sequestration	Biodiversity	Reference
	Land use change				
1.	Afforestation of fertile well-drained organic soils	452% ↑	69% ↑	0% →	Minkkinen et al., 1999; Schrier-Uijl et al., 2014; Weslien et al., 2009
2.	Afforestation of organic soil	73% ↑	50% ↑	4% ↑	Ausec et al., 2009; Mäkiranta et al., 2007; Maljanen et al., 2010; Minkkinen et al., 1999
3.	Conversion of some of the current annual crops to grassland	38% ↓	25% ↑	68% ↑	Gosling et al., 2017; Poeplau et al., 2011; Taghizadeh-Toosi and Olesen, 2016; West and Post, 2002
4.	Rewetting organic soils under grassland leads to these ecosystems becoming neutral or small C sinks	20% ↓	96% ↑	0% →	Karki et al., 2016; Maanavilja et al., 2015; Remm et al., 2013; Renou-Wilson et al., 2016
	Farm management				
5.	Use of farmyard manure and green manures along with returning crop residues	20% ↑	16% ↑	0% →	Bharali et al., 2017; Taghizadeh-Toosi and Olesen, 2016
6.	No-till increases fungal biomass in general, which leads to improved soil structure that increases infiltration and reduces erosion	2.6% ↑	10% ↑	21% ↑	Martínez et al., 2016; Nielsen et al., 2015; Ogle et al., 2005; Simpson et al., 2010;

No.	Management practise	Primary productivity	Carbon sequestration	Biodiversity	Reference
	Land use change				
					Van den Putte et al., 2010
7.	Preserve existing C stocks in soils	0% →	0% →	0% →	Renou-Wilson et al., 2016
8.	Short rotation plantation in riparian ecosystems on rich organic soil with periodical harvest	17% ↑	3% ↑	35% ↓	Dimitriou and Dominik, 2015; Hénault-Ethier et al., 2017; Laganière et al., 2010; Strazdiņa, 2015
9.	High-precision management of nutrients, chemistry, water, pests, and pathogens	27%↑	0% → No change because no evidence	0% → No change because no evidence	Hedley, 2015; Nielsen et al., 2015
10.	Minimum tillage with residue retention and use of green manure	5% ↓	3% ↑	6% ↑	Chan, 2001; Nielsen et al., 2015; Ogle et al., 2005; Van den Putte et al., 2010
11.	No-tillage leads to increase in species richness and overall density	9% ↓	10% ↑	21% ↑	de Ruiter and Brown, 2007
12.	Reed canary grass as a bioenergy crop on organic soils	20% ↓	45% ↑	23% ↑	Karki et al., 2016; Mander et al., 2012; Shurpali et al., 2009; Tavi et al., 2010
13.	Diversification of crop types, permanent plant cover, buffer strips	10% ↑	4% ↑	23% ↑	McDaniel et al., 2014; Nielsen et al., 2015; Osterholz et al., 2018; Zuber et al., 2015
14.	Improved grassland management through extensive grazing	55% ↓	7.7% ↑	128% ↑	Conant et al., 2001; Renou-Wilson et al., 2016; Van Vooren et al., 2018
15.	Increase groundwater level on organic soils for shallow rooting vegetable production	7% ↑	31% ↑	0% → No change because no evidence	Berglund and Berglund, 2010; Matysek et al., 2019; Musarika et al., 2017; Weslien et al., 2012
16.	Application of organic amendments in combination with inorganics in wheat cropping system	20% ↑	51% ↑	0% →	Bharali et al., 2017
17.	Water table management on organic soil (keep it stable)	19% ↓	31% ↑	0% →	Leppelt et al., 2014; Matysek et al., 2019

4.3. REGIONALISED APPROACHES TO SUSTAINABLE LAND MANAGEMENT

A high demand for primary productivity and carbon regulation function with short-term returns on investments is evident in region 9. Here, management practices number 1, 2, 5, 6, 9, 13, 15, and 16 from Table 1 could prove most effective. Region 5 has high potential to become a carbon sink and contribute to long-term commitments trough optimisation of land use, and therefore management practices number 1, 2, 3, and 4 are applicable in this region. Management practices number 6, 10, and 13 are suitable for regions 2 and 3, where supply of primary productivity broadly meets demand, but where additional demands are placed to deliver on the carbon regulation function and biodiversity; in region 8, management practice number 2 can also be applicable. In the highly biodiverse region 7, management practices 1, 2, 5, 6, 13, 15, and 16 may increase the supply of primary productivity and the carbon regulation function, without unduly affecting the biodiversity function. In regions 1 and 6, the supply of soil functions broadly matched demand, therefore management practice number 7 (which aims to maintain supply of primary productivity, the carbon regulation function and biodiversity) is most applicable in these regions, along with the maintenance of heterogeneity of the landscape.

4.4. LIMITATIONS

In our research, the selection of proxy indicators for quantifying supply and demand of soil functions strongly depends on available data which must be considered in the interpretation of results.

The demand for carbon regulation is framed at the national level without highlighting specific areas for intervention; as a result, the demand for carbon regulation function has not yet reached local levels of administration. At the same time, the 6% reduction target proposed by the EU Climate and Energy Framework 2030 will affect bioeconomics in Latvia: most likely, all non-ETS sectors will have to contribute to achieving the long term climate target. For the supply of the carbon regulation function, we only included carbon stocks in soil because of the national data availability, and did not include aboveground and belowground biomass, both of which also play an important role in carbon budget. Soil is the largest terrestrial carbon stock, and it stores approximately three times more carbon than the atmosphere and vegetation (Ramesh et al., 2019). The importance of sequestering carbon into agricultural soils also has been emphasised at the European scale, because those soils have high potential to reduce GHG emissions and at the same time to improve soil quality which gives benefit to farmers (Meredith, 2019).

We assessed the supply of biodiversity using habitat quality for bird species' richness and abundance and land use; indeed, habitat changes due to land use change are considered as one of the major drivers for the decline in global biodiversity (De Baan et al., 2013). Nevertheless, biodiversity has many dimensions at genetic, species and ecosystem level including abundance of microbial communities in soil, plant species richness and abundance which should be considered in future studies.

4.5. FURTHER RESEARCH

Farmers and foresters are expected to fulfil multiple functions for society: to produce food, fibre and fuel and to provide jobs for people living in rural areas whilst simultaneously protecting the environment, preserving the landscape and biodiversity. The EU has developed the Common Agricultural Policy (CAP) to attract young farmers to join the profession and to provide a sustainable and competitive agricultural sector that ensures safe, affordable and good quality food, while preserving biodiversity, and to mitigate the uncertainties arising from climate change, price fluctuations in agricultural markets, and political decision-making (EC, n.d.). The proposals for the post-2020 CAP focus on increased subsidiarity and result-based schemes, rather than centralised activity based interventions. The basic policy parameters, included in new CAP, will allow for more flexibility and require national level customisation in the form of a National Strategic Plans by each Member State that accounts for national contexts (EC, 2017). This development offers opportunities for the creation of targeted and effective policies for agricultural and environmental development that will allow for differentiation at regional level.

In the context of Latvia, such differentiation requires further quantification of and optimisation of the three soil functions, and validation of the proposed changes in land use and management practices, specifically for abandoned agricultural lands that provide opportunities for win:win:win outcomes. Abandoned agricultural land are typically naturally overgrown with bushes; targeted afforestation of these areas can not only lead to long-term economic benefits, but also create an important carbon sink of wood biomass (Hooker and Compton, 2017), while maintaining the heterogeneity of the landscape can have a positive impact on the bird species richness and abundance (Pedersen and Krøgli, 2017). The territory of Latvia is characterized by unstable climatic conditions with intermittent occurrences of frost, drought and rain events and shifting from crops to higher value-added products (without financial support for investments and insurance) can lead to financial losses. Therefore, expansion of current production is considered a more readily-achievable solution for short-term economic returns. However, of equal importance to the design of regional intervention packages is the identification of the gaps between design and implementation, known as the “think-do-gap” (O’Sullivan et al., 2017). This entails the identification of suitable pathways for the incentivisation of changes in land use and management practices for individual land managers. This combination of design and identification of transition pathways may then inform national policies to optimise the supply of soil functions and to achieve the socio-economic and climate objectives simultaneously in the context of national and international commitments and the new CAP.

5. CONCLUSIONS

- In conclusion, the supply and demand for soil functions differ between regions. The supply of soil functions can be improved by changes in land use and improvements in management practices, but these should be applied in accordance with regional and national targets and commitments without undue trade-offs with the supply of other soil functions.
- Increasing demand for bio-based products allows countries such as Latvia, where economic development has been impacted by various economical changes, to increase bio-based production and exports. Trade-offs between an increase in production and climate change mitigation play an important role in policy decisions.
- Our results show that regions have specific suites of soil functions depending on land use and soil classes; also, the demand for primary productivity varies between regions while the demand for biodiversity is locally spread, but the demand for climate mitigation is framed for the country as a whole.
- Regional differences define specific requirements for land use changes or improvements in management practices. In order to promote sustainable development of agriculture and forestry, policy-making should consider regional differences to achieve both socio-economic and climate objectives. We have identified spatial locations for specific land use changes and improvements in management practices related to the supply and demand for the three soil functions.
- Proposed changes to the common agricultural policy offer the opportunity for each Member State to form an agricultural policy at national scale to underpin agricultural practices that are effective and tailored towards local climate conditions and national implementation pathways.

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SUPPLEMENTARY MATERIAL

Supplementary Table S1. Tabular indexes of normalized regional bioeconomic GDP target and unemployment rate at municipality level for demand for primary productivity function.

	0 ≥ U < 17	**17 ≥ U < 34**	**34 ≥ U < 51**	**51 ≥ U < 68**	**68 ≥ U < 85**	**85 ≥ U < 102**
0 ≥ GDP < 17	1	2	3	4	5	6
17 ≥ GDP < 34	2	3	4	5	6	7
34 ≥ GDP < 51	3	4	5	6	7	8
51 ≥ GDP < 68	4	5	6	7	8	9
68 ≥ GDP < 85	5	6	7	8	9	10

Abbreviations: GDP – GDP target; U – unemployment rate.

Supplementary Table S2. Regional bioeconomic GDP target per area and unemployment rate at municipal level used to apply index from tabular indexes.

Region	**Municipality**	**Bio-economic GDP target, EUR**	**Unemployment rate, %**	**Percentiles for bio-economic GDP**	**Percentiles for unemployment rate**	**Index**
Kurzeme	Aizputes novads	63 012	9.60%	65.83%	77.500%	8
Kurzeme	Alsungas novads	63 012	6.70%	65.83%	47.500%	6
Kurzeme	Brocenu novads	63 012	6.40%	65.83%	46.667%	6
Kurzeme	Dundagas novads	63 012	6.80%	65.83%	50.000%	6
Kurzeme	Durbes novads	63 012	7.50%	65.83%	59.167%	7
Kurzeme	Grobinas novads	63 012	6.20%	65.83%	45.000%	6
Kurzeme	Kuldigas novads	63 012	8.70%	65.83%	68.333%	8
Kurzeme	Liepaja	63 012	8.60%	65.83%	67.500%	7
Kurzeme	Mersraga novads	63 012	9.40%	65.83%	74.167%	8
Kurzeme	Nicas novads	63 012	5.80%	65.83%	40.833%	6
Kurzeme	Pavilostas novads	63 012	6.10%	65.83%	43.333%	6
Kurzeme	Priekules novads	63 012	10.10%	65.83%	80.833%	8
Kurzeme	Rojas novads	63 012	6.20%	65.83%	45.000%	6
Kurzeme	Rucavas novads	63 012	8.90%	65.83%	69.167%	8
Kurzeme	Saldus novads	63 012	7.30%	65.83%	55.000%	7
Kurzeme	Skrundas novads	63 012	10.90%	65.83%	84.167%	8
Kurzeme	Talsu novads	63 012	8.20%	65.83%	65.000%	7
Kurzeme	Vainodes novads	63 012	9.70%	65.83%	78.333%	8
Kurzeme	Ventspils	63 012	4.20%	65.83%	37.500%	6
Kurzeme	Ventspils novads	63 012	5.60%	65.83%	56.667%	7
Latgale	Aglonas novads	63 012	7.40%	48.33%	93.333%	8
Latgale	Baltinavas novads	44 536	16.60%	48.33%	95.000%	8

Region	Municipality	Bio-economic GDP target, EUR	Unemployment rate, %	Percentiles for bio-economic GDP	Percentiles for unemployment rate	Index
Latgale	Balvu novads	44 536	18.60%	48.33%	89.167%	8
Latgale	Ciblas novads	44 536	13.50%	48.33%	100.000%	8
Latgale	Dagdas novads	44 536	24.00%	48.33%	94.167%	8
Latgale	Daugavpils	44 536	16.70%	48.33%	71.667%	7
Latgale	Ilukstes novads	44 536	9.10%	48.33%	70.833%	7
Latgale	Karsavas novads	44 536	9.00%	48.33%	97.500%	8
Latgale	Kraslavas novads	44 536	22.40%	48.33%	90.000%	8
Latgale	Livanu novads	44 536	14.40%	48.33%	92.500%	8
Latgale	Ludzas novads	44 536	15.10%	48.33%	95.833%	8
Latgale	Preilu novads	44 536	19.10%	48.33%	85.000%	8
Latgale	Rezekne	44 536	11.20%	48.33%	86.667%	8
Latgale	Rezeknes novads	44 536	11.80%	48.33%	96.667%	8
Latgale	Riebinu novads	44 536	19.90%	48.33%	90.000%	8
Latgale	Rugaju novads	44 536	14.40%	48.33%	88.333%	8
Latgale	Varkavas novads	44 536	13.20%	48.33%	73.333%	7
Latgale	Vilakas novads	44 536	9.30%	48.33%	91.667%	8
Latgale	Vilanu novads	44 536	14.70%	48.33%	99.167%	8
Latgale	Zilupes novads	44 536	23.50%	48.33%	98.333%	8
Latgale	Daugavpils novads	44 536	23.10%	48.33%	87.500%	8
Riga	Alojas novads	44 536	12.70%	0.83%	56.667%	4
Riga	Adazu novads	7 989	7.40%	0.83%	2.500%	1
Riga	Babites novads	7 989	3.20%	0.83%	5.000%	1
Riga	Baldones novads	7 989	3.30%	0.83%	6.667%	1
Riga	Carnikavas novads	7 989	3.70%	0.83%	15.833%	1
Riga	Engures novads	7 989	4.30%	0.83%	12.500%	1
Riga	Garkalnes novads	7 989	4.20%	0.83%	0.833%	1
Riga	Ikskiles novads	7 989	2.70%	0.83%	2.500%	1
Riga	Incukalna novads	7 989	3.20%	0.83%	33.333%	2
Riga	Jaunpils novads	7 989	5.30%	0.83%	25.833%	2
Riga	Jurmala	7 989	5.00%	0.83%	15.833%	1
Riga	Kandavas novads	7 989	4.30%	0.83%	34.167%	3
Riga	Krimuldas novads	7 989	5.40%	0.83%	19.167%	2
Riga	Keguma novads	7 989	4.60%	0.83%	12.500%	1
Riga	Kekavas novads	7 989	4.20%	0.83%	2.500%	1
Riga	Lielvardes novads	7 989	3.20%	0.83%	9.167%	1
Riga	Limbazu novads	7 989	4.00%	0.83%	64.167%	4
Riga	Malpils novads	7 989	8.10%	0.83%	19.167%	2
Riga	Marupes novads	7 989	4.60%	0.83%	1.667%	1
Riga	Ogres novads	7 989	2.90%	0.83%	7.500%	1
Riga	Olaines novads	7 989	3.90%	0.83%	30.000%	2
Riga	Riga	7 989	5.10%	0.83%	9.167%	1

Region	Municipality	Bio-economic GDP target, EUR	Unemployment rate, %	Percentiles for bio-economic GDP	Percentiles for unemployment rate	Index
Riga	Ropazu novads	7 989	4.00%	0.83%	5.000%	1
Riga	Salacgrivas novads	7 989	3.30%	0.83%	65.000%	4
Riga	Salaspils novads	7 989	8.20%	0.83%	21.667%	2
Riga	Saulkrastu novads	7 989	4.70%	0.83%	11.667%	1
Riga	Sejas novads	7 989	4.10%	0.83%	30.833%	2
Riga	Siguldas novads	7 989	5.20%	0.83%	25.833%	2
Riga	Stopinu novads	7 989	5.00%	0.83%	9.167%	1
Riga	Tukuma novads	7 989	4.00%	0.83%	35.833%	3
Vidzeme	Aluksnes novads	7 989	5.50%	25.83%	85.000%	7
Vidzeme	Amatas novads	15 493	11.20%	25.83%	37.500%	4
Vidzeme	Apes novads	15 493	5.60%	25.83%	54.167%	5
Vidzeme	Beverinas novads	15 493	7.20%	25.83%	56.667%	5
Vidzeme	Burtnieku novads	15 493	7.40%	25.83%	24.167%	3
Vidzeme	Cesvaines novads	15 493	4.80%	25.83%	81.667%	6
Vidzeme	Cesu novads	15 493	10.20%	25.83%	35.833%	4
Vidzeme	Erglu novads	15 493	5.50%	25.83%	80.000%	6
Vidzeme	Gulbenes novads	15 493	10.00%	25.83%	69.167%	6
Vidzeme	Jaunpiebalgas novads	15 493	8.90%	25.83%	25.000%	3
Vidzeme	Kocenu novads	15 493	4.90%	25.83%	25.833%	3
Vidzeme	Ligatnes novads	15 493	5.00%	25.83%	25.833%	3
Vidzeme	Lubanas novads	15 493	5.00%	25.83%	83.333%	6
Vidzeme	Madonas novads	15 493	10.70%	25.83%	81.667%	6
Vidzeme	Mazsalacas novads	15 493	10.20%	25.83%	19.167%	3
Vidzeme	Nauksenu novads	15 493	4.60%	25.83%	7.500%	2
Vidzeme	Pargaujas novads	15 493	3.90%	25.83%	43.333%	4
Vidzeme	Priekulu novads	15 493	6.10%	25.83%	39.167%	4
Vidzeme	Raunas novads	15 493	5.70%	25.83%	40.833%	4
Vidzeme	Rujienas novads	15 493	5.80%	25.83%	21.667%	3
Vidzeme	Smiltenes novads	15 493	4.70%	25.83%	25.833%	3
Vidzeme	Strencu novads	15 493	5.00%	25.83%	75.833%	6
Vidzeme	Valkas novads	15 493	9.50%	25.83%	47.500%	4
Vidzeme	Valmiera	15 493	6.70%	25.83%	12.500%	2
Vidzeme	Varaklanu novads	15 493	4.20%	25.83%	75.833%	6
Vidzeme	Vecpiebalgas novads	15 493	9.50%	25.83%	21.667%	3
Vidzeme	Valmieras novads	15 493	4.70%	25.83%	12.500%	2
Zemgale	Aizkraukles novads	87 588	7.10%	82.50%	53.333%	8
Zemgale	Aknistes novads	87 588	6.80%	82.50%	50.000%	7
Zemgale	Auces novads	87 588	9.80%	82.50%	79.167%	9
Zemgale	Bauskas novads	87 588	6.70%	82.50%	47.500%	7

Region	Municipality	Bio-economic GDP target, EUR	Unemployment rate, %	Percentiles for bio-economic GDP	Percentiles for unemployment rate	Index
Zemgale	Dobeles novads	87 588	7.30%	82.50%	55.000%	8
Zemgale	Iecavas novads	87 588	5.20%	82.50%	30.833%	6
Zemgale	Jaunjelgavas novads	87 588	7.80%	82.50%	62.500%	8
Zemgale	Jelgava	87 588	4.40%	82.50%	18.333%	6
Zemgale	Jelgavas novads	87 588	5.40%	82.50%	34.167%	7
Zemgale	Jekabpils	87 588	7.00%	82.50%	52.500%	8
Zemgale	Jekabpils novads	87 588	7.60%	82.50%	61.667%	8
Zemgale	Kokneses novads	87 588	6.90%	82.50%	51.667%	8
Zemgale	Krustpils novads	87 588	7.50%	82.50%	59.167%	8
Zemgale	Neretas novads	87 588	9.20%	82.50%	72.500%	9
Zemgale	Ozolnieku novads	87 588	4.30%	82.50%	15.833%	5
Zemgale	Plavinu novads	87 588	6.00%	82.50%	42.500%	7
Zemgale	Rundales novads	87 588	9.40%	82.50%	74.167%	9
Zemgale	Salas novads	87 588	8.50%	82.50%	66.667%	8
Zemgale	Skriveru novads	87 588	5.70%	82.50%	39.167%	7
Zemgale	Tervetes novads	87 588	7.50%	82.50%	59.167%	8
Zemgale	Vecumnieku novads	87 588	5.20%	82.50%	30.833%	6
Zemgale	Viesites novads	87 588	7.90%	82.50%	63.333%	8

Supplementary Table S3. Tabular indexes of profit and working hours in percentiles for supply of primary productivity.

	4 ≥ W < 19	**19 ≥ W < 34**	**34 ≥ W < 53**	**53 ≥ W < 72**	**72 ≥ W < 91**	**91 ≥ W < 110**
4 ≥ P < 24	1	2	3	4	5	6
24 ≥ P < 44	2	3	4	5	6	7
44 ≥ P < 64	3	4	5	6	7	8
64 ≥ P < 84	4	5	6	7	8	9
84 ≥ P < 104	5	6	7	8	9	10

Abbreviations: P – profit; W – working hours.

Supplementary Table S4. Data of profit and working hours for each land use and soil class combination for primary productivity function.

Combinations of land uses and soil type	Profit, eur/ha/year	Working hours, hours/ha/year	Percentiles for profit	Percentiles for working hours	Index
MGop	70	25	50%	65%	6
DGop	15	25	35%	65%	5
MVeg	1 450	500	96%	88%	9
DVeg	350	500	88%	88%	9
MPepl	2 900	600	100%	96%	10
DPepl	550	600	92%	96%	10

Combinations of land uses and soil type	Profit, eur/ha/year	Working hours, hours/ha/year	Percentiles for profit	Percentiles for working hours	Index
MOther	300	155	85%	81%	9
DOther	200	155	77%	81%	8
MGrass	100	30	65%	73%	8
MAban	0	0	4%	4%	1
DGrass	70	30	50%	73%	7
DAban	0	0	4%	4%	1
MCmin	270	3	81%	58%	7
MDmin	150	3	73%	58%	7
NCmin	135	2	69%	50%	6
NDmin	75	2	58%	50%	5
MCwet	81	0.9	62%	42%	5
MDwet	45	0.9	46%	42%	5
NCwet	41	0.6	42%	35%	4
NDwet	23	0.6	38%	35%	4
MCorg	0	0	4%	4%	1
MDorg	0	0	4%	4%	1
NCorg	0	0	4%	4%	1
NDorg	0	0	4%	4%	1

Abbreviations: DAban - abandoned on drained organic soil; DGop – grains, oilseeds and pulses on organic soil;DGrass – grassland on drained organic soil; DOther – other crops on organic soil; DPepl – perennial plantations on organic soil; DVeg – vegetables on organic soil; MAban – abandoned agricultural land on mineral soil; MCmin – managed coniferous forest on mineral soil; MCorg – managed coniferous forest on organic soil; MCwet – managed coniferous forest on drained organic soil; MDmin – managed deciduous forest on mineral soil; MDorg – managed deciduous forest on organic soil; natural coniferous forest on organic soil; MDwet – managed decidious on drained organic soil; MGop – grains, oilseeds and pulses on mineral soil; MGrass – grassland on mineral soil; MOther – other crops on mineral soil; MPepl – perennial plantations on mineral soil; MVeg – vegetables on mineral soil; NCmin – natural coniferous forest on mineral soil; NCorg – natural coniferous forest on organic soil; NCwet – natural coniferous forest on drained organic soil; NDmin – natural deciduous on mineral soil; NDorg – natural deciduous forest on organic soil; NDwet – natural deciduous forest on drained mineral soil.

Supplementary Table S5. Tabular indexes of normalized carbon stocks and emission factors for supply of carbon regulation function.

	101 > EF ≤ 85	**85 > EF ≤ 69**	**69 > EF ≤ 53**	**53 > EF ≤ 37**	**37 > EF ≤ 21**	**21 > EF ≤ 5**
5 ≥ C < 24	1	2	3	4	5	6
24 ≥ C < 43	2	3	4	5	6	7
43 ≥ C < 62	3	4	5	6	7	8
62 ≥ C < 81	4	5	6	7	8	9
81 ≥ C < 100	5	6	7	8	9	10

Abbreviations: C – carbon stock; EF – emission factor.

Supplementary Table S6. Data of carbon stocks and emission factors for each land use and soil class combination for carbon regulation function. Emission factors (EF) are normalized and percentiles of carbon stocks and normalized emission factors are calculated and further used to define index for each land use and soil class combination from tabular indexes.

Combinations of land uses and soil type	C stock, t/ha	EF, t CO_2-C/ha/year	EF normalization	Percentiles for C stock	Percentiles for EF norm.	Index
MAra	83.9	0	-0.69	5%	5%	6
MGrass	89.4	0	-0.69	10%	5%	6
MAban	97.8	0	-0.69	20%	5%	6
MCmin	99.06	0	-0.69	25%	5%	7
MDmin	102.02	0	-0.69	35%	5%	7
NCmin	99.06	0	-0.69	25%	5%	7
NDmin	102.02	0	-0.69	35%	5%	7
Dara	122	7.9	11.33	45%	100%	3
DGrass	208.2	6.1	8.60	60%	95%	3
DAban	268.5	3.8	5.10	80%	85%	4
MCwet	275.50	2.6	3.27	85%	65%	7
MDwet	144.33	2.6	3.27	50%	65%	5
NCwet	275.50	2.6	3.27	90%	65%	7
NDwet	144.33	2.6	3.27	50%	65%	5
MCorg	230.91	0	-0.69	65%	5%	9
MDorg	289.56	0	-0.69	95%	5%	10
NCorg	230.91	0	-0.69	65%	5%	9
NDorg	289.56	0	-0.69	95%	5%	10

Abbreviations: DAban- abandoned agricultural land on drained organic soil; DAra – arable on drained organic soil; DGrass – grassland on drained organic soil; MAban – abandoned agricultural land on mineral soil; MAra – arable on mineral soil; MCmin – managed coniferous forest on mineral soil; MCorg – managed coniferous forest on organic soil; MCwet – managed coniferous forest on drained organic soil; MDmin – managed deciduous forest on mineral soil; MDorg – managed deciduous forest on organic soil; MDwet – managed deciduous on drained organic soil; MGrass – grassland on mineral soil; NCmin – natural coniferous forest on mineral soil; NCorg – natural coniferous forest on organic soil; NCwet – natural coniferous forest on drained organic soil; NDmin – natural deciduous on mineral soil; NDorg – natural deciduous forest on organic soil; NDwet – natural deciduous forest on drained mineral soil.

Supplementary Table S7. Developed habitat quality indexes for agricultural land depending on agricultural systems and landscape (adapted from Reidsma et al. (2006) to Latvia).

Habitat quality from Reidsma et. al. (2006), %	Agricultural production system in Latvia	Landscape	Index
40	Extensive grassland	Hetero	10
35	Extensive organic	Hetero	9
34	Abandoned	Hetero	8
25	Extensive farming	Hetero	6

Habitat quality from Reidsma et. al. (2006), %	Agricultural production system in Latvia	Landscape	Index
20	Intensive grassland	Homo	4
20	Intensive organic	Homo	4
17	Abandoned	Homo	3
10	Intensive farming	Homo	1

Richness and diversity of forest bird species are positively affected by age of the forest stand; for instance cavity-nesting birds have higher richness and diversity when stand age is around 106 years while for deciduous forest birds is around 210 years (Reise et al., 2019). Also higher biodiversity is observed in deciduous rotation forests, where trees regenerate naturally from few seed trees, than in unmanaged forests, which are natural parks and reserves (Schulze, 2018). Considering the results of long-term forest bird monitoring, evaluation of habitat quality in forest land was made by Latvian forestry and bird experts within a project "Evaluation of the land use optimization opportunities within the Latvian climate policy framework" (Nipers, 2019). Index 1 indicates low habitat quality for forest birds, while index 10 indicates very good quality.

Supplementary Table S8. Habitat quality in natural forest depending on dominant species and age of stand.

Dominant species	Young stand	Middle age stand	Seasoning stand	Maturity stand	Overseasoned stand
Pine	1	3	6	7	8
Spruce	1	2.5	5	7	8
Birch	1	3	5	6	7
Alder	1	4	6.5	8	9
White alder	1	3	4	5	6
Poplar	1	5	7	9	10
Other	1	5	7	9	10

Supplementary Table S9. Habitat quality in managed forest depending on dominant species and age of stand.

Dominant species	Forest clearance	Young stand	Middle age stand	Seasoning stand	Maturity stand	Overseasoned stand
Pine	2	9	10	8	9	7
Spruce	1	10	7	7	6	5
Birch	2	10	10	9	8	7
Alder	5	4	10	7	8	6
White alder	4	8	1	2	9	10
Poplar	1	3	6	4	4	10
Other	6	9	9	3	9	10

Supplementary Table S10. Age groups for different woody species used in habitat quality evaluation if forest land.

Dominant species	Years				
	Young stand	Middle age stand	Seasoning stand	Maturity stand	Overseasoned stand
Pine	0-40	41-80	81-100	101-140	141+
Spruce	0-40	41-60	61-80	81-120	121+
Birch	0-20	21-60	61-70	71-90	91+
Alder	0-10	11-30	31-40	41-60	61+
White alder	0-20	21-60	61-70	71-90	91+
Poplar	0-10	11-25	26-30	31-40	41+
Other	0-40	41-60	61-80	81-120	121+

Chapter 4

Abandoned farmland: past failures or future opportunities for Europe's Green Deal? A Baltic case-study

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ABSTRACT

Competing societal demands on land require careful land management. In the era of the European Green Deal, farmers are required to meet some of these competing demands, specifically around production, greenhouse gas emission reductions, and biodiversity conservation. At the same time, 15.1% of total EU land is abandoned or underutilised, which means that it contributes neither to food, nor to ecosystem services, to its full potential. Reintegrating abandoned agricultural land back into production is therefore one of the potential pathways to deliver on the aspirations of the Common Agriculture Policy post-2020. In this paper we assess the potential of managing and reintegrating abandoned agricultural land in Europe to simultaneously increase primary productivity, carbon regulation and habitat for biodiversity, using Latvia as a national case-study that is representative of this challenge in a Baltic context.

Our results show that for some regions, reintegration of abandoned agricultural land can lead to “triple win” synergies. These opportunities can be further exploited by applying best management practices to these reintegrated lands. In other regions, where the area of abandoned agricultural land is limited because of favourable biophysical conditions for intensive agricultural production, such “triple-win” synergies are scarce. In such areas, abandoned land plays a role in maintaining ecosystem services at local and regional scales, and even small increases in primary productivity come at the expense of biodiversity. This calls for careful management that involves diverse actor groups, including land managers, in the decision-making process, and in priority setting in each of the regions.

Keywords: Management practices, Primary productivity, Biodiversity, Carbon regulation, Functional Land Management

1. INTRODUCTION

Europe's agricultural land is subject to competing societal demands to provide multiple ecosystem services in support of sustainable land use and human well-being (Schulte et al., 2019). Meeting these multiple common objectives requires careful land management, which in turn must be supported by evidence-based policymaking (Thomson et al., 2019). The European Commission has published the European Green Deal, a cross-cutting plan to trigger action across all sectors of the European Union (EU), to make its economy sustainable, including an ambitious target to make Europe the first climate-neutral continent by 2050 (EC, 2020b).

In 2020, the Farm-to-Fork Strategy and the Biodiversity Strategy were published, outlining specific objectives related to sustainable land use and proposing a strengthening of a range of policies, such as the Common Agriculture Policy (CAP) reforms post-2020. The new CAP reforms, which were agreed upon in July 2021, include a clause stating that, "the Commission should assess the consistency and contribution of the proposed CAP Strategic Plans to the Union's environmental and climate legislation and commitments and, in particular to the Union targets for 2030 set out in the Farm to Fork Strategy and the EU biodiversity strategy" (EC, 2021a). While member states will not be legally required to meet all the objectives outlined in the Green Deal, their National Strategic Plans will need to show consistency with those targets. This requires the strategic use of tools within the agreed CAP framework that tackle multiple objectives to provide "triple win" outcomes (EC, 2020c).

Within the context of sustainable land management, soil is the most important resource that provides food, feed, fibre, water purification and regulation, nutrient cycling, carbon sequestration and regulation, and habitat for biodiversity (Calzolari et al., 2016; Haygarth and Ritz, 2009; Schulte et al., 2014). Soils differ in their capacity to deliver on each of these ecosystem services, and we know that it is not possible for all soils to meet all of the societal demands for these services everywhere at the same time: applying the same set of management practices to augment the soil functions on all soils for all farm systems within a country will not achieve the desired achievement of policy targets at national scale, because of the prevalence of trade-offs between soil functions and between management practices (Schulte et al., 2019). Augmenting a single soil function, which is usually intended to achieve one individual policy objective, always affects the performance of other soil functions, potentially jeopardizing policy objectives from other sectors.

However, instead of maximising, we can optimise the delivery of multiple soil functions in order to meet societal demands at local, regional and national scales. Functional Land Management (FLM) provides a framework to assess both the societal demands for soil functions, and the capacity of soils to deliver on these demands (Schulte et al., 2014, 2015, 2019). The FLM concept takes the soil biophysical conditions, as well as their potential, into account to optimise rather than to maximise the supply of soil functions (namely primary productivity, water purification and regulation, carbon sequestration and regulation, the provision of habitats for biodiversity, and the provision and cycling of nutrients) in order to meet the functional and societal demands for soil functions defined at the local, national or international scales. Subsequently, it is then possible to assess the potential of each soil/land use combination to deliver soil functions (Coyle et al., 2016; Schulte et al., 2014). For instance, Schulte et al. (2016) uncovered several pathways for context-specific optimisation of production and ecosystem services in Ireland, in support of the development of knowledge-based agri-environmental policies, which have now been adopted in the draft Agri-Food Strategy 2030 by the Government of Ireland (DAFM, 2021). Through further case studies in Ireland and Latvia, (Valujeva et al., 2020, 2016) showed that such regionally differentiated approaches to the prioritisation of soil functions can indeed meet national targets at a national scale.

Thus far, these case studies were based on the assumption that the amount of land is limited and cannot be expanded further. However, Pinillos et al. (2020) showed the potential of abandoned land at the Amazon frontier to better contribute multiple ecosystem services, through carefully planned land use management, and with the inclusion of local actors. There are many economic, social and ecological factors that influence land abandonment: the migration of residents from rural areas to cities in search of prosperity and higher incomes; poor infrastructure; distance to regional centres; land management challenges; low soil fertility and the lack of funds for improvement; and reduced labour requirements that result from the development of agricultural equipment (Abolina and Luzadis, 2014; Suziedelyte Visockiene et al., 2019). Rural vitality requires an increase in social and economic opportunities, which encourages young people who have emigrated to the urban areas for myriad reasons (e.g. skill expansion, or career and identity development) to remain or return to the rural areas (Riethmuller et al., 2021). Abandoned land is often viewed as a relic of historical events and migration of residents. This paper assesses the extent to which a reversal of such processes can provide opportunities to revalue rural areas, to redevelop rural communities, to create additional jobs in the regions and to improve the regional capacity to attract investment. In addition, returning abandoned land to its previous state can improve their ecological status and provide a variety of ecosystem services. This is exemplified by the recultivation of drained and abandoned peatlands, which can increase carbon sequestration and biodiversity, and provide flood protection (Kløve et al., 2017). However, this synergy between economic returns and ecosystem services is not a given. For example, the removal of shrubs and reintegration of abandoned agricultural land into production can provide economic returns, food, fibre, fuel, and jobs—but can negatively affect environmental outcomes (Kennedy et al., 2016). Using abandoned agricultural land for short-rotation woody crops is a viable solution in areas with low-fertility and fragmented agricultural land, on which environmental, social and economic conditions are not suitable for agricultural production (Abolina and Luzadis, 2014).

In the EU, 40.4% of the total land area is actively managed by farmers. At the same time 15.1% of land is unused or abandoned with signs of previous use (Eurostat, 2020b, 2015). Land abandonment is a multidimensional process affected by a wide range of drivers and their interactions, specifically differences in the degree of land management and regional differences in competitiveness (Schuh et al., 2020). It can occur in socio-economically favourable countries with high agricultural potential (e.g. such as 11.7%, 12% and 7.8% abandoned agricultural land in the Netherlands, France, and Poland, respectively), as well as in countries that are still developing towards their socio-economic potential (e.g. 12.5%, 11.2%, 9.4% for Bulgaria, Latvia and Slovakia, respectively) (Table S1). Land abandonment is a continuous process, with a further 3% of total agricultural land in EU projected to be abandoned by 2030 (Perpiña Castillo et al., 2018). The highest rates of further abandonment are projected for Spain, Poland and Slovakia (5%, 4.8% and 4.6%, respectively), and the lowest for Cyprus, Luxembourg and Slovenia (0.4%, 0.4% and 0.6%, respectively). For Latvia, a further 2.9% of total agricultural land is projected to be abandoned (Table S1).

Typical causes of land abandonment include dependence on water resources and increases in tourism in Southern European countries, limited areas for agricultural production, remoteness and decreased accessibility to the market in Northern European countries (Schuh et al., 2020), and low agricultural productivity and expansion of the settlements in mountain areas (Dax et al., 2021). In Central and Eastern European countries, land abandonment was induced by the transition to post-socialism, coupled with a decline the perceived attractiveness of the remote countryside (Van Vliet et al., 2015). Latvia exemplifies this Central and Eastern European challenge, and is therefore used in this paper as a case-study to assess the potential of reintegrating abandoned land in Europe as one of the pathways to achieve the multiple objectives of the European Green Deal. From the above we hypothesised that the reintegration of abandoned land can contribute to the simultaneous achievement of the socio-economic and environmental sustainability objectives.

2. MATERIALS AND METHODS

2.1. CASE STUDIES

Latvia is a country in the Baltic region located in north-eastern Europe with total area of 64,600 km^2 (Figure 1). 52% of the total area is covered by forests, but agriculture occupies 36% of its total area. Natural conditions in Latvia are determined by its geographical location, which is in the western part of the Eastern European Plain (Nikodemus, 2019). The average annual precipitation in Latvia is 703 mm, which exceeds evaporation by an average of 245 mm each year (LVĢMC, 2017). As a result, Latvia is rich in waterbodies: large areas are occupied by bogs, and the predominant processes in soil genesis are podzolization and gleyzation, due to the positive moisture balance (Nikodemus, 2019). Agriculture and forestry in Latvia depend largely on land reclamation, which has had an effect on soil moisture and river runoff. Small-scale climatic variation, as well as differences in relief, have determined the soil formation processes and their spatial distribution in Latvia. This has led to regional differences in natural conditions (Nikodemus, 2020).

Latvian agriculture has undergone many historic shifts, including the division of land to landless inhabitants, the establishment of farms and the boom in agricultural production, as well as the establishment of collective farms and the nationalization of land (Zemītis et al., 2016). In 1990, the restructuring process led to fundamental changes in the structure of Latvian agriculture, namely (1) changes in land ownership and (2) the redistribution of fixed assets of large collective farms to private farms (Strīķis, 1997). These changes led to the collapse of agricultural activity with a decrease in the amount of agricultural land and livestock (Valujeva et al., 2020), and the abandonment of about 11% of agricultural land (Nipers, 2019). This lasted until Latvia joined the European Union in 2004 and benefitted from support payments of the Common Agricultural Policy (Zdanovskis and Pilvere, 2015).

In order to recover the potential of the Latvian economy, the Bioeconomy Strategy has defined two targets related to increasing production: (1) an increase in added value from the bio-economy sectors to at least EUR 3.8 billion in 2030 and (2) the promotion and maintenance of employment in bioeconomy sectors up to 128,000 inhabitants (LIBRA2030, 2017). Considering that this growth would increase emission, achievement of these targets is restricted by the EU Climate and Energy Framework 2030, which sets a 6% reduction in greenhouse gas (GHG) emissions from the Latvian non-ETS sector as compared to 2005.

In a previous study (Valujeva et al., 2020), we identified the supply and demand for three soil functions relevant to Latvia's agro-climatic conditions; namely, primary productivity (PP), carbon regulation (CR), and habitat for biodiversity (BD), using European and Latvian policies to guide the quantification of demand for soil functions, and the gradient from mineral to histic soils and land use for the quantification of supply of these same soil functions. In that paper, we explained the parameterisation of the demand for PP through the combination of regional bioeconomy GDP targets and unemployment rates at the municipal level using the tabular index approach by Greiner et al. (2018). Following the land use, soil characteristics, climatic conditions and the effect of management practices on the supply of PP, profits from farming and forestry were combined with labour-time requirements into one integrated societal supply metric for PP, again using the tabular index approach (Greiner et al., 2018). In addition, the demand for CR was framed according to international obligations, under which the EU is participating as a single signatory, and which divides the collective target asymmetrically between Member States depending on GDP. Therefore, 2030 target for Latvia of a six percent decrease in emissions from non-ETS sectors compared to 2005, was used and distributed evenly at the national scale. For the evaluation of CR supply soil carbon stock values from national studies (Bardule et al., 2017; Lazdins et al., 2014; Lazdiņš et al., 2015) were combined with CO_2 emission factors from drained organic soils from the IPCC Wetlands Supplement 2013 (IPCC, 2014), again using the tabular index approach (Greiner et al., 2018). The demand for BD was framed by the bird species richness and abundance as general indicators for BD. To this end, targets for forest and farmland birds from the National Development Plan of Latvia for 2014–2020 were used to derive societal demand for BD in Latvia; however, the supply indices for BD were derived from the relationships between habitat quality and land-use intensity in the EU (Reidsma et al., 2006). Mapping both the supply and demand for these soil functions showed regional differences in the challenges that land managers face, with some regions showing opportunities for short-term growth of the bioeconomy, and other regions being best placed to safeguard biodiversity and carbon storage in the long-term. For further details we refer to Valujeva et al. (2020).

For this current study on the potential role of reintegrating abandoned agricultural land in delivering on PP, CR and BD, we used three contrasting regions from Valujeva et al. (2020) to assess regionalised pathways for meeting both socio-economic and environmental targets (Figure 1). The performance of abandoned agricultural land in the provision of soil functions is reflected in the Valujeva et al. (2020) in Supplementary Material: supply of PP of abandoned agricultural land is assumed to 0, but it provides CR and BD.

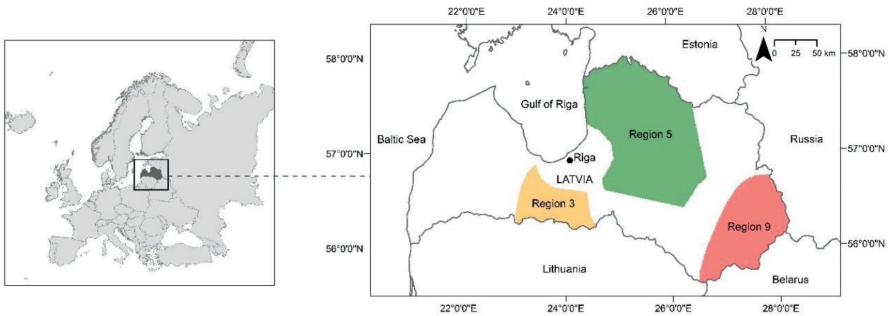

Figure 1. Map of studied regions in Latvia.

Region 3 is characterized by homogeneous agricultural landscapes with intensive agricultural production, resulting in large farms that occupy more than half the agricultural land (Figure 2). It is the largest cereal producer with higher soil fertility than other regions of Latvia (ZPR, 2015). While Region 3 is a highly productive agricultural region, it now faces new demands to also deliver BD and CR, without compromising productivity, and to continue to improve management practices Valujeva et al. (2020). Agricultural production in Region 5 is affected by uneven terrain and clay soils, and as a result, the majority of this region is used for grasslands and forests (VPR, 2015); there is no pressure to increase productivity in Region 5 in the short-term. This region offers opportunities to contribute to long-term environmental targets through knowledge-based and targeted land-use change (Valujeva et al., 2020). Region 9 is characterised by the widespread abandonment of farmsteads (which are historically characteristic of Latvian society), which has resulted in many abandoned agricultural fields. In this region, large and small farms account for the same amount of land, which in turn signifies that small farms outnumber large farms (ZM, 2017). Also, Region 9 is economically poor: here, increases in productivity, income, and employment are urgently needed without compromising the delivery of the CR and BD (Valujeva et al., 2020). More than 75% of agricultural lands in all regions can be found on mineral soils (Figure 2). The database used for the study was created within a project "Evaluation of the land use optimization opportunities within the Latvian climate policy framework" (funded by Joint Stock Company "Latvia's State Forests") (Nipers, 2019) and is described in detail by Valujeva et al. (2020): it consists of an agricultural spatial dataset at the scale of 1:5,000 from the Rural Support Service (http://www.lad.gov.lv/lv/) with detailed information of: area, crop type, and farming system; a forest spatial dataset at scale 1:10,000 from the State Forest Service (http://www.vmd.gov.lv/lv/) with detailed information of forest type, age of forest stand, main species in forest stand and restrictions in forest stand; a land use and landholder spatial dataset at the scale of 1:2,000 from the State Land Service (https://www.vzd.gov.lv/lv/) with information of property, landholder, land area, land use, value, encumbrances, buildings and their elements; the CORINE Land Cover database at the scale of 1:100,000; a land reclamation map at the scale of 1:10,000 from the State Limited Liability Company, "Ministry of Agriculture Real Estate" (https://www.melioracija.lv/) with information regarding the drainage status of agricultural fields; an agricultural soil dataset from digitized historical soil maps at the scale of 1:10,000. The database is static and consists of 4.4 million agricultural land-use polygons and 2.3 million forestry land-use polygons and represents the situation in 2016.

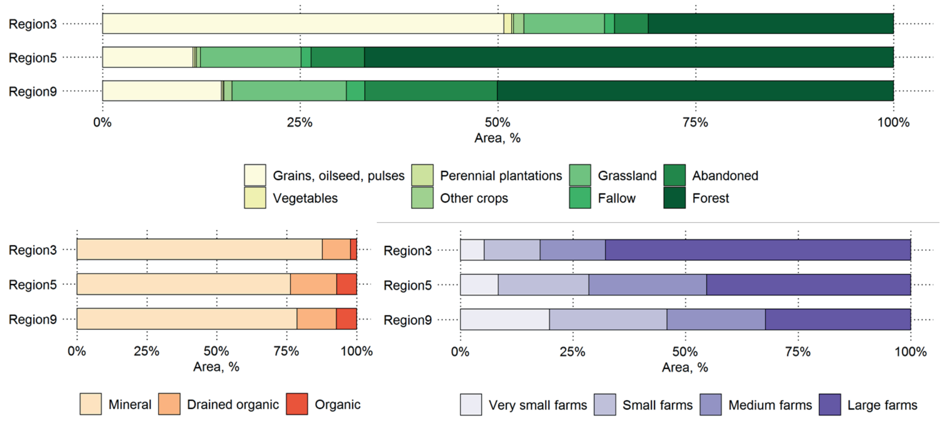

Figure 2. Overview of land use, soil type and farm distribution in regions. Groups of farm sizes for different agricultural sectors are described in Supplementary Material Table S2.

From the aforementioned database, we created data matrices for the optimisation of each region. The data matrix for each region consists of a combination of 53 land uses (grain, oilseed, pulses, vegetables, perennial plantations, other crops, fallow, grassland, abandoned agricultural land, forest), soil classes (mineral, drained organic, organic) and farm sizes (very small, small, medium, large) (Table 1).

Table 1. Data matrix for optimisation. The numerical labels are used in the coding of land use/soil class/farm size combinations of the study.

Land use	Mineral soil				Drained organic soil				Organic soil
	Very small	Small	Medium	Large	Very small	Small	Medium	Large	
Grain, oilseed, pulses	1	2	3	4	5	6	7	8	N/A
Vegetables	9	10	11	12	13	14	15	16	N/A
Perennial plantations	17	18	19	20	21	22	23	24	N/A
Other crops	25	26	27	28	29	30	31	32	N/A
Fallow	33	34	35	36	37	38	39	40	N/A
Grassland	41	42	43	44	45	46	47	48	N/A
Abandoned agricultural land	49				50				N/A
Forest	51				52				53

An overview of the farm size by main crop is summarized by Nipers (2019), in Supplementary Material Table S2. For each region, the total area of each combination is known. It is not possible to determine the farm size of the abandoned agricultural land and forest land. Furthermore, natural bog areas and peat extraction fields are excluded from the study, and therefore the organic soil class, which is defined as organic soil that is not affected by artificial drainage, is found only in forest land (Valujeva et al., 2020).

2.2. OPTIMISATION SCENARIOS

In the current study, we created optimisation scenarios for each region, specific to the supply and demand balances for each region (Table 2). All scenarios were run twice: in the first run, only two of the three functions were included as the primary objective variables (in most cases PP and CR), whereas in the second run, all three soil functions were included as objective variables for the optimisation. Furthermore, all runs of all scenarios were performed twice: first, where we only allowed changes in land use for the abandoned agricultural lands optimisation decision variables, and secondly, where we included the introduction of improved management practices as additional optimisation decision variables. These management practices and land-use changes to regions were selected from Valujeva et al. (2020) to improve or maintain the supply of the three soil functions, namely primary productivity, carbon regulation and biodiversity (taking into account the supply-demand balance for each soil function in each region).

Management practices included: A) Afforestation of fertile well drained organic soils; B) Use of farmyard manure and green manures along with returning crop residues; C) No till increases fungal biomass in general, which leads to improved soil structure that increases infiltration and reduces erosion; C) High-precision management of nutrients, chemistry, water, pests, and pathogens; D) Diversification of crop types, permanent plant cover, buffer strips; E) Increase groundwater level on organic soils for shallow rooting vegetable production; F) Application of organic amendments in combination with inorganics in wheat cropping system; G) Conversion of some of the current annual crops to grassland; H) Rewetting organic soils under grassland leads to these ecosystems becoming neutral or small C sinks. Expert judgement was used to contain the relevance and applicability of each of these management practices to region, land use, soil type and farm size (Supplementary Material Table S3).

Table 2. Overview of the optimisation scenarios applied to the regions in the study.

Region	Supply-demand balance from Valujeva et al. (2020)	Scenario	Run	Objective
Region 9	High demand for primary productivity and carbon regulation function with short-term returns on investments	Scenario 1	Run 1	Maximise PP and increases CR
			Run 2	Maximise PP, increase CR and BD
		Scenario 2	Run 1	Maximise CR and increase PP
			Run 2	Maximise CR, increase PP and BD
Region 5	Potential to increase supply of CR through longer-term measures, specifically relating to optimising land use	Scenario 1	Run 1	Maximise PP and increase CR
			Run 2	Maximise PP, increase CR and BD
		Scenario 2	Run 1	Maximise CR and increase PP
			Run 2	Maximise CR, increase PP and BD
Region 3	Highly productive area with additional demands for CR and BD. Opportunities for management practices that increase CR and BD while maintaining PP.	Scenario 1	Run 1	Maximise PP and increase CR
			Run 2	Maximise PP, increase CR and BD
		Scenario 3	Run 1	Maximise CR and increase BD
			Run 2	Maximise CR, increase BD and PP
		Scenario 4	Run 1	Maximise BD and increase CR
			Run 2	Maximise BD, increase CR and PP

2.3. OPTIMISATION

Considering the conflicting objectives of soil functions, the ε-Constraint approach for multi-objective optimisation (Kaim et al., 2018) was applied to identify the optimal land use for abandoned agricultural land that has been returned to production, using the lpSolveAPI package in R 3.6.3. LpSolveAPI is an interface for freely available lpSolve software; it is a Mixed Integer Linear Programming (MILP) solver for linear, integer, mixed integer, binary, semi-continuous and special ordered sets models (Konis, 2020). Figure 3 shows the concept of the optimisation model for this study.

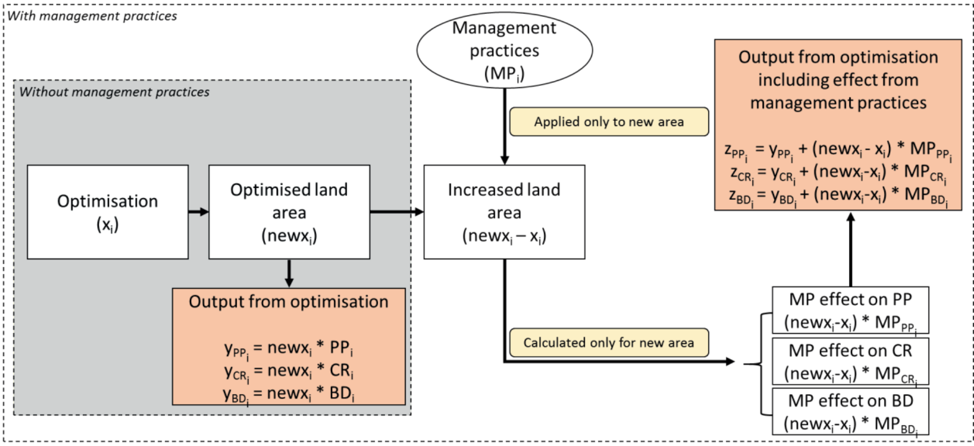

Figure 3. The modelling framework for the optimization of land uses and the assessment of the impact of the proposed management practices (x_i – area of land use i; $newx_i$ – area of land use i after optimisation; PP_i – index for primary productivity of land use i (Valujeva et al., 2020); CR_i - index for carbon regulation of land use I (Valujeva et al., 2020); BD_i - index for biodiversity of land use i (Valujeva et al., 2020); MP_i – sum of effect management practices to soil functions applied to land use

The following control parameters were used in the optimisation of each run:

a) Objective function: in our case studies, regional objectives were defined individually through a supply-demand balance for the three soil functions (Valujeva et al., 2020);

b) Decision variables: these represent land-use areas that can be changed during the optimisation to meet the objective functions. In our case, the decision variables are the areas divided into groups depending on land use and crop grown in 2016 (grains, oilseed, pulses, vegetables, perennial plantations, other crops, grassland, fallow, abandoned agricultural land, forests), soil type (mineral soil, drained organic soil, organic soil) and the farm size to which this area belongs (very small farm, small farm, medium farm, large farm). Also, for each 'land use-soil type-farm size' group, the supply indices of soil functions from Valujeva et al. (2020) were assigned; these indices are the constants that determine the suitability of land to provide the specified supply of soil function.

c) Constraints: these are boundaries for land areas to which the optimisation process must adhere:

- Total land availability: there are limitations of total land availability for agriculture and forestry; only abandoned agricultural land can transfer to the forest or agriculture.
- Land consolidation: land use changes via optimisation do not change the farm sizes; only abandoned agricultural land can move to production.

- Soil type: the total areas for mineral soils and organic soils remain constant; this means that soil type cannot change from mineral to organic or *vice versa*.

d) The effect of management practices: these were calculated only for abandoned agricultural land that was transferred back to production. In the scenario runs, we assumed that management practices remain unchanged in the areas that are currently already under cultivation, but improved management practices are optimised for new cultivation on previously abandoned agricultural land, as per the work of Valujeva et al. (2020). In addition, expert judgement was used to constrain management practices to associated farm sizes, depending on their financial capacities (Supplementary Material Table S3).

3. RESULTS

Figure 4 shows the results for Region 9 under all optimisation runs. It shows that there is a significant opportunity to improve PP in Region 9, simply by bringing abandoned agricultural land back into production. It is even possible to do so without increasing the environmental impact. Scenario 2 shows that it is even possible to increase PP, albeit to a lesser extent, while maintaining both CR and BD. If management practices are additionally added to the optimisation, opportunities for ”triple win” outcomes are further increased, and it would be possible to significantly increase PP and to simultaneously increase the supply for CR and BD.

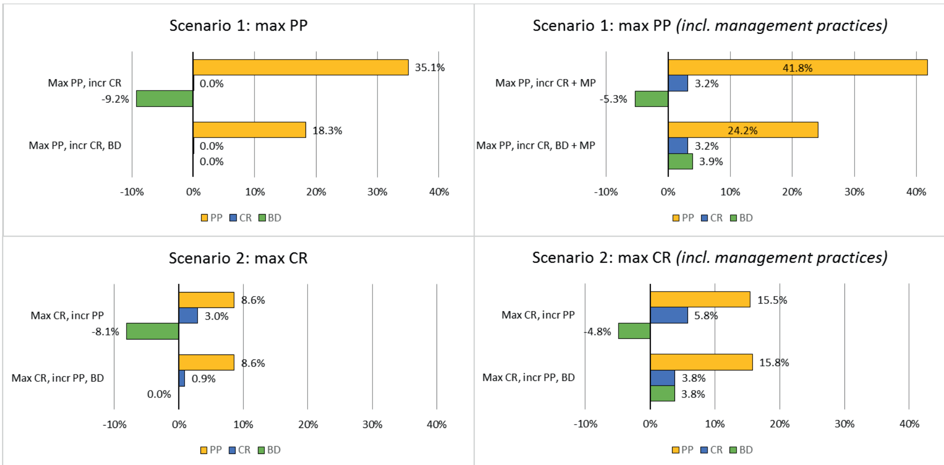

Figure 4. Outcomes of Region 9 optimisation. Changes in the supply of soil functions for two scenarios, with and without management practices, compared to the baseline (0%): PP - primary productivity; CR - carbon regulation, BD - biodiversity function.

Optimisation results for Region 5 also show the opportunity to improve the supply of PP, as was seen in Region 9. Smaller gains and smaller losses suggest that Region 5, too, has potential to optimise the supply and demand of three soil functions simultaneously, but to a lesser extent than in Region 9 (Figure 5). By adding management practices, the supply of soil functions increases for all three functions, but again, to a lesser extent than in Region 9.

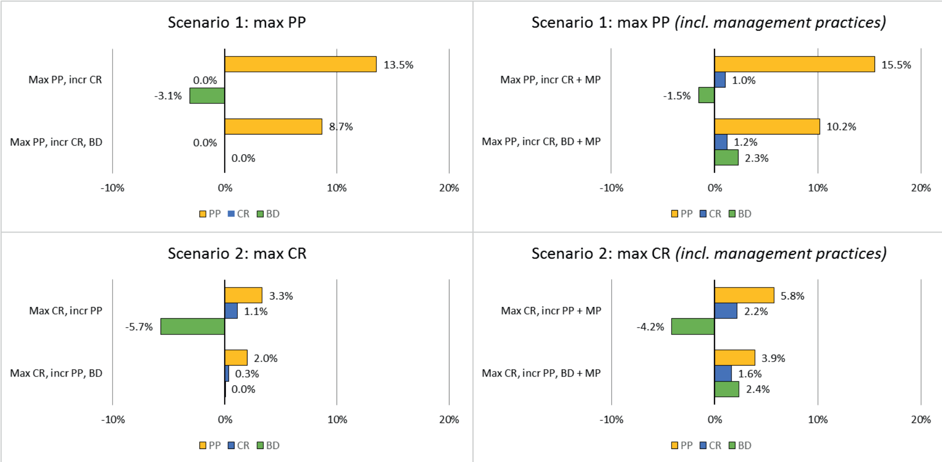

Figure 5. Outcomes of Region 5 optimisation. Changes in supply of soil functions for two scenarios with and without management practices compared to the baseline (0%): PP - primary productivity; CR - carbon regulation, BD - biodiversity function.

The results from Region 3 were markedly different from the other two regions' results. In Scenario 3 and Scenario 4, the increase or the decrease of supply of soil functions is below 1% compared to the baseline (Figure 6).

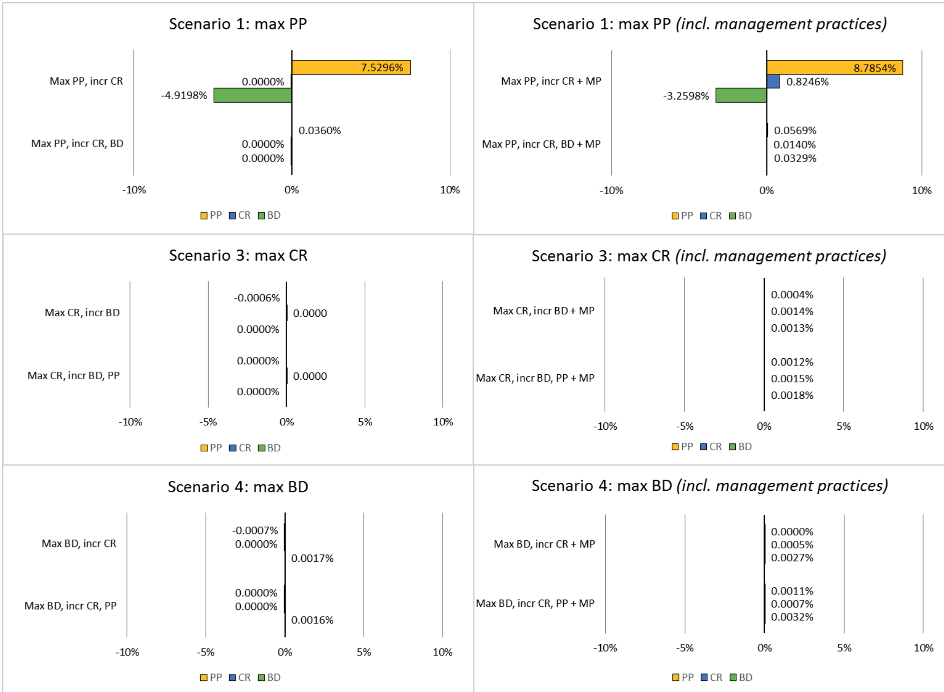

Figure 6. Outcomes of Region 3 optimisation. Changes in supply of soil functions for two scenarios with and without management practices compared to the baseline (0%): PP - primary productivity; CR - carbon regulation, BD - biodiversity function.

Opportunities for further optimisation are very limited; further increases in productivity are at the expense of BD, and also the opportunities to further augment CR or BD are insignificant. The area of abandoned agricultural land in Region 3 is relatively small, so their shift back to production has little impact on the supply of soil functions.

4. DISCUSSION

4.1. OPTIMISATION OF SOIL FUNCTIONS

Our Baltic case-study demonstrates that bringing abandoned agricultural land back into production is a promising pathway to develop the European bioeconomy while minimizing trade-offs with CR and BD; indeed we found plausible scenarios that benefit all three functions of land. For instance, in Regions 5 and 9, we can increase PP while maintaining CR and BD, or we can choose to increase PP to a lesser extent, and increase CR and BD at the same time. Soils can deliver multiple functions simultaneously, but we cannot expect that each farmer is able to maximise all of them at the same time; as shown by the Zwetsloot et al. (2020) following the FLM approach, it is possible to deliver three out of the five soil functions at a high capacity. These opportunities can be further enhanced by applying best management practices (that have a positive effect on soil functioning) to these reintegrated lands, provided that the suitability of these management practices are assessed for the specific region. For example, high-precision management of nutrients increases PP and reduces production costs for farmer without affecting CR and BF, while crop diversification, permanent plant cover and buffer strips simultaneously increase the supply of all soil functions (Hedley, 2015; McDaniel et al., 2014; Nielsen et al., 2015; Osterholz et al., 2018; Zuber et al., 2015). Within our national case-study, individual regions differed in their potential to contribute to such triple-win scenarios: Region 9 showed the most opportunities synergies arising from the revitalization of abandoned agricultural land, while Region 3 had already been optimised: here, even small increases in PP resulted in a decrease of BD, which underlines the importance of a regional approach. These differences show that our original hypothesis that reintegrating abandoned agricultural land contributes to triple-win scenarios must be nuanced with a regionally differentiated approach. This nuanced finding is supported by studies on land abandonment from other regions: for example, Beilin et al. (2014) found that in an Australian case study, well-managed abandonment of agricultural land that promotes the formation of forest patches is highly beneficial for biodiversity and brings opportunities for alternative rural development; whereas agricultural land abandonment in case studies in Sweden and Portugal were perceived as a threat to biodiversity and the heterogeneous landscape that is associated with high-nature-value farming areas (Beilin et al., 2014). Whilst our analysis is not aimed at determining the specific land use and management practices that should be applied to individual parcels of abandoned agricultural land, our results do inform policymakers in their allocation of limited resources (funding, knowledge transfer) to the areas where their effectiveness and contribution to regional and national policy objectives will be highest.

Scale is crucial in the optimization of soil functions, as land use change and the introduction of management practices operate at farm-scale. Farmers often prioritize PP, which affects the achievement of CR and BD objectives at the national level (Valujeva et al., 2016); as our results show, in some areas even small increases in productivity come at the expense of BD and CR. Adapting sustainable land management at the national scale, which includes both the development of production and the achievement of environmental objectives, requires financial support for land managers based on legal frameworks and the dissemination of additional knowledge around applicable management practices (Liniger et al., 2019). The farmer is a key actor in this arena, and should be included in the development of optimization scenarios; the major driving force for farmers in implementing management practices are short-term benefits and reductions in production costs (Lahmar, 2010). Moreover, to motivate conventional farmers to switch from monoculture systems to diversified cropping systems, new systems must go beyond profitability: they must also be mechanized (Teixeira et al., 2018). Educational programs, social pressure, and economic incentives can encourage behavioural changes among the farming community, and increase the implementation of changes that positively affect environmental outcomes (Bijttebier et al., 2018).

4.2. TARGETED REINTRODUCTION OF ABANDONED AGRICULTURAL LAND AS AN OPPORTUNITY FOR NATIONAL STRATEGIC PLANS

In this context, the reform of the EU CAP (2023-2027) offers opportunities to change the narrative on abandoned land: while the CAP was originally developed to provide farmers with support measures to compensate market volatility, it has since evolved into a tool to also reduce the environmental impacts of agriculture across Europe. The New Delivery Model of the CAP (2023-2027), will provide Member States more flexibility to design tailor-made measures through National Strategic Plans (NSP) (EC, 2021a). While the next CAP will not take effect until 2023 after a two-year transitional period, Member States will be submitting drafts of their NSPs by the end of 2021 to the European Commission (EC) for approval. In order to support the Member States' drafting of their NSPs, and to encourage the adoption of the Green Deal objectives in these plans, the EC published Staff Working Documents in December 2020, which outline, for each Member State, recommendations on how to: foster resilience, bolster environmental care, strengthen the socio-economic fabric of rural areas, and foster knowledge and innovation (EC, 2020d).

In this context, Latvia has been conducting its own national analysis of needs. For example, in 2019, regional discussions, led by the Latvian Rural Network Unit, with agri-environmental stakeholders in Latvia identified fair income, generational renewal, and competitiveness as key priorities for the post-2020 CAP (LLKC, 2019). A reduction in regional yield differences was identified as one of the main challenges. Our current study addresses this challenge by allowing for differentiated pathways for different regions while striving for similar outcomes in terms of socio-economic and environmental sustainability. Additionally, these discussions recognized the need to simultaneously support productive farms in their economic development, and small farms in maintaining a heterogeneous landscape, and therefore biodiversity, as shown by the optimisation results of Region 3: here, an increase in BD and CR can only be secured by preserving and promoting landscape heterogeneity. Therefore, it is necessary to define regionally clear objectives to support connectivity, heterogeneity and landscape elements in order to promote the conservation of biodiversity, because broad conservation measures at national or European scale do not consider the specific needs and values of individual regions (Concepción et al., 2020).

Addressing land abandonment is not listed as a primary objective in Latvia's draft recommendations from the EC (EC, 2020e), nor does it feature in the European Green Deal communications, such as the Farm to Fork Strategy and Biodiversity Strategy for 2030. It is only mentioned once in the European Commission's Long Term Vision for Rural Areas, stating that, "it is therefore important to account for the needs of small and medium sized farmers, attracting young, new and female farmers and preventing land abandonment as well as facilitating land access" (EC, 2021b). The measures in the CAP that could potentially address land abandonment, as outlined in a study by Schuh et al. (2020) commissioned by the European Parliament, are synergistic with the NSP recommendations for Latvia and the regional discussions led by the Latvian Rural Network. Tools such as: capping direct payments, complementary redistributive income support, small farmer schemes and young farmer measures have been proposed to address land abandonment as well as multiple other socio-economic objectives. The use of these tools, however, must be regionally-specific, and based on an understanding of the locally relevant drivers of land abandonment. Other measures identified by Schuh et al. (2020), such as payments for Areas with Natural Constraints (ANCs), may also promote beneficial production on abandoned land, depending on the region in which they are applied. For instance, increasing the budgetary ring-fencing for ANCs in Region 5 of this study may potentially be more effective than in Region 3, in which topography may not be such a driver of land abandonment.

The results of our study suggest that for Latvia and other Member States, policy makers can utilise regional differences within a country to meet national objectives and international commitments: Latvia's strength lies in its bioeconomy, in which natural resources are used for the sustainable production of food, feed, industrial products, and energy. However, the development of its bioeconomy has thus far been associated with an increase in GHG emissions. Our study shows that, if carefully managed, the reintroduction of abandoned agricultural land provides opportunities for "triple win" synergies between productivity, climate mitigation commitments and the preservation of biodiversity. However, without careful management, the reintroduction of abandoned agricultural land may lead to increases in only PP, with a failure to deliver on CR and BD objectives, or international commitments. This calls for the introduction of incentivisation mechanisms and knowledge programmes that involve land managers and other actors in the decision-making and priority-weighing processes across scales to translate "thinking solutions" into "doing solutions", which refer to as the Think-Do-Gap (O'Sullivan et al., 2017), for each of the regions; additionally it requires understanding of which stakeholders influence land-use decisions concerning soil functions, which is the subject of further ongoing studies. Understanding societal actors, networks and their interaction in land management issues will help to identify existing stakeholder alliances, gaps in networks and possible solutions in order to promote cooperation and entry points to steer stakeholders and decision-makers towards a regionally differentiated approach to reorienting abandoned agricultural land to achieve the regional and national policy objectives.

5. CONCLUSIONS

By using a regionalised approach to FLM in Latvia, we showed the untapped potential of revaluing, reintegrating and re-managing abandoned agricultural land in helping Member States meet socio-economic and environmental sustainability objectives simultaneously. Indeed, our conclusions call for a change in perspective towards abandoned land: from relics of past failures towards beacons of future opportunities.

Our optimization results confirm the merits of a regionalised approach to reintegrating abandoned agricultural land: trade-offs between soil functions, and regional differences in the societal demand for economic development, climate regulation and biodiversity preservation lead to contrasting opportunities for individual regions to contribute to national targets. While some regions may already be optimised towards the national bioeconomy, these may benefit from other regions that make larger relative contributions to climate regulation and biodiversity preservation.

However, such purposeful interregional development requires careful knowledge-based management and incentivisation. In absence of this, the reintegration of abandoned land may simply repeat the historic trajectory of increased productivity at the expense of environmental integrity. This calls for the development of clear and coherent guidance tools for actors involved in the formulation of the National Strategic Plans, from farmers at local level, to regional decision makers, to national policy makers, to facilitate priority setting, as well as effective incentivisation mechanisms across scales.

ACKNOWLEDGEMENTS

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SUPPLEMENTARY MATERIAL

Table S1. Agricultural land, forest land and abandoned land of the total area in the EU-27 countries in 2015 (Eurostat, 2020b) and agricultural land abandonment over the total utilized agricultural area in 2030 (Perpiña Castillo et al., 2018).

Country	Agricultural land, %	Forest land, %	Unused or abandoned land, %	Agricultural land abandonment in 2030, %
Belgium	50.8	22.1	4.3	0.9
Bulgaria	44.9	37.8	12.5	2.0
Czechia	48.9	35.4	5.7	1.8
Denmark	63.1	11.9	9.0	1.9
Germany	50.8	29.0	4.4	2.7
Estonia	25.7	54.2	10.4	2.5
Ireland	59.3	8.9	22.7	0.7
Greece	42.1	21.0	30.6	3.7
Spain	46.2	21.7	26.9	5.0
France	52.7	24.3	12.0	2.0
Croatia	28.2	32.5	33.4	2.0
Italy	44.5	22.5	22.7	3.4
Cyprus	36.9	12.4	41.7	0.4
Latvia	29.2	51.9	11.2	2.9
Lithuania	50.7	36.4	5.0	1.6
Luxembourg	51.1	35.2	2.0	0.4
Hungary	59.6	23.0	8.3	2.5
Malta	44.8	-	29.2	1.2
Netherlands	53.7	3.5	11.7	3.4
Austria	33.8	40.7	17.4	3.0
Poland	49.4	32.9	7.8	4.8
Portugal	38.0	37.3	17.9	3.4
Romania	58.1	33.2	4.2	1.7
Slovenia	27.7	55.5	9.0	0.6
Slovakia	40.4	43.0	9.4	4.6
Finland	7.4	63.2	15.0	3.5
Sweden	7.9	57.0	19.3	1.4

Table S2. Groups of farm sizes in different agricultural sectors (Nipers, 2019).

Crop	Farm size in ha			
	Large	Medium	Small	Very small
GOP (grain, oilseeds, pulses)	>300	>100, ≤300	>20, ≤100	≤20
Vegetables	>30	>10, ≤30	>2, ≤10	≤2
Perennial plantations	>30	>10, ≤30	>2, ≤10	≤2
Other crops	>150	>50, ≤150	>10, ≤50	≤10
Grassland	>300	>100, ≤300	>20, ≤100	≤20
Fallow	>300	>100, ≤300	>20, ≤100	≤20

Table S3. Expert assessment of the implementation of management practices selected by Valujeva et al. (2020).

Management practice	Afforestation of fertile well drained organic soils	Use of farmyard manure and green manures along with returning crop residues	No till increases fungal biomass in general, which leads to improved soil structure that increases infiltration and reduces erosion	High-precision management of nutrients, chemistry, water, pests, and pathogens	Diversification of crop types, permanent plant cover, buffer strips	Increase groundwater level on organic soils for shallow rooting vegetable production	Application of organic amendments in combination with inorganics in wheat cropping system	Conversion of some of the current annual crops to grassland	Rewetting organic soils under grassland leads to these ecosystems becoming neutral or small C sinks
Region									
Region 9	x	x	x	x	x	x	x		
Region 5	x							x	x
Region 3		x	x		x	x	x		
Land use									
Forest	x								
Fallow		x		x	x				
Grassland					x			x	x
Other crops		x		x	x				
Perennial plantations		x		x	x				
Vegetables		x		x	x	x			
GOP		x	x	x	x		x		
Soil type									
Mineral		x	x	x	x		x	x	
Drained organic	x	x	x	x	x	x	x	x	x
Organic									
Farm size									
Very small		x			x	x	x	x	x
Small		x			x	x	x	x	x
Medium			x		x	x		x	x
Large			x	x	x	x		x	x

4

Chapter 5

Pathways for governance opportunities: Social Network Analysis to create targeted and effective policies for agricultural and environmental development

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ABSTRACT

Participatory techniques are widely recognized as essential in addressing the challenges of agri-environmental policy and decision-making. Furthermore, it is well known that stakeholder analysis and social network analysis are useful methods in the identification of actors that are involved in a system and the connections between them. To identify key stakeholders and improve the transfer of information from national- to farm-level, we compared a stakeholder analysis with farmer-centric networks for primary productivity, carbon regulation and biodiversity through the case study of Latvia. Farmer-centric networks show a higher number of stakeholders communicating on the topic of primary productivity network comparing to other topics. We found three pathways for improving knowledge transfer in agri-environmental governance: horizontal strengthening of farming community, horizontal strengthening of policy departments, and vertical strengthening between policy departments and farmers. The first step is to ensure that policy-makers have a common understanding of the results that should be achieved. The second step is the transfer of know-how between farmers to develop new solutions. The third step is the training of advisers in the land multifunctionality and the strengthening of communication and knowledge transfer between policy departments and farmers in order to jointly achieve the desired direction at that national level. Long-term cooperation between many stakeholders, including knowledge transfer, the development and implementation of solutions, and monitoring are essential in order to adequately address global societal challenges. The application of our mixed methods approach to elucidate pathways for improved governance of knowledge and information is of direct relevance to other jurisdictions seeking to transition towards multifunctional and sustainable land management.

Keywords: Functional Land Management, agri-environmental governance, soil functions, Agricultural Knowledge Innovation System

1. INTRODUCTION

The interaction between farmers, society, and the nature is influenced by the increasing demand for resources, a growing population, increasing environmental pressures, the effects of climate change as well as shifting societal demands, and new technologies. Farming is not just for providing soil-originated resources, but also a means for providing income; as such, farmers expect their land to be both productive and healthy.

The sustainable land management principles become increasingly important and researchers seek knowledge and comprehension on processes to implement them. Soil is the most important resource for sustainable land management, since it provides food, feed, fiber, water purification and regulation, nutrient cycling, carbon sequestration and regulation, and a habitat for biodiversity (Calzolari et al., 2016; Haygarth and Ritz, 2009; Schulte et al., 2014). Functional and societal demands for these soil functions can be defined at the local, national, and international scales, while the supply depends on the soil biophysical properties and land-use. The Functional Land Management conceptual framework is used to look for trade-offs between the soil biophysical capacity to deliver these soil-based ecosystem services and societal demand for them (Schulte et al., 2014). Societal demands and the capacity of soils to meet the demand for soil functions have spatial variations that are influenced by the regional distribution of the population, agricultural intensity, geo-environmental conditions and landscape structure (Schulte et al., 2019). In order to find trade-offs between various policy targets and the ability of soils to deliver on these targets, we can apply additional management practices and land-use changes to guide a policy-making process adapted to local conditions (Valujeva et al., 2022, 2020). Investigating the effect of management practices and land-use change requires close cooperation between scientists, policy-makers and the farmers that will implement these changes on their land.

The Agricultural Knowledge Innovation System (AKIS) approach is being included by the European Commission in the post-2020 Common Agricultural Policy (CAP) as a strategy to contribute to farming-system resilience and support rural development through widespread dissemination of agriculture-related knowledge and innovation technologies (EC, 2018). The current AKIS 1.0 emphasizes the diverse agricultural-related groups of stakeholders who seek information and innovation exchanges, illustrating the necessity to improve collaboration between these groups. AKIS 1.0 does not take into consideration that farmers are not only the end-users of these innovations, but they also play a significant role in knowledge creation and dissemination (EC, 2018).

As a result, the updated AKIS 2.0 will be based on a knowledge exchange that is adapted to the needs of farmers, introducing peer-to-peer learning, and improving the interaction between research and practice, leading to jointly developed solutions that farmers are motivated to implement and from which they will benefit (EC, 2018). It requires the EU Member States to include a description of the organizational structure of the AKIS in the CAP Strategic Plans, the organizations involved in using and generating knowledge in agriculture and related fields, and the related knowledge flows. Another requirement is to show the outline of cooperation of advisory services, research and CAP networks within AKIS to provide advisory services and innovation (EU SCAR AKIS, 2019). For some Member States (e.g. Austria, Denmark, Ireland), AKIS already is very well established and integrated with a strong impact to support farmers. However, in other Member States (e.g. Latvia, Italy, Spain) AKIS is fragmented, with many public and private actors that operate from local to national levels (EU SCAR AKIS, 2019). Without a coordinating structure, the large number of involved actors leads to an overabundance of diverse information and knowledge, which is not aligned with national policies. Not all organisations that are involved in AKIS are active in communication with and knowledge transfer to farmers, so it is crucial to understand which key organisations are most valued by farmers.

Stakeholder analysis and social network analysis are well-known methods combined in various studies to identify stakeholders and establish their influence and interest, as well as their connections with each other (Ahmadi et al., 2019; Lienert et al., 2013; Prell et al., 2009; Wu et al., 2020). Both methods have complementary roles in highlighting the complexity of agri-environmental management systems, and allow for better decision-making and analysis. Hauck et al. (2016) found that social network analysis is a valuable tool not only to identify key stakeholders, but also gain an understanding of the various views that influence or are influenced by biodiversity governance. A study on the role of farmers' social networks in implementing no-till farming practices shows that farmers believe they have a higher level of knowledge due to practical experience compared to researchers and other organizations (Skaalsveen et al., 2020). This study also identified that knowledge is not equally available to all farmers due to geographic location, and formal consultations are unable to provide diverse, complex and highly specialized knowledge. Although farmers have accumulated experimental knowledge over the years, there is still a need for cooperation between farmers, consultants and researchers to critically evaluate and interpret the available information, and to ensure the dissemination of information. Farmers' perceptions and management practices are important factors in setting up the structure of the advisory network, and it is therefore necessary to raise farmers' awareness of their contribution to climate regulation and to encourage more involvement in the networks (Albizua et al., 2021).

Since the introduction of the CAP, farmers have access to both free and paid consultations, but not in all EU countries do farmers trust the information provided by consultants. Most often, farmers value each other as the best source of information. A number of studies highlight that advisors can play a key role in providing sound and scientific evidence to farmers (Micha et al., 2020; Mills et al., 2021, 2020; Schwilch et al., 2012; Šūmane et al., 2018), however the role of advisors in addressing environmental issues has received little attention. There is also a lack of information about other organisations providing information to farmers. Farmer decisions are not made in isolation and by understanding how farmers receive information on different topics especially related to environmental issues, we can better address the challenges of agri-environmental policy (O'Sullivan et al., 2022). Therefore, the aim of this study is to identify key actors in farmer-centric networks and potential pathways for improving information channels for primary productivity, carbon regulation and biodiversity. To do this, we appraise and combine four methodologies commonly used in social sciences. We use the AKIS of Latvia, part of the Baltic and Nordic regions of the EU, as our case study to evaluate how the gap between policy formation and farmer practices for sustainable land management can be bridged through improved governance of knowledge and information.

2. MATERIALS AND METHODS

2.1. DATA SOURCES AND DATA COLLECTION

This study had four main steps, as shown in Figure 1, and was focused on three soil functions: primary productivity (PP), carbon regulation (CR), and biodiversity (BD). The first step was to compile a list of stakeholders based on a review of organizations' websites and online resources. The second step was the evaluation (by experts) of stakeholders' interest and influence of land-use issues that were related to PP, CR, and BD. This step categorized each stakeholder based on their level of interest and level of influence. The third step was to identify stakeholders through farmer interviews. The fourth step was to conduct a social network analysis, where we investigated the relationships between farmers and different organizations for each soil function. Finally, the results obtained over the studied steps were compared for key recommendations.

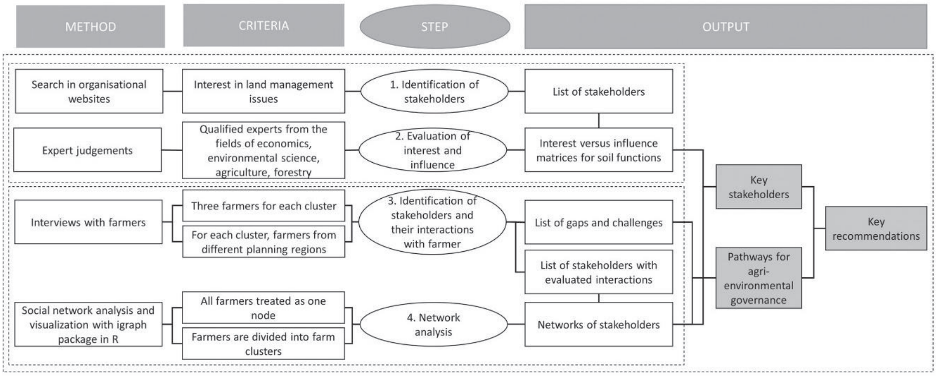

Figure 1. Schematic representation of key methodological steps.

2.2. SELECTION OF STAKEHOLDERS

In this study, the first selection of agri-environmental governance stakeholders in Latvia were identified through websites. Selection was started with the government ministry websites, followed by subordinate institutions, which are included in the stakeholder list. Next, we looked for other partners and organizations that were mentioned in the websites of the subordinate institutions. The search was ended when the organization found did not meet the criteria: interest in land management issues. To the stakeholder list we also added five clusters of Latvian agricultural farms defined by the EVIDEnT project (http://www.vpp-evident.lv/index.php/en/), where: (1) Cluster 1 represents intensive mixed specialization farms that keep animals in housing with a farm size greater than 400 ha; (2) Cluster 2 represents intensive cereal farms with a farm size greater than 200 ha; (3) Cluster 3 represents medium-sized mixed specialization farms with livestock grazing and a farm size greater than 400 ha; (4) Cluster 4 represents organic farms; (5) Cluster 5 represents backyard farms with a farm size less than 10 ha (Eory et al., 2018; Kreišmane et al., 2018). Backyard farms in Law on Land Reform in Rural Areas of the Republic of Latvia are defined as agricultural farms whose land user (owner) owns a residential house or buildings necessary for the work of a craftsman, and these farms have the character of an auxiliary farm (LR, 1990).

The list of stakeholders was sent to eight experts in the fields of economics, environmental science, agriculture, and forestry for the evaluation of interest and influence. All experts were representatives of their respective fields who have qualified for the status of experts of the Latvian Council of Science (https://sciencelatvia.lv/#/pub/eksperti/list). We asked them to evaluate the interest and influence of previously selected stakeholders in range from 1 to 10, where 1 is low and 10 is high. This is a frequently used method to understand the engagement of stakeholders in a given issue or decision-making process (Ahmadi et al., 2019; Prell et al., 2009; Reed et al., 2009; Reed and Curzon, 2015). We created three evaluation matrices where we asked: How much stakeholders are interested and how much they can influence the increase in (1) primary productivity, (2) carbon regulation, and (3) biodiversity. Also, experts were invited to add additional stakeholders if deemed necessary. We calculated average interest and influence for all stakeholders and developed an interest versus influence matrix for each soil function. We were particularly interested in stakeholders that have high interest and high influence or low interest but high influence. Those stakeholders were classified as “key players” and “context setters”. “Key players” are the most important stakeholders to work with because of the high interest in and influence over land management issues. Stakeholders classified as “context setters” do not have high interest, but they can inadvertently influence important processes related to land management. “Subjects” have high interest, but low influence, and are therefore supportive stakeholders and may become influential by forming alliances with others. Stakeholders with low interest and low influence form the "crowd" and there is little need to engage with them in decision-making processes. Based on review of organizations' websites, online resources and assessment of experts, 52 stakeholders were selected in total for stakeholder analysis.

2.3. SEMI-STRUCTURED INTERVIEWS

This study used semi-structured interviews to gain an understanding of who the powerful stakeholders are (in relation to the farmer perspective) to exchange information about PP, CR, and BD. The following two criteria were applied in selecting the targeted farmers for interviews: (1) we were looking for three farmers for each cluster, and (2) for each cluster, we chose farmers from different planning regions in Latvia in order to exclude specific regional impact. Interviews were done both face-to-face and online (11 and 4, respectively) during the period of June to November in 2021 (n=15). After the first interview, we decided to ask about communication with farmers in general in the remaining interviews, without asking each interviewed farmer to which cluster the farmers they communicate with belong. This decision was made, firstly, to reduce the time of interview, because the interviews were conducted during the period when the farmers were busy with harvesting, and secondly, the farmers have their own perception how to cluster farmers based on type of farming, area and output, which does not always correspond to the results of the previous studies. The interviews consisted of an introduction, in which the objective of the study, general information (age, farm size, land use, soil type, number of animals, priorities of farm), and information flows on PP, CR, and BD were stated. Interviewees were asked to characterize stakeholders from whom they have received or to whom they have sent information about PP, CR, and BD. Before asking about soil functions, we asked prompting questions:

1. Would you like to produce more products on your farm?
2. Who has made you think that it is possible to produce more?
3. Have you heard from anyone about farming practices that would increase production?
4. Do you think about increasing the carbon content in soil?
5. Are you aware of the benefits of increasing the carbon content in soil?
6. Do you know how you can increase carbon in soil?
7. How would you describe the landscape where your farm is located?
8. Do you think about conserving and maintaining biodiversity in your farm?
9. Have you called on others to take care of biodiversity in Latvia?

Additionally, we asked each stakeholder to rate the frequency of received/sent information (daily=5, weekly=4, monthly=3, yearly=2, annually=1) and the evaluation of received/sent information (high potential=4, medium-high potential=3, medium-low potential=2, low potential=1).

During the interviews, we filled in tables regarding the stakeholders from which farmers receive information and with whom they share information on each soil function. All interviews were recorded in audio format and then the statements that were associated with farmer views, perceptions, and knowledge relating to soil functions were transcribed.

2.4. DATA ANALYSIS: FARMER-CENTRIC SOCIAL NETWORK ANALYSIS

The main elements of a social network are: nodes, which represent different stakeholders; edges, which represent the links/relationships/ties between nodes; and edge weights, which indicate the frequency and impact potential of received/sent information. We systematized the data from interviews by creating a node catalogue with the names of all actors and their node attributes for each soil function. Further, we created an edge list defining all connections between farmers and other stakeholders, including edge attributes. We created networks from nodes, edges and edge weights by using the igraph package in R 4.0.5 (https://igraph.org/) (Nepusz, 2022). Duplicate edges were merged into single edges and edge weights were summed. The networks were aggregated for each soil function in two ways: (1) where all farmers were treated as one node and (2) where farmers were divided into farm clusters. Then, in-depth links for the farm cluster networks were analysed using degree centrality. The following equation indicates that the degree centrality C_D is the number of connections A of given node (Lizardo and Jilbert, 2022):

$$C_D(j) = \sum_{j=1}^{n} A_{ij} \tag{1}$$

In the graphical representation, node size and color intensity represent the degree centrality of a stakeholder. The edge weights demonstrate the 'frequency x potential' of communication, while the color shows the direction of communication.

3. RESULTS AND DISCUSSION

This section presents the main gaps in reaching an improved understanding of primary productivity, carbon regulation and biodiversity, key actors in farmer-centric networks, and potential pathways for improving information channels. To identify key stakeholders and improve the transfer of information from the national to the farm level, we compared the stakeholder analysis with the farmer-centric networks for each soil function. It is vital to understand not only the tools needed to implement changes, but also the main gaps and needs of farmers, in order to establish result-based agri-environmental policies.

3.2. PRIMARY PRODUCTIVITY

Traditionally, profit and productivity have been the highest priority for farmers as shown by the PP farmer-centric networks, in which the information exchange and the largest number of organisations are concentrated (Figure 2a). An increase in production was mentioned as a priority by 12 out of 15 farmers: "*Productive land must produce, while non-productive land must be used for other purposes".* For agriculture, like any other business, production and sale of products is a priority. Another farmer also mentioned: "*It is important to give the information to the consumer on what we produce and why the consumer should use it and leave for the consumer to decide for himself whether he needs it*". Almost all farmers indicated in the interviews that they communicate with other farmers on a daily basis, share farm events related to production, harvesting, sowing, latest technologies used in their farms, and provide each other with both technical support and knowledge. The social network analysis shows that the structures and communication channels for primary productivity are well established. The most important stakeholders with whom farmers have two-way communication about primary productivity are other farmers, the Latvian Rural Advisory and Training Centre (LLKC), the Farmers' Parliament (ZS) and the media.

3.3. CARBON REGULATION

5

Figure 2b denotes far fewer connections, which means that farmers lack knowledge about on-farm carbon regulation and its relation to different farming practices that are already implemented on-farm. During the interviews, seven of 15 farmers said that they were not aware of carbon regulation issues; they indicated that while such information may be disseminated, they are not paying attention to it due to the lack of both time and interest. Only one farmer indicated increasing the carbon content of the soil as a priority on his farm, as this farm manages soils with insufficient organic matter content and the farmer believes that it is not possible to obtain a competitive yield without additional measures for improving the organic matter in soil. At the same time, 3.8% of managed land among the interviewed farmers is on organic soils. Agricultural production on organic soils results in net GHG emissions and causes a loss of soil carbon (Buschmann et al., 2020; Purola and Lehtonen, 2022; Qiu et al., 2021; Stainforth and Bowyer, 2020), yet there is a lack of knowledge about organic soils in the farming community. One farmer stated: "*There is a lack of knowledge surrounding what in Latvia constitutes as organic soil according to the current soil classification*", while another said: "*It is difficult to grow anything on drained organic soils, because organic soils are unable to maintain the moisture that the plant needs (…) in hot summers it becomes dusty, but when organic soil is wet, it attracts frost in the spring*". Often farmers choose pathways that are most beneficial for their farms (Mattila et al., 2022), and sometimes that happens to be in line with climate change mitigation: "*We have abandoned ploughing because we realized that it is not suitable for the farm's heavy soils, because the amount of organic matter in the soil is reduced, we are telling other farmers about the minimum tillage on the farm, but not with the aim to sequester carbon, it is like a bonus that you do not realize and that comes with it".*

Soil physical, chemical, and biological properties are mainly affected by soil organic matter and directly relate to soil organic carbon content, because soil organic carbon is often used to measure soil organic matter (Ontl and Schulte, 2012), but this knowledge is either not disseminated in the farmer community or the link between 'organic matter' and 'carbon' is not established: "*The importance of carbon in the soil is more background information*", and "*(…) I did not connect that carbon is organic matter that leads to fertile soil and yield*". Confusion and misalignment in terminology were also highlighted in interviews: "*I do not know how much we need to think about carbon sequestration on the farm; we think more about liming and increasing organic matter, but we have not thought about increasing carbon in soil*", and another farmer also mentioned at the beginning of the interview that increasing the carbon content of the soils is a priority, but during the further interview admitted that: *"(…) it is relevant to us, we grow legumes, clover, alfalfa, which fix nitrogen (…) What is carbon? (…) then I mixed*".

3.4. BIODIVERSITY

The Figure 2c shows the same number of connections as Figure 2b, but with stronger links in both directions. In the last decade, biodiversity at the farm-scale has been garnering increased attention (Herzog et al., 2017; Maleksaeidi and Keshavarz, 2019), but still there is no clear opinion in the farming community regarding what constitutes on-farm biodiversity: "*There is a lack of qualitative and targeted information on ensuring biodiversity. What biodiversity is, is not defined and where it is naturally, where it could be artificially created and where it is clear that it will not be".* Five farmers mentioned that an increase in biodiversity is the least important attribute for their farms. Farmers can improve biodiversity on their farms (Stoeckli et al., 2017), and some see the necessity for close cooperation with scientists: "*There is a need for a scientific basis regarding what would improve [on the farm] and be necessary for the maintenance and enhancement of biodiversity*".

Because of the lack of knowledge in what constitutes biodiversity, farmers do not recognise themselves as an important stakeholder in its maintenance: "*We hear about biodiversity all the time, but we are not the ones to whom it should be told, we understand that for ourselves (…) those who farm normally are already taking care of surroundings and protect it*". The knowledge about biodiversity at the farm-level is affected by farmers' perception that environmental gains are considered to be losses in profitability (Dominati et al., 2019): "*We believe that productive land must produce, we must create the value of products, but in those land areas that are not suitable for production, we create biodiversity. We have a lot of old boreal forests on the farm, where there is a variety of insects, animals, birds, plants*", "*I will not leave one third or one fifth of agricultural land to nature, just to save the world*", and *"We should look at what already is, for example, the place of old houses, existing large trees, buffer strips*".

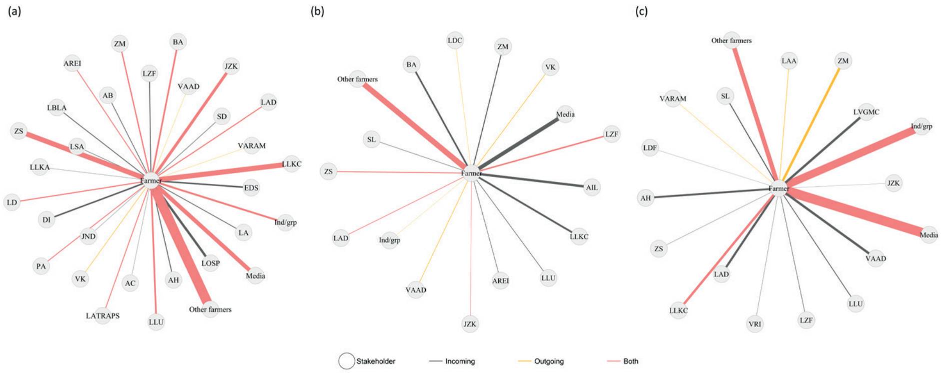

Figure 2. Farmer-centric networks for (a) primary productivity (b) carbon regulation and (c) biodiversity. The thickness of the lines represents the weight of edge. Acronyms are explained in Supplementary Material Table S1 and overview of the networks is given in Table S2.

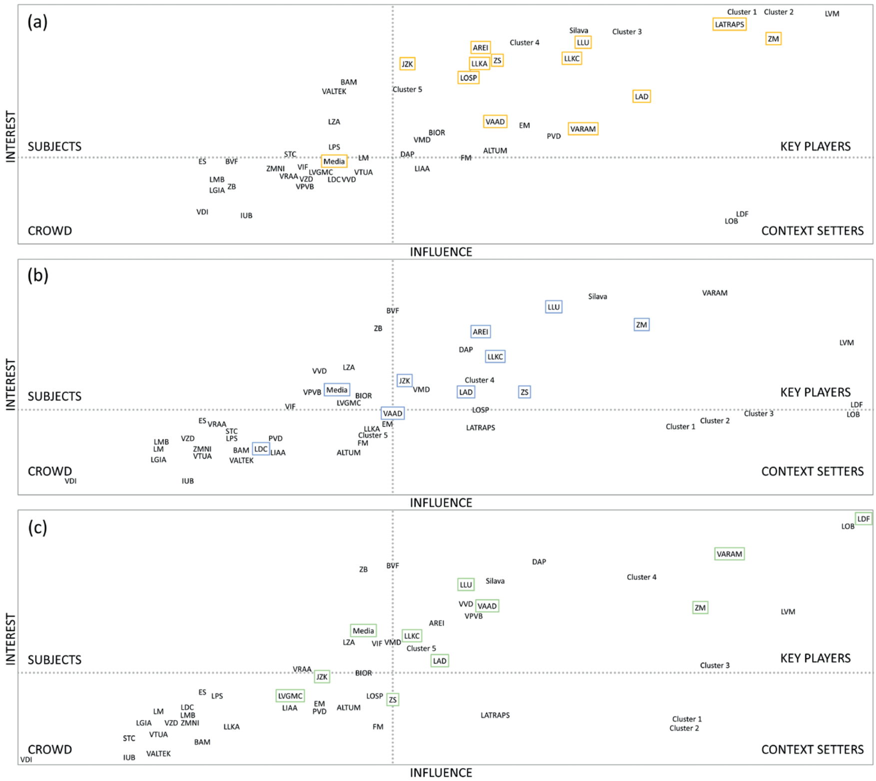

Figure 3. Interest versus influence matrices on (a) primary productivity, (b) carbon regulation, (c) biodiversity. Organisations with frames are stakeholders mentioned by farmers in interviews. Acronyms are explained in Supplementary Material Table S1.

3.5. STAKEHOLDER ANALYSIS

Figure 2 is a very farmer-centric view, but in reality, there is an entire ecosystem of stakeholders; farmers do not work in isolation, as they are a part of the AKIS. The experts ranked selected stakeholders from organisational websites, and those with the surrounding lines are also mentioned by the farmers themselves (Figure 3). We see the following discrepancies: (1) for PP, farmer interest and influence of are closely correlated; (2) but when for CR and BD, the interest of farmer clusters fall well below their influence.

3.6. DIVERSITY OF FARMERS

The farming community is not homogenous. The farmer-centric networks include a wide variety of different public administrations and scientific organizations, NGOs, private companies and the media, and there are also differences within the farming community. Farm clusters differ in how they communicate with different stakeholders, which is most likely related to both the specialization of the farm and the farmer's own willingness, interest and ability to engage in activities that do not directly impact on their on-farm activities. From Figure 4a, we can see that all clusters are quite active in communication about production except for Cluster 5, which represents small backyard farms (see also overview in Supplementary Material Table S3). Backyard farmers often combine the income generated from their jobs with both backyard gardening and touristic activities. Farm size sets the economic ability to adopt technologies and mechanization of farm processes (Foster and Rosenzweig, 2017), which consequently enrich the information exchange about production. The stakeholder analysis shows that large farm clusters (Cluster 1 and Cluster 2) are more interested (and influential) in production issues comparing to other clusters (Figure 4a).

Assessing the network in Figure 4b, the leader in communication regarding carbon regulation is Cluster 1, which represents large mixed specialization farms, which have the time and resources to be actively involved in the information exchange. Interestingly, Cluster 2 (representing large cereal farms) receives information on carbon regulation from only one organisation and does not disseminate this information further—and although these farms are also among those that have both the time and the resources to engage in various activities, these specific interviewed farms do not see the issue of carbon regulation as binding (see also overview in Supplementary Material Table S4). However, from the stakeholder analysis we can see that Cluster 1, Cluster 2 and Cluster 3 do not have a high interest, but experts rank them as having a large influence over carbon regulation issues (Figure 3b). While we have contradictory findings between large farmers' clusters, Koirala et al. (2022) found that adaptation responses to climate change are much higher for small-sized farmers, but the study of Peltonen-Sainio et al. (2021) found that organic farmers, female farmers and farmers with a farm size larger than 50 ha are most concerned about organic content in their fields.

From the Figure 4c, we can see that Cluster 3 communicates actively about biodiversity. This cluster represents medium, mixed specialization farms in which farmers themselves also do most of the work on the farm, which means that the time for off-farm activities is very limited. The second most active communicator is the cluster of organic farms (Cluster 4) (see also overview in Supplementary Material Table S5). Experts evaluate both clusters as "key players" in biodiversity (Figure 3c). The farm size is one of the factors that determines farm processes and management practices (Stringer et al., 2020), which in turn affects the ecosystem structure and biodiversity; therefore small-scale agricultural areas are extremely important for the abundance of birds, butterflies and bumblebees (Belfrage et al., 2005).

3.7. INFLUENTIAL STAKEHOLDERS IN CLUSTERED FARMER-CENTRIC NETWORKS

Key stakeholders differ between soil functions and farm clusters. Only 21 stakeholders out of 52 selected stakeholders in the stakeholder analysis are mentioned by farmers in interviews; and farmers mentioned an additional 20 organisations, which do not appear in the stakeholder analysis. In other words, the experts consulted for the stakeholder analysis failed to identify more than 25% of the actors that farmers interact with and found important enough to mention. This could be explained by the small-world phenomenon often found in SNA (e.g. O'Sullivan et al. (2022)), as experts and farmers may create their own small-worlds, where actors interact intensively with each other within small-world, but very little with other small-worlds. In order to transfer the knowledge and experience of one small-world to another small-world, a bridging actor or bridging organisation is needed, which accumulates knowledge and transfers it on when necessary.

In order to identify the most influential stakeholders in PP-, CR-, and BD-clustered farmer-centric networks, we used the degree centrality of each node in network, in which degree centrality is the number of edges incident upon a node (Figure 4).

3.7.1. Primary production

In the PP-clustered farmer-centric network, other farmers appear to be the most valued source of information. This was found in other studies as well: it is recognized that peer-to-peer learning amongst farmers is often the most trusted source of information.(Franz et al., 2010; Thomas et al., 2020). During the interviews, several farmers indicated that they both inspire farmers in their neighborhood to try a new technology, and also adopt technologies from other farmers, without delving into the pros and cons of the technology, but trusting that it is a trend and "*if my neighbor does it, then I will too*". The LLKC is valued as an important player by both farmers and experts, but the media is recognized as an important player only by farmers. The LLKC was established to train farmers to increase yields and competitiveness. Both objectives are still valued by farmers, especially in regard to the demonstration farms where various technical solutions have been shown in practice in animal husbandry, crop production, diversification of the rural economy and promotion of cooperation. This, organized by the LLKC, serves as a means to transfer technology and knowledge from farmer to farmer.

Two high-valued, non-governmental organizations that are related to agricultural production were mentioned by at least three clusters: the Farmers' Parliament (ZS) and the Latvian Young Farmers' Club (JZK). Both are also valued by experts as influential stakeholders. Conversations with individuals and groups play an important role in farmers' communication with others, as some farmers are open to receive guests and to talk about their production technologies and experience. Educational and scientific institutions (LLU, DI, AREI) are not highly valued in the exchange of information in the PP-clustered farmer-centric network, despite the fact that these institutions study different technologies and measures to improve the efficiency of production technologies and resources (Bankina et al., 2021; Gravite et al., 2021; Jansone et al., 2021; Lepse et al., 2021; Valujeva et al., 2022, 2020). This could be related to the type of information and communication-style that is produced by these institutes, because scientific reports and seminars may not be interpretable by a general farmer audience. In this sense, many other organisations may have high importance on translating available scientific evidence into lay-speech. However, LLU and AREI are recognised as influential stakeholders by experts (Figure 3a).

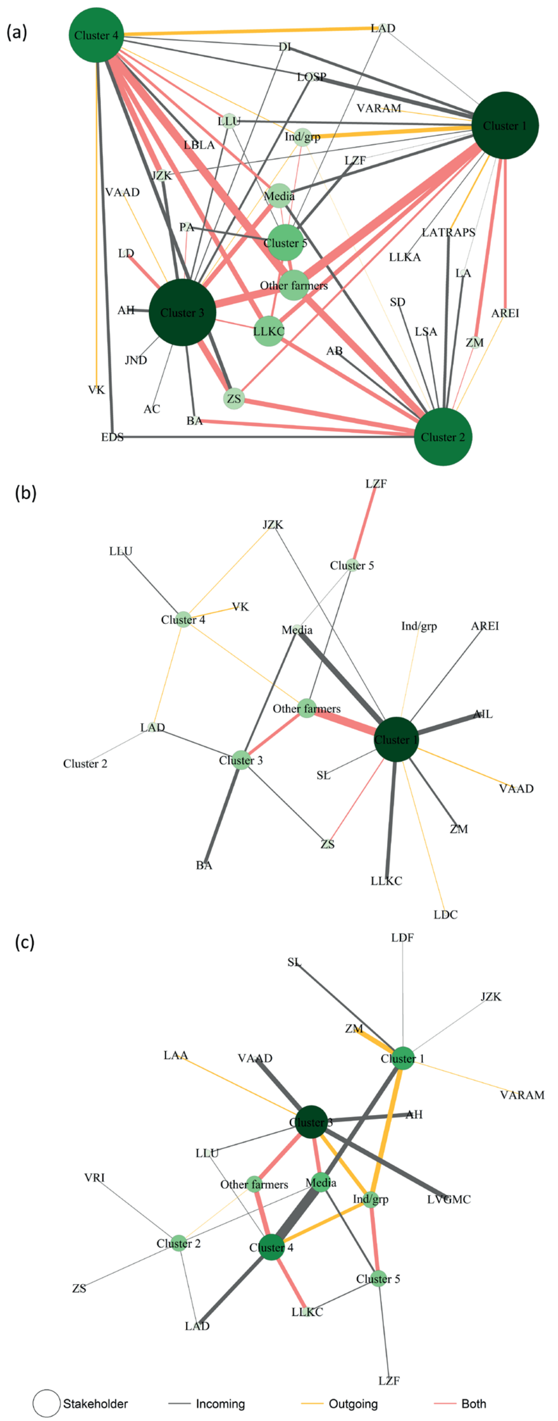

Figure 4. Farmer-centric networks based on farm clusters for (a) primary productivity (b) carbon regulation and (c) biodiversity. The thickness of the lines represents the weight of edge, but the size and color intensity of node represents degree centrality.

3.7.2. Carbon regulation

Other farmers and media are also influential actors in communication regarding carbon regulation. Rural Support Service (LAD) which is responsible for implementing unified state and the EU support policy for agriculture, forestry, fisheries and rural development, is recognised as an important player in the information exchange about carbon regulation by both farmers and experts. The role of LLKC in CR-clustered farmer-centric network is insignificant, which does not coincide with the experts' assessment. The ZS and Latvian Young Farmers' Club (JZK) are recognized non-governmental organizations by both farmers and experts.

3.7.3. Biodiversity

Although other farmers play an important role in the BD-clustered farmer-centric network, communication amongst the media,individuals, and groups is more important for farmers (Figure 4), which shows that there is a great public interest in biodiversity issues; this is fueled by various non-governmental media campaigns that aim to protect natural areas and decrease the negative effects of agriculture to biodiversity (for instance, #RestoreNature and "Save Bees and Farmers!"). Experts also recognise the important role of non-governmental organizations in biodiversity issues. The Latvian Ornithological Society (LOB) is one of the well-known non-governmental organizations that draws the attention of the public and of scientists towards biodiversity, but there is no interaction between farmers and LOB. The role of LLKC in the clustered farmer-centric network is also insignificant. Similar to CR-clustered farmer-centric network, the LAD is also mentioned as an important source, which is most likely because of the responsibilities of LAD for granting or refusing support payments, so it also indirectly provides information on biodiversity issues.

3.8. TRANSMISSION OF INFORMATION

Over the last decade, a variety of information is being circulated daily about agricultural issues in the news media and scientific arenas, which also directs the public opinion about agriculture (Akhter et al., 2021). Very often, the same information is republished by several sources/organisations. Farmers also emphasized in interviews that newsletters from various organisations are received by email every week, often duplicating messages. The way of presenting information has to be in accordance to the capabilities on the information receiver to process it; for instance, farmers do not have enough time to read each newsletter every week. A farmer (especially the owner of small and medium size farms) is an all-around worker who must be able to perform soil cultivation, harvesting, allocation of work and supervision, planning of fields where to sow, planning of fertilization, financial planning, and purchasing of materials. For each of the daily activities, many different organizations provide the latest information every week, often duplicating it. This results in information converging at the farm-level, and the farmer needs to distill it into practical actions and management plans (O'Sullivan et al., 2022). Different actors often have competing interests and desires, which influences on-farm sustainability (Bernard et al., 2014). Frequent changes in policy regulations and poor communication between farmers and the government undermine farmers' trust, leading to misinformation, a lack of information, and a widening gap between the farmer and the general public. Farmers and the general public rank their priorities differently (Valbuena et al., 2010). Farmers focus more on functional demands to the land in order to ensure productivity, while societal demands on land also include: protecting biodiversity, mitigating climate change, reducing flood risks, and improving water quality (Schulte et al., 2019).

In order to come up with solutions that satisfy all stakeholders, one of the stakeholders from the network has to act as a bridge between policy-makers, scientists and farmers. For instance, science-based understanding is not always in line with farmers' experiences and observations in growing conditions, productions risks and needed future measures to cope with the weather-related changes (Peltonen-Sainio et al., 2020). For the translation of science into practical farm advice, the advisory centres already take this role of a bridging organisation, providing consultations in agriculture, forestry, environment and climate, innovation and technology, as well as economic aspects and social legislation. The education, experience, and ability of advisors to work with each individual case-study are the most important factors that farmers will assess during the consultation. In our case, although the LLKC is the main state company for agricultural and rural advice, its role in environmental and climate networks were found to be low. Advisory centres have been recognised by farmers, but there is a strong opinion that the main focus of public authorities is to restrict activities, rather than to provide information on how to farm better. Strengthening the advisory centres and promoting the availability of advice in farming communities are also highlighted in the CAP for the period from 2021 to 2027 (ZM, 2022). However, advisers' environmental and climatic understanding needs to be improved in order to address the contemporary knowledge gaps for farmers. Also, the translation of policies and scientific evidence on the environment and climatic topics need to have practical interpretations in order to be convincingly communicated with the farmers. Advisers are in a unique position to influence on-farm decisions and to help achieve national and international objectives on sustainability and climate change.

3.9. NETWORKING AS A SUSTAINABILITY MEASURE

Collaboration between farmers and other stakeholders has been identified as a crucial method for achieving long-term agricultural sustainability. Farmers' voices are paramount when policy changes are being introduced, especially if these changes can affect their financial stability (in which case, the changes needs to be coupled with financial incentivisation mechanisms). It is extremely difficult for farmers to find and implement solutions alone, and creating acceptable solutions to all parties is a collaborative effort. We recommend the horizontal strengthening of the network within policy departments in order to increase the understanding and awareness of desired directions and outcomes. This could be achieved, for instance, by strengthening the cooperation, information exchange and achieving a common understanding of environmental protection and production between the Ministry of Environmental Protection and Regional Development of the Republic of Latvia (VARAM), which is responsible for implementing policy in environmental protection and regional development, and LLKC, which is recognized as a key player in the farmer-centric networks of primary productivity and biodiversity.

Because farmers value mostly information exchange with other farmers, strengthen horizontal networking among farmers can further enhance the dissemination of information on multifunctional land management practices. Farmers are interested in discussing new emerging ideas, especially if it accrues economic benefits, but actors new to the farming community find it challenging to initiate engagement with these farmer-peer groups. Therefore, one of the ways to facilitate the transfer of know-how between farmers is to leverage the existing practical trainings and demonstration events of good practices on farms, and to communicate the impact of practices not only on primary production, but also on other ecosystem services and national policy objectives.

Future climate action requires equal and close cooperation between farmers and other stakeholders from the beginning to avoid misunderstandings and confusion (Sorvali et al., 2021). Farmers are the most experienced experts in land use, so close cooperation between farmers and other stakeholders is a necessity. During the COVID-19 pandemic, the Ministry of Agriculture of the Republic of Latvia (ZM) introduced an information exchange between small groups of experts and the ministry in an online platform to discuss a variety of issues. This novel communication model can prove useful to encourage greater involvement of farmers in solving future challenges as well, because online platforms can be accessed from anywhere with proper internet connection and does not negates the need for travel time to meetings. The fragmentation of the AKIS in Latvia highlights the importance of strengthening closer cooperation between all parties involved (ZM, 2022). Training advisers in the multifunctionality of land would strengthen the vertical knowledge transfer between policy departments and farmers. Farmers do not necessarily connect their farms and applied management practices to terminology surrounding carbon sequestration/carbon stock/organic matter decomposition/biodiversity. Communication can be improved if some of the organisations use more practical terms and compare ‘scientific/policy’ terms with ‘practical’ examples to demonstrate how soil organic carbon contents are increased or decreased, and how farm management affects biodiversity. For the longevity of a collaboration and its accomplishments, it is not the absolute network density that matters, but rather the increase in network density over time (Velten et al., 2021). Long-term cooperation between many stakeholders, including knowledge transfer, the development and implementation of solutions, and monitoring are essential to adequately address global societal challenges.

This is how far we can bring our recommendations towards inclusive policy based on the small set of farmers that we interviewed. Each of these horizontal, vertical, horizontal tools requires further research in order to come to very concrete instruments would be most applicable.

4. CONCLUSIONS

Participatory techniques in addressing the challenges of agri-environmental policy and decision-making are essential to bridging the gap between the formulation of policy goals, and the actual implementation of land management practices. The methods used in this study provide entry points into gaining better insight into local contexts associated with the adoption of stakeholder participation in policy development on sustainable land use. Despite the small sample sizes of this study, the social network analysis clearly identified local players and influential stakeholders and allowed for the analysis of their relationships with the aim to streamline the dissemination and exchange of information and knowledge on sustainable land management. This study highlights the need for policies that further utilize existing knowledge and relationships between different stakeholders in order to achieve a common understanding of desired directions. The development of a shared understanding of intended directions, outcomes and knowledge requirements requires both horizontal and vertical strengthening of the national AKIS. Horizontal strengthening refers to the networks and information exchange between policy departments and between farmers’ communities. Vertical transfer of information and knowledge between policy-makers and farmers can be strengthened by a bridging organization, which in the Latvian case is the advisory centres. This requires the training of existing advisers on multifunctional land management.

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SUPPLEMENTARY MATERIAL

Table S1. Overview of stakeholders

No.	Abbreviation	Stakeholder	Stakeholder analysis	Social network analysis
1	AB	AgroBroker is an insurance brokerage company specializing in providing services to Latvian farmers		x
2	AC	Latvian Chamber of Agriculture, Forestry and Fisheries (*Agrichamber*) unites any Latvian agricultural, forestry and fisheries enterprise to more effectively help solve current problems in the industry		x
3	AH	The Institute of Plant Protection Research (*Agrihorts*) focuses on the research of useful organisms in agriculture, the development of new plant protection technologies and the research of resistance and residue of plant protection products		x
4	AIL	Association for Sustainable Rural Development and Agriculture (*Apvienība par ilgtspējīgu lauksaimniecību*) aims to promote objective, fact-based and research-based communication with the public		x
5	ALTUM	ALTUM is a state-owned development finance institution, which offers state aid for various target groups with the help of financial tools	x	
6	AREI	Institute of Agricultural Resources and Economics (*Agroresursu un ekonomikas institūts*) is leading institute for research on crop breeding and rural economics	x	x
7	BA	Baltic Agro provides farmers with the widest range of products, technologies, consultations and services		x
8	BAM	Baltic Agro Machinery is a dealer of agricultural, forestry, construction and utility machinery and spare parts	x	
9	BIOR	Institute "BIOR" is a research centre of national importance which develops innovative research methods and creates new practically applicable knowledge in the following areas of science: public and environmental health, food, fishery and veterinary medicine	x	
10	BVF	Baltic Environmental Forum (*Baltijas Vides Forums*) is a non-profit association with aim to strengthen co-operation and information between the Baltic authorities in the field of environmental protection	x	
11	Cluster 1	Cluster 1 represents intensive mixed specialization farms that keep animals in housing with farm size >400 ha	x	x
12	Cluster 2	Cluster 2 represents intensive cereal farms with farm size >200 ha	x	x
13	Cluster 3	Cluster 3 represents medium-sized mixed specialization farms with livestock grazing and farm size <400 ha	x	x
14	Cluster 4	Cluster 4 represents organic farms	x	x

No.	Abbreviation	Stakeholder	Stakeholder analysis	Social network analysis
15	Cluster 5	Cluster 5 represents backyard farms with farm size <10 ha	x	x
16	DAP	The Nature Conservation Agency (*Dabas aizsardzības pārvalde*) ensures implementation of unified nature protection policy in Latvia	x	
17	DI	Institute of Horticulture (*Dārzkopības institūts*) is the leading research centre for vegetable and fruit growing in Latvia		x
18	EDS	Equipment dealers/suppliers		x
19	EM	The Ministry of Economics (*Ekonomikas ministrija*) develop, organise and coordinate external economic, construction, energy, internal market, innovation development, commercial development, competitiveness development, housing, consumer protection, privatisation, industrial, standardisation and tourism policies, as well as structural economic policies	x	
20	ES	The European Union House (*ES Maja*) in Riga hosts the institutions that provide information about the European Union in Latvia	x	
21	FM	Ministry of Finance (*Finanšu ministrija*) is the leading state administration institution in the field of finances	x	
22	Ind/grp	Individuals and/or groups		x
23	IUB	The Procurement Monitoring Bureau (*Iepirkumu uzraudzības birojs*) implements policies in the field of labor relations and occupational safety and health	x	
24	JND	Jelgava County Council		x
25	JZK	Latvian Young Farmers club (*Jauno Zemnieku klubs*) is a voluntary youth organization, that gathers young farmers, their families, the young generation from rural area and other people who are interested in countryside expansion and life in countryside	x	x
26	LA	The Farmers' Association (*Lauksaimnieku apvienība*) brings together a number of regional farmers' associations in order to gain greater influence and voting rights in state and public organizations and to play an equal role in decisions that are important to farmers		x
27	LAA	Latvian Fruit Growers Association (*Latvijas Augļkopju asociācija*) aims to unite those interested in the sector in order to carry out reforms in Latvian fruit growing, developing it and making it an important agricultural sector in Latvia		x
28	LAD	The Rural Support Service (*Lauku atbalsta dienests*) is responsible for implementation of a unified state and European Union support policy in the sector of agriculture, forestry, fisheries and rural development	x	x
29	LATRAPS	Agricultural service cooperative society	x	x
30	LBLA	The Association of Latvian Organic Agriculture (*Latvijas Bioloģiskās lauksaimniecības asociācija*) is a legal, professional, non-governmental organisation		x

5

No.	Abbreviation	Stakeholder	Stakeholder analysis	Social network analysis
		that brings together producers, traders and processors of organic products: milk, meat, honey, fruit, vegetable and cereals, processors, traders and supporters of organic food in Latvia		
31	LD	Association of Latvian Gardeners (*Latvijas Darznieks*) represents the interests of gardeners in state institutions, creating an economic policy favourable to the development of horticulture		x
32	LDC	The State Animal Breeding Information and Data Processing Centre (*Lauksaimniecības datu centrs*) is a state institution to aggregate, process and analyse zootehnical, veterinarian and agricultural information in Latvia	x	x
33	LDF	Latvian Fund for Nature *(Latvijas Dabas fonds*) works with preservation of biological diversity by implementing wide range of projects, educating society and raising public awareness on environmental issues	x	x
34	LGIA	The Latvian Geospatial Information Agency (*Latvijas Ģeotelpiskās informācijas aģentūra*) is the leading institution in the realizing of the national policy in the field of geodesy, cartography and geospatial information	x	
35	LIAA	The Investment and Development Agency of Latvia (*Latvijas Investīciju un attīstības aģentūra*) promotes the competitiveness and export capacity of Latvian companies in international markets, promotes the growth of foreign investment, implements the state tourism development policy and the state policy in the field of innovation	x	
36	LLKA	Latvian Agricultural Cooperatives Association (*Latvijas Lauksaimniecības kooperatīvu asociācija*) is an association of agricultural and forestry cooperatives	x	x
37	LLKC	Latvian Rural Advisory and Training Centre (*Latvijas Lauku konsultāciju un izglītības centrs*) is the leading organization of consultancy services related to rural development in Latvia	x	x
38	LLU	Latvia University of Life Sciences and Technologies (*Latvijas Lauksaimniecības universitāte*) is one of the leading universities of science and technologies in the Baltic Sea region, specializing in the sustainable use of natural resources aimed at the enhancement of quality of life for society	x	x
39	LM	Ministry of Welfare (*Labklājības ministrija*) is the leading institution of the state administration in the areas of labour, social security, children's and family rights as well as equal rights for people with disability and gender equality	x	
40	LMB	Latvian Ameliorator Association (*Latvijas Melioratoru biedrība*) represents the interests of specialists	x	

No.	Abbreviation	Stakeholder	Stakeholder analysis	Social network analysis
		working and retired in land reclamation and related industries		
41	LOB	The Latvian Ornithological Society (*Latvijas Ornitologijas biedriba*) is the largest nongovernmental nature conservation organisation in Latvia that works on bird and habitat protection in order to maintain the numbers, diversity and geographic distribution of important sites, species and habitats in Latvia	x	
42	LOSP	Latvian Agricultural Organization Cooperation Council (*Lauksaimniecības organizāciju sadarbības padome*) is an association, which unites 58 non-governmental organizations of agricultural production and processing across the country, covering all the sectors and in total represent more than 15000 producers	x	x
43	LPS	The Latvian Association of Local and Regional Governments (*Latvijas Pašvaldību savienība*) is a public organisation associating local governments of the Republic of Latvia on voluntary basis	x	
44	LSA	The Latvian Association of Seed Growers (*Latvijas Seklaudzetaju asociacija*) is an association in which representatives of the seed growing industry - seed growers, seed preparers, seed traders, breeders and their representatives - have united for joint activities		x
45	LVGMC	State limited Liability Company "Latvian Environment, Geology and Meteorology Centre" (*Latvijas Vides, ģeoloģijas un meteoroloģijas centrs*) Ensures the collection, storage and provision of environmental information to the public and state and local government institutions	x	x
46	LVIF	The Latvian Environmental Investment Fund (*Latvijas Vides investīciju fonds*) aims to reduce environmental pollution by promoting the implementation of environmental protection projects and increasing the capacity of local governments and capital companies to prepare and implement high-quality and efficient environmental protection projects from the project idea to its implementation	x	
47	LVM	State joint stock company (*Latvijas valsts meži*) engaged in Latvian state forest management	x	
48	LZA	Latvian Academy of Sciences (*Latvijas Zinātņu akadēmija*) promotes the development of science, conducts scientific research in Latvia	x	
49	LZF	The Latvian Farmers' Federation (*Latvijas Zemnieku federācija*) is a non-governmental organization that stands for populated and economically active rural areas of Latvia		x
50	Media	Newspapers, television, radio, social media	x	x
51	PA	Partikas amatnieki is an association of home producers, craftsmen and small producers in Zemgale region		x

No.	Abbreviation	Stakeholder	Stakeholder analysis	Social network analysis
52	PVD	Food and Veterinary Service (*Pārtikas un veterinārais dienests*) ensures qualified and effective state supervision of the movement of safe and secure food, feed, animal by-products and veterinary medicinal products to consumers, as well as compliance with animal health and welfare, breeding requirements, and ensure border control of food and non-food safety and phytosanitary	x	
53	SD	Scandagra is an agro trading, and organic/conventional grain trading company		x
54	Silava	Latvian State Forest Research Institute "Silava" is the main centre of forest science in Latvia and leader of scientific ideas in forestry and the related research and development in the country	x	
55	SL	Scientific literature		x
56	STC	Certification and Testing Center (*Sertifikacijas un testesanas centrs*) is a capital company, which provide certification and laboratory services in regulated and non-regulated spheres	x	
57	VAAD	State Plant Protection Service (*Valsts augu aizsardzības dienests*) aimed at ensuring the sustainable use, protection and monitoring of crop and forest resources	x	x
58	VALTEK	Sale of agricultural machinery, equipment and supplies	x	
59	VARAM	Ministry of Environmental Protection and Regional Development (*Vides aizsardzības un reģionālās attīstības ministrija*) is responsible for implementing policy in three areas: environment protection, regional development as well as information and communication technologies	x	x
60	VDI	The State Labour Inspectorate (*Valsts darba inspekcija*) is the state institution that carries out the implementation of the policy in the field of labour legal relations and occupational safety and health	x	
61	VK	The certification body "Vides kvalitate" assesses the compliance of companies in accordance with the regulations in the fields of organic farming production, processing, as well as in the forestry and timber supply chain		x
62	VMD	The aim of the State Forest Service (*Valsts meža dienests*) is to ensure the sustainability of the forest and the forest sector	x	
63	VPVB	The State Environmental Monitoring Bureau (*Vides pārraudzības valsts birojs*) aims to prevent or reduce the adverse effects of the activities of natural or legal persons on the environment	x	
64	VRAA	The State Regional Development Agency (*Valsts reģionālās attīstības aģentūra*) is a public administration that promotes regional development	x	
65	VRI	Institute for Environmental Solutions (*Vides risinājumu institūts*) is an international network of		x

No.	Abbreviation	Stakeholder	Stakeholder analysis	Social network analysis
		scientists, artists, engineers and practitioners who care for environment and develop customized innovative environmental solutions		
66	VTUA	State Technical Supervision Agency (*Valsts tehniskās uzraudzības aģentūra*) ensures the technical and market supervision of the state-of-the-art tractor equipment and its trailers that are safe for human health, life and the environment	x	
67	VVD	The State Environmental Service (*Valsts vides dienests*) aims to ensure the compliance of implementation of legislation framework in the area of the environment and natural resources protection, and control on radiation and nuclear safety	x	
68	VZD	The State Land Service (*Valsts zemes dienests*) is in charge of real property object data accumulation and dissemination to institutions responsible for land management and supervision	x	
69	ZB	Green Liberty (*Zaļā brīvība*) is a non-profit NGO to contribute to the development of a society where people live in harmony with each other and the environment	x	
70	ZM	The Ministry of Agriculture (*Zemkopības ministrija*) is the main governmental institution responsible for the sector of agriculture, food, forestry and fisheries	x	x
71	ZMNI	Real estate of the Ministry of Agriculture (*Zemkopības ministrijas nekustamie īpašumi*) implements the drainage system and the maintenance of the hydraulic engineering and drainage cadastre, ensuring the sustainability of economically advantageous, environmentally friendly and socially responsible agricultural and forestry land resources	x	
72	ZSA	Farmers' Parliament (*Zemnieku saeima*) is the most influential and constructive non-governmental organization of agricultural and horticultural produce producers in Latvia	x	x

Table S2. Overview of farmer-centric networks for primary productivity carbon regulation, and biodiversity

Network	Number of nodes	Number of ties	In-degree centrality	Out-degree centrality	Sum of incoming weights	Sum of outgoing weight
Primary productivity	31	44	89	47	890	437
Carbon regulation	18	22	24	13	162	78
Biodiversity	19	22	31	15	254	144

Table S3. Degree centrality of farmer-centric networks based on farm clusters for primary productivity

PRIMARY PRODUCTIVITY					
Stakeholder	**In-degree centrality**	**Out-degree centrality**	**Degree centrality**	**Sum of incoming weights**	**Sum of outgoing weight**
AB	1	-	1	12	-
AC	1	-	1	4	-
AH	1	-	1	16	-
AREI	1	1	2	16	7
BA	2	1	3	32	20
Cluster 1	14	8	22	206	120
Cluster 2	12	7	19	196	104
Cluster 3	14	8	22	220	77
Cluster 4	10	8	18	191	123
Cluster 5	8	4	12	44	13
DI	3	1	4	28	-
EDS	2	-	2	28	-
Ind/grp	1	5	6	4	36
JND	1	-	1	4	-
JZK	3	1	4	56	3
LA	2	-	2	13	-
LAD	2	1	3	6	20
LATRAPS	1	1	2	16	8
LBLA	1	-	1	14	-
LD	1	1	2	20	20
LLKA	1	-	1	4	-
LLKC	5	5	10	99	50
LLU	4	1	5	32	12
LOSP	3	-	3	45	-
LSA	1	-	1	8	-
LZF	2	-	2	17	-
Media	5	3	8	79	24
Other farmers	5	5	10	192	169
PA	2	4	6	15	4
SD	1	-	1	8	-
VAAD	-	1	1	-	4
VARAM	-	1	1	-	4
VK	-	1	1	-	8
ZM	2	2	4	24	16
ZS	4	3	7	98	32

Table S4. Degree centrality of farmer-centric networks based on farm clusters for carbon regulation

CARBON REGULATION					
Stakeholder	**In-degree centrality**	**Out-degree centrality**	**Degree centrality**	**Sum of incoming weights**	**Sum of outgoing weight**
AIL	1	-	1	20	-
AREI	1	-	1	4	-
BA	1	-	1	14	-
Cluster 1	9	5	14	102	44

CARBON REGULATION					
Stakeholder	In-degree centrality	Out-degree centrality	Degree centrality	Sum of incoming weights	Sum of outgoing weight
Cluster 2	1	-	1	1	-
Cluster 3	5	1	6	42	12
Cluster 4	1	4	5	4	10
Cluster 5	3	1	4	13	12
Ind/grp	-	1	1	-	1
JZK	1	1	2	3	2
LAD	2	1	3	5	2
LDC	-	1	1	-	2
LLKC	1	-	1	15	-
LLU	1	-	1	4	-
LZF	1	1	2	8	-
Media	3	-	3	32	-
Other farmers	3	3	6	39	47
SL	1	-	1	3	-
VAAD	-	1	1	-	4
VK	-	1	1	-	4
ZM	1	-	1	8	-
ZS	2	1	3	7	4

Table S5. Degree centrality of farmer-centric networks based on farm clusters for biodiversity

BIODIVERSITY					
Stakeholder	In-degree centrality	Out-degree centrality	Degree centrality	Sum of incoming weights	Sum of outgoing weight
AH	1	-	1	16	-
Cluster 1	4	3	7	29	42
Cluster 2	4	1	5	8	1
Cluster 3	6	4	10	91	50
Cluster 4	5	3	8	94	35
Cluster 5	4	1	5	32	16
Ind/grp	1	4	5	16	66
JZK	1	-	1	1	-
LAA	-	1	1	-	4
LAD	2	-	2	18	-
LDF	1	-	1	1	-
LLKC	2	1	3	20	3
LLU	2	-	2	6	-
LVGMC	1	-	1	20	-
LZF	1	-	1	4	-
Media	5	1	6	82	16
Other farmers	2	3	5	38	33
SL	1	-	1	8	-
VAAD	1	-	1	20	-
VARAM	-	1	1	-	2
VRI	1	-	1	2	-
ZM	-	1	1	-	20
ZS	1	-	1	2	-

Chapter 6

General discussion

1. OVERVIEW OF THE MAIN FINDINGS

The growing world population, the effects of climate change on production in different regions of the world, and the recent war in Ukraine and the energy crisis in Europe, have all increased the demand for bioresources. Production through agriculture and forestry is becoming increasingly challenging due to these events. In this thesis, we found that we expect to receive many ecosystem services from our lands—but not all should be expected everywhere. For instance, as shown in Chapter 2, farmers can drain peatlands and gain additional areas for agricultural production, but drainage will simultaneously reduce the biodiversity that is inherent to such wet areas and will increase CO_2 and N_2O emissions, thus reducing the stored carbon. In this thesis, we established that if farmers afforest high-fertility agricultural areas to promote carbon sequestration and to mitigate climate change that will have a negative impact on local socio-economic conditions, which are essential for the viability of rural areas. By understanding the demand and supply for various ecosystem services at the national level, policy makers can introduce such incentivisation measures that would ensure both local demands and the achievement of national—and even international—objectives.

Given this context, the dual aim of this study was to 1) further develop the FLM methodology for implementation and to 2) provide the knowledge base for stakeholders to jointly optimise land-use and land management. First, we studied the implementation of FLM as a framework to meet the competing demands from our land. The results of Chapter 2 showed that there is potential for synergy between agronomic objectives and environmental requirements at national level, but it is not possible to achieve ambitious environmental or production targets by introducing only a specific land use change or management practice. To show that, we used a scenario analysis in which we tested five different scenarios in Ireland. The baseline represented livestock production in 2016; intensification was based on soil management that delivers higher productivity per hectare; expansion was based on land use change; and, in the drainage scenario, productivity of the land was increased by improving soil properties relating to drainage. We concluded that the combination of intensification, expansion, and drainage may give the expected result if management decision are based on knowledge of soil types, characteristics, fertility and carbon content.

Then we used Latvia as a case study to further explore opportunities with FLM, in how it could be used to harness regional differences in order to meet the trade-offs between increasing production, reducing greenhouse gas emissions, and conserving biodiversity (Chapter 3). In this chapter, our research showed for the first time that a regionally differentiated approach to land use and land management is needed to meet all socio-economic and environmental objectives at national-scale. By knowing both the regional differences, and objectives to be achieved at the local, national and even international scales, we can stimulate the use of those management practices and land use changes that will bring the desired outcomes.

Chapter 4 further studied how these regional differences in soil classes and land use can be utilised and harnessed to deliver on national objectives using three contrasting regions in Latvia as case studies. In this study, we showed untapped potential for reintegrating abandoned agricultural land to meet socio-economic and environmental sustainability objectives. The consideration of regions as separate entities leads to different opportunities for each individual region to contribute to national targets. Some areas are already optimised, and even small increases in productivity have a detrimental effect on the other functions. We suggested to specify the pathways for different regions in national policies in order to gain similar outcomes for socio-economic and environmental sustainability.

In Chapter 5, we studied how to bridge the gap between designing land use and land management plans and implementing them. As collaboration between farmers and other stakeholders is essential for achieving long-term sustainability in land management, we used participatory techniques to map and analyse the collaboration in the Agricultural Knowledge and Innovation Systems (AKIS) in Latvia. This collaborative effort is needed to create and implement solutions that are based on local and national needs. We identified the main stakeholders in agri-environmental governance in Latvia and the main gaps that they face in implementation. We first suggest the horizontal strengthening of the networks and information exchanges between policy departments and between farmers' communities, and we then suggest the vertical strengthening between policy departments and farmers.

In the following sections, I further discuss the main outcomes of this thesis. In section 2, I discuss the multiple expectations from different stakeholders. Further, in section 3, I look at the coordination of land resources at different levels that aim to meet those multiple expectations. In section 4, I look at synergies and trade-offs between soil functions at different scales. In section 5, I discuss how land managers can be incentivised to meet multiple societal demands. In section 6, I further emphasize the importance of collaboration between farmers and other stakeholders to facilitate the transition to result-oriented land management. In section 7, I discuss what changes are required at policy level to ensure result-based national development and to increase awareness of land multifunctionality. I end the thesis with a look to the future and concluding remarks, by presenting the required steps for moving towards sustainable land management.

2. MULTIPLE EXPECTATIONS FROM LAND

2.2. FARMERS

Farmers often prioritize productivity as their main functional demand to the land (Schulte et al., 2019). Food and land market prices, land productivity, climate change and urban sprawl may force farmers to adopt monocultures or intensive farming practices in order to maintain economic viability (EEA, 2019). Only the primary production function is currently monetised through the value chain. Schulte et al., (2019) argue that a distinction needs to be made between functional and social demands for all five soil functions. Society can expect farmers to oversee the functional demands of all five soil functions for their own good. But if society expects farmers to deliver over and above the functional demands for soil functions, then incentivisations and compensations are necessary.

2.3. FORESTERS

Forestry is an industry with long-term perspectives. Some private foresters do not receive economic benefits from forest areas during their lifetime, and the time, knowledge and work that they invest in forest management is aimed at ensuring forest resources for future generations (children and grandchildren). There is also continuous competition between agricultural and forest lands, where large areas are deforested for agricultural production, intensively managed and often abandoned when the soil resources are depleted (Pinillos et al., 2020). In the EU, however, the reverse process is taking place: afforestation is being implemented in countries that currently have few forests (DAFM, 2020), and there are many abandoned agricultural lands, in which agricultural production is no longer effective due to dependence on water resources, remoteness, decreased accessibility to the market, low agricultural productivity and expansion of settlements (Dax et al., 2021; Schuh et al., 2020; Van Vliet et al., 2015). As such, there is competition between agricultural and forestry land uses for these abandoned areas.

2.4. INDUSTRY

The extraction of local raw materials (e.g. peat, sand, coal, dolomite, limestone) is very important for the national economy's development in order to reduce the dependence on suppliers from outside of the EU, the transport costs, and the price of the final products. The extraction of raw materials also provides around 350,000 jobs at EU level and more than 30 million jobs are in the downstream processing industries (EU, 2021). As a result, many areas of agricultural land and forestry production are being reduced, due to land use.

2.5. SOCIETY

There are many societal expectations from land. Although the most important aspects for human beings are the supply of safe food and drinking water, residents also want to live in a clean and aesthetic environment; they want to be protected from various natural disasters, such as floods, forest fires, and furthermore want to relax in nature with high biodiversity. Society also places value on ecosystem functions and the intrinsic value of biodiversity. Societal involvement in land use decisions is influenced by economic, political, social, cultural, biophysical and demographic drivers. Malek et al., (2019) found that societal involvement in land-use decision-making is relatively high and most of the land-use decision-makers are well connected, but the power in social decisions is low: as such, small social groups have to form alliances with others in order to accomplish their objectives in land use issues.

Economic development of the countryside remains an important objective for society. Without incentivisation, the countryside risks abandonment, which can lead to deserted villages and underused land, such as what has happened in France (Jegouzo and Baylac, 2019). For this reason, the EU provides support through the Areas of Natural Constraints scheme (ANC), which compensates farmers for working under difficult natural conditions. Likewise, Ireland has explicit policies on decentralisation, which includes the movement of public service bodies away from the capital city in order to ease housing problems, to reduce transport congestion in capital, and to address under investment in other regions (Humphreys and O'Donnell, 2006).

2.6. POLICY MAKERS

Many countries have explicit policies to increase production along with meeting international requirements, such as the reduction of GHG emissions determined by the Paris Agreement. For instance, the Latvian Bioeconomy Strategy has set targets to increase production from bioresources, while the EU Biodiversity Strategy for 2030 has set the targets to protect the nature and reverse the degradation of ecosystems. Policy planning documents cover all sectors, and oftentimes contradict one another. Another interest for policy makers is the preservation of cultural and historical heritage at the national level, which is also an important objective in creating an aesthetic environment for the local people.

3. HOW TO COORDINATE CONTRASTING EXPECTATIONS?

The aforementioned stakeholders have many contrasting societal expectations from land, which affects policy formation. In order to achieve contrasting expectations, land management requires a diversified approach that accounts for multifunctionality. Each land parcel has different potential in terms of contributing to the achievement of policy objectives, based on its land use, climate, and soil properties. Schulte et al. (2015)suggested that multiple expectations can be managed by ensuring that each parcel of land delivers on those soil functions that are most suited to its pedo-climatic conditions. Zwetsloot et al. (2020) showed that most land parcels can deliver on at least three out of five soil functions at a high capacity. This means that in areas where, for instance, a farmer could reach very high yields, they could continue intensive production and bring the performance of at least two other functions closer to meeting societal demands without compromising the remaining functions. In other areas that are important habitats for biodiversity, farmers often leave these areas intact from a production point of view, but can still deliver on two other functions at the same time. From one side, this approach places some areas in a position where production is very limited, which, in some ways, delays development compared to areas where production is being stimulated. However, at the national level, using such an approach can make an equal contribution to achieving all the contrasting objectives. It requires an in-depth analysis of policy documents to determine the demand for each soil function, and the data of land uses and soil classes to evaluate the supply of those soil functions.

In this thesis, I used the FLM framework that optimises, rather than maximises, the supply of soil-based ecosystem services. Within the LANDMARK project, introduced in Chapter 1, the FLM framework was applied to quantify the current and potential supply of soil functions at the EU level. This thesis builds on the findings of LANDMARK, and further studies how the supply of soil functions can be utilised for delivering national objectives.

4. EXAMINING THE TRADE-OFFS AND SYNERGIES BETWEEN SOIL-BASED ECOSYSTEM SERVICES AT DIFFERENT SCALES

One of the most important questions I explored in this thesis was: **how to achieve the contrasting policy objectives at national level when solutions and actions take place at regional and local level**? Chapter 2 and Chapter 3 showed that there are synergies and trade-offs between land uses and land management to meet the local demands and the environmental and agricultural objectives at the national scale. The more we expect the land to deliver, the more complex the trade-offs and their associated management become. Making calculations based on available data, to develop guidelines for achieving national objectives for researchers, and for policy makers to change policies are all seemingly simple tasks, until it affects the landowner and the land user. Optimisation results look very easy to implement in theory, but in reality, making changes to the way of farming, the introduction of management practices, or the reduction in the number of farm animals or changes in land use, all can change the way that rural people live. The Chapter 4 theoretically showed that there is untapped potential in land use: in this case, in terms of abandoned agricultural land, the revaluation and reintegration of which can help countries achieve socio-economic and environmental objectives simultaneously—but this requires knowledge-based management and incentivisation. It is not enough to simply choose the best optimisation result at the regional or national level, but it is also necessary to explain, to train, to motivate and also to provide financial support in order to bring the desired actions to life as shown in Chapter 5.

5. DIVERSIFYING THE POINT OF INITIATIVE

Another question that I explored in this thesis is: **how can land managers be incentivised to meet multiple societal demands**? For some farmers, financial support for performing an activity will be sufficient motivation to implement changes on the farm; if the state has sufficient financial resources, then the problem would theoretically be solved. However, financial resources are often insufficient for such support, and thus knowledge transfer through learning from other farmers are equally important. A large number of farmers have already implemented various resource-saving measures on their farms, which they have experimentally found to be effective, or they simply do so because they are convinced that it is good for the environment. The implementation of such measures is based on the farmer's experience and confidence, and in this case, the researcher can specifically provide the farmer with information about the pros and cons of the specific measure, how it will affect water, air, soil quality and yield. In order for the farmer to contribute to meeting the multiple societal demands, mutual cooperation between the farmers, industry, scientists, and policy makers is necessary. Chapter 5 showed that farmers receive information through different stakeholders, and the topic of the information determines the number of involved stakeholders. The most important stakeholder in Latvia's AKIS system is the advisory center, which is now already recognized as an important player in relation to production issues, but for the implementation of the EU Green Deal and the development of AKIS, it is important that the advisory center also becomes a trusted stakeholder that informs farmers about environmental and climate issues.

This thesis shows that development objectives at the national level needs to be aligned with the land resource capabilities at the local level. By result-based management of land resources, national objectives can be achieved, but this requires close cooperation at all levels and in all directions. Although in this thesis I looked at three soil functions and how these functions are communicated in the Latvian AKIS, the results highlight the most important problems and possible solutions which could be of interest for other Member States where the AKIS system is fragmented.

In most cases, when developing a policy or action plan, the farmer is expected to do something different. Sometimes this is made explicit, and sometimes it is simply an implicit assumption. This thesis furthermore shows that there is a need to widen the scope when considering a starting point for the development of new policies; there is merit in first changing how advisory services work, to ensure that they are effective before incentivising farmers to change their practices.

6. STRENGTHENING HORIZONTAL INTEGRATION FOR COOPERATION-BASED SUSTAINABLE LAND MANAGEMENT

6.1. THE IMPORTANCE OF COOPERATION IN SUSTAINABLE LAND MANAGEMENT

For those people that have not worked directly with agriculture or forestry, it is difficult to understand the aspirations and needs of land users and managers. I was fortunate enough to have a grandmother with small farm with a vegetable garden, orchard, animals and diverse natural habitats. The farm was almost self-sufficient: we grew vegetables and berries for our own consumption and feed for the animals; we had milk, meat products and eggs. The farm's biggest challenges were the weather variability and the need for agricultural services for soil cultivation and harvesting from the nearby neighbours. Cooperation and friendship with neighbours was one of the most important factors for my grandmother’s farm’s viability. This experience taught me that good land management includes cooperation first between the land user and nature (in which land resources and natural habitats are treated well), next, cooperation between land users who are close in proximity, and then between land users and policy makers to ensure long-term development and prosperity.

6.2. ROLE OF COMMON AGRICULTURAL POLICY AND AGRICULTURAL KNOWLEDGE AND INNOVATION SYSTEMS

As one of the common cooperation initiatives in land management, the development of the Common Agricultural Policy (CAP) should be mentioned; when society recognized the role of farmers in food production, financial support for increasing production volumes was introduced, as well as support for developing rural regions and compensating for fluctuations in market prices. Support tools and policy objectives have changed several times since the introduction of the CAP in 1957. The role of farmers has also changed from intensive producers to those who also contribute to the provision of other societal demands, for instance maintaining clean waters, ensuring biodiversity, and mitigating climate change by promoting carbon sequestration. The previous CAP did not fully realize its environmental and climate potential, although it did offer a wide range of tools for sustainable natural resource management and climate action (EC, 2021c; Meredith and Hart, 2019). Therefore, the CAP post-2020, the implementation of which will begin in 2023, emphasizes an even greater role of farmers in solving environmental and sustainability issues. This new CAP provides tailored requirements to the needs of each Member State, taking into account local conditions and their needs, and directly links with 12 EU environmental and climate legislations, to achieve the Green Deal targets. This means that, in Latvia for instance, the CAP

Strategy Plan (approved on 11 November 2022) includes the development and maintenance of drainage infrastructure in agricultural and forestry lands, which is particularly important for rural development in the context of Latvia's climatic conditions.

Solving environmental and sustainability issues in the land management sector requires cooperation and innovation, so the development of Agricultural Knowledge and Innovation Systems (AKIS) is a very important part of the CAP. Knowledge transfer between farmers, scientists and policy makers is necessary for the agricultural sector to meet not only functional demands on land, but also social demands that will help to achieve the objectives set by the EU Green Deal. The importance of collaboration for knowledge transfer has also been highlighted in studies such as Fusco (2021), and O'Sullivan et al. (2017).

The five soil functions are all synergistic in meeting functional demands. For instance, crop cultivation is profitable for farmer, but high yields require nutrients in the soil, as well as clean water—soil health is important for the quality of grains, and soil carbon is important for the soil health. All these preconditions for soil fertility are also essential for ensuring clean water resources, for preserving biodiversity, and for sequestering carbon. But if we expect farmers to go beyond meeting functional demands, and to furthermore meet societal demands, then trade-offs begin to occur. Therefore, it is difficult (if not impossible) for individual farmers to meet all societal expectations for all five functions—but they can reach three out of five societal demands, while meeting all functional demands. The AKIS system is a network that can help farmers to more precisely define a problem, and to bring the farmers together with suppliers, scientists, processors, consumers, and various other service providers can problem solve and disseminate these solutions to other farmers. Farmers need support in solving their problems: they are often imposed with society's demands, with little support, despite society needing agriculture just as much as farmers need society. As shown in Chapter 5, the farmer is at the center of the AKIS system; however, one of the other main roles in the system is the bridging stakeholder, who drives this system, and is a moderator between practice and policy making. Sustainable land management requires a strong and well-functioning AKIS system that includes networking, information and knowledge exchange, innovative and collaborative problem-solving, trials, demonstrations, learning from others, and a shared long-term vision for development of the agricultural, forestry and rural sectors.

7. SCOPE FOR BETTER VERTICAL INTEGRATION OF POLICY PLANNING

In the context of territory development planning and land use management, the addition of objectives in the highest national and international policy planning documents is essential to ensuring a stable and constant framework for the development of the country. At the national level, it is necessary to clearly understand how international requirements are integrated into national planning documents, and the potential impact that they will have on the country's development—especially if there are penalties for the non-fulfilment of international obligations. As an example of inconsistency: despite the fact that the EU Farm to Fork Strategy proposes a 25% target for organic agriculture by 2030, the new National Development Plan of Latvia for 2021-2027 (NDP2027) does not include activities to promote organic agriculture in Latvia. Another major shortcoming of medium- and long-term planning documents is that their objectives are not updated or supplemented during the documents' lifetime, even though both international obligations and the overall situation in the country are constantly changing. Latvia's Sustainable Development Strategy (until 2030) is not reviewed during its years of implementation, which means that EU level strategies are not included in Latvian long-term development strategies. This may create a risk that the National Development Plan, as it is built on long-term strategy, does not include the development directions that are defined in the EU level documents. Additionally, if the Latvian long-term strategy is not reviewed until the end of the term, the subsequent mid-term strategy would also miss the development directions as defined within the EU level documents. The red line in

Figure 1 illustrates that, without changing the current procedure for developing and revising planning documents, after 2030 the planning path that was already initiated will continue, in which EU level strategies are incorporated at the national level with a delay of many years. To improve this, it is recommended to consider changing planning documents at the time that a new EU-level long-term strategy is released, rather than waiting until the current strategy term is finished. Furthermore, it should be noted that monitoring reports are prepared for planning documents both during and after their operation, but in the case of Latvia, these reports are prepared late For instance, the final evaluation of the National Development Plan for the implementation period of 2014 to 2020 was prepared in 2022, and yet the new plan for 2021-2027 was approved in 2020. This means that the fulfilment/non-fulfilment/partial fulfilment of the target values has not been followed by a specific evaluation that would be the basis for the plan of next period.

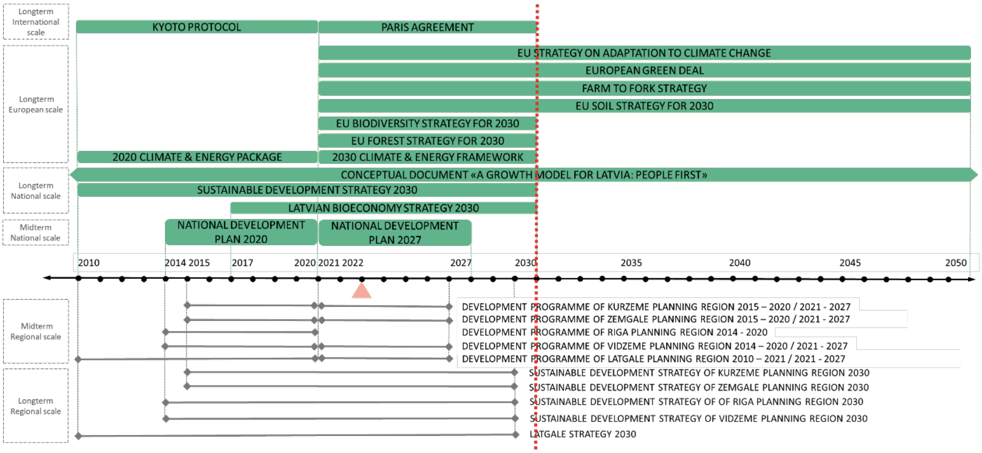

Figure 1. Summary of policies related to the land use management in Latvia.

It is also important to mention that the integration of various EU planning documents into national policies does not only depend on the type of legal document (e.g. directives are precisely incorporated into national regulatory acts), but is also very closely related to the vision and capabilities within an individual Member State. For instance, the Ministry of Environmental Protection and Regional Development of the Republic of Latvia is responsible for making an action plan detailing the manner in which Latvia will implement the proposed targets of the EU Biodiversity Strategy for 2030. If the Ministry of Environmental Protection and Regional Development must independently implement policy regarding protected areas (without involving the representatives of the Ministry of Agriculture), there is risk of trade-offs with bioeconomy. This illustrates that the development of action plans with strong horizontal collaboration between ministries is one of the key elements to achieving multiple social demands from our land.

If we evaluate planning documents by planning levels, the highest-level is the conceptual document, "A growth model for Latvia: People First", which emphasizes that the main resource for growth is the knowledge and wisdom of the Latvian people. The document entered into force in 2005 and has not been renewed since. As a scientist, I would argue that the human-centred growth model has been overtaken by newly emerging priorities after 17 years. Life-centred environmental ethics highlight that our moral obligation to nature is founded on its intrinsic value, not on any particular advantage it provides for us as a species (Palmer et al., 2014; Primack and Cafaro, 2007).

The long-term strategy of Latvia for 2030 is based on the aforementioned conceptual growth document. The strategy includes four objectives related to spatial development perspectives: 1) to create equal living and working conditions for all residents; 2) to promote entrepreneurship in the regions; 3) to strengthen the international competitiveness of Latvia and its regions; and 4) to preserve Latvia's diverse natural and cultural heritage, as well as its typical and unique landscapes. Despite these goals, land management issues are still fragmented in lower-level planning documents. If the strategy provides achievable results, but the actions to achieve these results are not traceable down to the local level, then the question arises: where is the problem? Are we not capable of results-oriented strategic planning, or are we not aware of our resources and capabilities?

One example of shortcomings lies in the National Development Plan of Latvia for 2021-2027 (NDP2027), in which the Latvian Bioeconomy Strategy 2030 is mentioned as one of the potential actions for productivity growth, for which the planning regions are indicated as the co-responsible implementing institutions . In order to understand how the objectives of the bioeconomy strategy are reflected at the regional level, I looked at the Development Program of the Zemgale Planning Region 2021-2027, because, due to its highly productive soils, this region is very important for agricultural production. The Development program is a midterm regional planning document and it highlights that bioeconomy is one of the main development opportunities in this region, without specific objectives for the bioeconomy. This means that, at the regional level, we do not know how to achieve the objectives of the Bioeconomy Strategy. Latvia has always been an agrarian country, in which agriculture and forestry are the main industries and the largest resources for growth, and this strong characteristic of Latvia is not reflected to its full potential in planning documents.

At the same time, a relevant example of inclusion in the Development Plan is the proportion of the specially protected nature areas. The target value in the National Development Plan is 18.2% of the total area for 2027, which coincides with the base-year value of 2018. On the other hand, the Zemgale Development Program states that 4.8% of all protected natural areas in Latvia are located in the Zemgale region. The Program determines the increase of this value in 2027 without a specific value, which means that at the regional level, the objective is to increase the proportion of protected areas, despite it not being specified in the national development plan. This example illustrates that there is scope to improve the coordination between planning documents.

Furthermore, the planning documents currently do not fulfil their potential for vertical integration in land use planning. Municipal development strategies and programs are also being developed at the local level, which could be used to include specific actions at the lowest planning level that would bring benefits to the regional and national levels. However, a number of significant shortcomings have been identified in the sustainable development strategies of municipalities: for instance, the content of the highest-level planning documents is quoted, and very general objectives and priorities are set; additionally, there is a weak public involvement in the development of this document (VARAM, 2021). The current development principles of regional and local level planning documents provide a good overview of the regions and counties, emphasizing the main sectors and desired development directions. As an example, the planning documents of the Bauska County that have been approved recently as an example, it can be concluded that it will be difficult to evaluate how much of what is desired has been achieved, because no target values were set at the county level. In the Bauska County Strategy of Sustainable Development (to 2035) long-term target values have been set, but these values do not cover all desired development sectors (Bauskas novada dome, 2022a). On the other hand, the Bauska County Development Program 2022-2028 defines medium-term priorities and a set of measures (Bauskas novada dome, 2022b). This again asks the question: how will the implemented measures be evaluated if no target values have been set? For instance, the Bauska County emphasizes in its planning documents that this county is one of the strongest in bioeconomic development. The Latvian Bioeconomy Strategy 2030 sets very specific target values, but there is a lack of measurable links in the regional level documents, where we could track how these target values (which are set at the national level) are achieved at the local level. Improvements in planning documents and the integration of nationally important objectives into lower level documents (so that we can track the contribution of each county to the achievement of national level objectives) would ensure not only a targeted common development direction of the country, but would also allow us to understand where the achievement of objectives has been impaired.

8. A LOOK TO THE FUTURE

By looking at a landscape, we already can get an initial idea of its bioresources. Our identities and values are also shaped by the place we are located and the landscape that characterizes it. There are landscapes that attract people, and which are included in the National Protection Network, because of the cultural and historical heritage. Landscapes also have aesthetical, ecological and economic functions. They show the existing and potential land uses, as well as problems that a particular region may face. In order to get an overview of the socio-economic, environmental, cultural-historical values of a landscape, a unified methodology is needed, which we apply at the field, regional or national level.

The FLM approach starts with the evaluation of supply and demand for soil functions, and it is a very effective starting point for understanding the state of land resources, as well as for summarizing the diverse policy objectives that are directly linked to them. A significant advantage of the FLM approach is that before applying it, it is not necessary to carry out extensive research and data collection, but rather existing data, databases and studies that have been created in the area of interest can be used. The FLM approach gives an overview of land resource management at the regional and national levels, which further can be used by policy departments, which often need to understand that we cannot ask every county to contribute equally to the achievement of national objectives, because even in a small country there are very large differences in soil resources that require regionalized approaches. In order to implement a regionalized approach, all involved stakeholders must have a common vision of why it is necessary, how it will be implemented, and each involved stakeholder's benefit. The FLM approach can give all of these answers.

This said, we have also reached the limits to which FLM can be used, which requires further studies that will build on this using other methodologies. These the limits are:

(a) The selection of indicators for characterizing soil functions is affected by the lack of detailed data at required levels, which leads to generalization of indicators;
(b) The generalization of indicators at the field level does not provide complete information about soil resources, because soil is not homogeneous within the field;
(c) The user of the method must be able to grasp a wide range of information from different fields of science;
(d) Land use, crops grown, and applied management practices change the chemical, physical and biological properties of the soil, so it is important to use the most recent soil data as possible.

9. CONCLUSIONS

The heterogeneity of soil properties and differences in the proportions of regional land uses create an opportunity for differentiated land management—and such differentiated local-level management may help to meet socioeconomic and environmental objectives at the national level.

Close collaboration and knowledge sharing between policy makers, researchers, industry and farmers is an inherent part of sustainable land management. Each stakeholder has its own unique position in agri-environmental governance based on experience and knowledge. Challenges in land management may affect all agri-environmental stakeholders, and therefore problem solving and result-based development must become a joint effort. In meeting multiple societal demands, it is important that each Member State identifies key stakeholders within AKIS that can both be trusted and can understand the concept of multifunctionality.

Sustainable land management requires coherence of policy documents across levels so that at the planning stage, it is already clear how the objectives will be achieved, as well as how this achievement will be evaluated. Differences in land use and soil characteristics between regions offer different potential contributions in the achievement of national objectives, which is why the differentiation needs to be integrated into policy planning documents. It is necessary to foresee that the planning documents are reviewed and updated during their implementation, in order to prevent a several-year delay in the incorporation of higher-level requirements into the national level documents.

Meeting multiple societal demands at the EU level requires that policy plans are comprehensive throughout planning scales, while at the same time, they also make use of the viability of each landscape to harness their unique potential; and, furthermore,, that stakeholder mapping is used for the transition, because mapping people is as important as mapping of soil functions.

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SUMMARY

Society expects many ecosystem services from land resources, but the supply of ecosystem services varies depending on soil and land management, while the demand varies between scales and stakeholders. For instance, policy makers seek to preserve biodiversity and to increase carbon sequestration at the national scale, while farmers are more interested in increasing yields and soil fertility at the local scale. Soils are multifunctional but have a different capacity to deliver on each of the ecosystem services. For example, some soils are better at providing food and feed, while other soils are better at providing carbon sequestration. This in turn determines what kind of land use would be most appropriate for that soil and therefore for society to gain the expected benefit from the land.

Using two national case-studies, namely Latvia and Ireland, this thesis further develops the Functional Land Management (FLM) methodology for implementation and to provide the knowledge base for stakeholders to jointly optimise land use and land management to meet competing expectations on land.

Chapter 2 describes the Irish case study where FLM is deployed and evaluated to understand to what extent agronomic and environmental targets can be met simultaneously. This chapter investigates how land management can be used to increase food production and simultaneously meet environmental targets, such as the protection of water and the mitigation of greenhouse gas emissions. The results of Chapter 2 shows that there is potential for synergy between agronomic objectives and environmental requirements at national level, but it is not possible to achieve ambitious production or environmental targets by introducing only single specific land use change or management practice.

In Chapter 3 FLM is used for the Latvian case study to further explore opportunities of FLM harnessing regional differences in order to meet the trade-offs between increasing production, reducing greenhouse gas emissions and conserving biodiversity. This chapter shows for the first time that a regionally differentiated approach to land use and land management is needed to meet all objectives at national scale. By capitalising on regional differences and objectives to be achieved at local, national and even international scales, EU Member States can stimulate those management practices and land use changes that will bring the desired outcomes.

Chapter 4 further studies how these regional differences in soil classes and land use can be utilised and harnessed to deliver on national objectives using three contrasting regions in Latvia as case studies. Results show the untapped potential for reintegrating abandoned agricultural land to meet socio-economic and environmental sustainability objectives. A differential regional approach provides opportunities for individual regions to contribute to national targets. Some areas are already optimised and even a small increase in productivity deteriorates other functions. This chapter calls for national policies to differentiate regional pathways in order to gain successful outcomes for socio-economic and environmental sustainability, simultaneously.

Chapter 5 shows how to bridge the gap between designing land use and land management plans and implementing them. In this chapter participatory techniques are used to map and analyse the collaboration in the Agricultural Knowledge and Innovation Systems (AKIS) in Latvia. This chapter shows the need for horizontal strengthening of the networks and information exchange between policy departments and between farmers' communities, as well as vertical strengthening between policy departments and farmers.

Finally, Chapter 6 brings the insights of the aforementioned chapters together by discussing the coordination of contrasting expectations, examining the trade-offs and synergies between soil-based ecosystem services at different scales, the importance of strengthening horizontal integration for cooperation-based sustainable land management, and the scope for better vertical integration of policy planning. In this chapter, I reflect on FLM as an approach to achieve socio-economic and environmental objectives simultaneously, as well as the importance of collaboration between stakeholders in implementing FLM. I also discuss some of the examples from policy planning documents to highlight the possible ways to improve the coherence of policy planning documents between scales.

Overall, I conclude that regional heterogeneity of soil properties and differences in the proportial of land uses create an opportunity for differentiated land management which may help to meet socioeconomic and environmental objectives at national level. Challenges in land management may affect all agri-environmental stakeholders, therefore problem solving and result-based development must become a joint effort. Sustainable land management requires coherence of policy documents across levels to provide clarity at the planning stage how the objectives will be achieved and how this achievement can be monitored and evaluated. It is necessary to schedule reviews and updates of planning documents throughout their operation, in order to prevent multiannual delays in the implementation of higher level objectives into national strategies.

KOPSAVILKUMS

Sabiedrība sagaida daudzus ekosistēmu pakalpojumus no zemes resursiem, bet ekosistēmu pakalpojumu piedāvājums atšķiras atkarībā no augsnes veida un zemes apsaimniekošanas, savukārt pieprasījuma atšķirības veidojas starp mērogiem un ieinteresētajām personām. Piemēram, politikas veidotāji tiecas saglabāt bioloģisko daudzveidību un palielināt oglekļa piesaisti valsts mērogā, savukārt lauksaimnieki ir vairāk ieinteresēti palielināt ražu un augsnes auglību vietējā mērogā. Augsnes ir daudzfunkcionālas, bet tām ir atšķirīgas spējas nodrošināt visus ekosistēmas pakalpojumus. Piemēram, dažas augsnes labāk nodrošina pārtiku un barību, savukārt citas augsnes labāk nodrošina oglekļa piesaisti. Tas savukārt nosaka, kāda veida zemes izmantošana būtu vispiemērotākā konkrētajam augsnes veidam un līdz ar to sabiedrībai, lai gūtu cerēto labumu no zemes resursiem.

Izmantojot divas gadījuma izpētes, Latviju un Īriju, šis doktora darbs tālāk attīsta Funkcionālās Zemes Pārvaldības (FLM) pielietošanas metodoloģiju, lai nodrošinātu ieinteresēto personu zināšanu bāzi kopīgai zemes izmantošanas un apsaimniekošanas optimizācijai un mērķu sasniegšanai.

2. nodaļā ir aprakstīta Īrijas gadījuma izpēte, kurā FLM tiek izmantota un novērtēta, lai saprastu, cik lielā mērā vienlaikus var sasniegt agronomiskos un vides mērķus. Šajā nodaļā pētīts, kā zemes apsaimniekošanu var izmantot, lai palielinātu pārtikas ražošanu un vienlaikus sasniegtu tādus vides mērķus kā ūdens aizsardzība un siltumnīcefekta gāzu emisiju samazināšana. 2. nodaļas rezultāti liecina, ka pastāv sinerģijas potenciāls starp agronomijas mērķiem un vides prasībām valsts līmenī, taču nav iespējams sasniegt vērienīgus ražošanas vai vides mērķus, ieviešot tikai vienu konkrētu zemes izmantošanas veida maiņu vai apsaimniekošanas praksi.

3. nodaļā FLM tiek izmantots Latvijas gadījuma izpētē, lai tālāk noteiktu FLM iespējas izmantot reģionālās atšķirības, lai panāktu kompromisu starp ražošanas palielināšanu, siltumnīcefekta gāzu emisiju samazināšanu un bioloģiskās daudzveidības saglabāšanu. Šī nodaļa parāda, ka ir nepieciešama reģionāli diferencēta pieeja zemes izmantošanai un zemes apsaimniekošanai, lai sasniegtu mērķus valsts mērogā. Izmantojot reģionālās atšķirības un mērķus, kas jāsasniedz vietējā, valsts un pat starptautiskā mērogā, ES dalībvalstis var veicināt tādu apsaimniekošanas prakšu ieviešanu un zemes izmantošanas veidu maiņas, kas dos vēlamos rezultātus.

4. nodaļa tālāk pēta, kā šīs reģionālās atšķirības augsnes veidos un zemes izmantošanā var izmantot, lai sasniegtu valsts mērķus, izmantojot trīs kontrastējošus reģionus Latvijā kā gadījumu pētījumus. Rezultāti liecina par neizmantoto potenciālu pamestās lauksaimniecības zemes reintegrēšanai, lai sasniegtu sociālekonomiskos un vides ilgtspējības mērķus. Diferencēta reģionāla pieeja sniedz atsevišķiem reģioniem iespējas dot ieguldījumu valsts mērķu sasniegšanā. Dažas jomas atsevišķos reģionos jau ir optimizētas, un pat neliels produktivitātes pieaugums pasliktinātu citu funkciju sniegumu. Šajā nodaļā pausts aicinājums valsts politikā diferencēt reģionālās iespējas, lai vienlaikus gūtu izdevīgus rezultātus attiecībā uz sociālekonomisko un vides ilgtspējību.

5. nodaļā parādīts, kā novērst plaisu starp zemes izmantošanas un zemes apsaimniekošanas plānu izstrādi un īstenošanu. Šajā nodaļā līdzdalības metodes tiek izmantotas, lai kartētu un analizētu sadarbību Lauksaimniecības zināšanu un inovāciju sistēmā (AKIS) Latvijā. Šajā nodaļā norādīta vajadzība horizontāli stiprināt tīklus un informācijas apmaiņu starp politikas departamentiem un starp lauksaimnieku kopienām, kā arī vertikālu stiprināšanu starp politikas departamentiem un lauksaimniekiem.

Visbeidzot, 6. nodaļā ir apkopoti secinājumi par iepriekš minētajām sadaļām, diskutējot koordinācijas nepieciešamību atšķirīgām vēlmēm, izskatot kompromisus un sinerģijas starp augsnes ekosistēmas pakalpojumiem dažādos mērogos, un horizontālās integrācijas stiprināšanas nozīmi ilgtspējīgā zemes apsaimniekošanā, kas balstīta uz sadarbību, kā arī politikas plānošanas labākas vertikālās integrācijas iespējas. Šajā nodaļā tiek uzsvērta FLM pieeja kā nozīmīgs rīks sociālekonomisko un vides mērķu vienlaicīgai sasniegšanai, kā arī uzsvērta ieinteresēto personu sadarbības nozīme, īstenojot FLM. Tiek pārrunāti arī piemēri no politikas plānošanas dokumentiem, lai uzsvērtu iespējamos veidus, kā uzlabot politikas plānošanas dokumentu saskaņotību starp līmeņiem.

Augsnes īpašību reģionālā neviendabība un atšķirības zemes izmantojuma proporcijās rada iespēju diferencētai zemes apsaimniekošanai, kas var palīdzēt sasniegt sociālekonomiskos un vides mērķus valsts līmenī. Izaicinājumi zemes apsaimniekošanā var skart visas agrovides ieinteresētās puses, tāpēc problēmu risināšanai un uz rezultātu balstītai attīstībai jākļūst par kopīgu darbu. Ilgtspējīga zemes apsaimniekošana prasa politikas dokumentu saskaņotību dažādos līmeņos, lai plānošanas posmā nodrošinātu skaidrību, kā tiks sasniegti mērķi un kā mērķu izpilde tiks uzraudzīta un novērtēta. Plānošanas dokumentu pārskatīšanu un aktualizāciju nepieciešams ieplānot visā to darbības laikā, lai novērstu daudzgadu kavēšanos augstāka līmeņa mērķu ieviešanā nacionālajās stratēģijās.

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ABOUT THE AUTHOR

Kristine Valujeva was born in Priekule, Latvia, on August 20, 1990. She grew up in small village close to Lithuanian border. As a child, she spent a lot of time at grandmother's farm where the interest in nature was created. She graduated from Kalni Secondary School, Nigrande parish in 2009.

In 2009, Kristine moved to Jelgava to study Environment Engineering and Water Management at Latvia University of Life Sciences and Technologies. After the completion of her BSc, she started a MSc degree of Engineering in Water Management. Along with her studies, she also started working as an assistant in various projects at the Department of Environmental Engineering and Water Management. Her MSc thesis resulted in a published book "Possibilities of using phytoremediation in Latvia". In 2015 she also conducted an internship in Teagasc, Ireland, where she became familiar with Functional Land Management. Her work in Ireland resulted in a scientific publication which is the second chapter of this thesis.

After 7 years of continuous studies at various Universities, she took a year off to work in different national and international research projects. Kristine also started working as a lecturer at the Department of Environmental Engineering and Water Management, teaching Ecology and Environmental Protection to bachelor students.

She started her external PhD in October 2017 at the Farming Systems Ecology Group at Wageningen University of which this thesis is the result. She combined her work at Latvia University of Life Sciences and Technologies and her PhD studies at Wageningen University.

PE&RC TRAINING AND EDUCATION STATEMENT

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Title of review / title project proposal (4.5 ECTS)

- Functional land management: the framework for optimisation of soil functions to achieve socio-economic and climate objectives simultaneously in continental climate zone / optimisation of functional land management in Latvia in the context of climate policies

Post-graduate courses (9.1 ECTS)

- Application of circular economy principles in borderlands; Linnaeus University (2018)
- Introduction to R for statistical analysis; PE&RC, SENSE (2018)
- International Summer School “Degraded Areas Revitalization and Sustainable Tourism Initiatives in Borderlands of European Union”; Linnaeus University (2019)
- Machine learning for spatial data; PE&RC, WIMEK (2019)

Deficiency, refresh, brush-up courses (3 ECTS)

- Research methodology in economy including introduction in statistical methods, scientific writing, presenting and ethics; Latvia University of Life Sciences and Technologies (2017/2018)

Competence strengthening / skills courses (2.5 ECTS)

- The essential of scientific writing and presenting; Wageningen int’o Language (2018)
- Competence assessment; WGS (2018)
- Making an impact how to increase the societal relevance of your PhD research; WGS (2020)

Scientific integrity / ethics in science activities (0.6 ECTS)

- Ethics in plant and environmental sciences; PE&RC (2018)
- Workshop in search of research integrity; Riga Technical University (2018)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC First years weekend (2017)
- PE&RC Last years online afternoon (2021)

Discussion groups / local seminars or scientific meetings (4.6 ECTS)

- Symposium sustainability in the European Union's forests and the energy challenge (2018)
- LANDMARK roundtable 7 in AGES; Department for Soil Health and Plant Production in VIENNA (2018)

- LIFE REstore seminar about the inventory of degraded peatlands in Latvia and assessment of ecosystem services (2018)
- Internal workshop: functional land management (2018)
- Discussion group on climate change mitigation in Latvia (2018/2019)
- Mini-symposium on sustainable intensification of agriculture (2020)
- R User discussion group (2020)
- Internal workshop: functional land management from local action to global impact (2020)

International symposia, workshops and conferences (5.2 ECTS)

- 18th International Multidisciplinary Scientific Conference on Earth and Geosciences SGEM; poster presentation; Albena, Bulgaria (2018)
- 19th International Multidisciplinary Scientific Conference on Earth and Geosciences SGEM; oral presentation; Albena, Bulgaria (2019)
- Wageningen Soil Conference; poster presentation; Wageningen, the Netherlands (2019)
- 25th Annual International Conference Research for Rural Development; oral presentation; Jelgava, Latvia (2019)

Lecturing/supervision of practicals/tutorials (7.5 ECTS)

- Ecology and environmental protection (2017-2022)
- Sustainable resource management (2022)

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