Functional Land Management for a sustainable land base in the EU

Lilian O'Sullivan

Propositions

1. Sustainable land management requires an integrated approach to meet societal demand for soil based ecosystem services.
   (This thesis).
2. A farm scale transition towards sustainable land management requires effort and engagement of actors across the whole agriculture knowledge innovation system.
   (This thesis).
3. Managing the trade-offs and synergies in the delivery of soil based ecosystem services remains a complex challenge, despite decadal investment in soil science.
4. Visual storytelling is an essential skill for scientists.
5. Technical solutions facilitate reduced individual accountability.
6. Setting a wedding date close to PhD submission date increases work efficiency.

Propositions belonging to the thesis entitled:
"Functional Land Management for a sustainable land base in the EU"

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Functional Land Management for a sustainable land base in the EU

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For Susan & Seán

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CHAPTER 1

Functional Land Management for a sustainable land base in the EU

General introduction and thesis outline

General introduction

Born in the late 1970s, one of seven children in west Cork in the south-west of Ireland, I had a rural upbringing. Farming was our way of life and the essence of who we were as people. Farming was not only what we did to survive but represented who we were in our community and wider society. Our home was intergenerational, as was common at that time and it was normal that everyone would contribute to household or farming activities. The "*meitheal*" tradition of people coming together during peak labour times, such as saving hay or picking potatoes, brought the necessary help to get the work done, but also the sense of friendship and comradery that often characterises farming communities. Trips to the bog to collect turf for winter fuel made for happy memories and hay was still the bulk of winter feed for livestock. Such was my life, as it was for so many others like me as fewer people lived in cities than in the countryside still. I spent many an afternoon picking stones from the fields, a task that gave me little pleasure. Even so, I look back on that time with a strong sense of pride that I am from a farm, that my father Seán was a farmer and that my connection to the land was a privilege.

Since joining the European Economic Community (EEC) in 1973, agriculture was recognised as a major growth area for the Irish economy. The 1980s was a time of recession in Ireland and farmers were expected to intensify production and were supported through the Common Agricultural Policy (CAP) to do so. I do not recall when the milk lorry started to collect the milk but prior to that, my father used to deliver the milk in churns to the local creamery. Agriculture was becoming more mechanised even though tractors and other agricultural machinery bear little resemblance to the machinery and horsepower typically found today. Local references informed field naming, sometimes providing insights into ownership or land use capability. I have an early memory of the *frying pan* (so-called for its shape), the field below the homestead, undergoing drainage operations. The drainage was implemented to improve the productive capacity of the field. I can still recall my sense of surprise when excavation works revealed the clay-like bluey grey tones of a gleysol and not the brown tones of soil that I had expected to see. By the end of 1980s, I had seen first-hand major changes in farming, in particular the shift towards productivist methods where technology was embraced and outputs were intensified in line with national and European ambitions. By the 1990s, awareness of the environmental consequences of intensive agriculture had begun to increase. Since then, the direction of farming has continued to evolve, and societal expectations from land have expanded beyond food production towards the delivery of other land based goods and services rooted in sustainability and ecosystem science.

Today, we see that the complexity of societal expectations has evolved such that it is giving rise to conflicts between farmers and wider society, in Ireland and across Europe. This societal debate requires facts and science-based input. My PhD sets out to do just that – to embrace the complexity and many dimensions of multifunctional land management with the aim to provide guidance for all actors involved, from farmers to advisors to policymakers. Bringing land management back to farm scale, the common theme throughout my journey through this complexity was the sustainable management of soils. If soils are so variable that they can be grey-blue as well as brown, then how can we guide farmers in making the most of their land?

Soil

Life on earth relies on soil. Soil is comprised of solid, semi-solid, liquid and gaseous constituents that are heterogeneous across many orders of magnitude and timescales ranging from seconds to millennia (Brady and Weil, 2002; Haygarth and Ritz, 2009). Soil is a key determinant of health and well-being, providing the basic material for life (MA, 2005). Soil formation is very slow which means that depletion rates exceed rates of regeneration, making it a finite resource (FAO, 2015). Traditionally, interest in agricultural soils has been driven by their productive capacity, in particular for food production. World population has increased from ~1 billion in 1800 to ~7.9 billion in 2019 (Roser et al., 2019). Agricultural intensification has been successful at increasing production and maintaining pace with population growth. However, agricultural intensification and agri-food systems place an enormous burden on the environment (e.g. Hoeskstra and Chapagain, 2008; Tiessen et al., 2011; Gerber et al., 2013; Uwizeye et al., 2016). Between 10 and 20% of land worldwide is degraded (MA, 2005) and more than half of agricultural land is severely impacted by soil degradation (ELD, 2015). By 2050, a world population of ~ 10 billion is expected and production losses linked to land degradation will increase food insecurity as food prices rise (Chasek et al., 2015).

Besides food, soils provide a wide range of goods and services to society. Several studies have categorised these ecosystem services: the EU Thematic Strategy on Soils (2006) identified seven ecosystem functions while Haygarth and Ritz (2009) proposed 18 ecosystem services that are central to soil and land use in the United Kingdom. Soil occupies a central space in the connectivity of the biosphere and when supported with soil management can enhance mitigation of environmental problems whilst providing services (Haygarth and Ritz, 2009).

The grand challenge and the need for multifunctional land management

The extent to which agricultural land can co-exist with environmental sustainability and the delivery of environmental goods while increasing food outputs represents an enormous challenge. Over time, land and land-based ecosystems are being degraded or lost, driven by the pressures of population increases, climate change, biodiversity loss and consumer demands. Agricultural land is the primary interface between the global food system and the global environment which makes land use and management uniquely positioned, being both impacted on and by the environment (Schulte et al., 2019). As expectations on land increase, sustainable land management becomes an even more complex challenge. An integrated approach that simultaneously considers the agronomic and environmental soil based ecosystem services delivered through agricultural landscapes is required. While Haygarth and Ritz (2009) proposed 18 soil based ecosystem services for agricultural soils, such a high number of services makes practical application or utility to guide policy development limited.

At a policy level, when compared to other resources land and soil are treated differently. The European Union (EU) has a water policy, the EU Water Framework Directive (2000/60/EC), that requires all member states (MS) to protect and improve water quality to achieve good ecological status by 2027 at the latest (EC, 2000). Air quality is legislated for under the Air Quality Framework Directive (2008/50/EC) and a National Emissions reduction Commitments (NEC) Directive. In contrast, there are few examples of legal protection of soils with international binding legal agreements for soils having failed thus far. In 2014, the European Commission (EC) withdrew its proposed Soil Framework Directive (2006/0086/COD) after lengthy debate.

In relation to the multifunctionality of agriculture, the concept has previously been considered at a policy level within the EU. Towards the end of the 1990s, agricultural multifunctionality was considered the delivery of ecosystem services that were linked to productivity, occurring as a positive externality. However, these externalities are uncommon. In addition, the World Trade Organisation (WTO) ruled against price supports coupled to production as being potentially trade distorting (Burrell, 2011). As a result, a two-tier approach under the CAP Pillar 1 and Pillar 2 has emerged in land-related policies that has decoupled output from support for public goods. For three decades, EU agricultural policy reforms have sought to include the provision of environmental public goods in rural areas supported by a greater share of government funding in agriculture towards this objective. With neither the environmental and climate needs of member states nor wider CAP objectives being met in the last CAP period (2014-2020), the efficacy of this model has been questioned (Meredith and Hart, 2019).

Existing knowledge

From threats to functions for functional land management

Worldwide the functionality of soils is threatened by unsustainable management practices. Owing to the finite nature of soil and the growing demands on land, it is considered that soils should be protected and conserved (Stolte et al., 2016). The EU Soil Thematic Strategy identified eight key soil threats: erosion, loss of organic matter, contamination, compaction, salinization, floods and landslides, soil sealing and loss of biodiversity (EC, 2006). The proposed Soil Framework Directive was intended to integrate soil concerns and address these threats, however the emphasis on threats and the potentially high costs of restoration were amongst reasons for the its withdrawal in 2014 (Stancovics et al., 2020).

In line with a move towards multifunctional land management, a shift in favour of soil functions as opposed to soil threats has gained traction. Unlike soil threats, the soil functions approach seeks to harness the capacity of the soil to meet the growing demands on land. Schulte et al. (2014) proposed Functional Land Management (FLM) in 2014. FLM is an integrated policy support framework that seeks to optimise the agronomic and environmental returns from the land (Coyle et al., 2016). It is underpinned by the multifunctionality of soil which is that all soils perform multiple functions simultaneously (Haygarth and Ritz, 2009). The FLM framework distils the multitude of soil-based ecosystem services to five key land based functions that are delivered across all agricultural soils; primary productivity, water regulation and purification, carbon and climate regulation, nutrient cycling, and habitat for biodiversity (Schulte et al., 2014). FLM, rather than maximising selective soil functions, focuses on optimising the delivery of the suite of soil functions for meeting societal expectations and demands on land.

Trade-offs and synergies - three is the magic number

A multifunctional approach to land management increases the complexity of land management as farmers have to balance increasing production demands with the delivery of other ecosystem services (O'Sullivan et al., 2022). Soils vary with respect to their capacity to deliver different soil functions/ecosystem services (Schulte et al., 2014). The inherent properties of soil interacting with environment and management governs the magnitude of the suite of soil functions supplied (O'Sullivan et al., 2015; Coyle et al., 2016). Soil is a complex medium occurring as a continuum across the landscape, which makes optimising sustainable land management highly challenging. This is further complicated as different soil functions may be positively or negatively related with land management giving rise to synergies and trade-offs in relation to the services provided (Zwetsloot et al., 2020). Previous research in the EU has found that three of the five key land based soil functions can be delivered at a high level prior to trade-offs occurring (Zwetsloot et al., 2020).

Governance, people and land

Land ownership is a central issue in relation to soil protection policies (Montanarella, 2015; Stankovics et al., 2020). The tradition of land ownership rights remain more respected than recent principles of environmental protection associated with land and soil (Stankovics et al, 2020). Beyond land ownership, research highlights an ongoing attachment between people and place (Comstock et al., 2010; Lewicka, 2010), often occurring on farms where human and natural systems intersect (Hildenbrand & Hennon, 2005). Society is increasing the demands on land use and management indicative of a cultural shift with respect to farming, from a productivist orientation to a much broader remit for the delivery of a wider range of goods and services. For farmers, this shift may be a perceived redundancy in their skills and traditions. At the same time, the implementation of FLM on farm relies on farmers and land managers and their existing knowledge. FLM is complex and solution pathways towards FLM will require instruments along with knowledge, skills and engagement with actors within and beyond the farm gate.

Knowledge gaps

Stakeholder demands

Functional Land Management is a mechanism to frame agricultural multifunctionality for sustainability. Different stakeholders have different expectations on land for the delivery of these five key soil functions. Oftentimes a gap arises between the demand for selected soil functions between farmers/land managers and other stakeholders. These gaps must be identified so that pathways towards FLM can be exposed. In short, to match the supply with the demand for soil functions, in the first instance clarity around the demands of different stakeholders is required. Related to this, another important consideration is that the demand for particular functions can manifest at different scales. Better understanding of the demands of different stakeholders, and the scale at which particular functions are demanded is necessary. Both will help to identify where points of intervention might be targeted.

Optimising soil functions and minimising trade-offs

In the past, the multifunctional nature of land was mostly considered with respect to biodiversity and production (e.g. Green et al., 2005; Benton, 2012; Fischer et al., 2014; Kremen, 2015; Phalan, 2018). Beyond the dichotomy of biodiversity and production, approaches to inform land use policies that aim to fulfil wider societal demands from agricultural landscapes are lacking. FLM implies proactive management of soil according to soil type with a spatially tailored approach to land management to enable the optimised delivery of soil functions (Schulte et al., 2016). Rather than maximising individual soil functions, selected soil functions should be optimised according to soil type. There is a need for research beyond biodiversity and production to consider the trade-offs and synergies in relation to other soil functions related to soil types, environment and management.

Entry points and pathways towards FLM

FLM represents a very high knowledge requirement for its practical implementation. While soil management occurs at local scale, the decisions related to soil management and land use may be informed by messages that farmers receive from a wide range of actors in the agricultural, knowledge and innovation system (AKIS). The extent to which messaging in relation to land management is or could be multifunctional has not been explored. Together with better understanding of stakeholder demands and the nature of trade-offs, scope to target actors for messaging in relation to FLM could help in the identification of pathways, specifically the targeting of messages for FLM.

Problem statement

Prior to 2015, research and policy fostered the maximisation of individual soil-based ecosystem services. Historically, this has translated to land use and management that maximised production. A key challenge for multifunctionality is the compartmentalised nature of expert driven science (Abson et al., 2014) that is mirrored in policy that lacks horizontal integration. Although the concept of ecosystem services has developed rapidly since the 1980s (Erlich and Erlich, 1980; Abson, 2014), tools to integrate ecosystem services to understand multifunctional landscapes are lacking (O'Farrell and Anderson, 2010). In the absence of an integrated framework, the traditional maximisation approach fails to acknowledge that all soil functions cannot be maximised in all locations simultaneously due to the intrinsic trade-offs that occur between soil functions (O'Sullivan et al., 2015; Zwetsloot et al., 2021). This blind spot has ultimately driven many of the high-level challenges that are undermining the agri-food sector today – including widespread soil degradation.

Sustainable use of soil and land means that we must take multiples functions into account, beyond just production and biodiversity. Detailed understanding of ecological systems, including thresholds and tipping points in relation to individual ecosystem services is important and field scale mechanistic assessments are necessary to support this understanding. However, it is important to understand the impacts of management at multiple scales. Trade-offs between soil functions can have implications beyond the scale of soil management. For example, the impacts of excess nutrients on water quality will have implications at catchment scale. Integrated assessments at multiple scales are necessary to understand the nature of trade-offs at different scales.

Different stakeholders have different demands on land. Satisfying the demands of all stakeholders is challenging. It is necessary to consider whether societal demands on land align or compete with the demands of those responsible for soil and land management decisions. From this, opportunities for targeting FLM can be identified particularly where the benefits of soil function service provision accrues at societal rather than local scale.

In order to move towards FLM implementation, gaps and solutions spaces must be identified. Enabling governance mechanisms should include incentivisation of land on the basis of soil types so that soils can perform the functions that they are best at. EU policies have traditionally provided public support in a blanketed fashion that heretofore has fallen short in relation to environment and climate ambitions. Public support should be targeted towards soil functions for which there is the greatest requirement. This does not equate to legislative zoning of land use but rather that incentives ensure actual land management that reflect policies (Schulte et al., 2014). This implies a need to identify where soil functions are needs most and how they can be targeted. With respect to solution spaces, it is important that a transition towards FLM is not only the responsibility of farmers and land managers. FLM has a high knowledge demand. Greater understanding of the agricultural, knowledge and innovation system (AKIS) is important to identify opportunities to manage messages between actors and to support a more coherent understanding and approach to FLM.

Objectives of the research:

Although the concept of multifunctionality offers promise, to date its application remains limited (Hölting et al., 2019). The aim of this research is to explore the FLM framework and pathways for enhancing multifunctionality towards a more sustainable land base in the EU. From the problem statement three key objectives are established that we aim to explore in this thesis:

- Understanding and managing expectations for soil functions of stakeholders from land
- The challenge of trade-offs between soil functions
- Implementation gaps and solution spaces

Structure and content of thesis

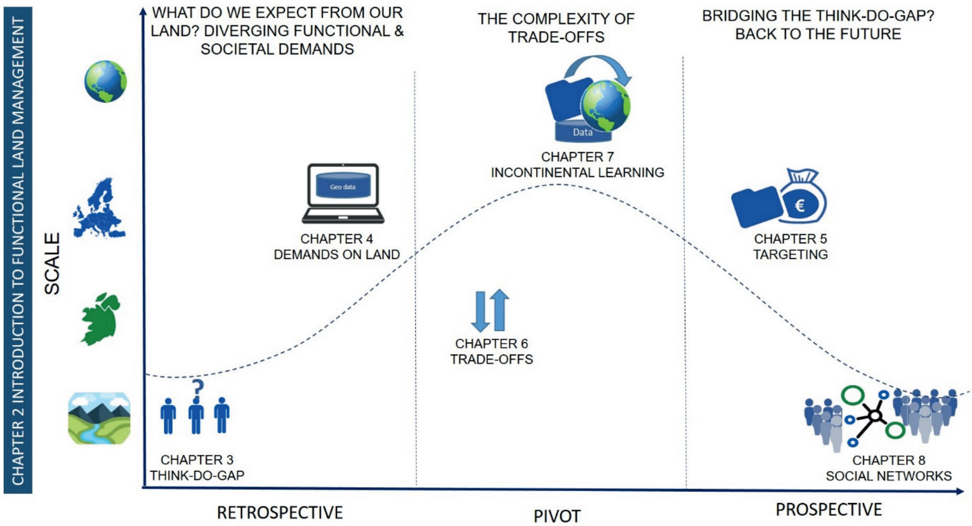

Figure 1. Layout of thesis

Scene setting

Figure 1 provides an overview of the structure of this thesis. The journey of this PhD commenced at a time when soil policy in Europe was quite simply stuck. The proposed Soil Framework Directive had sat for a period of seven years confronted with apathy and inertia and in doing so, effectively curbed space to think about soil and land differently. As presented in Chapter 2, *Functional Land Management: A Framework for Soil Policy Formation,* discussions on soil policies at that time were framed by the Thematic Strategy for Soil Protection (COM (2006) 231 final). The emphasis on soil threats and ultimately issues around ownership (Stankovics et al., 2020) led to the rejection of the Proposed Soil Framework Directive in 2014. Around this time, the concept of Functional Land Management (FLM) by Schulte et al. (2014) was proposed. An overview of the FLM framework and its utility as an entry point for soil policy formation is presented in Chapter 2 in the context of Ireland with pathways for matching supply with demand for soil functions proposed.

Shortly after the rejection of the Proposed Soil Framework Directive, the FLM framework became the subject of a large multi-stakeholder pan-European Horizon 2020 project called LANDMARK with international partners from Brazil and China. The LANDMARK project became central to the co-evolution of soil policy in Europe working with stakeholders across all scales (e,g, Fig. 2 – EU policy stakeholders). This PhD developed in line with the LANDMARK project and albeit simultaneously exhilarating and challenging, this thesis found itself at the heart of the science-policy discourse in Europe. Over the life of the PhD, the policy narrative has altered utterly. Chapter 2 was at the forefront in the discourse about soil functions and FLM as a policy support framework. By now, we have shifted from a narrative of threats to functions, to a mission in the area of soil heath and food and to a context where farmers do not need to be told about threats but rather need to be rewarded for multifunctionality.

Fig. 2 EU Policy Workshop Brussels 18 September 2017. Participants from different EU Directorates-Generals (DG) completing a Catchment Challenge exercise to match the supply of soil functions at local scale with wider societal demands.

Objective 1 - Understanding and managing expectations from land

The concept of multifunctionality as explored in this thesis is based on soil multifunctionality. Although not widely held at the start of this PhD journey, the 2021 foresight report on soil health and food adopted by the European Commission refers to the supply of multiple soil functions as 'multifunctionality' (Giuffré et al., 2021). It is this concept that has been explored in this thesis to frame our understanding of what we demand from the land. We know that different stakeholders have different demands and we know too that these demands vary by scale. To garner insight into the expectations of different stakeholders on land, in Chapter 3 – *Functional Land Management: Bridging the Think-Do-Gap using a multi-stakeholder science policy interface*, we publish a multi-stakeholder workshop methodology (O'Sullivan et al., 2018) – the so-called *Catchment Challenge.* This method offers stakeholders the opportunity to design a landscape management plan that considers the variable capacity of soil to supply soil functions. The method is readily adapted to represent contextual considerations related to landscape and policy targets anywhere in the world. As outlined, land holds emotional place based attachment for different stakeholders and through this method, we afford stakeholders space and opportunity to derive solutions for sustainable land management removed from the immediate emotion of their own land or locality. Furthermore, the challenge is structured around two challenges, that latter focusing on transition pathways for FLM. In the published example, we found a high level of consensus between stakeholders for the management measures to be implemented while key gaps to transition towards FLM included knowledge, a mix of market and voluntary incentives and mandatory measures. This method offers scope to understand the demands of stakeholders at more localised scale and was deployed across Europe as part of the EU LANDMARK project.

In contrast, in Chapter 4 **–** *Demands on land: Mapping competing societal expectations for the functionality of agricultural soils in Europe*, we abstract societal expectation for soil functions using the high level lens of EU policies. A highly complex regulatory environment for land management has evolved in Europe over time. Of central relevance to farmers and land managers are the CAP reforms. The post-2020 CAP aims to strengthen climate action and environmental protection and introduces strategic plans (SP) for member states (MS) to better target policies. To support better targeting, this chapter maps the variation of the societal demands for the five FLM soil functions across EU MS. An extensive literature review shows that the demands for these soil functions varies greatly between MS, determined by population, farming systems, livestock densities, geo-environmental conditions and landscape configuration (Schulte et al., 2019). The introduction of SP provides an opportunity for more effective and targeted incentivisation of sustainable land management.

Objective 2 - The challenge of trade-offs

Our science and our history tells us that maximising individual soil functions can lead to irreversible soil degradation. The FLM framework is underpinned by the variability of soil to provide soil functions. The augmentation of individual soil functions can lead to a suppression or an increase in the delivery of the other soil functions. Most agricultural fields can potentially supply three soil functions at an optimal level prior to trade-offs with other functions becoming observable (Zwetsloot et al., 2021). In chapter 2, the alteration of a static soil property was identified as a pathway to enhance one or more functions. To demonstrate this in Chapter 5, *Functional Land Management for managing soil functions: A case-study of the trade-off between primary productivity and carbon storage in response to the intervention of drainage systems in Ireland,* we take Ireland as a case study and simulate the implementation of subsurface land draining to change soil moisture dynamics of soil. In this, the first policy relevant paper utilising the FLM concept, the utility of the framework is demonstrated when we spatially model the trade-off between the primary productivity and carbon cycling and storage functions in response to the intervention of land drainage systems in ArcGIS (O'Sullivan et al., 2015). Importantly, a divergence in the prioritisation of soil functions between stakeholders is highlighted along with a need for policies that are more tailored to contrasting biophysical environments.

Trade-offs are not only confined to localised catchment scale or even national scale. The EU has put forth ambitions for European food to become a global standard in relation to sustainability. In light of this, it is necessary to explore how trade mediated governance affects ecosystem flows to avoid carbon leakage and environmental impacts. In Chapter 6, *Intercontinental learning – local management in a globalised context,* working in collaboration with international partners in the EU LANDMARK project, we take the FLM framework and a case study of the Upper Xingu River Basin in Brazil to map the flows of soil functions to expose how governance drivers mediated by trade impact sustainability. This work sheds light on the emerging issues of uni- and bi-lateralism particularly relevant in the context of the European Green Deal.

Objective 3 - Implementation gaps and solution spaces

Having explored the demands of different stakeholders, the issues around trade-offs and scales, the thesis moves towards implementation gaps and potential solutions for the future. EU MS have opportunity to design more context specific policies to target land management in favour of soil functions for which there is a high demand. Chapter 4 highlighted which soil functions are needed most where. To contribute to the knowledge base for the development of SPs, in this Chapter 7 – *National prioritisation of soil functions in the post-2020 CAP era,* we explore how soil functions have been prioritised in the 2014-2020 period based upon EU pillar 2 budgetary allocation. This is compared with the demands highlighted in chapter 3 to expose opportunities for targeting. We conclude that opportunities exist for greater targeting that better aligns incentivisation to meet societal demands. We also highlight where additional targeting could be exploited through Pillar 1 eco-schemes.

We also know that there is an urgency for all actors across the AKIS to work together to support a transition towards sustainable land management. A high knowledge requirement across multiple scientific domains and actors is required to meet sustainability demands to guarantee the provision of public goods and services from the land. In Chapter 7 – *Trust Versus Content in Multi-functional Land Management: Assessing Soil Function Messaging in Agricultural Networks,* we use a mixed-method approach combining social network analysis and surveys, to explore the networks for FLM soil functions in case studies in Germany, Ireland and the Netherlands. A diversity of contrasting networks that reflect local conditions, sustainability challenges, historic trajectories and governance structure is found. Farmers are at the heart of the agri-environmental governance network. The amount of information they receive became less relevant than the source of the signals when it came to the implementation of farm management actions. To harness the potential of networks to support FLM, two pathways for enhanced farmer uptake of multifunctionality are proposed. Firstly, to increase trust between farmers and actors that are agents of multifunctional messages and/or secondly, to increase the bundling or multifunctional breadth of messages (mandate) of actors currently trusted by farmers (O'Sullivan et al., 2022).

Statement of societal and scientific contribution of thesis

This research is at the frontier of addressing the key societal challenges of our time. The role of soil has altered radically in the research, innovation and policy spaces during the life of this PhD. At the outset of this chapter, I described my early connections with the land. As a child, I had a very simple perspective on soil - assuming that all soil was brown! Somehow, I think the complexity of soil had been lost in translation for a very long time, often overlooked. With a recently established EU mission in the area of soil health and food there is a sense that the urgency to target this narrative and embrace the complexity of soil and sustainable land management with real commitment and targeted action now exists. In part, the research in this thesis has participated in the changing narrative around soil in real-time.

The need for multifunctional land management is obvious but implementation in real terms remains a complex challenge. In recalling my first-hand experiences of farming in 1980s Ireland, I can see that farming has changed markedly in the decades since. At that time, farmers were responding to messages they were receiving in relation to intensification. The messages today are more complex, not only for farmers but for the science and policy communities too. It is plausible that messages today distract from the production orientation of farmers and do not resonate as readily when it may limit their livelihood potential. In this way, we show that bridging the gap between farm level demands and societal expectations will require targeted incentivisation mechanisms. It is also true that inter and transdisciplinary research and greater horizontal integration in the policy spheres is required to reduce the complexity of FLM. At a minimum, it is important to understand the divergent demands of stakeholders. In this research we have demonstrated how this can done, not only from a high level assessment perspective but also by way of developing a method that facilitates collaborative design and transition pathway for FLM using the Catchment Challenge method. Meeting the climate and environment objectives set for land requires a collective response across all actors in the AKIS. In addition to financial incentives for FLM, the exploration of networks in this research provides insights into ways that the network potential could be harnessed through increased knowledge information systems to support FLM going forward.

In this research, we have worked at the heart of and contributed to the rapidly evolving soil policy discourse of the day. Utilising the FLM framework, we demonstrate a framing for multifunctionality that has heretofore remained elusive. We have placed soil and their functions as the foundation of the capacity of land to supply the ecosystem services demanded by stakeholders. Through this PhD we have demonstrated a suite of methodological approaches that expand the potential of FLM beyond that of a conceptual framework. This PhD delivered directly on the policy pillar of the LANDMARK project. LANDMARK in turn has contributed directly to the establishment of the EU Mission on Soil Health and Food, one of the key mega-missions for Europe's Research and Innovation framework.

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CHAPTER 2

Functional Land Management: Introducing a framework for soil policy formation

Soil policy and functional land management with a focus on Ireland

This work was published as part of a World Soils Book Series as part of the Irish contribution. Ireland is used as a case study to present an overview of Functional Land Management.

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Abstract

Discussions on soil policies are framed by the *Thematic Strategy for Soil Protection* (COM (2006)231 final), launched by the European Commission (EC) in 2006. Eight main threats to soil were recognised within the EU. A proposal for a Soil Framework Directive (SFD) (COM (2006)232 final) was finally withdrawn in May 2014. The concept of Functional Land Management (FLM) has been developed as a utilitarian framework that specifically tries to optimise the delivery of five soil functions delivered through agricultural landscapes: 1) primary productivity, 2) water purification and regulation, 3) carbon storage and regulation, 4) provision of a habitat for biodiversity and 5) cycling of nutrients. Supply of soil functions is governed by the complex interaction of the inherent capacity of soil, the environment and the management. Within the FLM framework, demand is framed by agri-environmental policies which are considered a proxy for the societal demands on land. A case study of Ireland is presented to show the applicability of this framework. In relation to matching the supply of soil functions with demand, three distinguishing pathways have been identified: 1) Implement a change in a dynamic soil property at local scale, such as nutrient concentrations. 2) Alter a static soil property to enhance one or more functions. In Ireland, this could be the implementation of subsurface land drainage systems to change the soil moisture dynamics of the soil. 3) Land use change, such as from grassland to arable. Functional Land Management does not equate to a legislative tool for the zoning of land for individual functions but rather that individual soil functions may be incentivised through existing instruments available under the EU CAP.

Introduction

In 2015, the 68th United Nations (UN) General Assembly declared that year the International Year of Soils (IYS), with core objectives that included soil protection and sustainable soil management. Subsequently, the UN Development Programme officially launched the Sustainable Development Goals (SDG) in January 2016. World leaders adopted the 2030 Agenda for Sustainable Development which includes a set of 17 SDGs, four of which specifically cite soil in their title: 2.4, "land and soil quality"; 3.9, "soil pollution and contamination"; 12.4, "management of chemicals and all wastes…and significantly reduce their release to air, water and soil" and 15.3, "By 2030, combat desertification, restore degraded land and soil" (UN 2015). On the one hand, these initiatives indicate a growing recognition of the important role of soil in the delivery of soil functions and ecosystem services essential to sustain life on earth. On the other hand, these initiatives represent a call to action with heightened urgency that the soil resource must be afforded the same protection as air and water quality to guarantee the delivery of goods and services into the future. Also in 2015, the Food and Agriculture Organization published the '*Status of the World's Resources*' report, representing the first ever major global assessment of soil resources and related issues. The report concluded that the majority of the world's resources are in only fair, poor or very poor condition and also, that one-third of land is highly degraded due to erosion, salinisation, compaction, acidification and the chemical pollution of soils (FAO and ITPS 2015). Despite these conclusions, the report offers optimism that the delivery of ecosystem services can be safeguarded through sustainable soil management. In Ireland, the Environmental Protection Agency (EPA) previously determined that Irish soils are in good condition but that they are exceptionally vulnerable to land-use changes, particularly in relation to peat areas (EPA 2002).

Although there is growing recognition that soil is a non-renewable resource providing many benefits for society, there is a continued lack of direct legal protection from a policy point of view. At the European scale, the European Commission (EC) launched the *Thematic Strategy for Soil Protection* (COM (2006)231 final) in 2006 introducing the concept of soil functions and soil threats (EC, 2006). These were further reiterated in *The Implementation of the Soil Thematic Strategy and On-Going Activities* (COM (2012)46 final) in 2012 (EC, 2012). Eight main threats to soil are recognised within the EU; 1) erosion, 2) decline in organic matter, 3) local and diffuse contamination, 4) soil sealing, 5) compaction, 6) decline in biodiversity, 7) salinization, and 8) floods and landslides. Human activities, such as land management, urban sprawl and industrial activities are considered key drivers of increased pressure on the soil resource across the EU (EC 2012). A review by Creamer et al. (2010) based upon the agricultural management cycle for north Atlantic Europe, highlighted that the key threats to soil quality relevant to Ireland were loss of soil organic matter, erosion, compaction and contamination. Ultimately, the proposal for a Soil Framework Directive (SFD) (COM (2006)232 final) was designed to provide a legislative basis for soil protection and to unite soil protection measures under one directive to respond to these threats within the EU. However, the SFD was never ratified by member states and was finally withdrawn in May 2014. Like water or air, the soil provides many public goods to society, however unlike water or air, soil is typically privately owned. This and the emphasis of the SFD on threats to soil quality meant that it was met with resistance and elicited a strong negative response among many stakeholders, particularly the farming community. Despite the withdrawal of the SFD, the EC remains committed to the objective of soil protection.

Although there are no direct polices for soil at EU level, there are a number of policy statements that directly address soil as well as several policies that indirectly influence soil quality (Figure 1). The Resource Efficiency Roadmap (COM(2011)571) targets resource efficiency across many policy areas such as transport and raw materials, but in relation to soil and land, milestones include; no net land take by 2050, a reduction in soil erosion by 2050 and an increase in soil organic matter (EC, 2011). The Seventh Environment Action Programme (EAP) that guides environmental policy until 2020 notes the challenge of soil degradation and includes a binding legal framework to target soil quality (EU 2013) while the preparation of "Land as a Resource" communication is expected to recognise the finite nature of land and the need for sustainable EU land management. The Common Agricultural Policy (CAP) launched in 1962 is today faced with the growing challenges of global food security, climate change, sustainable management of natural resources, maintaining the countryside and keeping the rural economy alive. Instruments emphasise the economic and environmental competitiveness of farming but increasingly incentives are focused on supporting farmers to adopt sustainable farming methods. For example, Agri-Environment Measures support the build-up of soil organic matter, the reduction of soil erosion, contamination, compaction and an increase in soil biodiversity. Cross-compliance supports standardised mechanisms for farmers to support environmental, public, animal and plant health in lieu of the single-farm payment. Also, Good Agricultural and Environmental Condition (GAEC) support certain aspects of agricultural soil protection and allow member states to specify minimum requirements around soil protection such as minimum soil cover. The Areas of Natural Constraint (ANC) aid scheme aims to conserve the countryside and support farmers where soil and land have a natural handicap. In Ireland, soil moisture content and soil drainage are the major constraints for agricultural productivity. Slopes, rooting depth, soil texture and organic matter are also relevant physical characteristics with associated constraints in Ireland. Overtime CAP supports have evolved away from production-linked subsidies towards decoupling and are increasingly targeted towards measures that can facilitate sustainable intensification.

The EU is committed to the tackling climate change and more than ever before the role of soil in climate change mitigation is under consideration. Key climate and energy targets within the EU are set in the 2020 climate and energy package and the 2030 climate and energy framework. By 2030, the overall EU target is a reduction of 40% on 1990 greenhouse gas emission. Ireland will have to reduce its emissions by 30% by that time, relative to 2005 emissions. In October 2014, the European Council recognised the lower mitigation potential of agriculture and the land use sector along with the need to ensure coherence between the EU's food security and climate change objectives. This allowed the inclusion of the Land Use, Land Use Change and Forestry (LULUCF) within the EU climate change framework thus broadening the options for greenhouse gas emissions reductions through carbon sequestration. Ireland will have 5.6% (of the 2005 base year) flexibility from land use, larger than any other member state except Latvia indicative of the larger share of emissions associated with agriculture in Ireland. Internationally, the Paris Agreement was adopted in December in 2015 at the 21st Conference of the Parties (COP21) and represents a global milestone for collective action towards a low-carbon climate resilient society (EC 2016). The *4 pour 1000* is an important initiative to emerge from COP21 that seeks an annual growth rate of 4‰ of the soil carbon stock to stop the increase in atmospheric CO_2 thereby acknowledging the critical role of soils for climate change mitigation.

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Other policy directives are shown in Figure 1 including the EU Biodiversity Strategy to 2020 that have important implications for the soil resource.

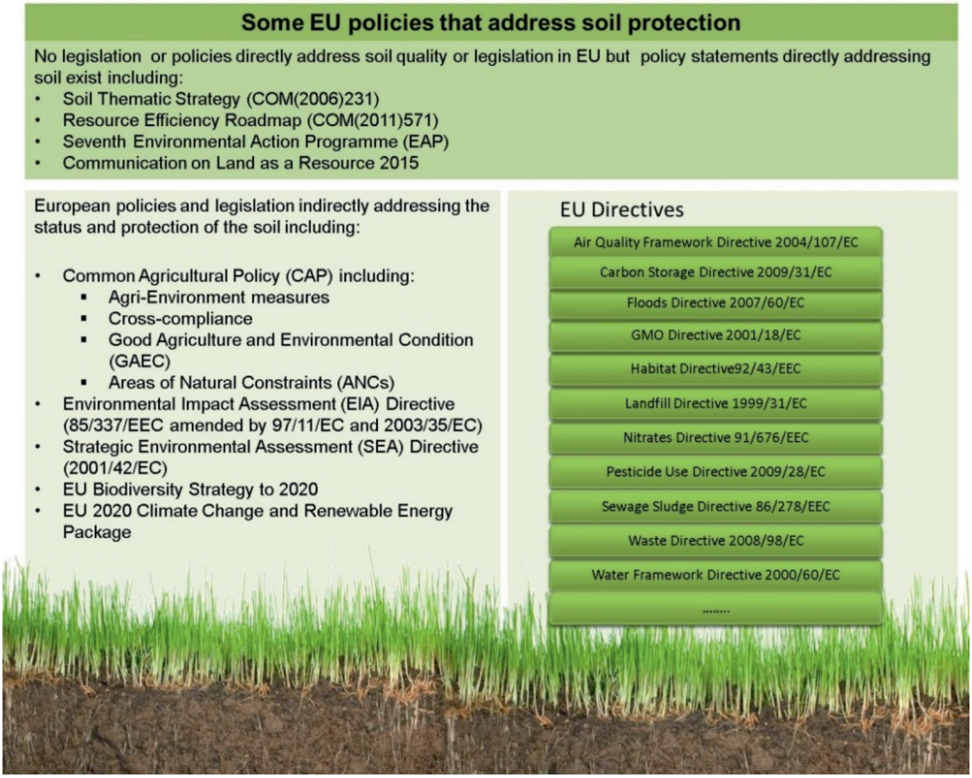

Figure 1. EU policies that address soil protection directly in policy statements or indirectly through policies targeted are other aspects of the environment. An extensive cross-policy analysis of European policies has been conducted by Glæsner et al. (2014).

Soil protection in Ireland – a fragmented approach

As of 2016, no legislation exists at national level in Ireland that specifically targets the protection of the soil resource however there are several national policies that do indirectly offer soil protection. Agriculture is the major land based activity in Ireland. In 2010, the Irish government *Food Harvest 2020* policy document outlined the agricultural industry led initiative for expansion following the removal of the EU milk quota in 2015. Targets included an increase in milk production of 50%. In acknowledgement of the increased environmental pressure associated with expansion, soil management was specifically mentioned as a necessary action for environmental sustainability (DAFF 2010). Food Harvest 2020 assumed growth driven by sustainability relying on knowledge intensification and farming that is more efficient. Since then, the *Food Wise 2025* strategy has superseded Food Harvest 2020 as the plan for the agricultural sector and insists that any further productivity gains are achieved through sustainable intensification. Within Food Wise 2025 soil health is recognised as a pillar of environmental sustainability with soil fertility and carbon sequestration as important areas for further research and knowledge transfer activities. Many other regulations and national policies exist including the Green, Low-Carbon, Agri-Environment Scheme (GLAS), the Second National Biodiversity Plan of 2011 and Good Agricultural Practice for Protection of Waters Regulations (9/2010). Altogether, at national level no single authority has responsibility for soil protection and monitoring. This means that any protection for soil tends to be fragmented with different agencies and government bodies, each with different objectives, having responsibility for different soil-related issues.

Functional Land Management

Although the removal of the SFD may be perceived as a strong lack of political will, its removal has created space to think differently about soils. It represents an opportunity to refocus attention away from the threats to soil quality towards an approach that emphasises the functional capacity of soil. In Ireland, the concept of Functional Land Management (FLM) developed by Schulte et al. (2014) adopts this approach and seeks to enhance soil quality and functioning by use of land management options that are fit for purpose and are underpinned at a local level by soil properties. FLM is a utilitarian framework that specifically tries to optimise the delivery of five soil functions delivered through agricultural landscapes: 1) primary productivity, 2) water purification and regulation, 3) carbon storage and regulation, 4) provision of a habitat for biodiversity and 5) cycling of nutrients (Figure 2).

Figure 2 Illustrative representation of the suite of soil functions proposed by Schulte et al. (2014). The white box represents primary production; blue, water purification; black, carbon storage and regulation; green, provision of a habitat for biodiversity; purple, cycling of nutrients

While all soils perform all of these functions some parts of the landscape provide different ‘suites’ of soil functions based upon soil type and land use. The challenge therefore is how best to manage the supply of soil functions to meet societal demands. To that end, demand for soil functions is shaped by the agri-environmental policy framework which is representative of societal demands and expectations for soil functions. Implicit in meeting societal demands is a requirement for sustainability to guarantee the supply of soil functions for future generations. This relies on maintaining soil quality. Definitions of soil quality have previously been described as, “the capacity of the soil to function, within natural or managed ecosystem boundaries, to sustain plant or animal productivity, maintain or enhance water and air quality, and support human health or habitation” (Karlen et al. 1997; Doran 2002). Although this definition emphasises the functional aspect of soil quality it does not include a scale or benchmark for the assessment of soil quality. Schulte et al. (2015) propose “The capacity of a specific kind of soil to provide functions *to meet demands within*…..” to allow a degree of elasticity to be included so that a benchmark for soil assessment can be included. This means that soil quality no longer only refers to soil properties and processes but could also vary through a change in demand. Importantly, this allows better assessment of whether demands (framed as policy objectives) are achievable by supply (soil biophysical criteria and land use). It also means that the supply of soil functions or specific functions need not be maximised but that a more balanced process of optimising soil functions can be deployed subject to the balances of supply and demand.

In the absence of a SFD an inventory of EU policies defined the relevant policy drivers to frame the demand for soil functions (Figure 3).

EU Policy Driver	Function(s) of relevance[1]	Scale at which demand is framed
Common Agricultural Policy (CAP)	P	EU
Areas of Natural Constraint (ANC)	P	EU / National
Greening Measures	C H	Ubiquitous
Nitrates Directive	W N	Ubiquitous / Regional
Water Framework Directive	W H	River Basin District
Habitat & Birds Directive	H	Multiple scales
Agri-Environmental Schemes	W C H	Farm / regional
EU 2030 Climate and Energy Framework	C	EU + National targets
Sewage Sludge Directive	N	Regional

1. P = primary productivity, W = water purification, C = carbon sequestration, H = habitat provision, N = nutrient cycling

Figure 3 Inventory of EU policy drivers that frame demand for the five soil functions, shown by the coloured boxes and the spatial scale to which each of these policies apply from Schulte et al. (2015).

Functional Land Management – the case of Ireland

To further explore the FLM concept, the spatial variability and patterns of supply of each of the soil functions were mapped at Irish national level by Schulte et al. (2015). When supply and demand were mapped, the results showed a high degree of granularity in relation to the supply of soil functions. While some regional variation emerged the supply of soil functions is primarily defined by local soil and land use characteristics (Figure 4, top row). In contrast, demand for soil functions mapped for Ireland (Figure 4, bottom row) highlighted spatial variation at small scale (primary productivity) to regional scale (nutrient cycling) and national scale (carbon sequestration). A comparison between supply and demand shows that in relation to primary productivity, supply exceeds demand in most regions. Although the demand for increased productivity is highest in areas with a plentiful supply of this function on soils that are traditionally considered good agricultural soils, exceptions can be found such as in the south-west which are characterised by poorly drained soils. To increase the supply of primary productivity in this area would require the installation of drainage systems. The supply of denitrification is used as a partial proxy for the water purification function and shows to be high in all regions, adequately meeting the demand that groundwater nitrate concentrations remain below 50 mg l^{-1} consistent which findings that a high proportion of land in Ireland is compliant with demand (Byrne and Fanning 2015). In relation to the carbon sequestration and storage function, the supply varies greatly between soil type, land use types, and management. Demand is shown as one colour as demand for the carbon sequestration function applies only at national scale. Previously, the EU 2030 Climate and Energy Framework only specified an EU-wide target but Ireland now has a national emissions reduction target of 30% relative to the

2005 emissions. In relation to the supply of the habitat function, designation of Natura 2000 sites has been met but the introduction of greening measures under the CAP will require an increase in this function on arable land through the allocation of Ecological Focus Areas which are traditionally associated with a low supply of this function (Schulte et al. 2015). The demand for nutrient cycling soil function is strongly regional but low relative to the supply of this function due to the low pig and human populations in Ireland. The size of the circles represents the total area required to dispose of these nutrients. The circles represent the ideal scenario where landowners are willing to import manure but in reality, accessing spread lands might require travelling long distances (Schulte et al. 2015).

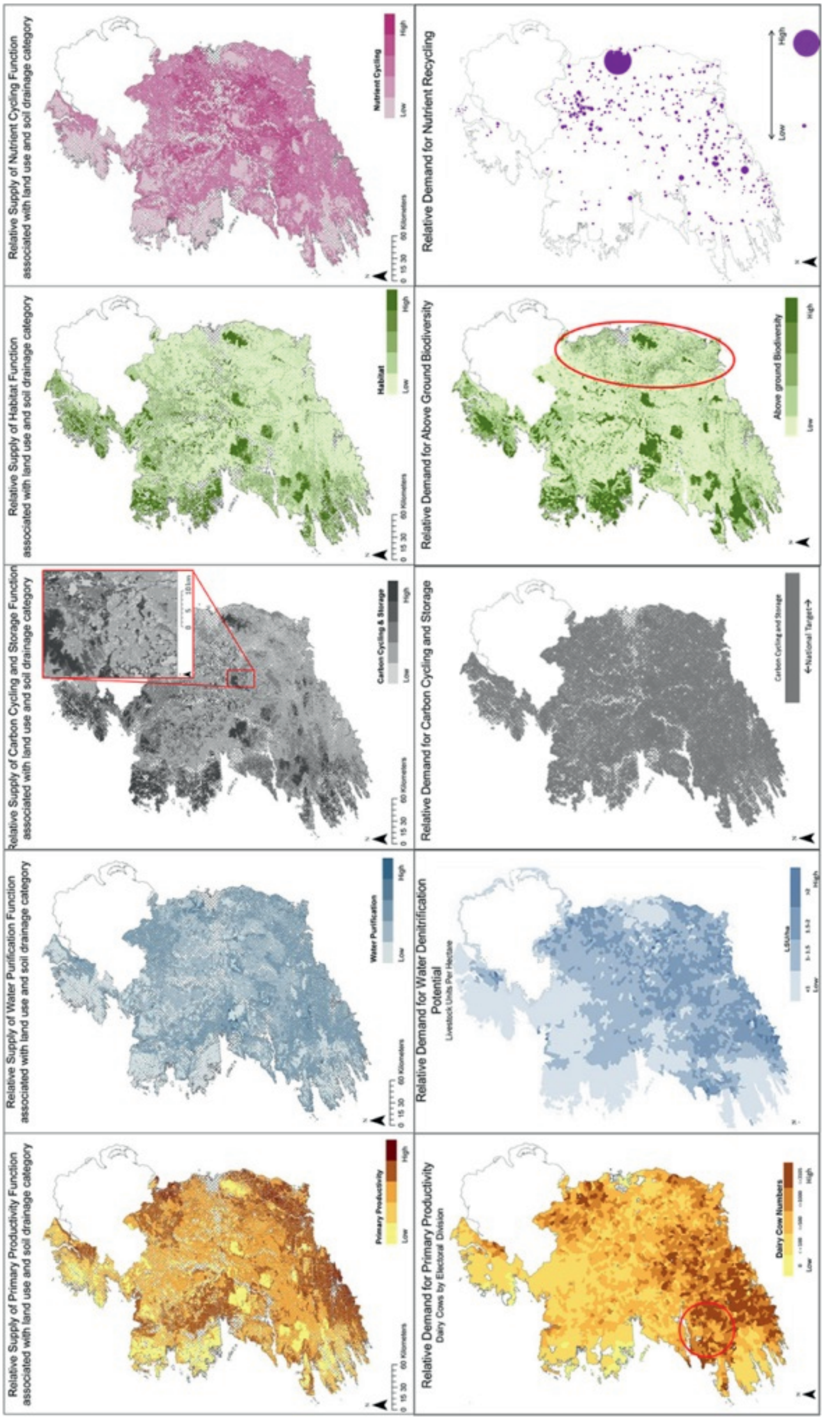

Figure 4 Indicative maps of the normalised supply (top row) and demand (bottom row) for the five soil functions, from left to right: primary productivity, water purification, carbon sequestration, biodiversity and nutrient cycling from Schulte et al. (2015).

Future management options

In relation to matching the supply of soil functions with demand, three distinguishing pathways have been identified:

1) Implement a change in a dynamic soil property at local scale, such as nutrient concentrations. Best management practices should allow the productivity soil function to be augmented without impacting on the other soil functions. In Ireland, as few as 10% of agricultural soils have optimum pH, as well as optimum phosphorus and potassium concentrations (Wall et al. 2015) highlighting the opportunity to improve productivity of Irish soils. Similarly, the increased use of animal manure in arable systems will improve the carbon sequestration and nutrient cycling functions.
2) Alter a static soil property to enhance one or more functions. In Ireland, this could be the implementation of subsurface land drainage systems to change the soil moisture dynamics of the soil. This results in longer growing and grazing seasons (Tuohy et al. 2015). While this represents an increase in the primary production soil function, this may come at the expense of the water purification function (Jahangir et al. 2012) or the carbon storage functions (Kechavarzi et al. 2010). Hence, the merit of such interventions must be considered on a case by case basis.
3) Land use change, such as from grassland to arable. As with pathway two, this option typically incurs a trade-off between soil functions. In this example, ploughing for arable conversion is likely to increase the primary productivity function but is simultaneously likely to reduce the supply of the other functions. Importantly, not all trade-offs are negative and even in this case, enhancing primary production might be appropriate where there is spare capacity for the water purification function. This might represent a better alternative than expansion of the production platform into areas where the supply of other functions such as carbon storage or biodiversity is high, which could occur in areas where the land is of high nature value.

The spatial scale of the demand driver is another important consideration when managing for soil functions. The scale will determine to what extent soil functions can be offset between soils or regions. A challenge in managing for soil functions relates to their private ownership and that management, and in turn supply, is at a local scale. In contrast, the demand for soil functions may range from local, regional, national or continental scales. For example, the demand for water quality function as framed by the Nitrates Directive insists that water quality is maintained everywhere. Thus, this soil function cannot therefore be traded between fields, farms or regions, where one location could make up for the failure of another area to provide clean drinking water. At the other end of the scale, the demand for soils to sequester carbon applies ultimately at the global scale with management necessary at the national scale. The nature of this larger scale allows a degree of off-setting between soils or regions. In practice, this means that meeting national targets might not be best achieved at a local scale by every farmer off-setting their emissions through land management, such as planting forestry, but rather by incentivising forestry on those soils which are less suitable for the primary production of food. In principle, the globalised nature of food production similarly suggests some off-setting potential of the primary productivity soil function. Notably, there are advantages associated with having regional or national food access due to the reliance of global food systems on an often fragile geopolitical context.

The biodiversity and nutrient cycling soil functions largely apply at an intermediate scale. The demand and supply for nutrient cycling relies on largely on transport considerations (Fealy and Schröder 2008) limiting the option to match supply and demand at larger scales. The demand for the biodiversity function cuts across multiple scales such as the protection of rare species at local level, entire habitats at regional scales and the protection of species throughout their natural range at national scale (Noss 1990). These discrepancies in relation to the supply and demand for soil functions associated with scale have implications for soil and land management: some soil functions must be managed at local field and farm scale, whilst others may be offset between regions with a view to meeting national or continental targets.

Functional Land Management does not equate to a legislative tool for the zoning of land for individual functions but rather that individual soil functions may be incentivised through existing instruments available under the EU CAP. Figure 5 from Schulte et al. (2015) shows these instruments categorised into the type of instrument (market, mandatory, voluntary) alongside their policy objective and the scale of application.

This inventory indicates that policy makers already have a wide range of instruments to incentivise soil and land management to meet policy objectives. Some of the policy tools are 'joined up' and can readily address multiple soil functions, such as the cross-compliance, GAEC and greening requirements for the single farm payment scheme. There are however a number of relevant instruments that operate in isolation of each other, such as the re-delineation of ANC. Also, EIA, while mandatory for large-scale land management interventions for drainage systems currently only considers the habitat function, whereas a more holistic approach to soil functions such as proposed by FLM would also consider the impact of drainage on the carbon sequestration function. In this way, FLM offers considerable possibility as a policy integrator for sustainability with potential to utilise existing policy instruments for FLM governance.

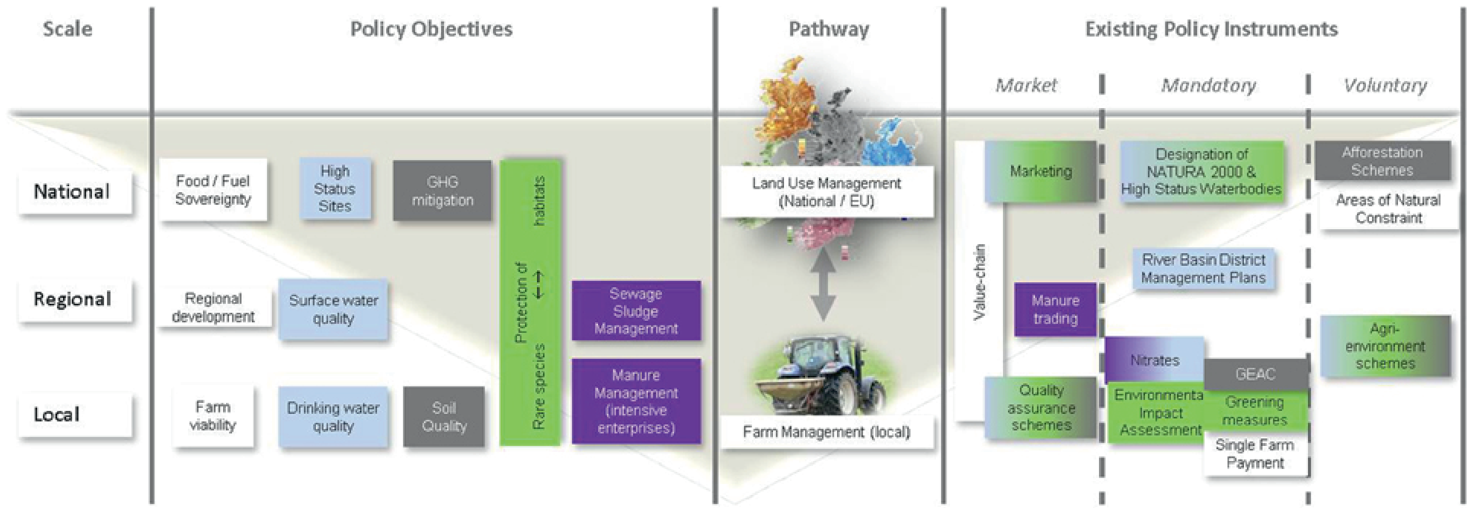

Figure 5 Inventory of policy objectives and policy instruments of relevance to the management of soil functions.

It is important too that most instruments do not take account for differences between soils in their capacity to supply soil functions. This is likely due to this historical tendency to maximise the delivery of soil function(s) simultaneously. The availability of land is and will be an increasing limiting factor and therefore soil data is essential to account for differences between soil types and to allow for the optimisation of soil functions. While the maps presented in this chapter demonstrate the granularity in the supply of soil functions they have been developed as the 1:250,000 scale. This means that while they can aid large scale geographical patterns, they are not appropriate for farm scale. Thus, local management decisions require knowledge of local soil type which can be acquired through direct observations.

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CHAPTER 3

Functional Land Management: Bridging the Think-Do-Gap using a multistakeholder science policy interface

The Catchment Challenge

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Abstract

Functional Land Management (FLM) is proposed as an integrator for sustainability policies and assesses the functional capacity of soil and land to deliver primary productivity, water purification and regulation, carbon cycling and storage, habitat for biodiversity and recycling of nutrients. This paper presents the catchment challenge as a method to bridge the gap between science, stakeholders and policy for the effective management of soils to deliver these functions. Two challenges were completed by a wide range of stakeholders focused around a physical catchment model – (1) to design an optimised catchment based on soil function targets, and (2) to identify gaps to implementation of the proposed design. In challenge 1, a high level of consensus between different stakeholders emerged on soil and management measures to be implemented to achieve soil function targets. Key gaps including knowledge, a mix of market and voluntary incentives and mandatory measures were identified in challenge 2.

Introduction

The growing demands on land and soil globally add ever growing complexity to policies aimed at agricultural and environmental land management. Agriculture is faced with the challenge of increasing primary productivity to meet the rising global demand for food security (Alexandratos and Bruinsma 2012). With United Nation (UN) population estimates of between 9.4 and 10 billion for 2050, increasing to between 10 and 12.5 billion by 2100 (UN 2015a), food security continues to be a priority on the political agenda. At the same time, society expects that any emphasis on increasing agricultural output is met with an equal emphasis on sustainability (Garnett et al. 2013). The intensification of agriculture, while not always, has often been associated with negative environmental consequences. Agriculture is the main source of nitrate and phosphate pollution to water (OECD 2001; FAO 2003) and is a major source of methane and nitrous oxide to the atmosphere with Agriculture, Forestry and Other Land Use (AFOLU) responsible for just under one-quarter of anthropogenic greenhouse gas emissions (FAO 2003; Smith et al. 2014). As well as contributing to climate change, agriculture is affected by it. While warmer temperatures can support the growth of specific crops in certain part of the world up to a point, if temperatures exceed an optimal level or if there are insufficient water and nutrients, a decrease in yields is anticipated, associated with climate change (FAO 2016). In relation to soil, the majority of the world's soil resources are in fair, poor or very poor condition, while one-third of land is moderately to highly degraded (FAO and ITPS 2015).

A response to these challenges is reflected in the Sustainable Development Goals (SDGs). Building on the forerunning Millennium Development Goals, the SDGs outline the action plan to be implemented by all countries and include four targets specifically citing soil (2.4, 3.9, 12.4 and 15.3) with two other targets that focus on land and soil functions. By 2030, these targets seek to progressively improve soil quality, reduce soil pollution and contamination and to restore degraded soils (UN 2015b). A global literature review of the relationship between soils and ecosystem services is presented by Adhikari and Hartemink (2016), and despite some emphasis on the role of soils in the contribution to ecosystem services (Blum 2005; EC 2006; Haygarth and Ritz 2009; Bouma 2014; Bouma et al. 2015), overall, soil is generally an overlooked component in studies related to ecosystem services and policy decision making (Hewitt et al. 2015). Within the European Union (EU), the withdrawal of the proposed Soil Framework Directive in 2014 highlighted the need for stakeholders and lobby groups to think differently about soils (Bouma and Montanarella 2016). The proposed Soil Framework Directive emphasised the need for soil protection which led to resistance from key agricultural stakeholders and arguably distracted from efforts to include soil functions in the development of land use and management policies (Robinson et al. 2012; Adhikari and Hartemink 2016).

Functional Land Management: the concept

In response, Schulte et al. (2014) proposed the Functional Land Management (FLM) framework. This utilitarian framework seeks to optimise the supply of soil functions from the land through sustainable use of Europe's soil resource. The core concept of FLM is the multifunctionality of soils, which is that all soils deliver multiple functions simultaneously, but that some soils are better at the delivery of certain soil-based ecosystem services over others. The subset of ecosystem services that rely on soil and land use for their delivery are recognised as “soil functions” (Bouma 2014) and were first described in the European Commission Thematic Strategy for Soil Protection (EC 2006). FLM focuses on the five soil functions that are delivered through agricultural landscapes: (1) primary productivity, (2) water purification and regulation, (3) carbon cycling and storage, (4) habitat for biodiversity and (5) recycling of (external) nutrients/agro-chemicals. The EU LAND Management: Assessment, Research, Knowledge base (LANDMARK) project (SFS-04-2014-soil quality and function) is quantifying the supply of soil functions across Europe. This quantification will recognise the variable intrinsic capacity of the soil under different land uses and management practices to simultaneously deliver soil functions to a greater or lesser extent (Coyle et al. 2016). It will therefore be determined by soil properties, environment, land use and soil management practices.

While the supply of soil functions depends upon biophysical criteria, environment and management, within the FLM framework, the contrasting demands for soil functions are framed as EU policies. For example, demands for the water purification and regulation function include the EU Water Framework Directive that requires all water bodies to be of ‘good’ ecological status (EU 2000) and the Nitrates Directive that indicates that groundwater nitrates-N (NO3-N) concentrations must not exceed 11.3 mg per litre (EU 1991). Altogether, FLM has the potential to combine inter- and trans-disciplinary research, along with a more holistic approach to the land base representing an integrator for sustainability policy. Integrated issues are complex, both to understand and to manage, and are associated with uncertainties that must be characterised in advance, so that potentially irreversible or long-term negative consequences can be avoided, but this relies on an increased knowledge demand (EC 2012a).

Functional Land Management: from research to implementation

Several research studies have thus far demonstrated the potential of the FLM framework. Coyle et al. (2016) extended the FLM framework to show the multi-functional capacity of soils for the European Atlantic pedo-climatic zone. A matrix was developed based upon land use and soil types clustered by drainage class to show the consequential changes to the capacity of the five soil functions including the potential trade-offs for individual functions and the overall impact on the multi-functional capacity (suite of five functions) of soil. To demonstrate this, O’Sullivan et al. (2015) provided a first example of the application of the FLM for policy decision making. The trade-offs between the soil functions ‘primary productivity’ and ‘carbon cycling and storage’ in response to the intervention of land drainage systems applied to ‘imperfectly’ and ‘poorly’ draining managed grasslands were explored. These trade-offs were expressed as a function of the nominal price of ‘Certified Emission Reductions’ and were characterised spatially using ArcGIS to account for spatial variability of the supply of soil functions. The results highlighted large geographic variation in the environmental cost:agronomic benefit ratio. This example demonstrated the potential of FLM to facilitate a shift away from blanket policies to develop policies that can be tailored to contrasting biophysical environments that can be more effective at the prioritisation of contrasting soil functions. To explore the FLM framework further, Valujeva et al. (2016) used a non-spatial land use model to assess the supply of soil functions for contrasting soil drainage and land use categories under different optimisation scenarios. As additional soil functions were added, the management requirements became more complex. This research highlighted a challenge for policy makers: in order to meet current and future agronomic and environmental targets, the supply of each soil function needs to be managed at the spatial scale at which the corresponding demand manifests itself, which may range from farm to national scale. As well as the spatial mismatch that exists between supply and demand, Valujeva et al. (2016) also emphasised a need to consider the temporal mismatch between the supply and demand for soil functions. These modelling studies are now underpinned by the Soil QUality Assessment and REsearch (SQUARE) project (DAFM Project Reference No: 13S468), which encompasses a national level field campaign that will provide a baseline of the delivery of the five soil functions for grassland management systems in Ireland.

Aims and objectives

Part of the challenge in developing the FLM concept rests in addressing how this research framework can be translated in practice and be implemented in reality. Based on FLM, governance instruments for managing the soil and land resource sustainably must account for the differences between soils and landscapes. Schulte et al. (2015) identified 15 existing governance instruments (divided into market, mandatory and voluntary) to manage soil functions from local to national/EU scale. They concluded that further research should explore if these could be realigned so that the differences between soils and landscapes are included (Schulte et al. 2015). Importantly, this does not necessarily equate to a legislative zoning of land management practice, but seeks to promote incentives that foster action to optimise the functionality of our land based on the soil resource. Given the long history of incentivisation within the EU, Schulte et al. (2015) conclude that in principle mechanisms for incentivisation are already in place and could be adapted for the implementation of FLM. The challenge then is how best to realign instruments to translate the research into practice. Currently, a gap exists between the scientific design of optimised land management as conceptualised in FLM and the implementation in practice. This research aims to bridge this knowledge gap—here called the Think-Do-Gap. Specifically, the aims and objectives of this work are to:

(1) Design an optimised catchment management plan to hypothetically reflect the implementation of FLM at catchment scale.
(2) Identify the gaps to implementation of catchment design/FLM.

The Functional Land Management catchment challenge: methods

We developed the 'catchment challenge' workshop method in order to bridge the Think-Do-Gap on sustainable land management, i.e. the discrepancy between the scientific design of FLM and the implementation in practice. The catchment challenge is designed as a multi-stakeholder science policy interface to support the translation of research to governance with the overall aim of landscape implementation of the FLM concept. The catchment challenge method can be used to harvest information and data on the gaps, actors and instruments necessary to implement FLM. The challenges are intended to get stakeholders to design a catchment with consideration of the need to supply all soil functions within a landscape. Stakeholders must match the supply of soil functions with the societal demand for soil functions through use of land use, land use change and land management options. With the exception of workshop No. 7, where farmers completed an outdoor workshop assessing three soil profiles, the workshops (approximately n = 235 participants) included the same core focus of designing the management and implementation of an optimised landscape (Table 1).

Table 1 Stakeholder workshops including institutional representation of eight stakeholder workshops, approximate number of participants and the format, facilitated in Ireland between 2014 and 2016

ID. Workshop	Stakeholders and institutional representation	No. (approx.)	Format		
1. Irish Soil Information System Launch 2014	Irish Department of Agriculture, Irish Environmental Protection Agency, Teagasc Agriculture and Food Development Authority, European Commission JRC, Universities, Students, Farming Press	19	a	Entry ranking of soil functions	Catchment challenges: (1) unconstrained design and (2) pathways
2. Crops and Nutrition Course 2014	Teagasc Advisory and Research, Private Advisory, Industry agrochemical/fertiliser, Farmers, Students	26	a	Entry ranking of soil functions	Catchment challenges: (1) unconstrained design and (2) pathways
3. LANDMARK Horizon 2020 Project Launch 2014	Teagasc; Universities: Denmark, Hungary, United Kingdom, Belgium, Romania, Sweden, Italy; European Commission JRC Italy; RIVM Netherlands; Chambers of Agriculture France; Chamber of Agriculture of Lower Saxony Germany; AGES Austria; INRA France; Institute of Social Science Chinese Academy of Sciences China; ETH Zurich Switzerland, Jozef Stefan Institute Slovenia	30	b	–	Catchment challenges: (1) Unconstrained design and (2) based on LANDMARK Pillar II (monitoring)
4. Catchment Science week 2015	Irish Department of Agriculture, Irish Environmental Protection Agency, Teagasc Agriculture and Food; AFBI Northern Ireland; European Commission JRC; Universities/Students (United Kingdom, New Zealand), Farmer, Consultancy, County Council	28	c	–	Catchment challenges: (1) unconstrained design and (2) pathways
5. Agricultural Catchments Programme 2015	Teagasc Advisory, Research, Student Researchers, Farmer, Farm Management	16	d	Entry and exit ranking of soil functions	Catchment challenges: (1) unconstrained design and (2) pathways
6. Co-operative Industry 2015	Processor Executive, Farmer Co-op Board Member, Processor Sustainability, Processor, Processor Nutrition, Processor Quality Control, Farm Sustainability Manager, Veterinary	22	d	Entry and exit ranking of soil functions	Catchment challenges: (1) unconstrained design and (2) pathways
7. Farming Group 2015	Farmers—tillage	30	e	Survey instrument	Profile pit assessments
8. International Farmer Scholarship 2016	International Researchers, Farmers, Students with Guest Panellists including NGO, Farmer, Department of Agriculture Food and the Marine, Northern Ireland EPA, Academic Policy Analyst, Co-operative Sustainability Manager	80 +	f	Role play	Catchment challenges: (1) unconstrained design and (2) pathways

Workshop participants represented a broad diversity of stakeholders including the academic and research community (national and international), farming community, public sector, private sector, processors including co-operatives, policy makers, advisory and lobby groups including non-governmental organisations (Table 1). Collectively, these stakeholders represent a broad cross-section of society with the potential to influence the implementation of FLM at multiple scales.

At the outset of the workshops, the key concept of FLM and the multi-functional capacity of soil as defined by Schulte et al. (2014) were explained with a poster series and a catchment model (Figure 1) which provided the centrepiece of the workshop discussion.

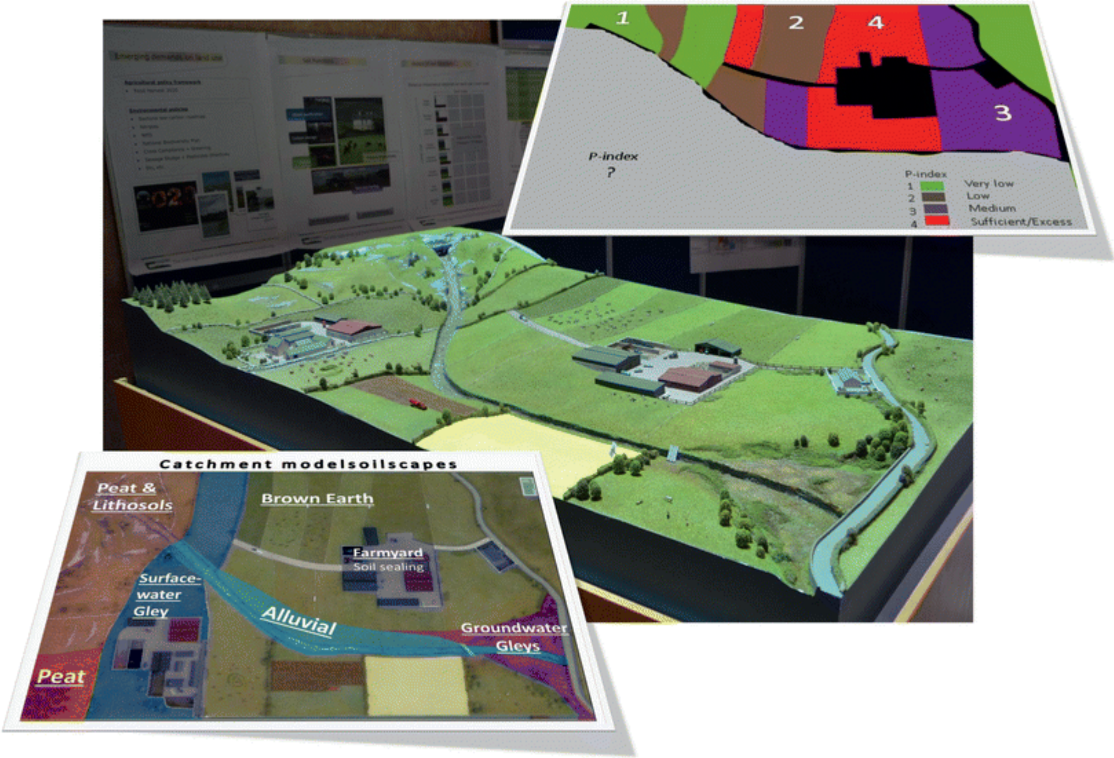

Figure 1 Catchment model used for FLM interactive learning and knowledge co-production (centre); the landscape model is described in terms of soil types (bottom left), and soil test phosphorus (P) status (top right)

The challenges were as follows:

- To increase the supply of two of the soil functions in the catchment to meet demands: (a) the primary productivity function by increasing milk production by 50% on one of the catchment farms (Ann's farm—described below). This challenge is consistent with the demand target outlined in Ireland's Food Harvest 2020 policy document (DAFF 2010); (b) the water quality function, by improving the water quality status from Q3 (moderate) to Q4 (good) under the EU Water Framework Directive (EU 2000). In addition, the delivery of the other soil functions must not to be reduced within the catchment design.

- To identify gaps, pathways and policies to facilitate the catchment designed in challenge 1 to become a reality. Information on existing mechanisms was presented along with the relative scale and respective function(s) that they apply to see Schulte et al. (2015).

Challenges were conducted in smaller breakout groups and A0 maps along with some options for land use and management on small pieces of paper were provided for the breakout groups. This facilitated groups to visually display the options decided/discussed being presented by their rapporteur for challenge 1. In challenge 2, the same breakout groups had to identify the gaps, pathways and policies to meet societal expectations of the land base which were also reported back to the group.

The farmers presented in this fictitious scenario represent two very different realities/systems with polarised ambitions for their farming futures. Ann is a young progressive, educated farmer, who is anxious to intensify her dairy business, whereas John is a middle-aged farmer, with off-farm income, who operates a suckler beef enterprise and is seeking to reduce the time commitment of his farm operation. Their commonalities include that both share a boundary with the river as well as grazing rights on the catchment hill. John has not had his soils sampled for nutrient analysis, whilst Ann has full knowledge of her soil resource. Soils found in this catchment range from very wet Peats (Histosols) and shallow soils (Histic Lithosols) to deep Surface-water Gleys (Stagnosols) and free-draining Brown Earths (Haplic Cambisols) found in the catchment heartland. The Alluvial (Fluvisols) soils bordering the river are frequently waterlogged and are associated with poor drainage and poor trafficability with Groundwater Gleys (Gleysols) found on the lowest ground due to a high water table (Fig. 1, bottom left). In relation to the phosphorus (P) status of the soils in the catchment, a lack of soil analysis on one-half of the catchment means that the P-index value is unknown (Fig. 1, top right). Elsewhere, the upland areas reflect very low P-status in comparison to the fields around Ann's farmyard, where a soil test P-index of four is indicative of a potential excess of P.

A photographic image of the catchment model was taken and using ArcGIS software the landscape was divided into polygons representative of different soil types typical of a catchment catena. These polygons were coloured in different colours after which the image was exported and saved in Microsoft PowerPoint 2010. For demonstration purposes, polygons were vertically projected by soil types, superimposed onto the physical catchment, whilst the workshop moderator described that particular soil type/part of the landscape. The PowerPoint soil map was printed out in A0 for workshop groups. The P-Index printouts were similarly created and printed in A4. As these workshops took place in Ireland, the catchment and fictitious scenario presented are typical for an Irish context but can be customised regionally based on location according to climate, pedology, land use and management as has been done in partner countries in the LANDMARK project.

Results from challenge one were recorded on A0 sheets with citations shown at workshop level. The results from challenge 2 were recorded on flip charts with additional note taking during open discussion.

Participants were asked to complete a ranking exercise where stakeholders indicated their prioritisation of soil functions. In workshops one and two, this was an ordinal ranking from one to five, representing the least to the most important respectively, for the five soil functions. In workshops 5 and 6, the ranking exercise was adapted so that stakeholders could allocate 15 points across the five functions, with a maximum of five for any one function. This allowed instances where a soil function has an equal weighting with another function, or where a soil function is not a priority at all, to be identified. Also at workshops 5 and 6, the same ranking exercise was completed at the end of the workshop, to capture any changes in prioritisation. Data were averaged by stakeholder group with means shown in radar diagrams. A t test to assess differences in before and after ranking by soil function was completed using Statistica with a significance value of $p < 0.05$.

Results recorded from the survey instrument in workshop 7 were cleaned, coded and input into a Microsoft access database.

Results and discussion

Challenge 1

The results from catchment challenge 1 are shown in Table 2 with breakout group responses presented at workshop level clustered into three categories: land use change, land management practices and knowledge intensification measures. Across all workshops, the top five options proposed were afforestation, the use of buffer strip/riparian zones, soil sampling and analysis, targeted inorganic nutrients and targeted slurry/organic amendments.

Table 2 Options proposed for an optimised catchment design to achieve an increase in primary productivity (50% on one farm) and an improvement in the water quality function (from Q3 to Q4 under the Water Framework Directive) while maintaining the carbon storage and cycling, habitat for biodiversity and nutrient recycling functions. Results are clustered into land use change options, land management practices and knowledge intensification measures. Options cited are highlighted in grey, whereas a white box indicates that the option was not proposed.

	Workshop	1	2	3	4	5	6	8
Land use change	Afforestation	■	■	■	■	■	■	■
	Agroforestry							■
	Bioenergy Crops	■	■	■	■		■	■
	Constructed Wetlands	■		■	■			
	Conversion to dairy farming	■	■		■	■		■
	Deforestation	■			■			
	Ecological Focus Areas		■					■
	Exit beef						■	
	Convert to grassland	■	■	■	■	■	■	
	Hedgerows	■	■				■	■
	Natura sites					■		
	Silvo-pasture	■		■				
	Tillage	■	■					
Land management practices	Buffer Strips/Riparian	■	■	■	■	■	■	■
	Clover		■				■	■
	Cover Crops	■		■				■
	Drainage	■	■				■	
	Fencing/Virtual Fencing	■	■		■	■	■	■
	Grassland - change in stocking rate/strip grazing	■						■
	Grassland - monoculture versus multi-species		■				■	■
	Grassland -inc. extended grazing	■	■		■	■	■	■
	Grassland- utilisation: grazing versus silage cutting	■			■		■	■
	Habitat maintenance and restoration	■	■	■	■			■
	Injection slurry (no splash plate)					■	■	
	Liming	■	■		■	■		
	Minimum tillage/No tillage	■	■	■				
	Mountain Sheep/Manage Sheep	■	■	■	■			
	River channelling							■
	Reseeding		■				■	■
Knowledge intensification	Contract Heifer Rearing	■	■		■	■	■	■
	Discussion group							■
	EBI - high economic breeding index		■			■	■	■
	GLAS-Green Low-Carbon Agri-Environment Scheme	■	■			■		
	Improved Farm Yard Management				■			
	Lease/Rent Land		■		■	■	■	■
	Nutrient Trading: Import/Export Slurry		■				■	■
	Partnership/farm collaboration							■
	Renewable Energy (Wind/Water/Solar)	■				■	■	■
	Soil sampling and analysis	■	■	■	■	■	■	■
	Targeted Inorganic Nutrients (NPK)	■	■	■	■	■	■	■
	Targeted slurry/Organic Nutrient Amendments	■	■	■	■	■	■	■

In relation to land use changes, afforestation, bioenergy crops, conversion to grassland and conversion to dairy were the options most frequently proposed in the optimised designs. Land management practices related to grass management were repeatedly cited, of which extending the grazing season was considered most important towards meeting the primary productivity target (n = 6). Buffer strips or fencing off high-risk areas were unanimous solutions (n = 7) towards the protection and improvement of water quality, targeted in areas considered to be critical source areas. The options of soil analysis, targeted organic nutrient amendments and inorganic nutrient management plans to augment nutrient efficiency and environmental gains were important having been cited by all groups. Other efficiency gains proposed, related to the specialisation of operations, such as the contract rearing of heifers, or the leasing of commonage shares to allow one farmer to take sole responsibility for sheep rearing on the hill areas of the catchment. Importantly, many of the options proposed assume a level of education and it is therefore an important consideration that if farmers are to deliver optimised management for soil functions, there is an implicit knowledge demand.

Despite the diversity of stakeholders, there was a high level of agreement in relation to the development of a catchment management plan to achieve the optimal delivery of soil functions and to meet the targets of challenge 1. Stakeholders were able to collectively achieve consensus about how to design an optimised catchment in an unconstrained scenario. All groups used the information in relation to soil types to design their ideal catchment. This signals another important consideration related to implementation of FLM: knowledge gaps related to soil and land use could impact local level decision making and could result in suboptimal decision making. Soil analysis and better nutrient management plans were proposed by all groups who completed workshop challenge 1 (n = 7), reflecting the importance of these options. The knowledge gap associated with farmer John's lack of soil analysis represented a barrier to the implementation of optimised catchment management. This lack of knowledge was further found to be associated with reduced economic opportunities for farmer-to-farmer collaboration, with a nutrient trading scheme cited as one potential missed opportunity in the scenario. A shared finding for all groups was that implementation of the optimised catchment extends beyond the farm and that farmer collaboration is a key requirement for achieving optimised landscape management. This is endorsed by the fact that several of the proposed measures rely on farmer-to-farmer or farmer-to-business interactions, such as contract heifer rearing, leasing land or nutrient trading as some cited examples.

Challenge 2

For challenge 2, participants were asked to identify the governance tools that might be necessary to achieve the catchment design proposed in challenge 1. These could include policy tools or market instruments, and participants were advised that they could utilise existing tools or develop new tools where a gap was found to exist. The key gaps and mechanisms for the achievement of the catchment management design from challenge 1 identified are shown in Figure 2.

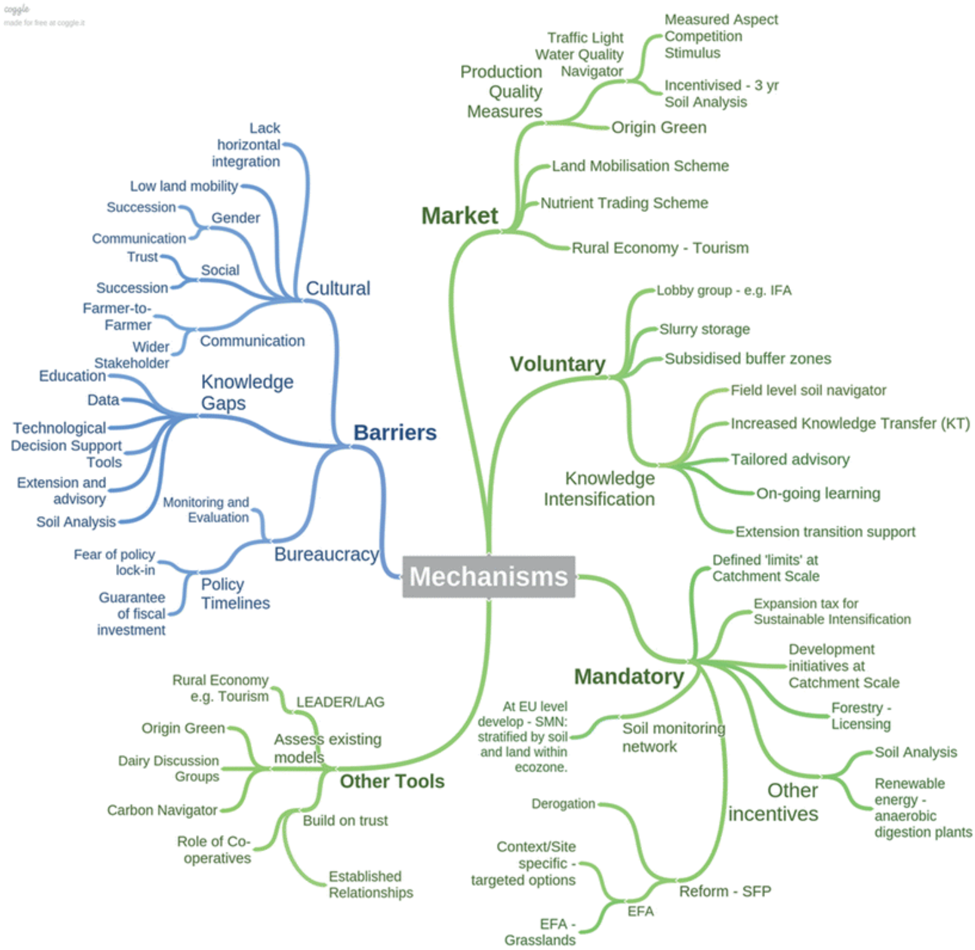

Figure 2 Gaps that inhibit optimised land and soil management, with barriers shown in blue and the policy instruments required to steer change shown in green (using http://coggle.ie/)

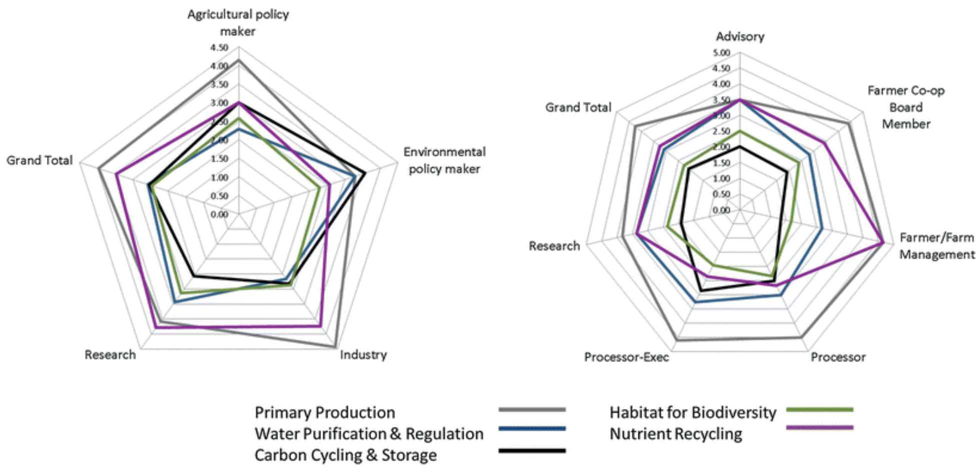

Figure 3 Prioritisation of soil functions by stakeholder groups. Radar diagram on the left representing the results from workshops 1 and 2, radar on the right from workshops 5 and 6. The first graph shows the ranking based from one to five for the soil functions. The second graph represents an optimisation of the ranking exercise where stakeholders are asked to rank five soil functions with a maximum of five for any one functions thereby highlighting instances where functions may not represent a priority at all. The second method has been adopted for use within LANDMARK workshops

In relation to gaps, cultural barriers were considered important with gender, social and communication gaps all hindering within-catchment level cooperation. Discussions around bureaucratic issues, including policy timelines, highlighted a clear misalignment, whereby farmers' fear of "policy lock-in" was in sharp contrast to policy makers and their preference for longer-term measures to guarantee the fiscal investment of policy incentives. This finding potentially indicates that the threshold for the uptake of voluntary policies could be raised. From a policy perspective, this indicates that higher fiscal incentives could be required for local level implementation. Knowledge gaps emerged as important, cited at all workshops (n = 7). Seven out of seven workshops cited that knowledge transfer, farm advisory services and farmer discussions, soil analysis and decision support tools were necessary at farm level. Specifically, more advisory support, training and education were emphasised by all groups. At policy scale, information gaps on the synergies between national level target setting and on-farm management practices were highlighted and are expressive of an on-going requirement to develop pathways that connect the two, cited in five of the workshops—1, 3, 4, 6 and 8.

Concerning mechanisms to overcome gaps to achieve the ideal catchment, suites of market, mandatory and voluntary measures were proposed. Market measures, largely driven by quality production measures were proposed. In Ireland, the green credentials of Irish produce as captured in the "Origin Green" initiative by Bord Bia (Irish Food Board) were highlighted in workshops 1 and 6, as one example whereby synergies could be achieved for producers and policy makers across ministries including agriculture and environment. In workshop 4, another example proposed was the development of a traffic light water quality navigator that could offer value in relation to sustainable branding. Mandatory measures included an expansion tax for sustainable intensification or the inclusion of defined catchment scale limits for environmental indicators. The implementation of Ecological Focus Areas (EFAs) for grasslands was proposed (workshops 2, 4, 5 and 6). A Soil Monitoring Network to afford soil the necessary protection to maintain its sustainability into the future was proposed at national and EU level (workshops 1, 3, 4 and 5). Consequently, options for a soil monitoring network for Ireland have been proposed (O'Sullivan et al., 2017). Related to this, monitoring and evaluation requirements were cited as essential considerations for the deployment of governance tools. Voluntary measures focussed on opportunities for knowledge intensification that included the introduction of a field level "soil navigator" a decision support tool for sustainable soil management, and increased knowledge transfer. The "other tools" cited, mostly referred to existing models, for example the "dairy discussion model" designed for farmer discussion groups. This model is one rural development measure under the 'Knowledge Transfer and Information Actions' co-funded by the EU's European Agricultural Fund for Rural Development (EAFRD), Pillar II of the Common Agricultural Policy and the Irish national exchequer (DAFM 2016). Farmer discussion groups are facilitated by advisors, and information and best practices are shared between farmers. These groups show to have a positive impact on technology adoption and profit levels (Hennessy and Heanue 2012). The dairy discussion model was proposed as having capability to be moulded for multiple farming systems for implementation at catchment scale. In this regard, the role of the co-operatives or the use of established trusted relationships was considered important for supporting farm level change including off-farm interaction.

Targeted policies are designed to pursue particular outcomes applied to identified groups or areas that are most likely to produce the desired outcome (Moreddu 2007). Options to increase targeted policies were discussed, but opinions as to how this could be achieved diverged. "Hard" policy instruments include legally binding rules such as regulations, directives and decisions (EC 2012b). A mapping approach based upon soil types was one such option proposed. A need for more tailored regulation that takes account of soil type and hydrology with respect to N and P losses has previously been identified for Ireland, versus blanket 'one size fits all' policies (Buckley 2012). Scientific evidence to support a shift away from blanket policies is essential, as widespread transgressions can emerge where regulation is perceived as unnecessary, resulting in high monitoring and enforcement costs (May and Winter 2001). The FLM approach seeks to respond to this challenge through the integration of policy instruments for multiple soil functions whilst promoting policy design that considers the variation in soil capacity. "Soft" policy instruments are more flexible approaches including recommendations (EC 2012b) and options related to education, knowledge transfer, one-to-one farm visits and discussion groups were proposed.

Soil functions: prioritisation, ranking and farmer perceptions

Across these stakeholders (workshops 1, 2, 3, 4), on average the primary productivity and the nutrient recycling functions emerged as the highest priorities. An exception to this was the environmental policy makers who prioritised the carbon cycling and storage function ahead of primary productivity which ranked second along with the water purification and regulation functions (Figure 3 left). Industry stakeholder groups similarly prioritised primary productivity and nutrient recycling, with the exception of the executive level processor stakeholders, who still prioritised primary productivity as highest but ranked water purification and regulation followed by carbon cycling and storage above the nutrient recycling soil function. In general, the carbon cycling and storage and habitat for biodiversity functions represented a lower priority, which may be indicative of potential knowledge gaps. At a policy level, this signals the need for better integration of policies or a potential need to elevate the importance of other soil functions within agricultural policies.

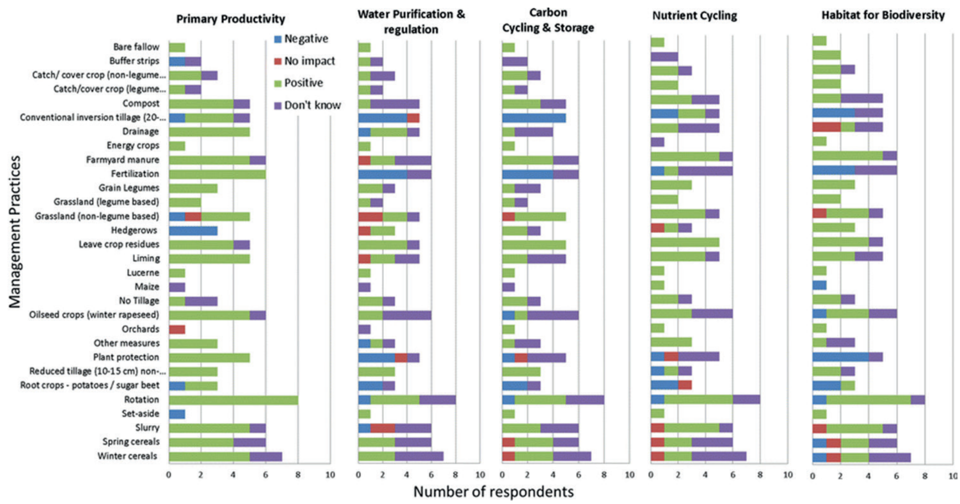

Figure 4 Farmer assessment of management impact on five soil functions delivered through agricultural landscape

Table 3 shows the results of a t-test to compare the entry and exit ranking of soil functions for workshops 5 and 6 combined. This result offers insight into immediate learning effect whilst acknowledging that the learning effect beyond this is not captured here. Results for the water purification and regulation and nutrient cycling functions reflected an increased and decreased significant difference in ranking, respectively.

Table 3 Entry and exit ranking of soil functions to quantify immediate learning effect for workshops 5 and 6*

Soil function**	Entry mean (SD)	Exit mean (SD)	df	P
Primary productivity	4.31 (± 0.63)	3.64 (± 1.11)	18	0.1
Water purification and regulation	3.02 (± 0.7)	4.0 (± 0.82)	30	0.02
Carbon cycling and storage	2.16 (± 0.81)	2.67 (± 0.82)	20	0.2
Habitat for biodiversity	2.42 (± 0.97)	2.43 (± 0.98)	23	0.98
Nutrient cycling	3.21 (± 0.88)	2.47 (± 0.47)	23	0.04

* A total of 15 marks were available to be assigned over five functions, with a maximum of five marks available for any individual function; ** Total respondents $n = 38$

In workshop 7 using a survey instrument, farmers were asked to indicate the impact of management practices on five soil functions. Figure 4 shows that farmer knowledge is strongest for the primary productivity function with knowledge gaps more prevalent across the other four soil functions. With the exception of 'conventional tillage', there is limited knowledge indicated on the negative impacts of management on soil functions, and in some instances knowledge may not be accurate, for example, the impact of drainage on the carbon cycling and storage function is rated as positive. Notably, the most 'don't know' responses were for the 'water purification and regulation' and 'carbon cycling and storage' functions despite national level emphasis on these soil functions in the regulatory landscape in Ireland. This result is consistent with the other workshops (1, 2, 3, 4, 5, 6, 8) whereby a continued need for education and advisory at farm scale to broaden understanding of the capacity and functions of soil beyond primary productivity is identified. This data harvesting has use in identifying knowledge gaps and can support targeting of policies and future education and dissemination efforts.

Notably, these results are reflective of an Irish example; however, when completed for a range of agro-climatic zones the results can support a more targeted approach towards soil function optimisation and sustainable use of the land base. This is based on the assumption that challenges to sustainability vary by location (Schulte et al. 2014) and will be accordingly reflected by stakeholder priorities and captured within the EU LANDMARK project.

The Think-Do-Gap

This research proposes the catchment challenge method as an important tool to identify solutions and actions necessary to bridge the gap between landscape level implementation of FLM and the scientific research that underpins FLM. This gap between science and implementation is referred to as the Think-Do-Gap (Figure 5). Using the catchment challenge model, stakeholders were consistently able to design an optimised catchment that could potentially realise the soil function targets set, i.e. ‘Think’ solutions to achieve FLM based on context specific soil, environment and management. Stakeholders were challenged to balance their demands to reach the optimised design. This learning effect was captured not only in the soil functions ranking exercise but in the catchment design which always resulted in a more balanced prioritisation. In this way, the catchment challenges facilitated knowledge production through the identification of more balanced and shared key actions necessary at multiple scales from the local to national scale. The results represent important target areas that require integration into the policy framework to facilitate implementation of FLM that can support more targeted policies based on context-specific social and biophysical conditions. This idea was expanded upon in challenge 2 where participants were asked what instruments would be necessary to support the implementation of the FLM catchment design from challenge 1. For example, the option to ‘lease land’ as proposed in challenge 1 might require a land mobilisation scheme, as identified in challenge 2, to bridge that particular gap (Figure 5) and so on.

Figure 5 Think-Do-Gap. The sustainable development goals (SDG) represent the global goals to end poverty, fight inequality and tackle climate change (UN 2016) (top from: Communications materials). Four of the SDGs specifically cite soil (2.4, 3.9, 12.4 and 15.3) (UN 2016). The FLM framework is a tool that can be utilised for sustainable agri-environmental development in-line with the SDGs. To transition farmers from their current situation to FLM, governance instruments (bridges) that can steer or incentivise action to bridge gaps must be implemented. However, the governance space includes many diverse actors with a potential role in achieving FLM

Further research

Supply and demand for soil functions across the EU will be mapped within the LANDMARK project using large datasets based on biophysical, environment and management data for supply, and policy driver indicators for demand. Beyond this, the workshop data are important to better understand the challenges and opportunities in matching the supply with demand for soil functions from a stakeholder perspective. Thus far, 32 LANDMARK catchment challenge workshops have been facilitated across five partner countries, to gain understanding as to how different soil functions are prioritised associated with location. Although engaging a wide range of stakeholders assumes a greater degree of complexity, this front-end investment in knowledge production can ultimately support more effective long-term change. Often policies represent conflicting goals and agendas which can result in uncertainty for stakeholder application (Carton et al. 2016). Stakeholder engagement can support more coherent policy setting and reduce the risk for unintended consequences to emerge as it includes a much broader consideration of a wide range of value judgements and expertise.

The implementation of FLM requires gaps to be bridged including socio-cultural, bureaucratic and knowledge/education barriers (Figure 5). Importantly, Figure 5 represents a starting point for the direction of further research. While all gaps are considered the same in Figure 5, future research will seek to classify these gaps. For example, policy gaps refer to "institutions", the so called rules of a game in society that are humanly devised to shape human interaction (North 1990). At a policy level, bridging the gap between science and implementation of FLM might require the introduction of a tax or incentive tool. In contrast, cultural gaps refer to informal rules, but these workshop results indicate that cultural factors are important in shaping agri-environmental governance and are therefore important to understand decision making for the implementation of FLM. Knowledge gaps may refer to technical solutions. While the workshops increase context-specific understanding of the stakeholder challenges and opportunities in relation to soil functions, understanding the societal actors, networks and their interactions is also important. Different actors face different challenges or gaps in the implementation of FLM. A network analysis of the governance space for soil functions in five countries is currently under development within the LANDMARK project. The results from the network analysis are expected to identify existing coalitions or gaps in networks, collaboration opportunities and points of entry that could be targeted to steer stakeholders/decision makers towards FLM.

Concluding remarks

Although the new SDGs include targets that directly and indirectly relate to soil (UN 2015b), the achievement of these SDGs will remain elusive unless there is inter-disciplinary cooperation between different scientific disciplines along with the continued involvement of stakeholders and policy makers in a trans-disciplinary context (Bouma 2015). With environmental and agricultural policies increasingly framed within a context of ecosystem services, this demand is apparent. As identified in the workshops, the historical approach of utilising single-issue policy measures is likely to be insufficient to achieve multiple objectives from the soil resource. In applied research, a lack of interaction with broader stakeholders groups, such as land managers or policy makers, is likely to result in a breakdown in relation to knowledge production and governance for implementation. Applied research provides an essential foundation towards the validation of policy making; however, it is also important that this research can be scaled up and appropriately translated into policy instruments. Hence, inter-disciplinary scientific input that also considers socio-economics, natural sciences, political science and ethnopedology is likely to result in greater knowledge of systems, and in this case, the gaps and mechanisms to support the delivery of soil functions at a landscape level. In this regard, the trans-disciplinary FLM workshops, through an informal setting, allowed for many value judgements and expertise of a range of stakeholders to be moderated and integrated in a process aimed at informing more effective change. Also, the intrinsic relationship between soil and land means that soil scientists can assume a pivotal role as knowledge brokers in a context of greater inter-disciplinary and trans-disciplinary research (Bouma 2015). With 2015 as the international year of the soil and initiatives such as the 4/1000 for food security and climate change increasing the affinity between society and soils, soil science is well positioned to forward the agenda on sustainable agri-environmental policies.

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CHAPTER 4

Demands on land: Mapping competing societal expectations for the functionality of agricultural soils in Europe

The Bigger picture

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Abstract

The Common Agricultural Policy (CAP) of the European Union (EU) has been highly successful in securing the supply of food from Europe's agricultural land. However, new expectations have emerged from society on the functions that agricultural land should deliver, including the expectations that land should regulate and purify water, should sequester carbon to contribute to the mitigation of climate change, should provide a home for biodiversity and allow for the sustainable cycling of nutrients in animal and human waste streams. Through a series of reforms of the CAP, these expectations, or 'societal demands' have translated into a myriad of EU and national level policies aimed at safeguarding the sustainability and multifunctionality of European agriculture, resulting in a highly complex regulatory environment for land managers. The current reform of the CAP aims to simultaneously simplify and strengthen policy making on environmental protection and climate action, through the development of Strategic Plans at national level, which allow for more targeted and context-specific policy formation. In this paper, we contribute to the knowledge base underpinning the development of these Strategic Plans by mapping the variation in the societal demands for soil functions across EU Member States, based on an extensive review of the existing policy environment relating to sustainable and multifunctional land management. We show that the societal demands for primary production, water regulation and purification, carbon sequestration, biodiversity and nutrient cycling vary greatly between Member States, as determined by population, farming systems and livestock densities, geo-environmental conditions and landscape configuration. Moreover, the total societal demands for multifunctionality differs between Member States, with the lowest demands found in Member States that have designated the higher shares of EU CAP funding towards 'Pillar 2′ expenditure, aimed at environmental protection and regional development. We review which lessons can be learnt from these observations, in the context of the proposals for the new CAP for the period 2021–2027, which include enhanced conditionality of direct income support for farmers and the instigation of eco-schemes in Pillar 1, in addition to Agri-Environmental and Climate Measures in Pillar 2. We conclude that the devolution of planning to Strategic Plans at national level provides an opportunity for more effective and targeted incentivisation of sustainable land management, provided that these plans take account for variations in the societal demand for soil functions, as well as the capacity of contrasting soils to deliver on this multifunctionality

1. Introduction

1.1 Urgency

Agricultural land is the main interface between the global food system and the global environment, with land management impacting on, and being impacted by, the environment. Globally, agriculture contributes to the extraction of water (Hoekstra and Chapagain, 2008), deterioration of water quality, greenhouse gas emissions (Gerber et al., 2013) and regional depletion and accumulation of nutrients (Uwizeye et al., 2016). Dietary changes associated with rising affluence, growing populations and urbanisation are driving demand for livestock products with a global increase of 70% anticipated by 2050 (Gerber et al., 2013). Compared to the total agricultural sector, Leip et al. (2015) estimated that, in Europe, the livestock agricultural share accounts for 73% of water pollution including phosphorus and nitrogen losses and 81% of total greenhouse gas emissions. At the same time, agriculture is being affected by the very changes in the environment that it contributes to. Already between 2007–2016 land temperatures have increased by 1.6 °C since pre-industrial time with summer temperatures especially affecting southern Europe (EC, 2018b). These changes are leading to changes in crop suitability in parts of Europe (Maracchi et al., 2005; Falloon and Betts, 2010; Kovats et al., 2014) with droughts and heat stress affecting plant production in Southern Europe, with a 30% yield decline possible by 2050 dependent upon the crop (Olesen and Bindi, 2002; Hart et al., 2017). Although longer crop growing seasons may occur in Northern Europe (e.g. Semenov, 2009), this region is likely to experience increased pest and disease pressures, increased nutrient leaching and a reduction in soil organic matter due to increased mineralisation associated with rising temperatures (Maracchi et al., 2005). Land use and land cover (LULC) in tandem with climate are driving patterns of biodiversity decline, which together are expected to continue to be a threat to agricultural biodiversity worldwide (Ostberg et al., 2015) including the decline of pollination insects such as the bumblebee (Marshall et al., 2018).

However, the effects of these environmental changes extend beyond agriculture and impact on society as a whole. At least 11% of the European population and 17% of its territory have been affected by water scarcity to date (SEC(2007) 993 & SEC(2007) 999). Climate change will almost certainly exacerbate these adverse impacts in the future, with more frequent and severe droughts expected across Europe. This incidence of floods has also increased, with over 213 major damaging floods between 1998 and 2009, causing the displacement of about half a million people and at least €52 billion in insured economic losses (EEA, 2011). The coming decades are likely to see a higher flood risk in Europe and greater economic damage due to increased urbanization and climate change. Water quality remains at risk of eutrophication (EC, 2017), resulting *inter alia* from losses of surplus nutrients from agricultural land to water (Grizzetti et al., 2011; European Commission (EC), 2018a).

Such are the changes in land management and the environment, that the structural integrity of Europe's ecosystems may be at risk: the EU assessment for the Habitats Directive for the period 2007–2012 showed that only 23% of animal and plant species assessments were considered to be in a favourable conservation status, with 60% of species assessed as facing unfavourable conditions. According to the latest data on European common birds, brought together by the Pan- European Common Bird Monitoring Scheme (PECBMS), farmland birds show a 55% decline since 1980 (EBCC, 2018). Similarly, there has been a decline in grassland butterflies of almost 50% between 1990 and 2011, without any sign of recovery (EEA, 2013a). Encouragingly, some populations of European bats (EEA, 2013b) and large carnivores (EC, 2012) appear to have recovered to some extent from past declines, reflecting the effectiveness of targeted conservation actions.

1.2 Policy context

During the first three decades of the EU Common Agricultural Policy (CAP), efforts were focussed on supporting the management of land for food production. Since the 1990s, EU policies have increasingly responded to the evolution of societal expectations that land management should also aim to maintain, restore and where necessary enhance the provision of ecosystem services such as flood mitigation and climate mitigation. This has led to the formulation of a multitude of Environmental Directives and successive reviews and reforms of the CAP, which we review in this paper. Many of these policies have been developed independently from each other, leading to the development of a myriad of policy instruments that apply to land management at farm scale and at national scale (Schulte et al., 2015). From the perspective of European land managers, this has resulted in one of the most complex agricultural policy environments in the world (O'Sullivan et al., 2019a; Schulte et al., 2017).

In preparation for the next CAP period of 2021–2027, the European Commission presented its proposals for modernising and simplifying the CAP in June 2018. Key elements of this proposal are: 1) Better targeting of funding towards small and medium sized farms; 2) guaranteeing a higher ambition on environmental and climate action; 3) putting agriculture at the heart of European society and 4) making greater use of knowledge and innovation (EC, 2018c). Central to the delivery of these ambitions is the increased subsidiarity of the Commission to Member States (MS). This means that the current centralised top-down approach towards the formation of agricultural and agri-environmental policies and policy instruments will be replaced by more targeted and results-based approaches at MS level reflecting goals set at EU level. Individual MS will each be required to develop a Strategic Plan that will deliver on the overall objectives of the new CAP within the specific agri-environmental and societal context of that MS (EC, 2018d).

1.3 Research context

In order for these Strategic Plans to deliver on the "higher ambition on environmental and climate action", national policy makers require knowledge and data to set appropriate agri-environmental targets and to devise land management strategies that can deliver on these targets. Put simply, knowledge is required on A) which ecosystem services are needed where; and B) which land management practices can be used to ensure that the these 'demands' for ecosystem services are met for contrasting soils, farm systems and environments.

In preparation for these policy developments, the European Commission funded the LANDMARK (LAND Management: Assessment, Research, Knowledge base) project (www.landmark2020.eu) as part of the Horizon 2020 Research & Innovation Strategy. LANDMARK is a multi-actor consortium of 22 knowledge institutes, including universities, research institutes and extension services, from 14 EU countries and Switzerland, China and Brazil. It applies the framework of Functional Land Management (FLM) (Schulte et al., 2014) at European scale. FLM is an approach to optimising (rather than maximising) the delivery of land-based ecosystem services to meet societal expectations. FLM builds on, and simplifies, these land-based ecosystem services into five ubiquitous 'soil functions', i.e. 1) primary production of food, feed, fuel and fibre; 2) regulation and purification of water; 3) carbon storage, sequestration and climate regulation; 4) provision of habitats for biodiversity and 5) provision and cycling of nutrients.

Bringing together the knowledge, long-term datasets and models on this topic, LANDMARK has delivered a framework for quantifying the degree to which each of the soil functions can be 'supplied' by combinations of soil type, land use types, and land management practices, for the six main agri-environmental zones in Europe (Henriksen et al., 2018; Rutgers et al., 2018; Schröder et al., 2018; Vrebos et al., 2018; Wall et al., 2018; Wenng et al., 2018). In this paper, we complement this work with an assessment of the 'demand' for each of the five soil functions across Europe.

1.4 Quantifying the demands for soil functions

Different stakeholders with influence on how the land is managed, may have diverging expectations or demands for the extent to which land delivers each of the soil functions (e.g. LANDMARK, 2018; Bampa et al., 2019). For example, farmers may seek to increase carbon content of their soils up to levels deemed adequate to support soil structure, nutrient cycling and hence primary production at local scale (Eliasson et al., 2010; Jones et al., 2013). Contrastingly, environmental NGOs or governments may be interested to further increase carbon stocks with a view to mitigate climate change at national or global scale. Table 1 lists the functional and societal objectives for EU and national policies relating to each of the soil functions, based on the policy assessment by Schulte et al. (2015).

It is important to distinguish between these functional objectives and societal objectives as their realisation may require different approaches to incentivisation: functional objectives are of direct interest and relevance to land managers, and may be expected to provide a sustainable return on investment. Contrastingly, societal objectives may require additional land management practices for which the return on investment materialises at societal, rather than at farm level, which necessitates the formulation of financial or non-financial support instruments.

The degree of soil functioning that is required to meet the local functional objectives for a range of farm systems, soil types and environments has already been well studied and reported on (e.g. Schröder et al., 2016; Henriksen et al., 2018; Rutgers et al., 2018; Trajanov et al., 2018; Vrebos et al., 2018; Wall et al., 2018; Wenng et al., 2018). In this paper, we instead focus on the degree of additional soil functioning required to meet the societal objectives in the context of agriculture in the EU. We assume that national and European policies reflect (be it perfectly or imperfectly) the aggregate requirements and expectations of the various societal stakeholder groups. By mapping the spatial variation in these policy demands for each of the five soil functions, we explore differences in the societal expectations put on land managers across the MS. We relate this to the choices that individual MS have made during the current CAP in terms of funding instruments and amounts of funding targeted towards meeting agri-environmental objectives. From the lessons learnt from this evaluation, we assess opportunities for better alignment of agri-environmental instruments and expenditure to societal demands from land in the context of the negotiations on the new EU CAP for the period 2021–2027.

Table 1: Functional and societal objectives of EU and national policies relating to soil functions (adapted from Schulte et al., 2015)

Soil Function	**Functional objective (farm scale)**	**Societal objective (EU / national scale)**
Primary production	Provide farm income	Self-sufficiency
Water regulation & purification	Minimise water stress and provision of clean drinking water	Sufficient quantity of good quality water for human ecosystems
Carbon sequestration	Soil structure and functioning	Mitigation of climate change
Biodiversity	Supporting functional biodiversity	Supporting both functional and intrinsic biodiversity
Nutrient cycling	Valorisation of organic nutrients (Minimise expenditure on fertilizers) Developing a circular bio-economy	Nutrient cycling

2. Theory and calculations

2.1 Generic approach

Our approach builds upon the outcomes of an EU level workshop, entitled “Are you getting what you want from your Land?” organized by the LANDMARK consortium at the COPA-COGECA offices in Brussels on 20 October 2016 (LANDMARK, 2018). At this workshop, a range of European stakeholders (Supplementary Material, Table S1) identified the main future environmental and socio-economic developments for European agriculture, along with the related demands on soil and land resources.

This was followed by an assessment of European policies that frame the societal demands for each of the five soil functions, building upon the work of Schulte et al. (2015) and Vrebos et al. (2017). This included the a) identification of relevant EU policies and b) EU policy objectives, as well as c) appropriate demand metrics that are a representation of the societal demand for each soil function, or at least a significant part thereof. Criteria used for the selection of demand metrics included the following:

- Demand metrics must be integrative of the various policy demands for each of the soil functions at MS scale;
- European datasets must be readily and publicly available for each of the demand metrics;
- Data are spatially available and can be mapped at least at NUTS1 level or higher;
- Demand metrics must be sensitive to both spatial and temporal variations, i.e. they can show differences between countries or regions and between years;
- Demand metrics for soil functions can be quantitatively linked to indicators for the supply of soil functions across Europe, as reported on by the LANDMARK consortium (Henriksen et al., 2018; Rutgers et al., 2018; Schröder et al., 2018; Wall et al., 2018; Wenng et al., 2018).

Below, we describe this process in detail for each of the soil functions. Subsequently, we mapped the societal demands for soil functions using various publicly available datasets from e.g. Eurostat, EEA, JRC. Data were aggregated at NUTS levels and expressed as a demand per unit of Utilised Agricultural Area. Maps were produced using ArcGIS 10.2.

Finally, in order to compare the relative societal demands for all soil functions for individual MS, we converted the values for each of the soil functions to z-scores, similar to the approach used by Schulte et al. (2015).

2.2 Policy objectives and demand metrics for soil functions

2.2.1 Primary production

2.2.1.1 Policy context. As Europe emerged from its most recent period of food shortages in the 1940s, the EU Common Agricultural Policy (CAP) was introduced in 1962 as a "partnership between agriculture and society", with the overall objective to "provide affordable food for EU citizens and a fair standard of living for farmers". Such was its success in incentivising the productivity of European farms, that supply exceeded domestic demand by the end of the 1970s. During subsequent decades, the CAP has been reformed on a number of occasions and now includes objectives on rural development, job creation, tackling climate change and the sustainable use of natural resources. At the same time, food security remains the principal stated objective of the CAP today (European Commission (EC), 2018e).

Dietary demands for more exotic foods, and increased imports over time, mean that the demand for food in the EU is partially met by cultivation outside of the EU Concurrently, EU meat and dairy production is increasingly relying on imported protein crops and in particular soybean (Boerema et al., 2016). In 2013, the EU had net imports of around 27 million tons of soybeans and soybean products for oil production and animal feed, which has rendered the domestic cultivation of protein crops unprofitable. This geographic relocation of fodder crops to countries with less stringent environmental legislation has had far-reaching environmental impacts in regions outside of the focus of the CAP, thus effectively constituting an export of externalities (Meyfroid et al., 2013; Uwizeye et al., 2016 under review; O'Sullivan et al., 2019b). A circular economy would comprise of a scenario in which the EU is producing sufficient fodder and recycle nutrients locally or at least within the EU-territory.

Since the 2000′s, the EU has witnessed the emergence of a new demand, namely the production of agrichemicals and biofuels. Launched and adopted on 13 February 2012, the EU's Bioeconomy Strategy addresses the production of renewable resources and their conversion into products and bio-energy. A low-emission economy that includes novel crops for oils and fibre for the biochemistry industry, will add a significant claim on land resources within and outside the EU (Weinzettel et al., 2013). Over time, concerns that the 10% target for conventional biofuels would compete with food crops has prompted the shift from first generation to second generation biofuels (i.e. fuel from waste and by-products) (Mohr and Raman, 2013; Boutesteijn et al., 2017). Table 2 indicates the key policies, the associated targets and related constraints to the sector.

The EU demand for biofuel extends beyond production within Europe with some 53% of EU biodiesel derived from imported feed- stock, of which 33% is made from imported palm oil. Europe's imports of vegetable oils amounted to 10.1 million tons in 2016, of which 6.6 million tons of palm oil (Bentivoglio et al., 2018). As EU production rules for biofuels are not applicable outside the EU, the sustainability of these imports is unknown and may therefore not contribute to the global challenge of climate mitigation (Widengard et al., 2018) or sustainable development. As of 2018, the European Parliament voted to limit the support to biofuels made from food crops to 2017 consumption levels and never higher than 7% of all transport fuels (European Parliament, 2018). Other changes included the removal of palm oil biodiesel as a contributing source towards the 2021 renewable target, along with an overall transport target of 12% containing a 10% blending mandate for ‘advanced’ fuels, which includes renewable electricity, waste-based biofuels and “recycled carbon fuels”. Palm oil based biodiesel production will continue to receive subsidies until 2030.

Thus, the key policy challenge is to manage the competing demands for food, feed, fuel and fibre in such a way that they all can co-exist in a sustainable way.

Table 2: EU policies including key targets and constraints related to bio-economy sector

2009 Renewable Energy Directive (RED I)	• 20% energy mix from renewable fuels – with 7% cap of biofuels in energy sector; • Biofuel efficiency ≥ 35%, compared to fossil fuel; • Must not be grown on land that is currently used for food production; • Must not be grown on forests, wetlands and high biodiversity grassland; • Biofuels should not occupy > 7% of agricultural land.
The ILUC (Indirect Land Use Change) Directive (EU) 2015/2013	• EU executive proposed reducing the contribution of conventional biofuels in transport from a maximum of 7% in 2021 to 3.8% in 2030; • Set an obligation to raise the share of other “low emissions fuels” such as renewable electricity and advanced biofuels in transport to 6.8%.
Revised RED (RED II) November 30, 2016	• Cap of food crop-based biofuels from 7% in 2021 to 3.8% in 2030; • A minimum share of energy from advanced biofuels from 1.5% in 2021 to 6.8% by 2030. EC lists of acceptable feedstock for the production of advanced biofuels in Annex IX Part A & B; • A sub-target from 0.5 % in 2021 to 3.6% by 2030 for advanced biofuels produced with feedstocks listed in part A, Annex IX; • Advanced alternative fuels used for aviation and maritime can be counted 1.2 times toward the 6.8% renewable energy mandate.

***2.2.1.2 Metrics for the societal demand for the production of food, feed, fuel and fibre*:**

Food: The average European consumes about 2.5 kg of food per day, of which 40% are dairy products, eggs and meat products. Based on earlier work by Meier and Christen (2013) we assume a 2000 m² requirement of land per person per year. Wiegmann et al. (2005) calculated that the production of this food requires approximately 2400 m² per capita, of which approximately 700 m² (29%) for grassland (dairy), 600 m² (25%) for animal feed (meat), 900 m² (40%) for grains and 200 m² (8%) for vegetables and fruits. Because we will calculate feed for animals as a separate demand factor, we excluded these from the calculations for food production. As a result, the demand for land to produce food equates to approximately 0.2 ha (incl. meat, eggs and dairy) or 0.1 ha (excl. meat, eggs and dairy) per capita, translating into c. 50,000,000 ha of farmland to produce the grains, vegetables and fruits needed for self-sufficiency at EU scale.

Feed: The EU-28 is home to about 89 million cows, 147 million pigs, 86 million sheep, 12.5 million goats and 13 billion chickens (https://ec.europa.eu/eurostat/cache/metadata/en/apro_anip_esms.htm). The total feed demand, as calculated by using generic dietary needs based on the following assumptions listed in Supplementary Table S2, sums up to roughly 600 million tonnes. Assuming a dry matter yield of feed crops of 10 tons ha^{-1}, this equates to a demand for 60,000,000 hectares of farmland. Data on the number of animals is available at NUTS 2 level (tgs00045) and was mapped accordingly.

Fibre: We estimated the current demand for bio-based industrial production from the import of non-wood based products listed in the EUROSTAT trade database (https://ec.europa.eu/eurostat/web/ international-trade-in-goods/data). Net imports of agriculture-based non-edible products amounted to roughly 1 billion tonnes per year for the EU-28 territory (for period 2012–2017). Future additional demand will include novel crops suitable for the production of synthetic products that can be used in the chemical industry and allow for the manufacturing of a much higher diversity of end-products.

Fuel: for the quantification of demand for fuel, we used the “Shares” dataset from Eurostat (http://ec.europa.eu/eurostat/web/energy/data/ shares). The total amount of fuel used in transport in 2016 amounted to 309,774 ktoe (kilo tons of oil equivalent). We adopted the 10% target for biofuel feedstock production as the metric for the demand. For crop biodiesel specifically, only 47% of the feedstocks were grown in the EU in 2015, a decline from 60% (5977 ktoe) in 2010 (Gerasimchuk, 2013; Ecofys, 2014). Biodiesel is produced by pressing and refining of, among others rapeseed, linseed, sunflower, castor. If we assume an average yield of 3 tons of rapeseed per hectare and an extractable oil fraction of 40%, one hectare can produce 1.2 tons of biodiesel, or about 14,000 l. Bioethanol is produced from wheat, maize, sugar beet, and other crops, through microbial fermentation of sugars (starch). One ton of wheat yields about 340 l of bioethanol. With a yield of 8 ton wheat per hectare (Brisson et al., 2010; Palosuo et al., 2011), this sums up to 2720 l ha^{-1}.

2.2.2 Water regulation and purification

2.2.2.1 Policy context. The main overall objective of EU water policy is to ensure access to good quality water in sufficient quantity for all citizens, and to ensure the good status of all water bodies. This relates to both the regulation of water quantities, and the safeguarding of water quality of all waterbodies, including surface waters, groundwater and estuarine waters. There are various directives, communications and other policy documents that relate to the regulation and purification of water by agricultural land, of which the most important are:

- EC Communication - Water scarcity and droughts in the European Union (COM/2007/0414)
- Water Scarcity & Droughts – 2012 Policy Review – Building blocks Non-Paper
- EC Communication - Blueprint to Safeguard Europe's Water Resources (COM(2012) 673)
- EU Water Framework Directive (2000/60/EC)
- The Nitrates Directive (2000/60/EC)

Drought in Europe is a hazard with a wide range of transboundary, environmental and socio-economic impacts on various sectors including agriculture, energy production, public water supply and water quality (Blauhut et al., 2015). Agriculture is the main pressure on renewable water resources in the EU, accounting for 66% of total water usage in spring 2014, with 80% of total water abstraction for agriculture taking place in the Mediterranean region: whilst the total irrigated area in southern Europe increased by 12% between 2002 and 2014, the total harvested agricultural production decreased by 36% in the same period in this region (EEA, 2017). Building on the Water Scarcity and Droughts Communication, the Blueprint to Safeguard Europe's Water Resources outlines actions that concentrate on better implementation of current water legislation and integration of water policy objectives into other policies. It addresses the need for more quantitative water management, including the identification and implementation of the concept of ecological flow, as well as a legal framework for addressing illegal abstraction of water.

Notwithstanding the complexity of causal relationships associated with deteriorating water quality (Grizzetti et al., 2017), high N inputs to agricultural systems in many regions of the EU has resulted, *inter alia,* in the leaching of nitrogen to groundwater and surface waters (Velthof et al., 2009), setting off a cascade of environmental and human health problems (Erisman et al., 2008; Galloway et al., 2008) at a high societal cost (Van Grinsven et al., 2012, 2014). The Nitrates Directive (91/676/EEC) (European Union (EU, 2000) aims to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices. Surface freshwater and groundwater should be considered affected by nitrate pollution when their nitrate contents exceed 50 mg l^{-1}, necessitating the designation of nitrate vulnerable zones (NVZ). The Water Framework Directive (WFD), (Directive 2000/ 60/EC) requires MS to draw up River Basin Management Plans to safeguard the 110 river basins across the EU. Under the WFD, all surface waters are required to achieve good ecological and chemical status, while high status waters must be maintained in this condition.

2.2.2.2 Metrics for the societal demand for water regulation and purification. Flood mitigation: under the Flood Directive, MS are required to make Flood Risk Management Plans every 5 years; they are free to set targets to reduce flooding in the various categories (various severity classes / return frequencies). But these targets are only partially and weakly related to soil management in agricultural areas, which makes it difficult to derive meaningful and spatially explicit metrics for the for societal demand for flood mitigation. Therefore, no demand metric was produced.

Droughts: we considered three demand metrics for the societal demand for drought mitigation:
- Drought frequency, severity and duration statistics, based on Spinoni et al. (2016) and Jonathan et al. (2018);
- The qualitative likelihood of impact occurrence by Blauhut et al. (2016);
- The crop water deficit, i.e. the difference between the crop-specific water requirement and the water available through precipitation.

Of these metrics, only the crop water deficit allows for the spatially explicit mapping of the agricultural demand for water as computed by the EU Joint Research Centre using WOFOST crop simulation model (Peltonen-Sainio et al., 2016; De Wit et al., 2018) at a 25 km resolution (see e.g. https://www.eea.europa.eu/data-and-maps/indicators/water-requirement-2/assessment). Because this crop water deficit simulation does not take irrigation into account, it is an appropriate proxy for the total irrigation demand.

Water purification: EU MS have established Nutrient Management Plans (NMPs) to meet requirements under the Water Framework Directive and Nitrates Directive with a view to minimising surpluses of agricultural N and phosphorus (P). We modified the “Gross nutrient balance on agricultural land” (t2020_rn310) as the overarching metric for Water Quality regulation. The metric is part of the Resource Efficiency Scoreboard and is used to monitor progress towards a resource efficient Europe (i.e. the implementation of the Europe 2020 Resource Efficient Flagship initiative) on the key thematic objective of 'Land and soils' (see e.g. http://ec.europa.eu/eurostat/cache/metadata/en/t2020_rn310_esmsip2.htm and http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=aei_pr_gnb&lang=en). The metric measures the potential threat to the environment of N and P surpluses or deficits in agricultural soils. Land types included are arable land, permanent crops and permanent grassland. These nutrient balance calculations are available for NUTS1 through the Eurostat databases (Şaban Özbek et al., 2015). Because certain losses of nitrogen to the environment are unavoidable in agricultural systems (Uwizeye et al., 2016, we define the demand for water purification as the amount of the nitrogen surplus that must be mitigated to ensure that the net nitrate concentrations of the receiving waterbodies stays below the maximum allowable concentration of 50 mg l^{-1} of nitrate (corresponding to 11.3 mg l^{-1} of nitrate-N).

This demand can be calculated as: $\Delta N - 0.113 * Er$, where ΔN represents the nitrogen surplus and Er represents effective rainfall calculated as precipitation less evapotranspiration 2005–2015 derived from the MARS Agriforecast Toolbox provided by the European Commission (http://agri4cast.jrc.ec.europa.eu/).

2.2.3 Carbon sequestration and regulation

2.2.3.1 Policy objectives. Climate change is a global challenge, where causes and impacts are spatially connected at planetary level. Therefore, the societal demand for carbon sequestration is framed in the first instance by the United Nations Convention on Climate Change (UNFCCC), supported by the Intergovernmental Panel on Climate Change (IPCC). The most recent policy objectives are framed in the Paris Agreement (2015), and include a target to limit global temperature rise to 2 degrees C, with an aspiration to a limit of 1.5 degrees C. Countries commit to Independent Nationally Determined Contributions (INDCs), which are expected to expand in ambition over time, as new technologies and practices become available. The EU participates in the UNFCCC negotiations as a single bloc.

EU policies are framed by the EU Roadmap for a 2050 low-carbon economy (EC, 2011), which is consistent with the Paris Agreement and sets out the overall goals and ambition for the EU as follows:

- by 2050, the EU should cut greenhouse gas emissions to 80% below 1990 levels
- Milestones to achieve this are 40% emissions cuts by 2030 and 60% by 2040
- All sectors need to contribute

For agriculture, the EU Roadmap states:

> "As global food demand grows, the share of agriculture in the EU's total emissions will rise to about a third by 2050, but reductions are possible. Agriculture will need to cut emissions from fertilisers, manure and live- stock and can contribute to the storage of CO_2 in soils and forests. Changes towards a more healthy diet with more vegetables and less meat can also reduce emission."

In practice, this means that agricultural emissions are projected to be reduced by approximately 50% by 2050, compared to 1990.

In the medium term, the recent EU Climate and Energy Framework for 2030 (for the period 2021–2030) sets targets of a 43% reduction in greenhouse gas (GHG) emissions for the Emission Trading Sectors (ETS) and -30% for the Non-Emission Trading Sectors (non-ETS), which includes the agricultural sector and the Land Use, Land Use Change and Forestry (LULUCF) sector. This overall EU target is differentiated by MS, and translates into specific targets for the Non-ETS sectors of individual MS (Supplementary Material, Table S3).

Agricultural emissions relate to a basket of gases, mainly methane, nitrous oxides and carbon dioxide. As a result, the mitigation of agricultural emissions requires a concerted approach to animal management, crop management and soil management that is context specific for individual countries (Eory et al., 2018). For soil management, the policy discourse has recently focused on the preservation and potential for further storage of soil carbon through a reduction in the emissions that result from drained wetlands, as specified in the IPCC wetlands supplement (IPCC, 2014) and land degradation, or the augmentation of carbon sequestration (see e.g. Schulte et al., 2016; Rumpel et al., 2018).

In contrast to the EU Climate and Energy Package for 2020, the new 2030 Framework allows for the preservation and sequestration to be (partially) accounted in the form of LULUCF credits in meeting Non-ETS targets, subject to strict conditions. This is known as the "flexibility" mechanism. Each MS has been allocated a maximum amount of credits that can be included from the land use sector to the Effort Sharing Regulation (Supplementary Material Table S3). This country-specific amount specifies the maximum amount of soil carbon sequestration that can be used by each MS as a valid climate mitigation strategy for the 2021–2030 period in Europe.

Similar to Kyoto commitments, each MS must ensure that the LULUCF sector in its territory has no net emissions. The proposed regulation on LULUCF contains specific rules for afforestation and deforestation, managed cropland, managed grassland, managed wetland and managed forest land.

2.2.3.2 Metrics for societal demand for carbon sequestration. We selected the maximum amount of C-sequestration that can be accounted for at MS scale as the metric for the societal demand on agricultural land management to contribute to climate change mitigation. The percentages in the right-hand column of Appendix 1 refer to the percentage of total national non-ETS emissions. Therefore, the maximum demand for carbon sequestration (DCS) can be computed for each MS as follows:

$$DCS = Flexibility\% \times E_{non\text{-}ETS}$$

Where $E_{non\text{-}ETS}$ is the total amount of national non-ETS emissions (Supplementary Material, Table S3).

2.2.4 Biodiversity

2.2.4.1 Policy objectives. The main EU policy frameworks for the preservation and restoration of biodiversity in agricultural areas are the Birds Directive, the Habitat Directive, the Biodiversity Strategy and the CAP.

The Birds Directive (79/409/EEC), adopted in 1979 and amended in 2009 (2009/147/EC), was one of the first environmental legislations of the EU. It focussed on the protection of habitats for endangered and migratory bird species and required MS to designate Special Protection Areas (SPAs). In 1994, these SPAs were incorporated into the Natura 2000 ecological network, established under the Habitats Directive (92/ 43/EEC), which was aimed at protecting rare and endangered flora and fauna in general.

In May 2011, the European Union adopted a new Biodiversity Strategy in line with the Conference of the Parties to the Convention on Biological Diversity in Nagoya, Japan, in 2010. This EU strategy aims to halt the loss of biodiversity and the degradation of ecosystem services in the EU by 2020. However, the 2015 State and Outlook report of the European Environment Agency suggests that these objectives are unlikely to be met since loss of biodiversity and the degradation of ecosystem services have continued since the 2010 baseline. Specifically, the continuing decline in the status of species and habitats associated with agriculture indicates that additional measures may be required.

The CAP addresses the preservation of habitats and biodiversity through two mechanisms:

1. The co-financing of national agri-environmental schemes (under CAP Pillar 2) that facilitate specific measures for the preservation of habitats and biodiversity. Under these voluntary schemes, farmers may adopt environmentally friendly farming techniques, over and above legal obligations, for a minimum period of at least five years, in return for payments that provide compensation for additional costs and income foregone. Examples of commitments covered by national/regional agri-environmental schemes include low-intensity pasture systems, integrated farm management, organic agriculture, the preservation of landscape and historical features such as hedgerows, ditches and woods and the conservation of high-value habitats and their associated biodiversity.

2. The inclusion of 'greening measures' within the scope of cross- compliance: this innovation, brought in under the 2013 CAP reform makes 30% of the direct income support payments to farmers (under CAP Pillar 1) conditional on compliance with practices that are beneficial to the environment and the climate. These include:
    - crop diversification: this requires at least two crops to be grown on arable farms larger than 10 ha and three crops on arable farms larger 30 ha;
    - maintenance of permanent grasslands in at least 5% of their farmland;
    - the designation of 'ecologically beneficial elements' or 'Ecological Focus Areas', (EFAs) to 5% of the land area (applicable only to farms with over 15 ha of arable land). EFAs may cover a broad spectre of features, including fallow land, field margins, hedges and trees, buffer strips or catch crops or nitrogen-fixing crops.

The effectiveness of these greening measures has been questioned (Pe'er et al., 2014, 2017). Because EFAs apply only to farms with more than 15 ha of arable land, and MS can reduce their required spatial extent to 2.5% or lower in some regions, more than 88% of EU farms are exempted from the regulation, accounting for over 48% of farmed area. Furthermore, EFAs are not required on farms with permanent crops, grasslands, or pastures. The European Court of Auditors (2017) found that greening measure added significant complexity to the CAP as a result of overlaps with other environmental instruments of the CAP, including standards on good agricultural and environmental condition of land (GAECs).

2.2.4.2 Metrics for the societal demand for the preservation of biodiversity. Soil biodiversity (both below- and aboveground) plays a key role in regulating processes that underpin the delivery of a wide variety of ecosystem services. Nevertheless, the lack of a European-wide standardised set of indicators of soil biodiversity and of reference values (Van Leeuwen et al., 2017), as well as an insufficient understanding of the relationships between the various components of soil biodiversity, the different agricultural practices and the delivery of ecosystem services, renders the mapping of the demand for farmland biodiversity based on soil bio-indicators currently implausible.

Therefore, we used the agri-environmental metric ‘population trends of farmland birds’. This is the sole biodiversity-related indicator out of the 28 agri-environmental indicators (AEI) selected by the European Commission (COM/2006/0508fin.l) to monitor the integration of environmental concerns into the CAP.

Birds are recognised as an ecological indicator taxon and are considered to be good proxies for measuring the diversity and integrity of ecosystems as they tend to be at the top of the food chain, present large ranges and the ability to move elsewhere when their environment becomes unsuitable; they are therefore responsive to changes in their habitat. More specifically we used the ‘Common farmland birds’ (39 species), which have a high dependence on agricultural habitats in the nesting season and for feeding. The indices are based on data from 26 EU MSs, derived from annually operated surveys of national breeding birds collated by the Pan-European Common Bird Monitoring Scheme (PECBMS). For each MS, we computed the compound annual rate of change of common farmland species at national level. This compound annual rate of change makes it possible to compare the average annual rates of change in countries with different starting and end years of their time series.

2.2.5 Nutrient cycling

2.2.5.1 Policy context. The EU Circular Economy Action Plan, and the linked Directive on Critical Raw Materials (CRM), highlights the need for an integrated approach to raw materials that are deemed essential for the production of a broad range of goods used in everyday life and are crucial for a strong industrial base (Mathieux et al., 2017).

Of the critical raw materials, P is the only one that relates directly to agriculture: it is an essential nutrient for plants, animals and humans and is therefore crucial for all life on the planet - in this context it underpins the bio-economy. The historically abundant availability of P fertilizers has contributed to the decoupling of crop production and livestock production (Uwizeye et al., 2016). This specialisation has resulted in manure (and thus P) applications in excess of agronomic requirements in some regions, and full dependency on mineral fertilizer P in others. This disruption to the cycling of P is compensated for by imports into the EU in the form of animal feed and (feedstocks for) fertilizers. In its natural form, P only exists as phosphate rocks, a finite resource, mainly used for the production of fertilisers (86%), but also for the production of detergents and animal feedstock. The EU is dependent on mined P from concentrated production from three external countries, which represents a significant supply risk.

Building on previous policies concerned with both the environmental impact and future geopolitical consequences of the non-cyclic use of P (Table 3), the Circular Economy Action Plan encourages practices that replace nutrients from primary raw materials with recycled nutrients from waste streams.

Table 3 European policies related to the environmental impact of the non-cyclic use of phosphorus.

Year	Name	Reference
1986	EU Directive on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:31986L0278
1991	Nitrates Directive (Council Directive of 12 December 1991 Concerning the Protection of Waters Against Pollution Caused by Nitrates from Agricultural Sources) (91/676/EEC)	http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991LO676.
1991	Waste Water Directive	http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271
2000	Water Framework Directive	http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060
2008	Waste Directive	http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098
2015	Closing the loop: an EU action plan for the circular economy.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015DC0614
2017	Report on the implementation status and programmes for implementation of Council directive concerning urban waste water treatment.	http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2017:749:FIN
2017	Review of waste policy and legislation.	http://ec.europa.eu/docsroom/documents/27348

2.2.5.2 Metrics for the demand for nutrient cycling. The demand for the soil function 'nutrient cycling' is quantified by estimating the amount of agricultural land needed in the EU as a whole and per individual nuts region, to accommodate the recycling of P present in livestock manures, whilst minimizing accumulation or depletion of P in soils.

Livestock manures: the amount of P can be derived from the sum product of livestock numbers and livestock-specific P excretions. Information on livestock numbers was derived from the Eurostat database: http://ec.europa.eu/eurostat/data/database. Total farm livestock populations were estimated at 147 million pigs, 88 million cattle (˜25% dairy cattle), 1.3 billion poultry (mostly broilers and laying hens), 83 million sheep and 10 million goats. Total P excretion by livestock was estimated at 1.8 Mt a^{-1} P and has not changed substantially over the last fifteen years (Sutton and Reis, 2011; Leip et al., 2015; Velthof, 2015; Hou et al., 2016; Van Dijk et al., 2016; Hou et al., 2017). More information on livestock-specific P excretions can be found in Sebek et al. (2014) and Anonymous (2011).

3. Results

Figure 1 shows the spatial variation in the societal demands for the functionality of agricultural land, specifically for the five soil functions. It shows that for each of these functions, the societal demands vary greatly across the EU. The demand for primary production is loosely related to the regional variation in population density (see e.g. https://ec.europa.eu/eurostat/statistics-explained/images/c/c6/GEOSTAT_population_grid_2011.png). Contrastingly, the demands for water purification and nutrient cycling are loosely related to regional patterns in farming intensity (see e.g. https://ec.europa.eu/agriculture/cap- indicators/context/2017/c33_en.jpg). Spatial patterns for the demands for carbon sequestration and biodiversity are more ambiguous, with the highest demands for the restoration of biodiversity in South- Eastern and Northern MS.

The correlation matrix in Figure 2 illustrates that the demands for food, fibre and feed are correlated ($p < 0.001$), as are the demands for carbon sequestration, feed and nutrient cycling, all these latter demands relating to the presence of livestock farming. Of equal interest is the lack of correlation between the demands for some of the functions, specifically between the demands for biodiversity and water regulation when compared with the demands for other functions. These latter demands are defined by neither population nor livestock densities, and are instead determined by landscape configurations and the combination of cropping systems and geoclimatic conditions, respectively.

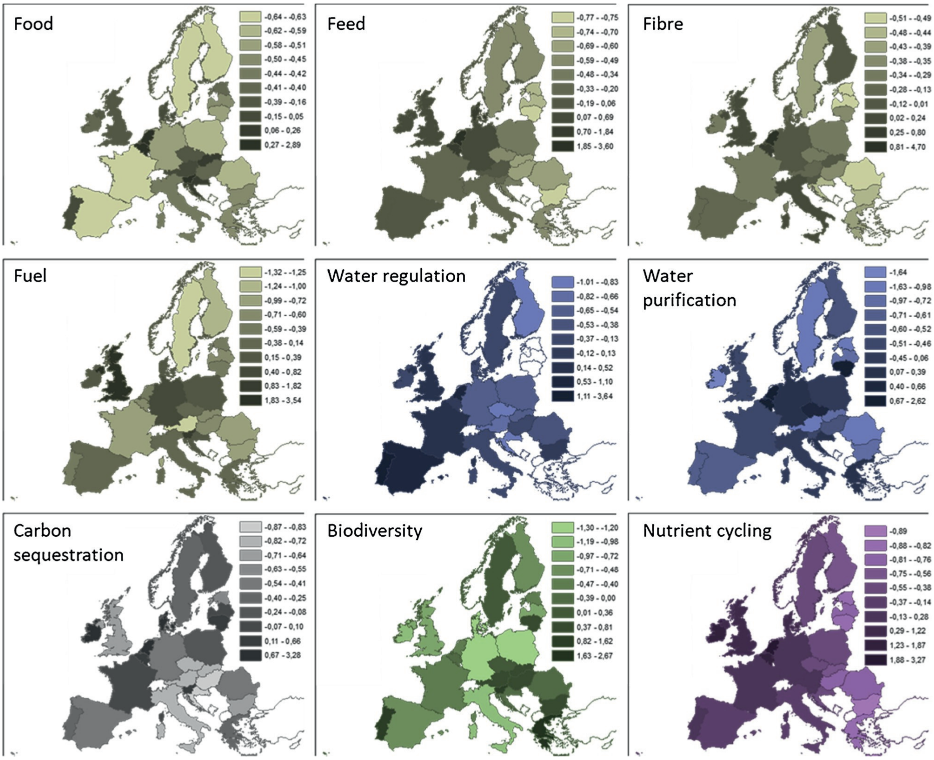

Figure 1. Distribution (z-scores) of societal demands for the five soil functions: primary production (composed of the societal demands for food, feed, fuel and fibre), water regulation and purification, carbon sequestration, biodiversity and nutrient cycling. Darker shades areas indicate a higher-than-average demand, while paler shades indicate a lower-than-average demand. White areas indicate no data available.

4

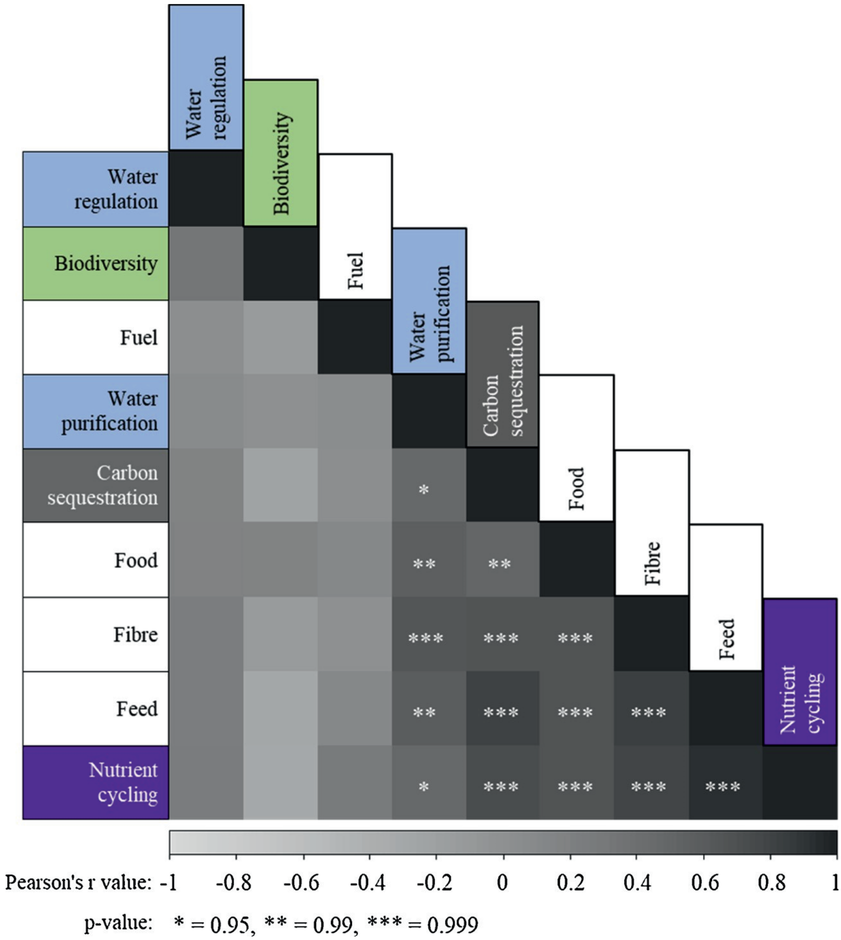

Figure 2. Correlation matrix of the societal demand for the five soil functions

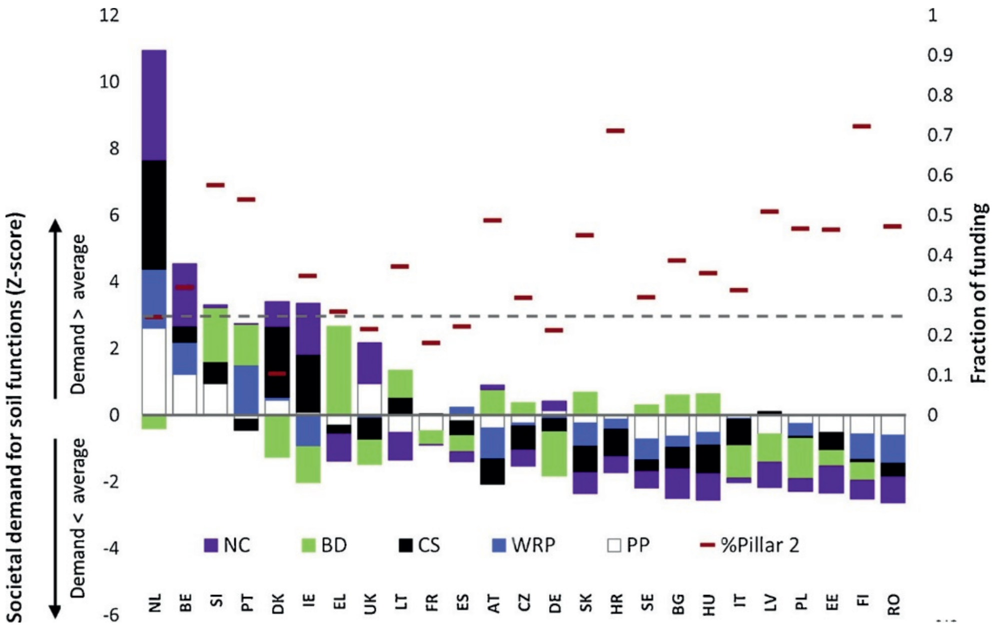

Figure 3. Relative demand for soil functions from agricultural land among EU MS (left axis), and relative expenditure on Pillar 2 schemes by each MS (dashed line = 25%).

NC = Nutrient Cycling, BD = Biodiversity, CS = Carbon Sequestration, WRP = Water Regulation and Purification, PP = Primary Production. P1 = Pillar 1; P2 = Pillar 2. NL = Netherlands, BE = Belgium, SI = Slovenia, PT = Portugal, DK = Denmark, IE = Ireland, EL = Greece, UK = United Kingdom, LT = Lithuania, FR = France, ES = Spain, AT = Austria, CZ = Czech Republic, DE = Germany, SK = Slovakia, HR = Croatia, SE = Sweden, BG = Bulgaria, HU = Hungary, IT = Italy, LV = Latvia, PL = Poland, EE = Estonia, FI = Finland, RO = Romania.

4. Discussion

4.1 Constraints

In this assessment, we simplified each societal demand to one or two metrics per soil functions or EU policy. In practice, policies, as well as the associated demand metrics, are intertwined. For example, the WFD aims to achieve "good quality status" for all waterbodies across Europe. "Good quality" is benchmarked against both chemical and biological criteria, which in turn are composed of multiple indicators. Chemical indicators include both the nitrate and the phosphorus content (and their temporal dynamics) of waterbodies, which are, *inter alia*, a function of nutrient balances on land. These same nutrient balances are also pivotal in determining the demand for nutrient cycling (the fifth soil function). Similar linkages exist between the demands for nutrient cycling and primary production, with the former being a precursor to the latter (Schröder et al., 2016). In order to avoid double accounting in the computation of z-scores, we disentangled the societal demands for nutrient cycling by pragmatically attributing the nitrogen balance to computations for the demand for water purification, and the phosphorus balance to the assessment of the demand for nutrient cycling.

Secondly, our assessment was limited to societal demands for soil functions that are mediated by soil and land management. While land management is a pivotal interface between agriculture and the environment. Agri-environmental management comprises more than land management alone. For example, reductions in emissions of ammonia or greenhouse gases other than CO_2 typically require changes to farm management practices unrelated to soils (e.g. Eory et al., 2018). The societal demand for soil functions presented in this paper is therefore part of, but not synonymous with, the societal demand for ecosystem services in general.

Finally, we applied our assessment at MS scale, which may hide regional variation and 'pressure points', for example for the demand for the function nutrient cycling, as well as regional variation in the environmental conditions, such as the rainfall surplus used for the computation of the water purification function. The project "Regionalisation of Gross Nitrogen Balances with the CAPRI model" (RegNiBal) provides methodological information on the gross nutrient balance for HSMU (Homogeneous Soil Mapping Units). The objective of the pilot project was to evaluate differences between national Eurostat/ OECD GNB figures and the GNB figures calculated using CAPRI, and to assess the feasibility of using the CAPRI model to (operationally) provide regional GNB data to complement the national GNBs. The report indicates that Regional GNB estimations produce more accurate results than the national estimations, especially for countries that experience different climates or have regionally differing agricultural production systems (Şaban Özbek et al., 2015; Leip et al., 2015).

4.2 Implications for the new CAP and Strategic Plans

The purpose of this exercise, therefore, is not to pinpoint specific geographical areas that fall short of meeting EU policy objectives; rather, our aim is to guide policy making and elucidate relative priorities for land management for individual MS. This approach is consistent with the objectives of the European Commission in the development of a framework for 'Land as a Resource', in particular in addressing the gap between demand and availability of land and by setting synergies and trade-offs between land uses and functions (Deloitte, 2014).

Figure 3 illustrates this point by showing the heterogeneity in the relative demand for each of the soil functions across Europe. For example, the challenges of meeting societal demands in Portugal, Ireland, Greece and the UK are of markedly different natures, and suggest prioritisation of the land functions water regulation, carbon sequestration, biodiversity and primary production (specifically biofuel), respectively. Also, differences in the overall challenge of meeting all societal demands become clear, with very large demands placed on farmers in the Netherlands, and to a lesser extent Belgium. By and large, the challenge of meeting multiple policy demands is lower in newer MS, with the exception of Slovenia.

The same figure shows the relative spending on the second pillar of the CAP for each MS over the period 2014–2018, as a fraction of total expenditure (Pillars 1 and 2, including national co-financing contributions), based on figures compiled by ECORYS (2016) and the European Commission (https://ec.europa.eu/agriculture/sites/agriculture/files/ cap-funding/budget/mff-2014-2020/mff-figures-and-cap_en.pdf), and excluding small MS such as Malta and Luxembourg with CAP expenditure < 1bn. This second pillar is "designed to support rural areas of the Union and meet the wide range of economic, environmental and societal challenges of the 21st century." A higher degree of flexibility (in comparison with the first pillar) enables regional, national and local authorities to formulate their individual seven-year rural development programmes based on a European 'menu of measures' (http://www.europarl.europa.eu/factsheets/en/sheet/110/second-pillar-of-the-cap- rural-development-policy). This flexibility suggests that these national programmes can be considered harbingers of the national Strategic Plans to be developed as part of the new CAP 2021–2027. In this context, it is striking that MS in which the societal demands, equating to the challenges associated with meeting EU policy objectives, are below average for at least four of the five functions, have consistently (with the exception of Spain) dedicated more than 25% of their CAP expenditure to Pillar 2 payments. Conversely, the lowest expenditure on Pillar 2 can be observed in MS in which farmers are faced with multiple above-average demands, with the Netherlands, Denmark and the UK notably devoting less than 25% to the rural development programmes under the current CAP.

Whilst no causality can be implied from these correlations (for example, new MS may have allocated a larger amount of Pillar 2 funding for the purposes of regional economic development, rather than for the purpose of incentivising environmentally sustainable land management (Matthews, 2018a), valuable lessons may be drawn for the design and implementation of the Strategic Plans under the next CAP. In the draft Strategic Plans regulation proposed by the Commission, the "higher environmental and climate action ambition" is proposed to be secured through a three-pronged approach (Matthews, 2018b):

1. Enhanced conditionality: enhancing the effectiveness of the cross-compliance regulations for the single farm payment by modification of measures (e.g. replacing crop diversity with crop rotation), the introduction of new measures (e.g. the protection of carbon-rich soils) and the removal of current exemptions to the greening requirements;
2. The continuation of agri-environmental and climate measures (AECM) schemes under Pillar 2; these schemes will be mandatory for MS to offer to land managers as voluntary measures. Funding is limited to compensating for 'costs-incurred' and must be co-financed by MS;
3. The introduction of a new 'eco-scheme' in Pillar 1 which, similar to the AECMs, must be offered by MSs as voluntary measures to farmers. In contrast to the AECM scheme, funding under this eco-scheme can be offered as income support, limiting eligibility to those meeting the 'active farmers' definition, defined by MS.

The rationale behind having both an AECM scheme under Pillar 2 and an eco-scheme under Pillar 1 is as of yet unclear (pers. comm. Allan Matthews), other than that it permits larger expenditure on environmental and climate initiatives without necessitating large budgetary transfers between Pillar 1 and Pillar 2. Of particular relevance here is the planned 15% reduction in co-financing on Pillar 2, as opposed to single digit reductions for Pillar 1, (Matthews, 2018), with the expectation of increased national contributions to the AECMs.

This allows MS two pathways to facilitate farmers in meeting the societal demands for soil functions: 1) by formulating attractive eco-schemes and 2) by increasing national contributions to AECMs. The success of these schemes in delivering on the "higher ambition for environmental and climate action" will depend on their design and implementation of the Strategic Plans. The design of these plans may be augmented if they are cognisant of the relative priorities in the demand for soil functions in each of the MS, and when they selectively incentivise land management practices that promote the synergistic delivery of those soil functions for which demand is highest.

However, while many synergies exist between management practices for augmenting soil functions, e.g. between nutrient cycling and primary production, nutrient cycling and water purification and biodiversity and soil carbon sequestration, trade-offs between management practices also occur, which makes it difficult to augment *all* functions on *all* soils for *all* farm systems. Neither may this be necessary: while all policy objectives must be delivered at MS level, this may be achieved by a composite of actions at farm scale or regional scale that are aimed at meeting individual policy demands. The scale of management is typically defined within the policy demand and is reflective of the extent to which competing demand can be off-set. For example, within the Nitrates Directive, all farmers in Nitrate Vulnerable Zones are expected to manage nutrients with a view to maintaining nitrate concentrations below 50 mg l^{-1}. In contrast, national carbon sequestration targets must be met at larger scales and so incentivisation schemes to respond to this challenge can be managed at the regional or national scale. The proposed formulation of Strategic Plans at national level provides an opportunity to target incentives towards soil/land use combinations that are best placed to deliver on the local or national societal expectations.

To aid the process of optimising the utilisation of land as a resource, the LANDMARK project has developed models that quantify the potential supply of each of the soil functions as dependent on farm type, soil type, environment and management, based on a meta-analyses of European datasets (Henriksen et al., 2018; Rutgers et al., 2018; Schröder et al., 2018; Vrebos et al., 2018; Wall et al., 2018; Wenng et al., 2018). These models are operationalised by the Soil Navigator: a Decision Support Tool (DST) that guides farmers, land managers and extension agents in selecting the most relevant and effective management practices to optimise synergies and minimise trade-offs. It provides straight-forward advice on land management, based on the ca- pacity of the local soil to deliver on the five soil functions, as well as the societal demands for each of these functions, as specified by the user. It thus allows for evidence-based yet low-complexity decision making on sustainable land management.

The subsequent implementation of the Strategic Plans may be aided by the provision of such targeted DSTs in order to meet both the functional and societal demands for soil functions on individual farms. Indeed, as part of the drive to make greater use of knowledge and in- novation, national rollout of such DSTs is a mandatory requirement for MSs under the new proposed enhanced conditionality measures. The delivery of such tools that synthesise and translate the complexities of the interactions between soils, environment, policy requirements and land management into advice to practitioners is currently subject to further studies by the LANDMARK consortium (O'Sullivan et al., 2019b).

5. Conclusions

We conclude that land managers in the EU are operating in a complex policy and regulatory environment, that manifests itself in a myriad of EU and national regulations and voluntary schemes relating to the sustainable management of land. The current review of the EU agricultural policy seeks to simultaneously simplify this regulatory environment and raise the ambition for safeguarding environmental sustainability and climate action, through the development of targeted Strategic Plans at national level, which allows for a more targeted and context-specific approach to incentivising sustainable land management practices.

In this paper, we have demonstrated that:

- The societal demands for the five functions that our land provides vary between MSs, allowing for a degree of targeting in the Strategic Plans (put simply: different countries may prioritise different functions from the land);
- The aggregated societal demand for all soil functions differs between MSs, with lowest demands found in countries that currently designate the highest percentages of EU CAP funding to Pillar 2 expenditure, which is associated with higher (relative) rates of national exchequer co-funding; this may provide valuable lessons for countries with higher societal demands for soil functions.

The CAP proposals for the period 2021–2027 provide an opportunity for MSs to design schemes that can specifically target those challenges that represent key areas for concern and are likely to cost national exchequers in fines should they not meet their prescribed targets. The challenge thus is for MS to make these schemes sufficiently attractive to stimulate farmer uptake. The new design allows schemes to be tailored to better fit their context, which provides an opportunity to engage experts in priority areas for their design at MS level.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.envsci.2019.06.011.

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CHAPTER 5

Functional land management for managing soil functions

A case-study of the trade-off between primary productivity and carbon storage in response to the intervention of drainage systems in Ireland

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Abstract

Globally, there is growing demand for increased agricultural outputs. At the same time, the agricultural industry is expected to meet increasingly stringent environmental targets. Thus, there is an urgent pressure on the soil resource to deliver multiple functions simultaneously. The Functional Land Management framework (Schulte et al., 2014) is a conceptual tool designed to support policy making to manage soil functions to meet these multiple demands. This paper provides a first example of a practical application of the Functional Land Management concept relevant to policy stakeholders. In this study we examine the trade-offs, between the soil functions 'primary productivity' and 'carbon cycling and storage', in response to the intervention of land drainage systems applied to 'imperfectly' and 'poorly' draining managed grasslands in Ireland. These trade-offs are explored as a function of the nominal price of 'Certified Emission Reductions' or 'carbon credits'. Also, these trade-offs are characterised spatially using ArcGIS to account for spatial variability in the supply of soil functions.

To manage soil functions, it is essential to understand how individual soil functions are prioritised by those that are responsible for the supply of soil functions – generally farmers and foresters, and those who frame demand for soil functions – policy makers. Here, in relation to these two soil functions, a gap exists in relation to this prioritisation between these two stakeholder groups. Currently, the prioritisation and incentivisation of these competing soil functions is primarily a function of CO_2 price. At current CO_2 prices, the agronomic benefits outweigh the monetised environmental costs. The value of CO_2 loss would only exceed productivity gains at either higher CO_2 prices or at a reduced discount period rate. Finally, this study shows large geographic variation in the environmental cost: agronomic benefit ratio. Therein, the Functional Land Management framework can support the development of policies that are more tailored to contrasting biophysical environments and are therefore more effective than 'blanket approaches' allowing more specific and effective prioritisation of contrasting soil functions.

Introduction

The challenge for agriculture – food security and the environment

A growing global population and dietary changes are amongst the factors that are fuelling a demand for increased agricultural output (Godfray et al., 2010). Increasing demand places urgent and growing pressure on soils to support the intensification of agriculture, which is an essential component of food security (RSC, 2012). The productive capacity of soils is diminishing and has already diminished in many parts of the world and there are limited opportunities for land expansion (Wild, 2003). Thus far, agricultural intensification has been very effective at achieving increased production. Production increases of 115% between 1967 and 2007 have been achieved on modest land area increases of approximately 8% (Foresight, 2011). However, a further increase in productivity is likely to be associated with additional stress on the natural resource base. Whilst not synonymous, in many cases intensification has been accompanied by unsustainable environmental impacts such as biodiversity loss and the use of resources such as inorganic nitrogen, phosphate fertiliser, fuel use, and water (Foresight, 2011, UK NEA, 2011). Concerns about these deleterious impacts have stimulated a societal demand for improved environmental sustainability. Consequently, the agricultural industry along with increasing productivity is also expected to meet increasingly stringent environmental targets. Within the European Union (EU), environmental targets include inter alia targets such as those under the Sustainable Use Directive (2009/128/EC) (EU, 2009a) and the Water Framework Directive (2000/60/EC) (EU, 2000) that requires that water bodies be of good ecological status. In Ireland, the Nitrates Directive (91/676/EEC) is the agricultural programme of measures (POM) that sets out a regulatory framework for nutrient management (EU, 1991) to achieve this status. Also, the Habitats Directive (92/43/EEC) (EU, 1992), Birds Directive (2009/147/EC) (EU, 2009b), and EU EIA Directive (2011/92/EU) (EU, 2012) through Natura 2000 seek to halt the loss of biodiversity. In summary, the world needs more food (Godfray et al., 2010), notwithstanding this, agricultural development cannot be intensified beyond the carrying capacity of soils, ecosystems and the socio-economic environment (Mueller et al., 2011).

In this context, ecosystem services are the benefits that people obtain from ecosystems and include the attributes and processes through which natural and managed ecosystems can sustain ecosystem functions (MA, 2005). Many ecosystem services rely on soils and land use for their delivery (Bouma, 2014). These include provisioning services such as food and water, regulating services such as disease control, cultural services and supporting services such as nutrient cycling (Haygarth and Ritz, 2009). This subset of ecosystem services, hereafter soil functions, are described in the Thematic Strategy for Soil Protection (EC, 2006), and these define the role of soils in the contribution to ecosystem services (Bouma, 2014). Although the concept of ecosystem services has been extensively studied and reviewed (Abson et al., 2014), there are a lack of tools to understand and manage multifunctional landscapes (O'Farrell and Anderson, 2010). A major challenge exists in how to satisfy all demands on land and soil simultaneously, particularly as these are often competing demands. The demand for solutions that support the co-existence of environmental sustainability with increased food outputs has prompted the development of the Functional Land Management framework (Schulte et al., 2014).

Functional Land Management

Functional Land Management seeks to optimise the agronomic and environmental returns from land and relies on the multifunctionality of soils. This framework focuses on five soil functions that are specifically related to agricultural land use: (1) Primary production; (2) Water purification and regulation; (3) Carbon cycling and storage; (4) Functional and intrinsic biodiversity, and (5) Nutrient cycling and provision (Bouma et al., 2012, Schulte et al., 2014). Although soils are multifunctional, the heterogeneity of soils means that soils will vary in their relative capacity to deliver individual soil functions which means that challenges to sustainability will vary spatially based on location. Ultimately, the suite of soil functions that a soil provides depends on both land use and soil type. To meet the challenge of the sustainable intensification of agriculture, Functional Land Management seeks to optimise the suite of soil functions that it provides by matching the supply of soil functions with demand (Schulte et al., 2014). For example, the demand for the soil function 'Water purification' is framed by the Nitrates Directive, which requires groundwater nitrates concentrations to be maintained below 50 mg l^{-1}, through denitrification of (part of) the nitrogen surplus. To present the delivery of soil functions, Schulte et al. (2014) used Ireland as a case-study. Importantly, Functional Land Management is not designed as a tool for zoning, but for use at a scale that can consider what Benton et al. (2011) refer to as the net landscape effect across all affected land.

Case study: agriculture in Ireland – trade-offs between two soil functions

Ireland's response to the global imperative of food security is captured in the Food Harvest 2020 strategy. Food Harvest 2020 is the industry-led roadmap for agricultural growth in Ireland. The abolition of the EU milk quota in 2015 is a prime driver that will allow farmers to increase their dairy output. As a result, the roadmap foresees a volume increase target of 50% for the dairy sector by 2020, in contrast to the targets for other agricultural sectors, which are value based (DAFF, 2010). The dairy volume increase target for the dairy sector requires a level of intensification, expansion or augmented resource use efficiency, to be achieved. All targets under Food Harvest 2020 aim to both intensify output whilst concurrently reducing the environmental footprint of production. For example, a target of increasing dairy production by 50% will simultaneously seek to reduce greenhouse gas (GHG) emissions for every litre of milk produced and provide sustainable returns (DAFF, 2010).

Ireland has a temperate maritime climate which means that it has a natural advantage in relation to grass growing potential. Ireland's success as a major milk producer globally relies on its grass based system and it is this low-cost system that provides Ireland with its competitive advantage. In general, the volatility of agricultural input prices, such as fertilisers or concentrates, requires producers to adjust to minimise this impact on their profitability (Donnellan et al., 2011). In Ireland, whilst a grass-based system allows producers a level of insulation against these input price fluctuations, seasonality and lower yields can represent a challenge not associated with intensive concentrate based systems (Donnellan et al., 2011). Amongst other measures, improved grass utilisation and extending the grazing season are essential to the continued success and competitiveness of the Irish dairy sector. Furthermore, in relation to GHG emission, temperate grass-based systems like Ireland and New Zealand have the lowest emissions per unit fat and protein-correct milk when compared to tropical and arid grassland systems (Teagasc, 2011a). Thus, to reduce the potential of carbon (C) leakage associated with dairy production, the environmental rationale to optimise production in temperate grass-based systems, such as in Ireland, exists.

In North Atlantic maritime climates, however, excess soil moisture is a key constraint to achieving these twin targets, as it simultaneously constrains primary productivity and increases the risk of negative environmental impacts (Schulte et al., 2012). Wet soils are easily damaged and so their ability to deliver soil functions can be compromised. Surface compaction and subsurface compaction have been identified as major threats associated with the climatic regime of North Atlantic Europe related to the trafficking or working of soil under inappropriate soil moisture conditions (Creamer et al., 2010). Wet soils have lower load-bearing capacity and grazing damage can lower herbage production by 20% or more (Humphreys et al., 2011). Furthermore, Schulte et al. (2006) demonstrated that the length of the grass growing season can be reduced by as many as five months at a regional level as a result of excess soil moisture conditions. Overall, wet soil conditions are considered the most important factor limiting the utilisation of grazed grass on Irish farms (Shalloo et al., 2004, Creighton et al., 2011).

In this setting, land drainage systems on existing land in production or on new land areas that fulfil EIA criteria, offer potential as part of a suite of measures to overcome such constraints. Any land drainage works aim to siphon excess water from the soil and maintain the water table at a designated depth below the rooting zone, thereby increasing soil water storage capacity. Primarily from a farm management perspective such an investment improves trafficability for machinery and livestock as the recovery time after episodic rainfall events is shorter (Tuohy et al., 2014). The average cost of milk production is reduced by over 1 € cent/l for a 2.5% increase in grazed grass in the cow diet where the diet of the cow is comprised of more than 50% grazed grass (Dillon et al., 1995, Lapple et al., 2012). Therefore a key objective for land drainage design is to extend the grazing season. The extent of land drainage in Ireland of the utilisable agricultural area is currently low at 25%, relative to other contexts, such as England with 65% (Humphreys et al., 2012).

There are potential threats associated with achieving productivity targets in relation to land drainage (Skaggs et al., 1994, Jacinthe et al., 2001). Soil moisture is a key driver that affects the accumulation and storage of C in soil. Globally, Jobbágy and Jackson (2000) found that soil C stocks are positively correlated with mean annual precipitation and negatively with mean annual temperatures. Thus, larger C stocks are found in latitudinal gradients with moist cold ecosystems and frequently saturated soils (Moyano et al., 2013) as is typical in the Irish context. Conditions where the water filled pore spaces of the soil is close to saturation results in the decreased metabolic activity of aerobic organisms as respiration rates are reduced due to oxygen deprivation and slow diffusion (Franzluebbers, 1999, Dessureault-Rompré et al., 2011). At its simplest drainage of very wet soils promotes aeration which results in the optimisation of microbial oxidation of organic matter and the release of carbon dioxide (CO2) to the atmosphere (Kechavarzi et al., 2010, Willems et al., 2011, Necpálová et al., 2014, Burchill et al., 2014).

Objectives

In this paper, we examine the trade-offs between the soil functions ‘primary productivity’ and ‘carbon cycling and storage’, in response to the intervention of agricultural land drainage systems of imperfectly and poorly draining managed grasslands. Specifically, we examine these trade-offs as a function of the nominal price of Certified Emission Reductions (CER's) or ‘carbon credits’. This is achieved whereby the economic value of productivity gains associated with the installation of land drainage systems is compared to a range of CO2 prices. This is shown spatially to account for geographical variation. This paper therefore constitutes the first example of a practical application of the concept of Functional Land Management that is of direct relevance to policy stakeholders.

Materials and methods

Land use data

Schulte et al. (2014) related the relative functionality of soil functions in the first instance to land use (Figure 1) and added that further categorisation is required in relation to soil drainage categories, which is the subject of current research (Coyle et al., in preparation). Figure 1 shows that all soils deliver a suite of soil functions but the delivery of individual functions relies on land use. Although land drainage systems are installed across different drainage classes, we focus on poorly and imperfectly drained managed grasslands as these represent the vast majority of sites. Grasslands on soils with an organic layer of greater than 40 cm depth or on histic lithosols are not included in this analysis as drainage requirements for peat depend on the parent material underlying the peat layer; furthermore this relates to more long term projects that are commonly outside the scope of individual farmers (Tuohy et al., 2013). Therefore, as a first step in our spatial analysis, we needed to establish the location and geographical extents of land use in combination with the drainage classes poorly drained and imperfectly drained (Schulte et al., submitted for publication).

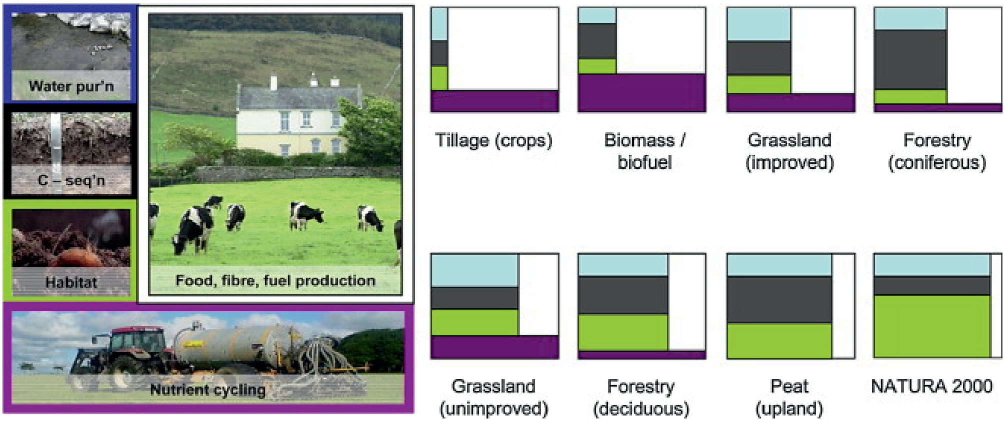

Fig. 1. Freestyle illustration of typical suites of soil functions under contrasting land use types. Schulte et al. (2014)

5

We used the following datasets:

•Land Parcel Identification Service (LPIS), Department of Food, Agriculture and the Marine – data show the farm outlines of all land held by farmers who have applied for support payments from the EU. Data are held electronically on the DAFF mainframe and maps are updated annually by Mallon Technology since 1995 (Mallon Technology, 2014). Data were reclassified on the basis of the main land uses required to populate the matrix in Figure 1. Any other listed land uses were classified as 'other'.

• Forest Service – since 1995 the Forest Service have produced spatial datasets detailing the extent of the forest estate in Ireland. The current dataset, Forest07, includes detailed species information. This information was placed in 'forest type' categories based on the Forest Type definitions using a standardised system of nomenclature adopted to classify forests based on the composition of tree canopy cover, available at: Forest Type Methodology (DAFM, 2013). This was further reclassified wherein all broadleaf and mixed forestry were combined into one category, coniferous stayed as an exclusive category and all remaining forestry was reclassified as other forestry 'OF' to be included in the 'other' land use category.

• Natura 2000 – The National Parks and Wildlife Service (NPWS) is responsible for the designation of conservation sites in Ireland and includes four categories: (1) SPA, special protection areas; (2) SAC, special areas of conservation; (3) NHA, national heritage areas, and (4) PNHA, proposed national heritage areas. Status definitions available at: Protected sites Ireland (NPWS, 2014). Natura 2000 is included as a land use as it represents an important indicator for Functional Land Management. Natura 2000 occurs on all land uses, and this designation defines the management options and the suite of soil functions available. Therefore, in our analysis we use Natura 2000 as a separate land use. Shapefiles were combined to provide one Natura 2000 data layer. Custom python script was used to overcome issues associated with duplicate geometry for sites of more than one designation.

We combined spatial datasets in ArcGIS 10.2.2 using overlay analysis, and maps were generated in Arc Map 10.2.2. Datasets were processed in polygon shapefile format allowing the calculation of geometry and spatial extents of land areas. Figure 2 below shows the workflow schema for the datasets and results are shown in Fig. 3. All datasets were set to projected coordinate system (PCS) of the Irish National Grid TM65_Irish_Grid.

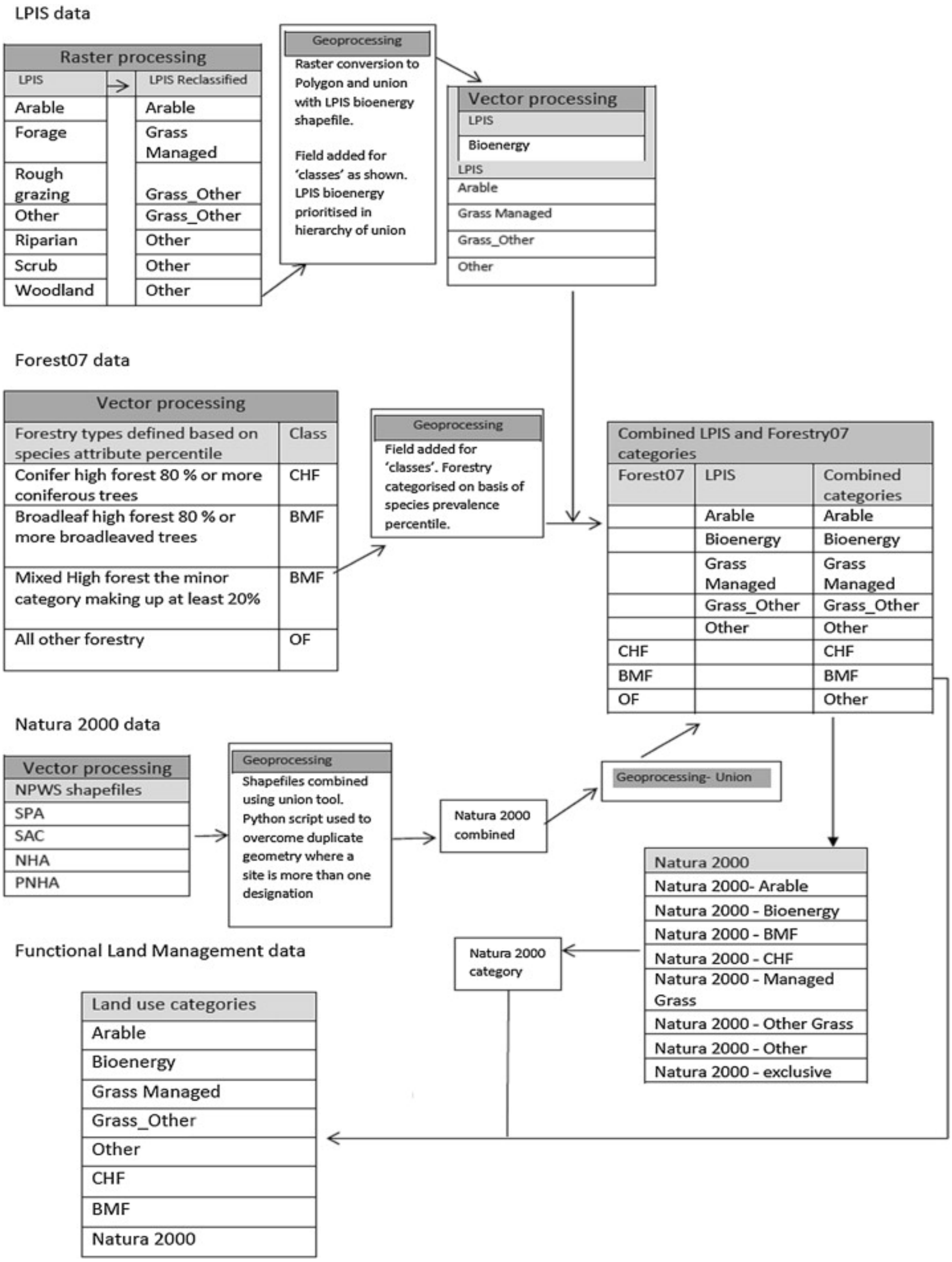

Figure 2. Land use mapping data schema.

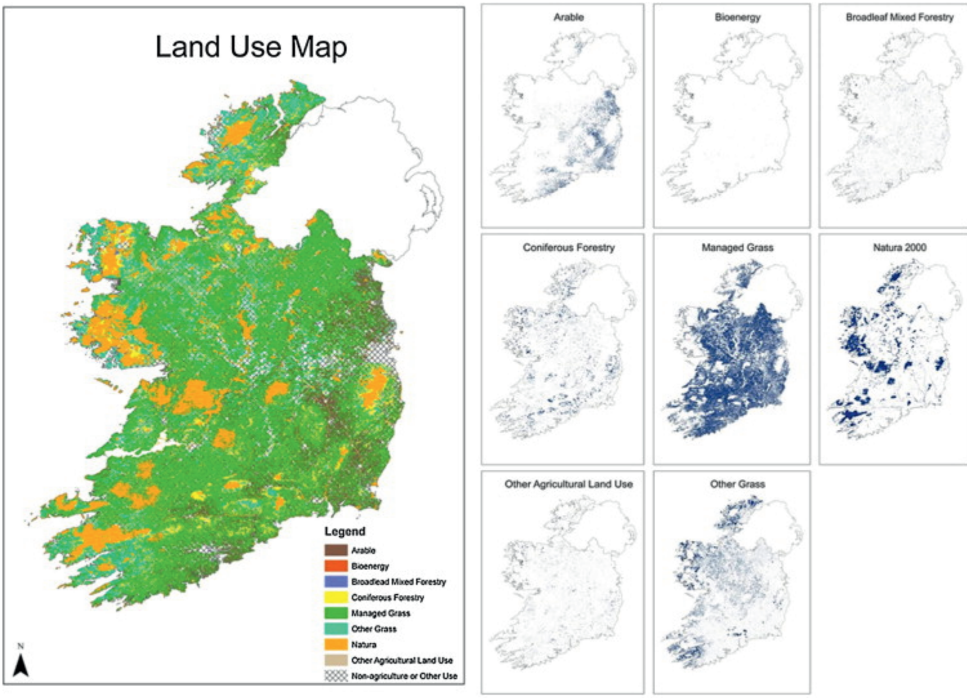

Fig. 3. Indicative land use map of Ireland.

Soil drainage

To extend this and include soil type in addition to land use type, the land use data were overlaid with an indicative drainage map (Schulte et al., 2005, Schulte, (under review)). The indicative drainage map is based upon the Irish Soil Information System National Soil Map of the Republic of Ireland, constructed at 1:250,000 (Creamer et al., 2014a). Importantly, land drainage works in Ireland typically are <10 hectares (ha) in size, where soils are heterogeneous and standardised drainage system designs are not appropriate as these are intrinsically site specific. Consequently, characterisation of Functional Land Management is generalised to a scale that is usable at a national policy level and is not suitable at a farm or local level. Based on the Irish Soil Information System, this scale is 1:250,000 which can account for spatial variability at a soil association level. Drainage categories were assigned on the basis of diagnostic features based on field based descriptions (Schulte et al., submitted). This enabled us to calculate the spatial extent of each drainage class for every land use category (Table 1). Poorly draining soils were defined as those showing mottling throughout the profile and have an argic or spodic horizon resulting in stagnation. Soils with much more than 40 cm of an organic layer are classified as peat. Moderately drained soils present mottling at depth, but lack any organic matter accumulation but an argic or spodic horizon may be present. Mottling at the same depth but with a presence of some organic matter accumulation and an argic or spodic horizon present were categorised as imperfectly drained. Well drained soils are those that showed no evidence of water-logging and have no argic or spodic horizon present. For the small number of soils where the presence of sandy loam or sandy textural classes is dominant, this soil subgroup was considered excessively drained. A detailed description of the diagnostic criteria will be published in Schulte et al. (submitted).

Table 1. Land use with drainage category based on Irish Soil Information System (ha).

	Arable	**Bioenergy**	**Broadleaf mixed forestry**	**Coniferous forestry**	**Managed grass**	**Other grass**	**Natura 2000**	**Other agricultural land use**
Excessively	3631	35	200	91	10,499	803	3771	137
Well	160,589	961	42,238	61,420	1,287,372	93,010	71,495	28,290
Moderately	124,152	721	16,826	23,234	661,375	42,447	15,102	11,345
Imperfectly	8358	79	6345	22,383	157,985	44,611	54,698	6614
Poor	65,746	595	33,016	57,534	797,567	87,663	148,449	24,438
Peat	7605	101	48,272	171,572	236,938	456,646	478,529	47,642
Other*	1441	13	2649	2057	26,310	60,086	268,963	1536
Grand total	371,522	2505	149,546	338,291	3,178,046	785,265	1,041,005	120,001

* Includes mask, urban, tidal marine, rock, island.

5

Carbon loss model

Biogeochemical modelling

We used a modified version of the DNDC model (version 9.4; see Li et al., 2011, Abdalla et al., 2013) to assess the impact of drainage on Irish soils. DNDC contains four main sub-models (Li et al., 1992, Li, 2000, Li, 2011); the soil climate sub-model calculates hourly and daily soil temperature and moisture fluxes, the crop growth sub-model, the decomposition sub-model and the denitrification sub-model.

The model calculates soil organic matter sequestration from simulated organic matter turnover, crop growth (which simulates crop biomass accumulation and partitioning) and decomposition (which calculates decomposition, nitrification, ammonia (NH_3) volatilisation and CO_2 production through heterotrophic and autotrophic respiration). When grass is cut or grazed, all of the root biomass and a specified fraction of the stem biomass are added to the soil litter pool of carbon. C and nitrogen (N) inputs from agricultural management (i.e. animals and fertilisers) are also inputted via management and grazing sub-routines. Leached carbon is calculated from the hydrological model which simulates hydrological flows. The denitrification sub-model tracks the sequential biochemical reduction from nitrate (NO_3) to nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) and nitrogen (N_2) based on soil redox potential and dissolved organic carbon.

Daily measured values of meteorological parameters, management and soil properties were used as input variables to the DNDC model (see below). Field N_2O flux data were used for DNDC model validations by comparing previous measured and predicted gas fluxes (see Li et al., 2011). As soil C sequestration is sensitive to the distribution of C between recalcitrant and labile pools, the models were run for 200 years until soil C pools reached equilibrium. The model was then run with (a) the water table set near the surface (10 cm) (near saturated conditions which would represent and un-drained scenario), and (b) with the water table depth dropped to 1.5 m below the surface (drainage system represents deepest piped drains possible). Both depths are chosen as representing the full range of conditions in relation to land drainage.

Parameters

• Synoptic station data – weather data from five main weather stations geographically spread across the republic of Ireland were used: (1) Valentia; (2) Malin Head; (3) Belmullet; (4) Mullingar, and (5) Dublin. Data were recorded by Met Éireann (the meteorological service of Ireland).

• Clay content values for drainage classes were defined using the modal series for soil types. Soils were categorised on the basis of drainage (well, imperfect and poor) and type (histic, humose or typical). Horizons were disaggregated to depths of 0–25 cm; 25–40 cm; 40–60 cm and 80 cm plus. The clay values by horizon for the different soil types were averaged to develop a clay horizon curve based on data analysed for the National Soil Map (Creamer et al., 2014a).

• The livestock density was set at two typical dairy cows per hectare (ha) with an implied organic manure deposition of 85 kg per animal and 170 kg ha^{-1}. These figures are above the average livestock density in Ireland, but typical for farms, predominantly dairy enterprises, that are currently installing drainage systems in anticipation of the abolition of EU milk quota. This livestock density also corresponds to the lower limit of the derogation requirement by Ireland pursuant to Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources to be sufficiently accounted.

Indicative carbon map for imperfect and poorly draining grasslands

The potential C loss was computed from the difference in soil C stocks associated with each of the modelled groundwater depth. We accounted for the spatial heterogeneity of soils by using the Irish Soil Information System, which provides an inventory of the diversity of soils and their properties as well as geographic extents (Creamer et al., 2014b). As a result, we produced an indicative soil C loss map that, at an association level (1: 250,000), accounts for the spatial variation in the potential soil C loss. Output data from the C model was plotted indicating the soil organic carbon (SOC) (tonne C $ha^{-1}a^{-1}$) loss associated with drainage for both imperfect and poorly draining soils used for managed grass. These data were splined using a tension spline set at 0.1 and 4 points in ArcGIS 10.2.2 and converted to shapefile format. These steps were processed separately for the imperfectly draining and the poorly draining soils. Finally, these shapefiles were unioned to produce a combined indicative SOC loss map.

Productivity data

The impact of drainage on productivity was approximated by computing the extent to which land drainage decreases the number of days at which soils are untrafficable (Schulte et al., 2012). In their review, Schulte et al. (2012) found that a variety of trafficability thresholds are used in the literature, ranging from 0 to 10 mm soil moisture deficit (SMD). For the purpose of this exercise, we used a threshold of 5 mm. Here, we assumed that land drainage moves soils from the poorly drained or imperfectly drained categories into the moderately drained drainage category, as defined by the Hybrid Soil Moisture Deficit model (Schulte et al., 2005). The Hybrid Soil Moisture Deficit model has been widely applied and is used at a national level by Met Éireann and is cited in more than 50 scientific papers. It has been extensively calibrated for Irish conditions. An important caveat in this regard, is that the extent to which land drainage could move from imperfectly or poorly draining category to the next drainage category is site specific and may not be accurate for some of the wettest soils. However, for simplicity we made the zero-order assumption that the drainage works would be appropriately customised to the site-specific drainage requirements. By doing so, we quantify the potential increase in trafficability for all drainage scenarios in Ireland. For 104 climatic weather stations operated by Met Éireann, we computed the daily SMD for a 30-year period from 1979 to 2008 for poorly drained and moderately drained soils. Subsequently, for each of these weather stations we derived the median number of field capacity (FC) days for both drainage categories. The difference between these two median values was taken as an indicative value for the increase in the length of time that the soil is trafficable, and hence the increase in the length of the potential grazing season.

Expressing this increase in herbage productivity and utilisation in economic terms, previous research (reviewed in Schulte et al., 2012) has shown that this longer grazing season translates into an increase in the gross margin of dairy farming of between €2.30 and €3.20 per cow per day (Shalloo, 2009, Kinsella et al., 2010). Here, we used €2.75 as the average within that range. Similar to the C loss model, we assumed an average stocking rate of two cows per ha, resulting in an increase in €5.50 per ha per day of increased grazing season.

The economic data were added to the productivity file which was plotted in ArcGIS 10.2.2 and splined using a tension spline set at 0.1 and 4 points to develop an indicative productivity shapefile for Ireland. Once converted to a shapefile this was unioned and clipped with the imperfectly and poorly draining grasslands to give the final productivity file.

Carbon maintenance versus land drainage

The indicative soil C loss map (Figure 4a) was unioned in ArcGIS 10.2.2 with the difference in trafficability days map (Figure 4b). When combined a field was added and the final hectare extent of each polygon was calculated.

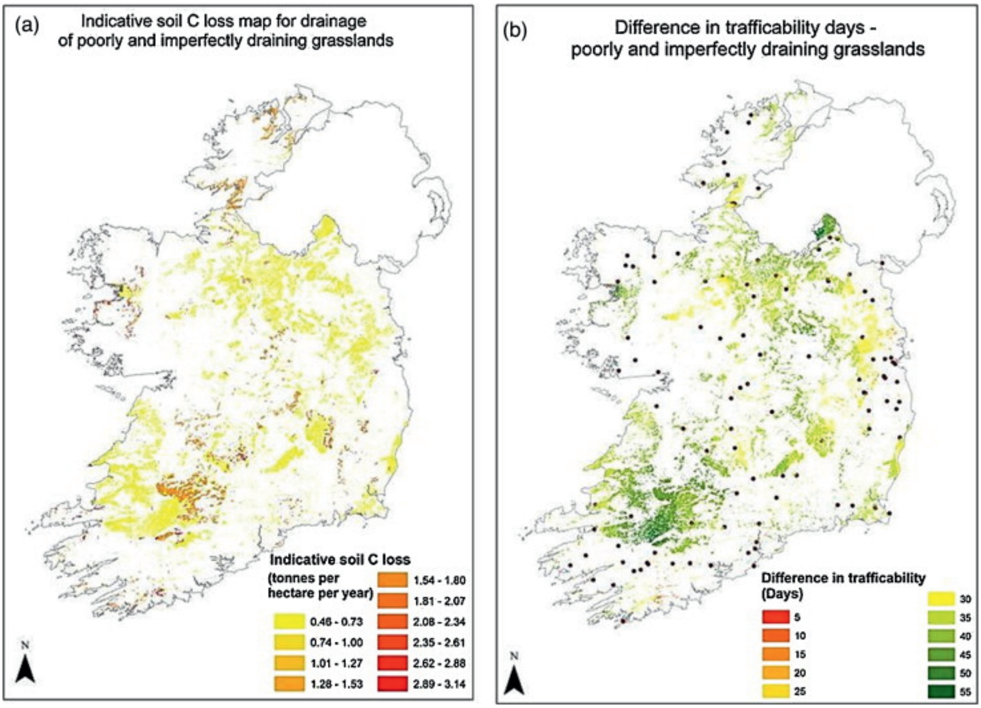

Figure 4. (a) Indicative annual soil C loss for poorly and imperfectly draining grasslands in Ireland associated with drainage in one year, using a 30 year discount period. Data are categorised using equal intervals for illustrative purposes. (b) Difference in trafficability days for the same soils. The data for both figures were combined to compare (a) variable carbon price against productivity as defined by trafficability days.

To add the productivity value gains associated with drainage a field was added and populated as follows:

Productivity value gain = [hectares] x [days] x [€5.50]

To add the SOC loss value, a field was added and populated by calculating the value by:

$$Annual\ SOC\ loss = \frac{\text{[Final SOC value]}}{\text{[Discount rate 30 years]}}$$

To quantify CO_2 emissions the C stock changes were converted to units of CO_2 emissions by multiplying the C stock change by a conversion factor 3.667 (US EPA, 2004):

$CO_2\ loss = [Annual\ SOC\ loss] \times [hectares] \times [variable\ price]$

We calculated the value of CO_2 loss for each polygon by multiplying the area extent by a variable price:

CO_2 loss values = CO_2 loss x [hectares] x [variable price]

The differential value of soil functions was calculated as: the difference between drainage benefit and the variable C prices:

Differential values of soil function = [Productivity value gain] – [CO_2 loss value]

Results

Spatial extent of land use

Figure 3 represents the first coherent land use map that combines agricultural land use categories, as defined within the Functional Land Management concept. Irish agriculture is primarily a grass-based industry (Teagasc, 2014). In line with this, excluding Natura 2000 designated grass, 'managed grass' accounts for over half (53%) of the agricultural land area and when combined with the 'other grass' category accounts for two-thirds of this area (66%). Arable represents almost 377 kHa, which aligns with findings of the Teagasc Tillage Crop Stakeholder Consultative Group (TTCSCG, 2012). Bioenergy continues to be a minor land use (<1%), reflecting little change since the end of the government pilot scheme in 2009 to support the development of non-food energy crops (McDonough, 2010). Coniferous plantations represent a much larger portion of land area compared to the broadleaf mixed forestry, and this is consistent with the focus on commercial timber and pulp production largely composed of non-native conifers that grow quickly in temperate moist climates (Bosbeer, 2012).

Table 1 reflects the spatial extents of land uses in their respective soil drainage categories. This table, whilst providing an aggregate spatial extent of the suite of soil functions in relation to drainage categories, does not distinguish between soil types but this is the subject of ongoing research. Soils in the poorly, imperfectly and peat drainage categories combined make up almost half (49.19%) of the soil drainage categories in Ireland. As these categories are considered 'wet soils' this finding aligns with that of Humphreys et al. (2011) who proposed that drainage problems account for almost half of soils in Ireland. In their research, Creighton et al. (2011) found wet soil conditions are likely the most important limiting factor restricting grass utilisation on Irish farms. Notably, even on well-drained soils, the number of field capacity days (Van Orshoven et al., 2013) is the main constraint to herbage utilisation (Creighton et al., 2011, Schulte et al., 2012). Given that a majority of agricultural land use in Ireland (Table 1) is dedicated to grasslands, wet soil conditions represent a major limitation in Irish agriculture. In relation to forestry, 75% of coniferous forestry can be found on wet soils, 51% of which is found on the peat drainage category. Similarly, 59% of broadleaf and mixed forestry are found on wet soils. In contrast, a majority of arable production (78%) is found on the drier soil drainage categories.

Trade-offs within Functional Land Management – the case of carbon storage and productivity gains associated with land drainage

Figure 4a shows the spatial variability of potential SOC (tonne C $ha^{-1}a^{-1}$) loss in response to the installation of drainage systems, with greatest losses observable in the north-western and coastal locations of the country. The spatial variability of the delivery of the productivity function is represented in Figure 4b and shows that the greatest benefits associated with drainage in relation to productivity gains can be found mostly in the south-west. This aligns with on-going research in relation to 'heavy' soils that are found in the south-west region, where these areas are known to be negatively impacted economically, due to excess soil moisture conditions (O'Loughlin et al., 2012; Tuohy et al., 2015).

Figure 5a illustrates that at today's international CO_2 price of €6 per tonne (Thomson Reuters, 2014) productivity gains by far exceed the monetary value of potential CO_2 losses for almost 100% of the total grassland area. In contrast, at €150 per tonne, as illustrated in Figure 5d, productivity gains are exceeded by this nominal CO_2 value in almost all areas (99.9%). Figure 6 below, shows this relationship as the proportion of wet grassland where the value of CO_2 exceeds the value of productivity gains.

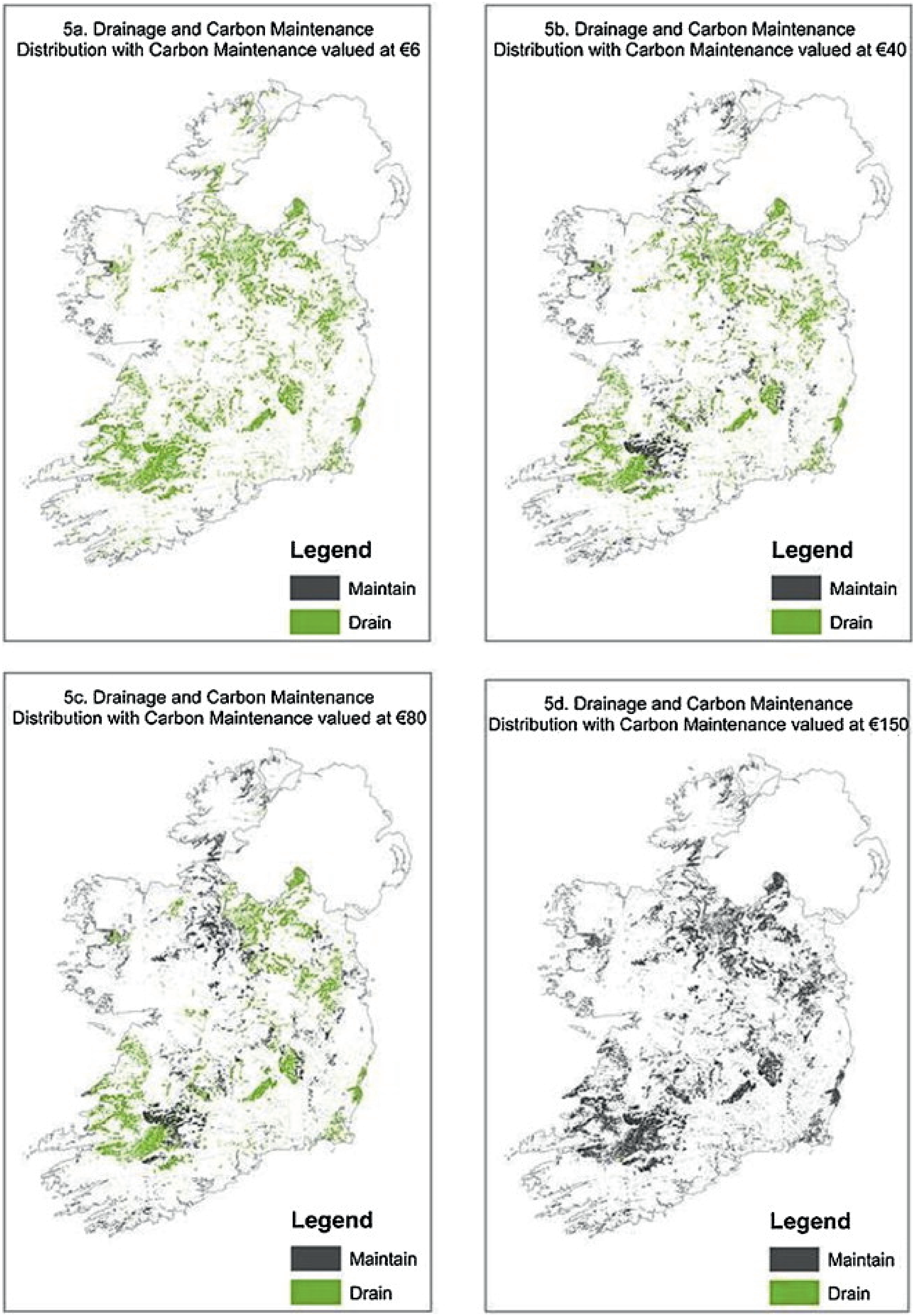

Figure 5. (a–d) Drainage and carbon maintenance distribution relative to C values ranging €6–€150.

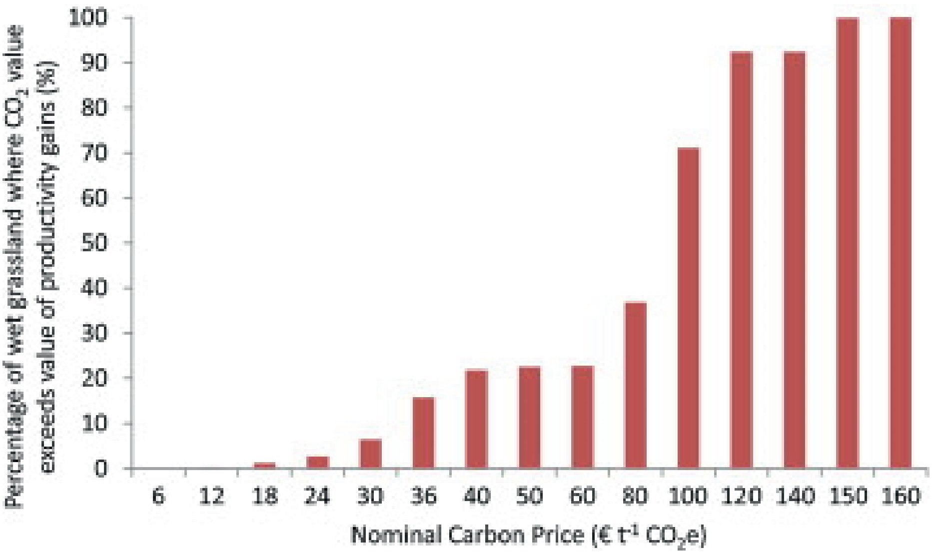

Figure 6. Proportion of poorly and imperfectly drained grasslands on which the value of soil carbon loss is projected to exceed the value of productivity gains, in response to the installation of drainage systems.

Discussion

Model constraints

The explicit aim of this paper was to assess trade-offs between two soil functions, namely carbon storage and primary productivity, in response to a management intervention, in this case artificial land drainage systems. In the context of studying the impact of land drainage on GHG balance sheets, this paper only considers soil carbon cycling and storage as the pertinent soil function being examined. A full GHG analysis would involve a full life cycle analysis (LCA) that quantifies changes in nitrous oxide (N_2O) and methane (CH_4) emissions, as well as changes in productivity in order to account for land use and indirect land use effects, which was outside the scope of this study. Also the time period for the loss of SOC was set at 30 years post-drainage. However, the impacts of land management on grassland soils can vary from 10 years to >100 years depending on (a) the magnitude of the disturbance and (b) the soil type and climate (Poeplau and Don, 2013). For similar reasons, we did not consider the capital costs associated with drainage systems in our economic analysis; instead, we constrained our analysis to the change in the value of the soil function 'primary productivity'. On a grassland site, specific drainage requirements and therefore design (spacing and depth) vary depending on soil physical parameters, site geometry and drainage criteria (rainfall minus evapo-transpiration). As a result, the current cost of a field drainage system ranges from €125 ha^{-1} for a shallow mole drainage system to €8600 ha^{-1} for the piped drainage conventional system (Anon., 2013). A cost benefit analysis, not based on empirical data, of the economics of land drainage for dairy systems has previously been quantified by Crosson et al. (2013) which found that where land drainage costs exceed €7413 ha^{-1} there is only economic benefit where grass growth increases by 30% at a milk price above 28 cent/l and 20% above 34 cent/l. These capital costs should be taken into account in the interpretation of Fig. 5. Where these costs are high, this will reduce the monetary value of gains in primary productivity, and will reduce the price of C at which these gains are equalled by loss in the value of soil C.

For the indicative soil C map, five synoptic weather stations were used, and although geographically spread across the country, this reflects a lower spatial resolution of the C model as opposed to the trafficability model which was based on daily data from 104 climatic weather stations. This difference in the number of weather stations used for the two maps is consistent with the difference in resolution or precision between the C model and trafficability model, with the latter having been extensively calibrated, validated and used, specifically under Irish conditions: this allowed for a greater resolution in input data.

We arbitrarily set the threshold for trafficability at 5 mm of SMD, this being the middle of the range of thresholds reviewed by Schulte et al. (2012). Our experience with the Hybrid Soil Moisture Deficit model is that this is also the range at which the model predictions on SMD diverge most prominently between drainage categories: the model converges when the SMD approaches either 0 mm or exceeds 10 mm.

Sensitivity analysis

We based our analyses on a discount period of the soil C losses of 30 years following the installation of drainage systems. However, the rules governing the accounting of the Land Use, Land Use Change and Forestry (LULUCF) sector are currently under development and subject to change. In Figure 7, we present a sensitivity analysis in relation to both the nominal CO_2 price and the discount rate over which the loss of SOC is applied for reporting purposes. The results show a high degree of sensitivity to the discount period. At a discount rate of 10 years the increased value of productivity could be outstripped by the environmental value of CO_2 loss almost at a carbon price as low as €40 per tonne. In contrast, when we apply a discount period of 40 years at the same price, productivity gains exceed CO_2 value in almost all areas.

Trade-off between soil functions 'primary productivity' and 'carbon cycling and storage'

Using Ireland as a case-study, we explored the trade-offs between the two soil functions. Specifically, we examined these trade-offs as a function of the nominal price of 'carbon credits'. This trade-off has been demonstrated spatially using a range of C prices (Figure 5a–d). In relation to the delivery of soil functions it is essential to understand how individual soil functions are prioritised. In particular, it is necessary to understand the perspectives of those that are responsible for the delivery of the supply of soil functions (generally farmers and foresters), and those that frame demand for soil functions (i.e. policy makers).

Farmers value primary productivity as it directly affects farm income. Land drainage offers increases in productivity potential. At the scale presented in this study, the research indicates that land drainage could potentially increase the trafficable period by as many as 55 days per year (Figure 4b), which translates to productivity gains of €302.50 ha^{-1} a^{-1}. Based on current CO_2 prices of €6 per tonne (Thomson Reuters, 2014), Figure 6 shows that the value of these gains in productivity exceed the "carbon cost" on almost 100% of the grasslands in the study. For farmers, the environmental cost does not translate into a change in income, or into a direct and observable change in the quality of the countryside, especially at today's CO_2 price. Even if future CO_2 prices were to increase to €40 tonne, this finding still holds true for almost 80% of the relevant area.

In contrast, the C cycling and storage function of soils is a high priority for policy makers who are focused on reducing EU GHG emissions. To this stakeholder group, land drainage may represent a potential threat. Whilst recognising the agronomic opportunity cost in relation to decisions to forego land drainage, they may consider this cost small compared to the long-run environmental cost.

Our paper shows that these divergent perspectives can be explained, at least partially, by the different monetary values that these two stakeholder groups assign to soil organic carbon. EU Commission, developing a policy for 2030, bases their assessments on the projected CO_2 price by 2030, which they set at €40 per tonne CO_2 (EC, 2014a). Allowing for an inflation rate of 2% per annum, this would equate to a value of €30 per tonne in today's money. Based on these assumptions, Fig. 5 indicates that should this higher CO_2 price materialise by 2030, the environmental cost of C loss would outstrip the financial benefits of increased production for 21.78% of the area at a discount rate of 30 years. CO_2 loss would only exceed productivity gains at either higher CO_2 prices, or at reduced discount rates (e.g. 10 years) that are currently being considered. Figure 7 demonstrates that the outputs are indeed very sensitive to the discount period rate.

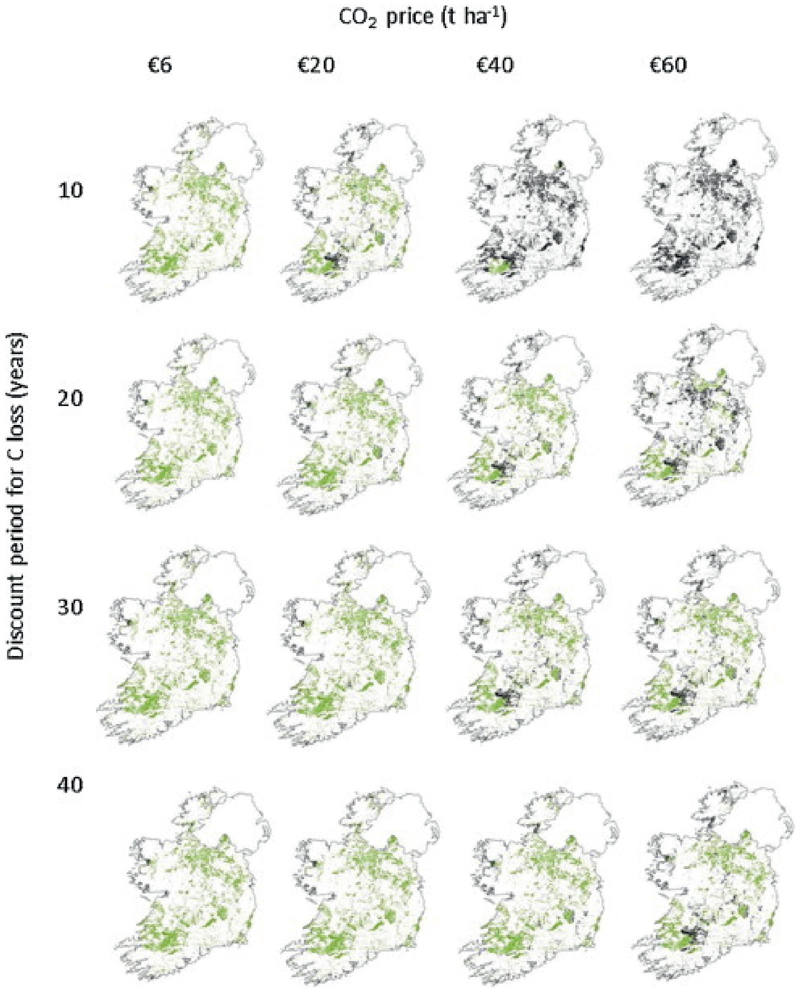

Figure 7. Drainage (green) and carbon maintenance (black) distribution as a function of the nominal value of carbon and variable discount periods ranging from 10 to 40 years.

At this point, it is unclear to what extent the C price can be managed or manipulated to incentivise maintenance of soil C stocks. Currently, this price is determined by the international market price. GHG emissions from agriculture are aggregated at national scale and any compliance or non-compliance with EU targets is burdened by the national exchequer. Opportunities for farm-level incentivisation are limited: two key issues emerge in this regard. In the first instance, the rules of EU agri-environmental schemes under the Common Agricultural Policy (CAP) Pillar II only allow for actual costs to be remunerated. The calculation of premia for EU funded schemes is derived on the basis of costs incurred and income foregone by the farmer in the participation of the agri-environmental measure (Murphy et al., 2013). Not draining land does not represent an actual cost, but is instead an opportunity cost and as such is not eligible to be included under Pillar II payments (Murphy et al., 2013). Secondly, monitoring, reporting and verification (MRV) or carbon-auditing at a farm scale are associated with significant operational challenges that include high administrative transaction costs, low accuracy, issues of equitability (Teagasc, 2011b).

In conclusion, this research highlights that in relation to 'primary productivity' and 'carbon cycling and storage' a considerable gap exists in relation to the prioritisation of these soil functions from two diverging stakeholder perspectives. Whilst the current CO_2 price fails to incentivise the maintenance of SOC stocks this equation is likely to change, depending on the discount period applied in MRV of the LULUCF sector. Moreover, the metrics used for EU funded schemes would require more flexible mechanisms that could also take account of opportunity costs.

Functional Land Management for supporting targeted policies

Forest and agricultural land currently covers more than three-quarters of the EU territory and naturally hold large C stocks (EC, 2014b). The release of just 0.1% of the C stored in these soils would equal the annual emissions from 100 million cars (EC, 2014c). In Ireland, despite a downward trajectory in carbon emissions since 2005, agriculture still accounted for 40% of the non-ETS emission and 30% of all GHGs in 2011 (Farrelly et al., 2014). Within the EU, expanding on previous climate and energy packages, European leaders have committed to reductions in both the emissions trading sector (ETS) and the non-ETS amounting to a 43% and 30% reduction by 2030 compared to 2005 respectively (European Council, 2014). Given the size of the agricultural sector in Ireland, and its contribution to GHG emissions, any meaningful reduction in GHG emissions will require a marked reduction in agricultural emissions.

Where a divergence in the prioritisation of soil functions exists, such as was highlighted here, a need to harmonise and incentivise the delivery of soil functions to meet multiple objectives exists. Here, we performed a sensitivity analysis at a range of C values in relation to biophysical criteria at a scale that is potentially usable for policy makers in constructing a realistic value to satisfy the demand for an individual soil function, in this case C cycling and storage, in relation to the primary productivity function. Moreover, we performed a sensitivity analysis in relation to variable discount periods, the results of which yielded a high degree of sensitivity to the discount rate. Both of these, enable policy makers to develop agri-environmental policies that support the optimisation of soil functions by contrasting the potential trade-offs between soil functions. This would allow soil functions to be altered in such a way that some functions can be incentivised or suppressed. At a time of ever increasing demands on the soil resource, the Functional Land Management framework can facilitate the development of land use policies that are more harmonised and result in land use management decisions that better reflect policy goals and targets. The spatial analysis presented in this paper enabled the characterisation of the spatial dimension of the complex interaction between land use and biophysical constraints/endowments, as defined by soil drainage categories. The Functional Land Management framework thus allows for the development of policies that are specifically tailored to contrasting biophysical environments, and are therefore potentially more effective than 'blanket approaches'. By design, Functional Land

Management is not intended to be a legislative instrument for the ‘zoning’ of land use, but rather a tool to support policy decision making that incentivises appropriate land management decisions (O'Sullivan et al., 2014, Schulte et al., 2014).

Whilst this research is focused on the development of Functional Land Management as a tool for national or regional policy formation, it is important to briefly consider how national target setting relates to changes in management practices at farm level and vice versa. Notwithstanding the challenges associated with translating a national objective into an agricultural cost or incentive, synergies exist between national and farm level priorities. The success of Ireland's significant food exports is intrinsically linked to the green credentials associated with management practices at farm level. It is a contemporary imperative to demonstrate and further improve the C efficiency of production to maintain these credentials (Murphy et al., 2013). Farm level tools, such as the Carbon Navigator that measure and guide adoption of technologies to reduce GHG emissions on farms, provide one mechanism to support this. It is important that such tools are flexible and can incorporate new research findings, for example in relation to decision making on drainage. As such, these tools can then provide a pathway to connect national policy objectives to on-farm decision making.

Further research

As a first example of Functional Land Management, we have investigated the impact of a manipulation of soil functions by direct alteration of soil properties. Therein, this study provides one example of the trade-offs between two soil functions. Further research would seek to build on this case study by exploring trade-offs in relation to the delivery of the other soil functions: water purification, habitat and nutrient cycling in response to land drainage interventions. In relation to the technicalities of land drainage, there remain knowledge gaps in relation to spatial extent of different types of drainage systems and further investigation could expand on and refine the current model. Equally, it is important to investigate further opportunities for synergies between national level target setting and on-farm management practices and develop pathways to connect these two.

Conclusions

- We have explicitly quantified an example of the trade-offs between two soil functions: primary productivity and C cycling and storage.
- We used drainage systems for this example: these can increase productivity by up to €302.50 ha^{-1} a^{-1}, but decreases soil carbon stocks.
- We showed that the prioritisation and incentivisation of these competing soil functions is primarily a function of the CO_2 price.
- At the current CO_2 price, the agronomic benefits are larger than the monetised environmental costs. This results in an incentive for farmers to drain.
- Even at future projected prices, this finding remains true for almost 80% of the land area however this is highly dependent on the discount period.

- Should the discount period be reduced to ten years could result in an inverse observation materialising. This scenario could result in incentives for policy makers and legislators to discourage the installation of drainage systems.
- Finally, our study shows large geographic variation in this environmental cost: agronomic benefit ratio. This allows for more specific and hence effective prioritisation of the two contrasting soil functions.

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CHAPTER 6

Functional land management: Managing soil functions at intercontinental scale

Intercontinental learning – local management in a globalised context

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Intercontinental learning – local management in a globalised context

Introduction

The European Union (EU) has put forth ambitions for European food to become a global standard in relation to sustainability (EC, 2020). Notwithstanding major progress in relation to traceability, abundance and quality, EU food systems remain characterised by environmental degradation, climate change impacts and a reliance on excessive inputs (EC, 2020). The European Green Deal sets out a target of climate neutrality by 2050, with a series of targets and actions under the Farm to Fork (F2F) and Biodiversity strategies that strengthen the sustainability criteria that EU farmers must meet. The Common Agricultural Policy (CAP) is the key agri-environmental framework that aims to support farmers to provide affordable, safe and nutritious food to European citizens (EC, 2018a). Increased subsidiarity via strategic plans developed at national level should enable common EU level objectives to be implemented in a more targeted approach on the ground (EC, 2018b). This opportunity challenges member states (MS) to look inward to identify context specific targeting to reach higher ambitions on climate and environment objectives in line with targets set.

However, EU societal demand for land based ecosystem services is only partially satisfied by EU domestic supply with the import of agricultural products an important factor in meeting demand requirements (Staes et al., 2018; Schulte et al., 2019; Vrebos et al., 2019, EC, 2018c). Markets, while facilitating the transfer of primary goods, often do not fully account for the delivery of other land-based public goods. This has been shown in multiple studies that map the global flows of ecosystem services (e.g. Erb et al., 2009; Yu et al., 2013; Rulli et al., 2013; Boerema et al., 2016; Chaudhary and Kastner, 2016; Uwizeye et al., 2016, Nesme et al., 2018, Escobar, 2020). These studies highlight significant environmental impacts, such as embodied greenhouse gas (GHG) emissions and negative impacts on biodiversity associated with land use and land use change. If the environmental impact associated with traded goods is not reflected in market prices, it is not internalised by consumers or producers, giving rise to spillover effects or negative environmental externalities that have a social cost (OECD, 2003). Trade underpins the displacement of environmental burdens associated with production through the value chain (West et al., 2014), typically from resource-abundant to resource-scarce countries (Kastner et al., 2014; Macdonald et al., 2015). As a result, globally traded agricultural commodities with their complex supply chains present a major challenge for climate change mitigation and environmental governance (Escobar et al., 2020). This raises questions in relation to the external dimensions of European Green Deal.

It is important that solving a problem in one region does not generate unintended negative consequences in another region. Stringent unilateral environmental policies can give rise to carbon leakage as GHG emissions can increase by shifting production to a second country with lower standards and costs. High standards can alter the playing field for producers by affecting competitiveness, not only for EU producers but also for developing countries for whom the achievement of such standards may be cost prohibitive. These costs are sometimes put forward as reasons to side-line environmental concerns however there is no conclusive evidence that environmental policies undermine trade agreements (Cordero et al., 2004). In the context of the climate and environment ambitions put forth in the European Green Deal, it is necessary to consider how mediation of trade by governance can affect ecosystem flows to avoid carbon leakage or environmental impacts.

The displacement of ecosystem services through trade of is often viewed through the lens of a singular ancillary service or co-benefit, e.g. climate regulation carbon foot printing, with few concepts that capture the multiple embedded ecosystem flows associated with the wider multifunctional nature of land. Currently, primary productivity, nutrient cycling, water regulation and purification, carbon and climate regulation and habitat for biodiversity are recognised as the key soil based ecosystem services or soil functions delivered simultaneously across agricultural land (Haygarth and Ritz, 2009, Schulte et al., 2014, 2019; Creamer et al., 2022). Collectively, this suite of soil functions underpins the functional land management (FLM) framework. In this paper, we use this framework to quantify soil-based ecosystem services in response to national/EU policy interventions. In the context of emergent EU policies, if we want to avoid C-leakage and other environmental consequences, what can we learn in relation to the impact of past EU policies? Quantifying ecosystem flows of soil functions and visualising governance signals here is intended to expose these impacts to contribute to the discourse in relation to current ambitions on increasing sustainability requirements for agri-food systems in the EU while drawing wider conclusions for policy stakeholders. We hypothesise that governance drivers can inform local land management choices at intercontinental scale.

Aims and objectives

In this paper, we take the FLM integrated framework to assess soil based ecosystem flows. Taking soybeans, a key traded commodity at the international scale, we aim to quantify the ecosystem flows in the context of three case studies - Brazil, China and the Netherlands. Along with the quantification of these flows, we conduct a literature review of the main policies across the case studies with implications for land use and management. With this cross scalar case study approach, we aim to visualise land use and management in the Upper Xingu River Basin (UXRB) region in Brazil as a function of governance signals at continental scales. The main objectives of this research are to:

- quantify the flows of soil functions directly and indirectly (embodied) with soybean exports from Xingu region in Brazil to the Netherlands and China;
- visualise the key governance drivers of the case studies in the context of land use and land use change of the Xingu region of Brazil;
- Explore how signals for soil functions are altered when translated across border/governance space at continental scale.

Context of case study areas - Brazil, China and the Netherlands

Brazil

The environmental impacts of soybean production in Brazil are a much researched topic receiving global attention, including the environmental pressures associated with global trade (e.g. Zaks et al, 2009; Barona et al., 2010; Galford et al., 2010; 2011; Karstensen et al., 2013; Lathuillière et al., 2014). Brazil is a major agricultural producer worldwide and is the second largest global producer of soybean since 1975, the majority (85%) of which undergoes processing to produce soybean meal (78.5%) and oil (19%) with ~ 2.5% lost in the production process (Lima-Brown et al., 2012). Soybean meal is used to make animal feed and is the largest source of protein feed in the world that is indirectly consumed by humans. Located in the state of Mato Grosso in the southern part of the Amazon, accounting for ~2% (~170, 000 km^2) of the land area of Brazil, the Upper Xingu River Basin (UXRB) is one of the world's most rapidly expanding and intensifying agricultural frontiers (Kastens et al., 2017; Garcia et al., 2019). The UXRB is home to the Amazon and Cerrado biomes, both characterised by high endemism. Government financial incentives, including for settlers and companies to establish in the region, technological advancements such as efficient seeds and fertilisers have supported the growth of the agro-industrial sector, the latter making millions of hectares of previously unproductive areas utilisable (Miccolis et al., 2014; Nepstad, 2014). Favourable market conditions, soils (oxisols) that respond well to inputs and flat topography have positioned UXRB as a major agricultural producer in Brazil (Kastens et al., 2017). Across four decades, increased cattle ranching and global demand for soybean firstly from Europe and subsequently China, have fuelled deforestation due to increasing demand for meat. The Mato Grosso region has benefitted economically from agriculture (Richards et al., 2014) but it may also be associated with social issues including displacement of smallholder farmers and traditional communities, commodity crop production over staple foods, as well as environmental impacts, particularly in relation to biodiversity loss and greenhouse gas (GHG) emissions (Barona et al., 2010; Galford et al., 2011). Pesticide use has increased rapidly (Schiesari et al., 2018), such that Brazil has become one of the largest users of pesticides globally. The soils in Mato Grosso exhibit high phosphorus (P)-binding capacity (Ahamed et al., 2006) and therefore require high levels of P additions to maintain yields.

China

In China, population pressure and rapid development are placing immense pressure on water resources (see Liu & Yang, 2012 for succinct overview). Despite having the sixth largest freshwater resources in the world, per capita water resource availability is only one fourth the global average (Wang et al., 2008). As many as 300 million rural residents lack access to clean drinking water with cities experiencing water shortages while rivers and lakes are severely polluted (CAS, 2007 in Liu and Yang, 2012). This is compounded by a spatial mismatch between population and water resources (Akiyama et al., 2018). In 2021, for the 18th consecutive year, the No 1 Central Document, indicative of priority setting by the Chinese Government, was devoted to agriculture, farmers and rural areas. Securing supply of certain products and the need to rely on imports of products in short supply has previously been highlighted (China SCIO, 2019). Soybeans have traditionally been grown in northern China but their cultivation has been associated with water tables dropping by 3-10 feet a year (Brown, 2011). Products with a high natural resource requirement per unit of output are more prominently imported (Gale et al., 2014) and it is considered that China is effectively importing 14% of agricultural water needs based on a 1,500 tonnes of water requirement to produce 1 tonne of soybeans (Lima-Brown, 2012). Since accession to the World Trade Organisation (WTO) Chinese imports have surged, in particular from the United States (US). Supply-side structural reform where national grain security is guaranteed and prioritised over domestic protein production, a zero increase in pesticides and fertiliser, and vigorous control over water usage in the sector are amongst priorities in China (MARA, 2018).

The Netherlands

The Netherlands is an EU MS, which means that agricultural policy has been shaped for more than 50 years by EU policies. Since economic integration in Europe, the EU CAP has been a cornerstone policy, founded initially with a focus on food security and free trade at European scale following the food shortages of World War II. Emphasis on food security, supported by guaranteed price supports under the CAP served to drive intensification, resulting in over-production and major environmental consequences. Globally, the doubling of land-based cycling of nitrogen (N) and phosphorus (P) means that world N and P cycles are out of balance and can be associated with major global challenges related to economic, health and environmental concerns (Galloway, 1998; Tiessen et al., 2011; Sutton et al., 2013). In Europe, this is aggravated historically through international trade agreements (GATT and 1992 Blair House Agreement) to protect EU cereal production in return for duty-free imports of protein crops and oilseeds (EC, 2012). This has propagated an internal protein deficit with EU dairy and milk production largely reliant on imported protein crops, in particular soybean (Boerema et al., 2016). Although the EU CAP 2008 Health check effectively removed restrictions on the EU oilseed area, agricultural policy in the Netherlands remains committed to food security and a market orientation in agricultural policy that positions it as the second largest agri-foods exporter worldwide (WTO, 2018). Population growth, increased economic development and urbanisation occurring outside the EU, associated with growing demand for animal, fruit, vegetable and processed products are key drivers of the Dutch agri-food sector (LEI, 2010). The removal of the EU milk quota in 2015 is prompting intensification of the dairy sector as farmers are now fully exposed to world milk prices. In the Netherlands, through derogation, farmers have been allowed to apply 230 or 250 kg N per ha (where 70% of farm is grassland) as opposed to 170 Kg N per ha permissible under the Nitrates Directive (van Grinsven and Bleeker, 2016). The milk quota indirectly limited manure production, so its absence increases environmental concerns. Greater specialisation (Hooda et al., 2000) and limited land availability mean that adequate land to spread excess manure has been a particular issue in the Netherlands for decades but dairy expansion makes it a heightened concern. In shallow groundwater, nitrate levels in excess of 50 mg/l NO_3 remain an issue in sandy soils, with ecological N and P thresholds often exceeded in lakes and streams (Van Grinsven et al., 2016). In addition to the Dutch Manure and Fertilisers Act enforced in 1987 to enforce the 1991 Nitrates Directive application rules, tradable manure production quotas for pigs (1998) and poultry (2001) were implemented (van Grinsven et al., 2016). Rapid dairy sector growth since milk quota removal has caused national phosphate usage to exceed the 172.9m kg ceiling under the Nitrates Directive by more than 4% in 2015 (Jongeneel et al., 2017). Since 2018, dairy farms have been allocated tradable phosphate rights based on 2015 herd numbers proportionate to land area. Increased specialisation with confined feeding livestock systems reliant on protein feed imports had decoupled production from the land. The introduction of tradable phosphate rights represents a mechanism to re-establish land-based farming. To retain the nitrates derogation, a package of measures to reduce phosphate production by 8.2 m kg in 2017 were introduced and included measures to reduce the phosphate content in dairy feed, supports to terminate dairy farm businesses and the phosphate production reduction decree (PPRD) (Jongeneel et al., 2017). In 2019, the Council of State ruled that the strategy to reduce N in vulnerable natural areas was in breach of EU law and an integrated approach to N was implemented to reduce N in Dutch Natura 2002 areas (RIVM, 2022). As a result, new economic development permissible only when new n-emitting activities remain within allowable limits (RIVM, 2022).

Materials and methods

Data inputs:

Global trade flows of soil functions are presented in relation to traded soybean of the case studies. As the primary focus of this work is governance mediation of global flows, we focus this assessment to soybean exports/imports, building upon previously calculated metrics where available. Consistent, high temporal- and spatial-resolution time series data published by Garcia et al. (2019) show land use land cover (LULC) and LUC in the UXRB over time. These data, coupled with production and harvest data for Mato Grosso from the Brazilian National Institute of Geography and Statistics ("Instituto Brasiliero de Geografia e Estatística") (IBGE), calculated at municipality level for the UXRB form the basis to estimate area and production of soybean from UXRB and are used to estimate soil function flows to case study regions over time. Previous literature values are utilised (Table 1) to quantify export flow estimates associated with soybean production in the UXRB.

Table 1 Soil function, indicator, unit, assessment and literature values

Related soil function	Indicator	Unit	Calculation method description	Data sources/literature values and related descriptions	Reference source
Land use (LU)	Soybean - production / export	tons/ha	UXRB area * output across time series. Land area allocated based on proportional export data.	IBDG, Aliceweb and FAOStat. Apportioned to export regions based on export data over time.	Calculated here
Land footprint (LF)	Land footprint (LF) for soybean production	m^2/tonne	[UXRB harvested area (m2)/Production (tonnes)] across time series	IBDG, Aliceweb and FAOStat. LF refers to the total amount of harvested land per year and amount required per unit production. The LF originally defined by Yang et al. (2009) to quantify the amount of land used to produce a unit of biofuel is similarly applied here using agricultural yield of soybeans	Calculated here, Willaarts et al., (2011) following Yang et al. (2009)

				(m2/tonne) as applied previously by Willaarts et al., (2011)	
Water footprint (WF)	WF associated with soybean production - virtual and embedded	hm^3/year using regional calculations at m^3/ton	Multiplied by exported tons to quantify UXRB export to case study regions.	Literature values calculated to IBDG for UXRB. Mato Gross values by Lathuillière et al., (2014) who utilise same planting calendar with land use land cover data model by Garcia et al. (2019). The green (rainfall) and grey (polluted waters) water per unit of soybean produced at m^3/ton to calculate the total water embedded in annual production (hm^3/year) applied to Mato Grosso soybean export data to China/Netherlands. Blue (irrigation) water is excluded at irrigation is not utilised in UXRB.	Allan (1998);Mekonnen et al. (2011); Willaarts et al., (2011); Lathuillière et al., (2014). Other studies include: Tuninetti et al. (2015)
Carbon footprint (CF)	Carbon footprint soybean	kg CO_2eq kg^{-1}	Carbon footprint (CF) data is based upon the GHG intensity for the state of Mato Grosso which is calculated at 0.186kg CO2eq kg-1 soybeans by Raucci et al., 2015.	Results by Raucci et al. (2015) indicated that the largest source of GHG in the soybean production is the decomposition of crop residues (36%), followed by fuel use (19%), fertilizer application (16%), liming (13%), pesticides (7%), seeds (8%) and electricity consumed at the farms (<1%). This represents the production but does not include the transport carbon costs.	Calculated here based on kg soybean produced following regional value by Raucci et al., (2015)
Biodiversity - Land use change	Land - LULC Time step data - including deforestation	ha	UXRB LULC data by Garcia et al. (2019) as indicator for biodiversity.	Landsat surface reflectance images; MODIS EVI with 832 MODIS scenes (~210 per year) for 2000, 2005, 2010, 2015 with 8 day temporal resolution and 20m spatial resolution; ~2000 ground truth data points (training) + ~1500 ground truth (validation); Landsat 8 RapidEye images. Full description Garcia et al. (2019).	Garcia et al., (2019)
Nutrients	Phosphorus (P) inputs	$kgPha^{-1}y^{-1}$	Averaging 35 kilograms (kg) of phosphorus (P) per hectare (ha) per year applied to production statistics from IBGE.	Combination of literature values of regional estimates and farm data collected on fertiliser consumption rates. National data for P applications to estimate fraction at state level for comparison purposes also considered.	Riskin et al. (2013) values applied to areal extents of case study areas. For harvested exports 0.52% estimated harvested P content.

To estimate the land required for soybean production, the concept of the land footprint (LF) (Yang et al., 2009) representing the amount of land used to produce a unit of output is applied. Here the agricultural yield of soybeans (m^2/tonne) as applied previously by Willaarts et al., (2011) is used. For the UXRB, the LF is calculated using production and the harvested land area per year (km^2/year). Production and harvest data for Mato Grosso were obtained from the Brazilian National Institute of Geography and Statistics ("Instituto Brasiliero de Geografia e Estatística") (IBGE). The external land requirement is based upon the harvested area (ha) data for the UXRB proportional to export destination as indicated by data (Aliceweb data).

Water footprint (WF) data on the total quantity of freshwater embedded in soybean production were previously calculated on a regional basis for Brazil by Willaarts et al. (2011) after Hoeskstra et al., (2011) at a value of 1938 m^3/ton which is less than the Brazilian average of 2186 m^3/ton. Similar values have been recorded for Mato Grosso expressing increasing efficiency over time. Accordingly, a more recently calculated annual WF value by Lathuillière et al., (2014) of 1908 m^3/ton is applied to calculate the exported WF by export proportion (Aliceweb data). This value is based on the same planting calendar as utilised in the LULC model by Garcia et al. (2019) and is applied to regional exports from Brazil plotted across time series.

Carbon footprint (CF) data is based upon the GHG intensity for the state of Mato Grosso which is calculated at 0.186kg CO_2eq kg^{-1} soybeans (Raucci et al., 2015). This represents the production but does not include the transport carbon costs. No significant differences resulted due to land use intensity and production areas. See Raucci et al. (2015) for a detailed description of cradle to farm gate emissions. In addition to deforestation and land area used for production, pesticide use data are included.

For biodiversity, deforestation rates in the UXRB associated with Land Use Change are shown based on high resolution data calculated by Garcia et al. (2019).
Phosphorus (P) in traded soybean based on Riskin et al. (2013) of P budgets in intensive soybean agriculture is used as the indicator for nutrient cycling. Both the average input production P and P off take are considered (Riskin et al., 2013).

Governance data

A literature review to derive an inventory of governance instruments available to policy makers to manage the supply of soil functions with relevance to land use and management is completed in the context of Brazil and China to add to existing EU reviews by Schulte et al. (2015; 2019) and Vrebos et al., (2018). A timeline of key policies relevant to soil functions and related targets is plotted to visualise the policy transition for particular soil functions over time. This will contextualise how governance signalling mediates the flow of soil functions.

Results

UXRB land use for soybean production, associated agro-ecological footprints and external land requirement of importing case studies

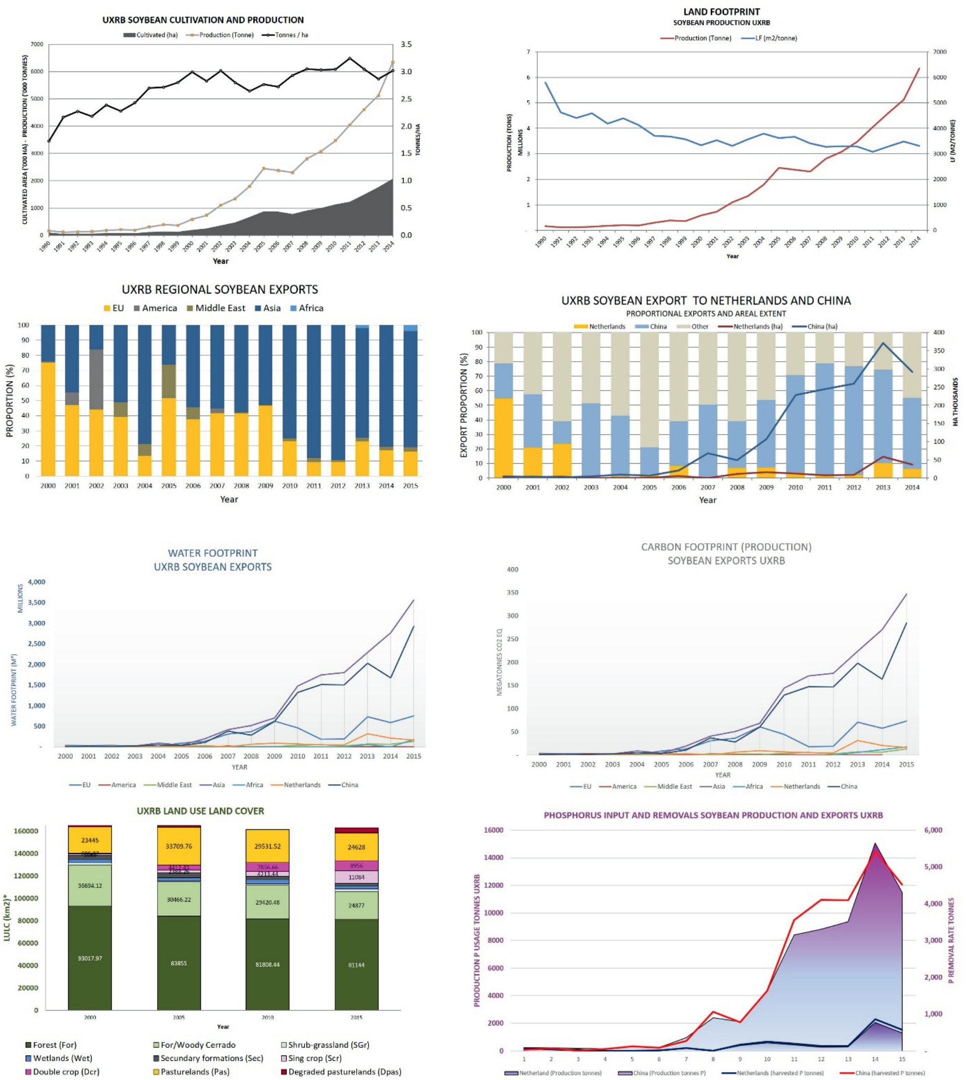

Figure 1 (top left) UXRB cultivated area and production data (left axis) and tons per hectare (right axis) showing both the expansion and intensification of soybean production over time. Data from IBGE calculated at county (municipality) level. Figure. 1 (top right) Land footprint for soybean production in the UXRB Mato Grosso calculated as Production (tonnes) associated with the UXRB harvested area (m2) across time series. Figure 1 (centre top left) shows global proportional regional exports and to case studies (centre top right) with an increasing external land requirement over time. In terms of the water footprint (m^3) almost 3,000 million m^3 (3,000 hm^3) of virtual freshwater resources were exported to China in 2016 (centre bottom right). In relation to carbon, this translates to a high of 31.4 Mt CO_2 eq associated with soybean production imported into the Netherlands in 2013, increasing from 2.7 Mt CO_2 eq in 2000. In Asia embedded carbon for 2014 is estimated at ~284.9 Mt CO_2 eq. Figure 1 (bottom left) Land use land cover in the Upper Xingu River Basin based on Garcia et al. (2019) across four time steps. For the full land use land cover transition tables see Garcia et al. (2019), *Areas less than 1% not shown. Forest clearance to create pastures and successively conversion to croplands is the historical land use trajectory in the region. Approximately 13,000 and 2,000 tonnes of P have been used in the soybean production associated with exports to China and the Netherland respectively in 2012.

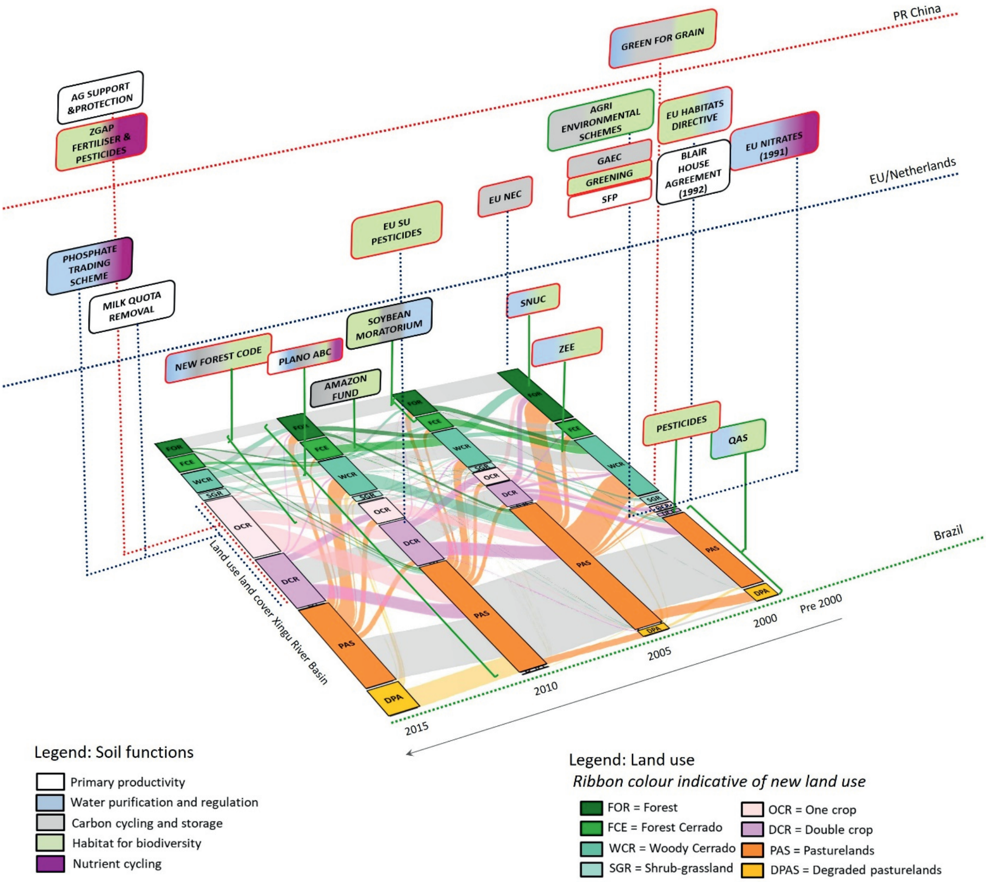

Figure 2 shows land use and land use change in the UXRB over time – right to left (see the land use legend). The main policy mechanisms with relevance for land use and management for UXRB are shown - directly Brazil (green line) and indirectly for Netherlands (dotted navy line) and China (dotted red line). The colour of the policy mechanism border indicates whether that policy is mandatory (red), market (black) or voluntary (green). The soil functions of relevance are reflected by colours shown in the boxes indicated by soil functions legend.

Discussion

Quantifying soil function flows over time

The results show that Brazilian agriculture in the UXRB is strongly connected at a global scale via the soybean trade network and that these connections have expanded and intensified over time. It is also the case that this network is not simply limited to the primary production of soybeans but encompasses a suite of other embedded soil functions. Land use transition pathways observed by Garcia et al. (2019) confirm a land use change cascade whereby deforestation is primarily linked in the first instance to pasture expansion and successively to croplands (fig. 1 bottom left). In 2014, this area accounted for ~2 million (m) ha. Forest clearance to create pastures is the historical land use trajectory in the region, successively to croplands with a very rapid growth of row-crop agriculture observed more recently (Garcia et al., 2019; Galford et al., 2010; Arima et al., 2011). This intensification is confirmed by increased production occurring in the context of decreasing LF. The absolute external land requirement for soybean production has increased from 801ha in 1997 to 596,741 ha in 2014 with an associated increase in harvested area for exports from less than 1% (0.71%) to 28% of the cultivated hectares. The associated quantity of soybeans exported from the region has increased from 2,162 tonnes in 1997 to ~2.4 m tonnes in 2015 (IBGE, 2018) and while Europe has declined in importance as an export destination relative to China, the absolute quantity exported to Europe has still increased (Fig. 1, centre top left and right). The embedded freshwater footprint of soybean exports to China is estimated at ~ 3,000 million m^3 in 2016 growing annually in line with volume of soybeans traded which makes UXRB agriculture strongly connected indirectly via its global water network. It is important to note that soil functions are not only impacted in Brazil but receiving countries are also impacted, for example, the perpetuation of nutrient imbalances.

The role of governance for soil functions

Agricultural policies in Brazil historically supported a closed economic model through price interventions and import substitutions. Since the 1990s, trade liberalisation reforms, deregulation of domestic markets and the establishment of the Mercosur customs union signified a shift towards increased openness (OECD, 2021). Favourable market conditions and reduced licensing requirements for agricultural produce meant greater access to world commodity and input markets for Brazilian producers, prompting rapid agricultural growth (OECD, 2005; Kastens et al., 2017). Although agricultural development brought aggregate economic gains, local challenges for smallholder farmers emerged alongside international pressure to address the rapid acceleration of Amazon deforestation (Richards et al., 2014; Amaral et al., 2021). Efforts to counter these trends were supported by strengthened domestic policies to address the Amazon Biome (Fig. 2). In 2000, a National System of Protected Areas (SNUC) (Law No. 9.985/2000) was introduced, followed by Ecological and Environmental Zoning (ZEE) zoning legislation in 2002. The Soy Moratorium (2006) which was renewed indefinitely in 2016, and the industry-led Zero Net Deforestation and Degradation (ZNDD) target have been introduced to limit deforestation in lieu of soybean production in the Amazon, primarily by targeting the supply chain. This Soy Moratorium initiative, implemented by companies is credited with dissociating the expansion of soybean crops in the deforested Amazon biome after July of 2006, which critically, received recognition from European customers (Amaral et al., 2021). While the Soy Moratorium initiative is lauded as a major conservation success with an 84% decrease in the rate of the Amazon deforestation (Heilmayr et al., 2020), dramatic agricultural expansion in the Cerrado biome occurred concurrently (Fig. 2) (Garcia et al., 2019). The Amazon Fund was set up in 2008 and further prioritised the Amazon by supporting protection through international donations amid growing concerns around climate change (Pelicice and Castello, 2020). However, protective mechanisms to limit deforestation of the Amazon are indirectly promoting expansion elsewhere, particularly as 65% of the land area in the Cerrado could legally be brought into productive use (Machado and Anderson, 2016), as opposed to 20% in the Amazon biome. The domestic spillover annual deforestation rate of the Cerrado is estimated to have increased by 156% from 2009 to 2012, from 2,989 km^2 to 7,652 km^2 (Soares-Filho et al., 2014) and the Cerrado is by now recognised as a deforestation hotspot associated with land use change (Lima et al., 2019). Efforts to address this were since included in the 'New Forest Code 2012', which is the main instrument to target deforestation. The key enforcing mechanism for this is the Environmental Rural Registry (CAR), which is an electronic registration system that must capture Permanent Preservation Areas (PPA) and Legal Reserves (LR). Under the National Climate Change policy the government voluntarily aims to reduce GHG emissions by 36.1-38.9% by 2020 requiring an absolute emissions reduction between 1168 $GtCO_2$-eq and 1259 $GtCO_2$-eq (Brazil, 2010). This includes a 40% reduction in deforestation rates in the Cerrado between 2008—2020 compared to the deforestation average from 1999-2008 (Miccolis et al., 2014).

Over time, governance mechanisms are evolving to respond to changing market and sustainability demands. As shown, the market demand for soybean has increased but this has occurred in the context of decreasing land availability due to more stringent measures related to deforestation. As the area available for agricultural expansion contracts, intensification of existing agricultural land is observable, for instance, in favour of double cropping (Fig. 2). The intensification of agriculture from single to double cropping increases pressure on the soil to deliver all soil functions as input levels increase further. In response, a new policy cascade emerges to target relevant soil functions in favour of sustainable land management. For example, the 2010 Plano ABC, low carbon agriculture payment-based measures to address soil quality and protection through sustainable resource practices. These measures included no-till planting, biological nitrogen (N)-fixation over chemical fertilisers, integrated crop-livestock farming systems and area of planted forests (Miccolis et al., 2014).

Several insights unfold from this assessment. In this research we show that global scale demands are driving local level decisions, whereby farmers in Brazil are producing soybean to respond to remote market demands. Also, a pattern of cascading governance is reflected with new mechanisms introduced to respond to emerging issues, sometimes in response to an earlier intervention. Instruments that are too narrowly focused, such as those that foster protective measures for the Amazon but failed to consider the Cerrado, highlight a need for greater consideration of land use within the context of the landscape setting. Opportunities to support the management of multiple functions exist (Zwetsloot et al., 2020) but require more integrated consideration between soil functions and land uses to minimise trade-offs and to optimise synergies.

The world economy is increasingly interconnected, with globalised flows of food commodities and biomass products rising (Erb et al., 2009; Yu and Husbacek, 2013; Chaudhary and Kastner, 2016). In this research, we see these interconnections borne out via the soybean supply chain. Instruments with implications for land use and management are shown in fig. 2 for Netherlands and China. In the absence of closed nutrient cycles, nutrient transfers at intercontinental scale means that N and P cycles are out of balance. A history of imported protein has supported the development of specialist confined feeding systems in the Netherlands that with the removal of the EU milk quota could see an increase in animal numbers. Already water quality and sufficient land to spread excess manure has been an issue in the Netherlands (Van Grinsven et al., 2016). New instruments have been introduced to counter this challenge, including the tradable phosphate rights based on 2015 livestock numbers proportionate to land area as a means to cap livestock expansion through reconnecting livestock to land base (Jongeneel et al., 2017). Europe acknowledges the need for an internal response to the protein deficit that require structural issues and bottlenecks in EU agriculture to be addressed. Aside from the challenge of agronomic conditions in Europe, the main constraints for plant protein production are socio-technical in nature, such as economic profitability, competitiveness of EU protein crops compared to imported proteins and a lack of research in breeding and agronomic practices. It is also acknowledged that stability of markets and EU supply chain may be threatened by demand from customers, such as China who may have fewer demands with respect to production conditions (EP, 2011). Altogether a similar pattern with respect to a policy cascade can be seen for the Netherlands and China.

Lessons learned and wider conclusions

An intercontinental assessment of policies of these case studies indicates that shared governance occurs through the value chain via the market and is associated with cross-scalar implications for soil function management. Domestic policies and international agreements impact land use in Brazil but the national and local policies of other continents are also influencing land use in Brazil. Often, global pressure to protect globally important highly biodiverse regions of the world is exerted locally, however it is also relevant that remote governance levers can be a contributing source to the regional challenge, such as the rapid deforestation of the Cerrado or intensification of agriculture. In light of the higher ambitions on climate and environment objectives at EU scale, this conclusion requires MS to not only look inwards but also to consider potential perverse outcomes elsewhere.

In relation to multifunctionality and signals for soil functions, market signals for production represented a higher factor in decision making related to land use. Subsequent pressure to address deforestation of the Amazon reflected responses that were rooted primarily in a need to satisfy export market demands. From this observation, several questions and considerations arise: Does a hierarchy for singular soil functions occur? This research indicates that irrespective of the scale of production, market signals are a key driver in land related decision-making and often ignore the associated trade-offs in the delivery of other soil functions. Accordingly, targeting the market represents a key pathway to target and enable sustainable practices/transitions. Although there are limitations associated with the Soy Moratorium, not least the rapid deforestation of the Cerrado, there are still lessons to be learned. Through the mobilisation of a wide range of actors (e.g. commodity producers, authorities) and mechanisms (structural, fiscal, legal) with deforestation monitoring technology and stringent regulations on finance and land use (e.g. Forest Code) a management system for the soybean supply chain that curbed deforestation of the Amazon was implemented (Pelicice and Castello, 2021). Agribusiness production remained largely unaffected (Nepstad et al., 2014) while deforestation rates reduced over time, remaining low until 2015 (Tollefson, 2016).

Value chain actors have been sending price signals that drive production demand at the global scale. We have shown that signals for other soil functions are indirectly transmitted. While market signals, translated by price, emerge as prioritised it may also be the case that other soil functions are either not valorised or are not clearly defined. Although a global agreement and commitments exist for climate along with a carbon price, objectives for biodiversity are not matched with universal commitments or price. Often biodiversity requires localised or regionalised responses, for which the benefits accrue at larger scales, even if responsibility sits at local scale. To some extent, the Amazon Fund supports conservation of the Amazon and is an example where an external financial support is made available however, for many biodiversity or ecosystem services there are few examples of such co-operation. For water regulation and purification, in the EU, river basin management plans are used whereas regional arrangements can be found elsewhere, however, water signals extend beyond river basins. While there is an obvious need for greater valorisation of ecosystem services in general to support the delivery of soil functions, there is a need for greater co-operation across scales to support such initiatives.

Also important is the role that better bundling of soil functions could play. Whether sufficiently defined or not, high level agreements typically refer to one ecosystem service. Often, consideration of other ecosystem services are either positively related via co-benefits or negatively associated with trade-offs. Already the five key soil functions are considered to capture the majority of soil based ecosystem services delivered through agricultural landscapes (Schulte et al., 2019). Collectively the supply of soil functions is commonly referred to as multifunctionality within the EU (Giuffré et al., 2021). Although the application of multifunctionality is limited (Hölting et al., 2019) such an approach offers promise as an integrative framework through which the delivery of all soil functions can be considered simultaneously. Such an approach could have relevance and application potential irrespective of scale with utility at global, bi- tri-lateral, regional or national scales.

Finally, the case studies in this paper indicate that the external dimensions of EU policies have historically failed to account for leakage effects. A key challenge going forward is that the external dimensions of policies, such as the European Green Deal and the F2F and Biodiversity Strategies, are considered. The Joint Research Committee (JRC) of the European Commission modelled three scenarios to assess the impacts on EU agriculture taking into account four quantitative targets under the F2F and Biodiversity strategies due to their high impact potential on agricultural production and environment (Barreiro Hurle et al., 2021). Notwithstanding the modelling limitations highlighted, reaching the four targets under CAP implementation were found to have significant environmental benefits but were coupled with a decline in production but with a limited impact on international markets (Barreiro Hurle et al., 2021). How the EU responds to supply side impacts will determine the extent of c-leakage or off shoring of environmental impacts, if a reduction in EU production translates to an increase in imports from countries with reduced environmental standards. To understand these external dimensions of the European Green Deal a suite of reviews and proposals are underway including a proposal for a Regulation on Sustainable Food Systems Framework. This seeks greater sustainability of all foods placed on the EU market, including the avoidance of externalisation of unsustainable practices (Baldock and Hart, 2021). So called mirror clauses have also been proposed, but there remain issues with respect to coverage and their enforcement (Matthews, 2022). While intended to raise the sustainability standards for imports, a perverse outcome may be the expansion into other markets with less stringent standards as is reflected in the context of Brazilian exports to China as shown here (Fig. 1 & 2). At international scale, markets for primary production are governed under WTO international agreements. Trade policies are being explored under EU Trade Policy Review 2021 (EU, 2021) with a review of WTO and support for implementation and enforcement of trade agreements considered necessary to ensure a level playing field. Multilateral agreements have most scope to raise global standards and to reduce C-leakage. Within the EU, the digital transformation, cooperation and strategic partnerships are all part of the suite of considerations to shift to a greener future (EU, 2021). However, with growing global uncertainty, and a shift in favour of unilateralism over multilateral governance (EU, 2021) mitigating leakage effects will be particularly challenging.

Conclusions

- Our case study areas are strongly connected at a global scale via the soybean trade network and that these connections have expanded and intensified over time.
- Bundling of key land based soil functions under the FLM framework can support a transition towards greater multifunctionality at all scales offering scope to better account for transfers of soil based ecosystem services.
- Historically, the external dimensions of EU policies have not accounted sufficiently for leakage or environmental impacts.

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CHAPTER 7

National prioritisation of soil functions in the post-2020 CAP era

Targeting soil functions

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Abstract

Recent policies place land related ecosystem services, underpinned by soil, at the heart of sustainable development. Sustainable soil management is specified as having a critical role in meeting goals and targets for many actions, including those outlined under the European Green Deal. Different stakeholders have different expectations for soil functions and matching the supply of soil functions to meet the demands of all stakeholders remains a challenging task. Increased subsidiarity under the 2022-2027 Common Agricultural Policy (CAP) of the European Union (EU) has created opportunities for EU member states (MS) to design more context specific policies that could target land management practices in favour of soil functions for which there is a high demand. In this study, the delivery of EU climate and environment objectives is conceptualised through the lens of five key land-based soil functions. We assess how soil functions were prioritised in the 2014-2020 period based upon EU pillar 2 budgetary allocation and compare that to demands for soil functions to expose opportunities for greater targeting in support of sustainability. We propose that meeting higher ambitions on climate and environment objectives in the future will require a targeted approach that can better align incentivisation opportunities to meet societal demands. This work offers insights into how demand and support for soil functions vary within and between member states, highlighting that opportunities for more targeted incentivisation exist. We conclude that one-size does not fit all, and that opportunities exist to better align support with societal demands for soil functions. Additional targeting is required and could be exploited through Pillar 1 eco-schemes.

Introduction

Soil as a priority

Soil is critical to sustain life on the planet and agricultural soils provide a range of benefits that contribute to human well-being (Power, 2010; Schulte et al., 2014). The role of soil in the provision of land based goods and ecosystem services is widely recognised (EC, 2006; Haygarth and Ritz, 2009; Schulte et al., 2014). The European Union (EU) *Thematic Strategy for Soil Protection (COM (2006) 231 final)* identified seven environmental, economic, social and cultural functions (EC, 2006). For 15 years, this strategy was central to discussions related to soil policies at EU level. A related proposal to legislate soil protection under a singular directive, the *Soil Framework Directive (COM (2006) 232 final),* was rejected in 2014. The reasons for its rejection included objections by some member states surrounding the public governance of land that is primarily a private resource, as well as the proposed emphasis on soil threats (Stankovics et al., 2020). In the absence of a specific directive for soils, several other Regulations and Directives implemented measures and policies that indirectly address soils and their functions (Glaesner et al., 2014; Vrebos et al., 2017). More recently, soils have emerged as a priority at international level with sustainable land management considered key to achieving the Sustainable Development Goals (SDGs) by 2030 (Bouma et al., 2019; Visser et al., 2019).

EU Policy context

Evidence of climate change, biodiversity decline and environmental degradation is well documented (e.g. IPCC, 2018; IPBES 2018; EEA, 2019). These challenges are linked to agricultural land use (e.g. Tiessen et al., 2011). In response, the EU has put forth the European Green Deal (EGD) as Europe's cross-sectoral strategy to raise ambition on sustainable production and consumption in the EU (EC, 2019a). European food is already abundant, traceable and of high quality. Nevertheless, ambitions are now for European food to become a global standard for sustainability (EC, 2020a). Historically, EU food systems have been a key driver of environmental degradation and climate change and have been characterised by a reliance on excessive inputs, biodiversity loss, limited organic farming and a need for improved animal welfare (EC, 2020a). Objectives of emergent policies emerging under the EGD, such as the Farm-to-Fork-Strategy, seek to halt degradation and benefit soil health. Targets include reduced pesticides (50%), a decrease in excess nutrients (50%), reduced fertiliser (by 20% at least), an increase in organic farming (25%) and an increase in protected land (30%) and landscape features (Montanarella and Panganos, 2021).

The renewed interest in soils at policy level, has led to a sharp focus on soil research, innovation and policy. In 2021, the European Commission commenced a 'mission' on soil health and food; one of only five missions, equating to a high-level commitment to support soil by way of funding for research and innovation through the Horizon Europe framework. The goal of the mission proposed by the Soil Health and Food Mission Board aims to "ensure that 75% of soils are healthy by 2030 and are able to provide essential ecosystem services"

(MBM, 2020). Furthermore, a new EU soil strategy outlining an overarching policy framework for soil health has been launched that envisions more resilient healthy soil ecosystems achieved through concrete measures that protect, restore and promote sustainable use of soils (EC, 2021a).

Preceding the publication of the EGD, legislative proposals on the future of the Common Agricultural Policy (CAP) were published in 2018. Strategic plans (SPs) have been proposed as a means to facilitate more context-specific policy formation by developing targeted policies that reflect territorial and sectorial specificities (EC, 2018; ENRD, 2018). SPs increase MS subsidiarity as opposed to centralised interventions, giving rise to opportunities for differentiated policy targeting at national or regional level. Key features include enhanced conditionality related to obligations linked to CAP payments. This includes fewer exemptions related to greening requirements, the modification of certain cross-compliance requirements and new Good Agriculture and Environmental Conditions (GAECs) such as the protection of organic soils. Agri-environmental and climate measures (AECMs) will continue under Pillar 2 to compensate farmers/land managers for costs incurred while eco-schemes under Pillar 1 are a new feature of the CAP. Eco-schemes are a key innovation in the green architecture of the CAP and are mandatory instruments at MS level. This means that MS must allocate a proportion of their Pillar 1 payments to schemes that benefit the environment and climate (beyond Pillar 2 AECMs) with the proportion of budget determined at MS scale (EC, 2018). Farmer participation is voluntary but linked to land eligible for direct payment, thereby representing an optional income support measure for farmers under Pillar 1. For the first time, this approach to sustainable farm practice features in both CAP pillars: Pillar 1 direct income support payments to farmers and support for wider rural development under Pillar 2.

Research context

Agriculture is a private enterprise with food sold in markets thus constituting a private rather than a public good (Bateman and Balmford, 2018). At the same time, land, including agricultural land, has a vital role in the delivery of public goods and services. As a result, different stakeholders have different expectations in terms of their demands on land (Bampa et al., 2019). This difference gives rise to a distinction between functional objectives reflective of local demands from land managers, versus societal objectives reflective of national or EU demands (Schulte et al., 2019). For example, farmers may be interested in soil organic matter to improve soil structure to increase their yield. At the same time, policy stakeholders may have a demand to increase soil carbon stocks to reduce atmospheric carbon dioxide (CO_2) in line with the Paris Agreement. Satisfying functional objectives at farm scale can represent a sustainable investment for farmers as agro-economic benefits accrue at that scale (Schulte et al., 2015; 2019). The incentivisation of additional management practices for which the demand, and return on investment, is at societal rather than at local level typically require monetary policy instruments. Already, such pathways exist, including cross-compliance, greening requirements and direct supports under CAP Pillars 1 and 2.

Already several conceptual approaches have been developed to evaluate the supply of soil-based ecosystem services (e.g. Dominati et al., 2010; Calzolari et al., 2016; Kabindra and Hartemink, 2016; Greiner et al., 2017). Land use and management interaction with soils govern the provision of these ecosystem services (Coyle et al., 2015; Valujeva et al., 2020). Functional Land Management (FLM) is one approach that aims to optimise the delivery of land-based ecosystem services (Schulte et al., 2014). Five ubiquitous agricultural land-based ecosystem services, or soil functions, were identified by Schulte et al. (2014), based on Haygarth and Ritz (2009): 1) primary production of food, feed, fuel and fibre; 2) water purification and regulation; 3) carbon storage, sequestration and climate regulation; 4) provision of habitats for biodiversity and 5) provision and cycling of nutrients. Using the FLM framework, an EU level assessment found that the societal demands (reflected by policy indicators) for multi-functionality differed significantly between MS. The variation in demands was reflective of differences in population, farming systems, livestock densities, geo-environmental conditions and landscape configuration (Schulte et al., 2019). This indicates that SPs represent an opportunity for more targeted incentivisation of sustainable land management (Schulte et al., 2019). Furthermore, the work highlighted that a large gap exists between farm scale and societal expectations for soil functions thereby quantifying the degree of additional soil functioning necessary to meet societal objectives.

Challenge and opportunity

Matching the supply of soil functions with the expectations of different stakeholders is challenging. At a practical level for farmers, this means balancing competing demands on their land, which is associated with increased management complexity due to the trade-offs and synergies between soil functions, that may arise from specific agricultural practices (Zwetsloot et al., 2020). From a policy perspective, it requires enabling and horizontally integrated policies, including incentivisation mechanisms, to support land management decisions aimed at meeting the diverging expectations and demands on land (Valujeva et al., 2016, 2020, 2022).

Greater subsidiarity in the new CAP provides MS with the tools through SPs to target land management practices where they are needed most. Reports on the previous more centralised CAP model 2014-2020, indicated that green payments for sustainable agriculture had neither met the environment and climate needs of MS, nor wider CAP objectives (Meredith and Hart, 2019). Historically, bridging the gap between farm level demand for soil functions and that expected by society has relied primarily on the voluntary uptake of Pillar 2 AECMs. Given the greater emphasis on the role of soils and the potential of soils to contribute to climate and environment it is timely to assess the extent to which particular soil functions were supported under EU CAP Pillar 2 (2014 – 2020 period). It is also relevant to explore the extent to which supports aligned with the relative demand for soil functions at MS scale.

Aims and objectives

The design of SPs at MS level has a key role in achieving future CAP ambitions and requires that monetary incentives towards soil functions target land management practices in favour of soil functions for which there is a high demand. This relative societal demand has been identified by Schulte et al. (2019) for each EU MS. Here, we aim to assess how individual soil functions have been prioritised by each MS, based upon pillar 2 budgetary allocation, relative to these societal demands, in order to shed light on opportunities for greater targeting in favour of greater sustainability.

Methods

Allocating budget to soil functions

To determine how soil functions were prioritised, we used budget allocation as a proxy for the prioritisation of soil functions. Budgetary data for the period 2014-2020 were allocated to the five soil functions, namely primary production, water regulation and purification, climate regulation, habitat for biodiversity and cycling of nutrients. Data from the publicly available MS factsheets, from the European Commission's country files on Pillar 2 expenditure were used (https://ec.europa.eu/agriculture/rural-development-2014-2020/country-files_en). These MS data sheets include the indicative public support for the Rural Development Programme (RDP) allocated for particular measures implemented within priority areas. The EU Pillar 2 RDP includes six priority areas: 1) knowledge transfer and innovation, 2) farm viability and competitiveness, 3) Food chain organisation and risk management, 4) Restoring, preserving and enhancing ecosystems, 5) Resource-efficient, climate resilient economy and 6) social inclusion and economic development (EP, 2018). Priorities 4 and 5 specifically address climate and environmental objectives, having direct relevance for soil functions. In this study, these were used to assess the budgetary allocation towards soil functions. Within priority areas, budgets were distributed across 20 measures (Annex 1), thus applicable measures (indicated in tables 1 and 2) were allocated to soil functions within priority areas 4 and 5. Under priority 4, measures potentially applied to all soil functions (Table 1) whereas measures under priority 5 specifically addressed water regulation, carbon cycling and storage and nutrient cycling and provision (Table 2). Where a measure was relevant for more than one function, budget allocation was attributed equally between soil functions. Water purification and regulation were counted as one function unless otherwise specified by the measure. Altogether, data from the 28 MS reported during the second CAP period were included. For those seven MS where regional implementation takes place, RDPs were assessed at the regional level: Belgium (n=2), Finland (n=2), France (n=28), Germany (n=12), Italy (n=21), Portugal (n=3), Spain (n=16) and UK (n=4). In the cases of Germany and Spain, regional data were unavailable for Baden Wurtenburg and Catalunya, respectively. Regional data were then presented at MS level based upon the calculated average budget allocation for each soil function. Altogether a total of n=108 data sheets were analysed.

Table 1 Priority 4 - Restoring, preserving and enhancing ecosystems, measures and associated soil function allocation (PP = primary production; WP= water purification; water regulation = WR; CS= carbon cycling and storage; HB = functional and intrinsic biodiversity, and NC = nutrient cycling and provision)

Priority	Measure	Broad Measure	Soil Function – WP & WR are one function unless specified differently in measure.

4	M01	Knowledge transfer and information actions (Art. 14)	PP	WP	WR	CS	HB	NC
4	M02	Advisory services, farm management and farm relief services (Art. 15)	PP	WP	WR	CS	HB	NC
4	M04	Investments in physical assets (Art. 17)	PP	WP	WR	CS	HB	NC
4	M07	Basic services and village renewal in rural areas	PP	WP	WR	CS	HB	NC
4	M08*	Investments in forest area development and improvement of the viability of forests	PP			CS	HB	
4	M10	Agri-Environment-Climate		WP	WR	CS	HB	NC
4	M11**	Organic farming	PP	WP			HB	NC
4	M12***	Natura 2000 & Water Framework Directive		WP	WR		HB	NC
4	M13****	Payments to areas facing natural or other constraints	PP				HB	
4	M15*****	Forest environmental and climate services and forest conservation				CS		
4	M16	Co-operation	PP	WP	WR	CS	HB	NC

Decision rules based on implementation choices for Member States under the Rural Development Reg. (EU) No.1305/2013 (EC, 2013; EC, 2014) (expanded explanation of sub-measure available in synthesis by Ecorys et al., (2016)) pertaining to:

M08*: Investments in forest area development and improvement of the viability of forests: (of Regulation (EU) No 1305/2013), includes sub-measures: M8.1 (Article 21): support for afforestation/creation of woodland; M8.2 (Article 22): support of establishment and maintenance of agro-forestry systems and M8.5 (Article 25): support for investments improving the resilience and environmental value of forest ecosystems. Funding was allocated equally between PP, CS and HB based upon specific reference to agroforestry, afforestation and woodlands.

M11**: Organic Farming: (Article 29 of Regulation (EU) No 1305/2013), includes sub-measure M11.1 Payment to convert to organic farming practices and methods and M11.2 Payment to maintain organic farming practices and methods. This measure includes support for transaction costs and income foregone (PP). Also, based on EC (2019b), organics pertains to the maintenance of biodiversity (HB); enhancement of soil fertility (NC) and maintenance of water quality (WP).

M12: Natura 2000 and Water Framework Directive*** (Article 30 of Regulation (EU) No 1305/2013) includes M12.1 and M12.2 pertaining specifically to Natura 2000 (HB) as the coordinated network of habitats in the EU (EC, 2019c). M12.3 refers to compensation payment for agricultural areas in river basin management plans (WP, WR, NC). Budgetary allocation determined based on country level sheets where often it pertained to Natura 2000 alone.

M13*: Payments to areas facing natural or other constraints*** (Article 31 of Regulation (EU) 1303/2013). The area designation is based on objective bio-physical criteria laid down in the respective Rural Development legislation (EC, 2019d). Targets biodiversity loss (HB) associated with land abandonment through income support (PP).

M15**: Forest environmental and climate services and forest conservation*** (Article 34 of Regulation (EU) No 1305/2013) for areas requiring forest management plan. Target allocated to CS function.

Table 2 Priority 5 - Resource efficiency and shift towards a low carbon and climate resilient economy (WR = water regulation; CS = carbon cycling and storage; NC = nutrient cycling)

Priority	Measure	Broad Measure	Soil Function		
5A - Water efficiency (irrigation measures)	M01	Knowledge transfer and information actions (Art. 14)	WR		
	M02	Advisory services, farm management and farm relief services (Art. 15)	WR		
	M04	Investments in physical assets (Art. 17)	WR		
	M16	Co-operation	WR		
5B - Energy efficiency*	M08	Investments in forest area development and improvement of the viability of forests		CS	
5C - Renewable energy **	M10	Agri-Environment-Climate		CS	
5D - Reducing GHG and NH3	M01	Knowledge transfer and information actions (Art. 14)		CS	NC
	M02	Advisory services, farm management and farm relief services (Art. 15)		CS	NC
	M10	Agri-Environment-Climate		CS	NC
	M16	Co-operation		CS	NC
5E- Carbon conservation/ sequestration	M01	Knowledge transfer and information actions (Art. 14)		CS	
	M02	Advisory services, farm management and farm relief services (Art. 15)		CS	
	M16	Co-operation		CS	

Decision rules based on implementation choices for Member States under the Rural Development Reg. (EU) No.1305/2013 (EC, 2013; EC, 2014) (expanded explanation of sub-measure available in synthesis by Ecorys et al., (2016)) pertaining to:

5A, 5D and 5E explicitly identify soil functions, WR, CS & NC and CS respectively based on sub-priority area.

5B – Energy efficiency* - only included where specific reference to biomass is included in the MS factsheet and was then populated as 'CS'. Otherwise, the 5B emphasis primarily concerned with value chain development beyond farm gate and was thereby excluded as not having a direct impact on soil use and management for soil functions.

5C – Renewable energy** - only included where specific reference to biomass is included in the MS factsheet and was then populated as 'CS'. Otherwise, the 5C emphasis primarily concerned with value chain development beyond farm gate and was thereby excluded as not having a direct impact on soil use and management for soil functions.

Budget data from each datasheet were assigned to soil functions within priority areas 4 and 5 and summed to calculate the aggregate budgetary allocation dedicated towards each soil function.

Comparing demand and prioritisation for soil functions

To identify opportunities for future alignment, the prioritisation of soil functions (vis-à-vis budget allocation) was compared with the demands for soil functions as assessed by Schulte et al. (2019). For comparison purposes, data were divided by the Utilisable Agricultural Area (UAA), log transformed to normalise and subsequently converted to z-scores in line with the assessment completed by Schulte et al., (2019). A z-score (or standardized score) represents the number of standard deviations that a value diverts from the mean and represents a measure of position. It was calculated by subtracting the mean value from the value of the observation and dividing by the standard deviation. As a relative ranking, a z-score of "0" represents the average budget allocation across the MSs analysed. As well as being a relative ranking, z-scores allowed the raw scores from different distributions for soil functions to be compared.

Results

Pillar 2 budget allocation for soil functions 2014-2020

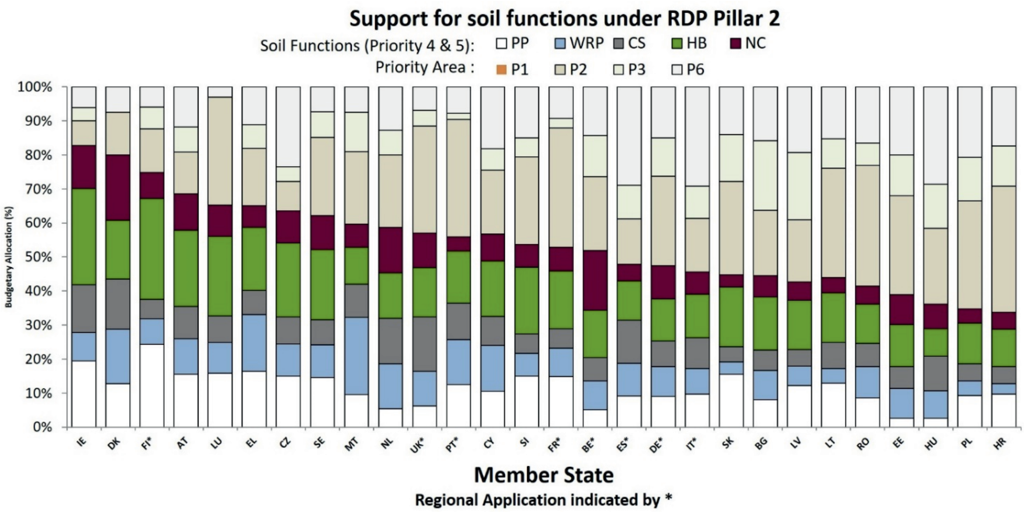

Figure 1 Member State EU RDP Pillar 2 budgetary allocation for 2014-2021 period relevant to soil functions: PP= primary productivity, WRP = water purification and regulation, CS = carbon cycling and storage, HB = habitat for biodiversity, NC = nutrient cycling representing priorities 4 and 5. P1, P2, P3 and P6 refer to the other rural development priorities (indicated in text). MS abbreviations: Austria=AT; Belgium=BE; Bulgaria=BG; Croatia=HR; Czech Republic=CZ; Denmark=DK; Estonia=EE; Finland=FI; France=FR; Germany=De; Greece=EL; Hungary=HU; Ireland=IE; Italy=IT; Latvia=LV; Lithuania= LT; Netherlands=NL; Poland=PL; Portugal=PT; Romania=RO; Slovakia=SK; Slovenia= SI; Spain=ES; Sweden=SE. Regional implementation is indicated by *

On aggregate, budget targeted under Pillar 2 priorities 4 and 5 with relevance for soil functions exceeds 50% in over half of the MS, with Ireland being the highest (80% Figure 1). Overall, across the five soil functions, for the majority of MS the HB function represents a high budgetary priority. This is largely due to support to minimise land abandonment that is linked to biodiversity loss in areas facing natural or other constraints. Land abandonment has been a political priority for some time as an estimated 120 M ha of cropland has been abandoned since 1990 (Levers et al., 2018) with a further 11% of the European UAA considered at risk of abandonment between the period 2015-2030 (Perpina Castillo et al., 2018; Valujeva *et al.*, 2020). In general, the varying allocation to individual soil functions reflects specific geographic conditions and highlights how soil functions represent different priorities across the MS. For example, Finland has the highest allocation towards primary productivity (forest biomass) while Malta and Greece allocate a larger budget for water regulation, reflecting their generally drier climates and issues related to water quality and quantity (Pedero et al., 2010; Koutroulis et al., 2011; Reitano, 2011). Belgium, Denmark and Netherlands allocate among the largest proportional budgets towards the nutrient cycling soil function where high livestock numbers and separation of crop and livestock are drivers of nutrient surpluses (e.g Haase et al., 2017; Wang et al., 2018). For other MS, farm viability and competitiveness (P2) and social inclusion and economic development (P6) represent important priorities for rural development.

Comparing relative demand and relative priority of soil functions by member state

Figures 2-6 shows the relative demand and the indicative relative prioritisation for soil functions by MS for each individual soil function through z-scores. Countries close to the y=x line represent the cases where relative demand is matched with relative priority (both are either high or low), i.e. budgetary targeting is in alignment with societal demands. These areas are represented in the green gradient areas. Deviation from the 1:1 line is indicative of potential mismatches increasing towards the top left (high priority low demand) and bottom right (low demand high priority) quadrants as the colour gradient shifts to red. MS abbreviations: Austria=AT; Belgium=BE; Bulgaria=BG; Croatia=HR; Czech Republic=CZ; Denmark=DK; Estonia=EE; Finland=FI; France=FR; Germany=De; Greece=EL; Hungary=HU; Ireland=IE; Italy=IT; Latvia=LV; Lithuania= LT; Netherlands=NL; Poland=PL; Portugal=PT; Romania=RO; Slovakia=SK; Slovenia= SI; Spain=ES; Sweden=SE. Regional implementation is indicated by *.

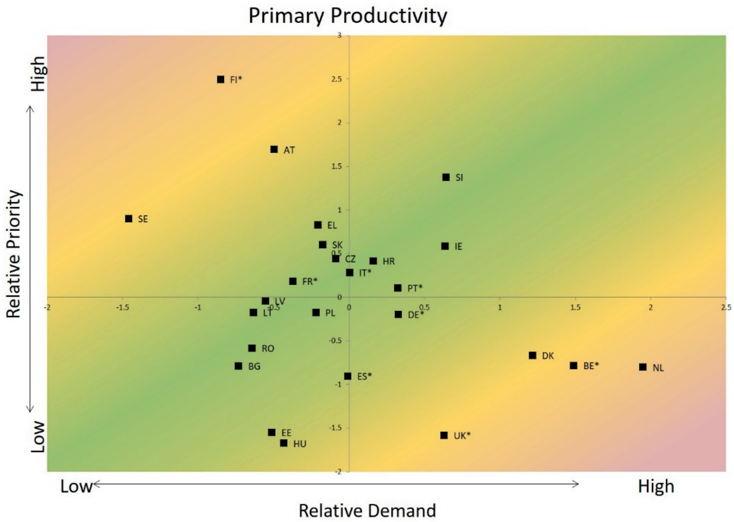

Figure 2: Primary productivity additional demand versus priority as determined by Pillar 2 budget allocation by Member State. Axes given in z-scores.

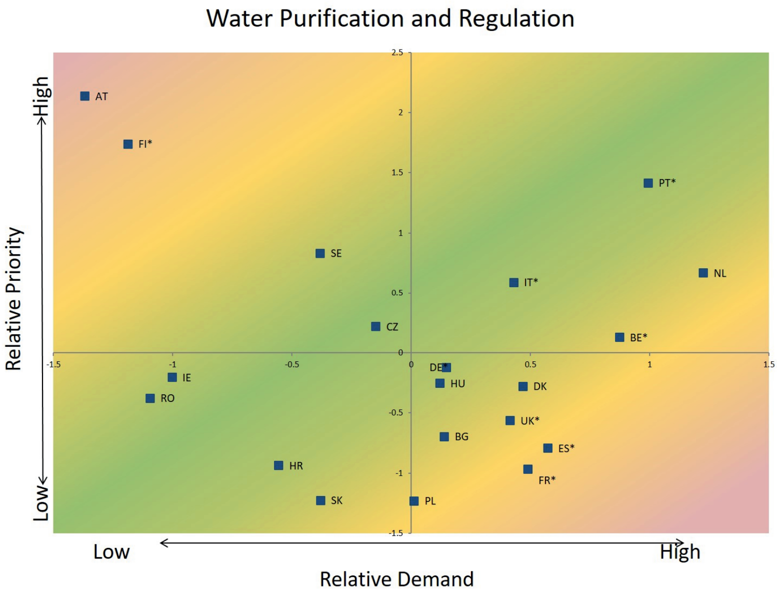

Figure 3: Water purification and regulation additional demand versus priority by MS (Demand data unavailable for EE, EL, LT, LV, SI so excluded here). Axes given in z-scores.

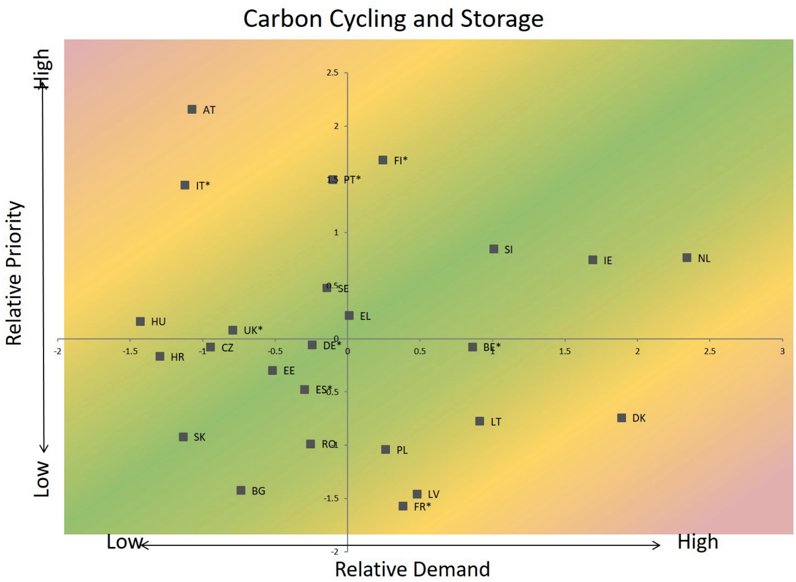

Figure 4: Carbon cycling and storage additional demand versus priority by Member State. Axes given in z-scores.

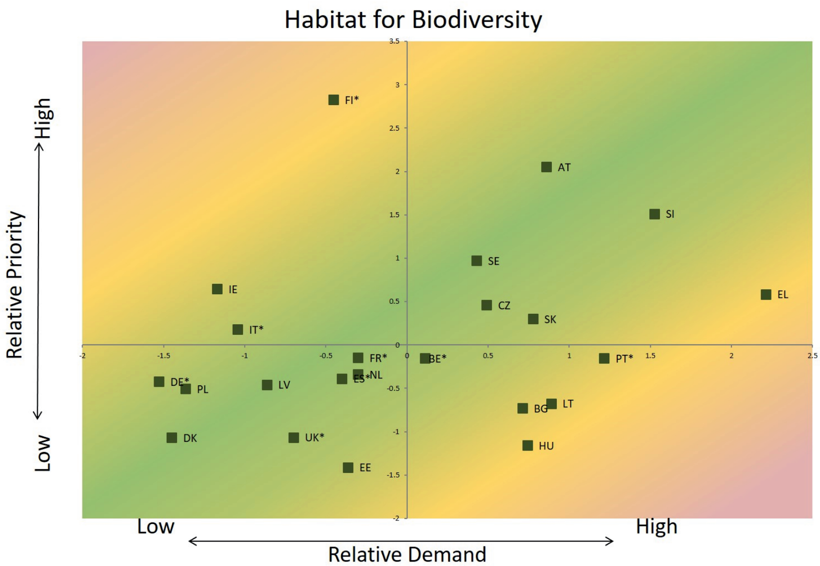

Figure 5: Habitat for Biodiversity additional demand versus priority by Member State. Axes given in z-scores.

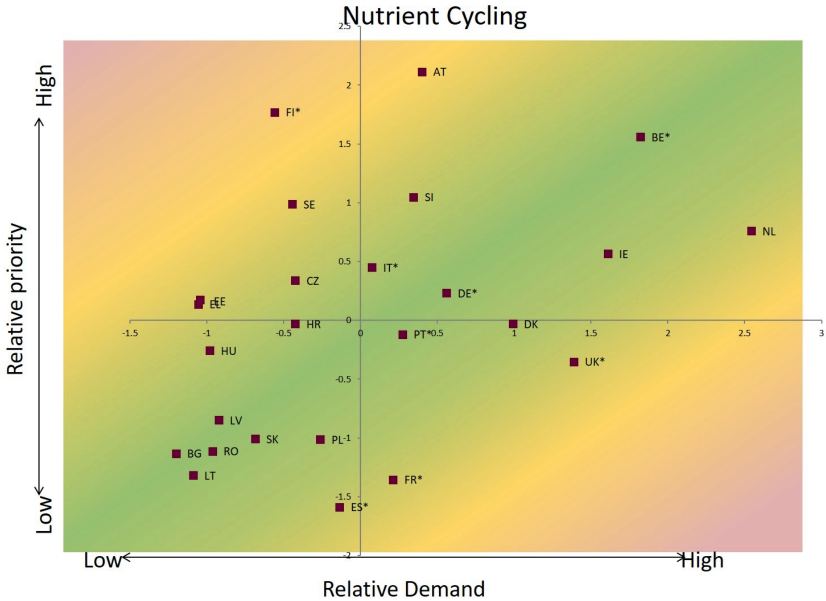

Figure 6: Nutrient cycling additional demand versus priority by Member state. Axes given in z-scores.

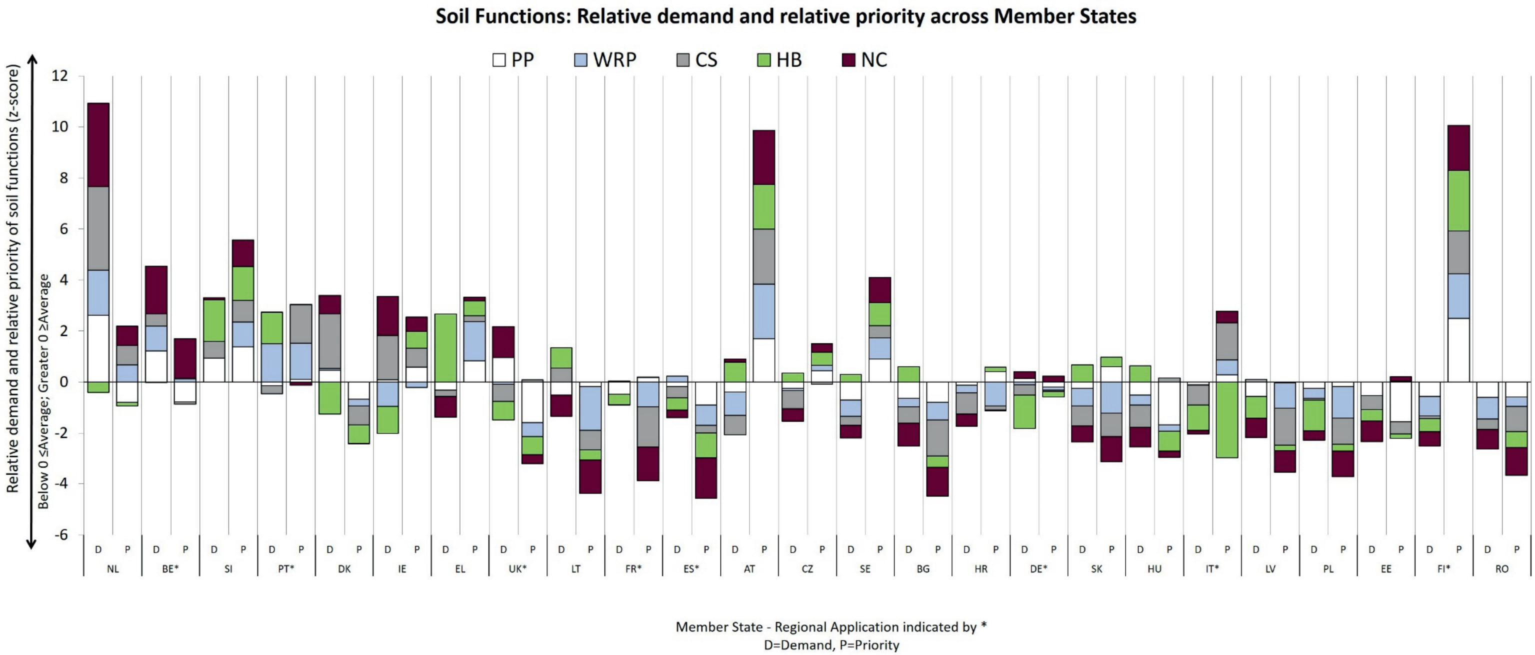

Figure 7 Relative demand and Relative Priority for soil functions. Soil functions legend as per figure 1

Figure 7 shows the relative demand and prioritisation for soil functions both within and between MS. A high variability is found in relation to the relative priority placed on climate and environment objectives between MS. For example, in the case of Denmark, although a high proportional Pillar 2 budget is allocated towards soil functions (figure 1), this is less than average for each soil function relative to other MS. Austria and Finland place a high priority on soil functions indicative of high ambitions and public support in favour of climate and environment objectives. In general, a high variability exists with no correlation when overall demands and overall priorities are compared.

Discussion

The aim of this work was to situate and assess how the five major soil functions were monetarily targeted in the CAP period 2014-2020, and to compare that with the societal demands for soil functions, in order to reveal opportunities at MS scale for alignment. The demands expressed by Schulte et al. (2019) utilise policy drivers to frame societal demand for soil functions. The gap between functional (on-farm) demands and societal demands for land-based public goods often manifest in a market failure that in the absence of functional markets requires incentivisation or other instruments to support their provision. This work offers insights into which soil functions are required most where and the extent to which these have been supported in the past. This has relevance in a context where there are increasing demands on land but simultaneously scope for more context-specific policy making at MS scale.

Alignment opportunities

A high level of heterogeneity was identified between MS: the challenge of meeting demands varying markedly for different soil functions, pointing towards different prioritisation in the development of SPs at MS level (Schulte et al., 2019). This research shows that the budgetary prioritisation of soil functions has been similarly heterogeneous and in many cases poorly aligned with these demands at MS scale (Figure 7). This indicates opportunities to better target soil functions where they are needed most. This is consistent with previous findings that highlight a disconnect between green direct payments implementation and the environmental and climate needs of MS and in turn the achievement of wider CAP objectives (Alliance Environnement and Thünen-Institut, 2017). At MS level, implementation choices have favoured income support for farmers and maintaining existing management practices (Meredith and Hart, 2019). This and a lack of clarity on the objectives of the green direct payments at EU level offer possible explanations for this disconnect (Meredith and Hart, 2019). This highlights a more general need for greater clarity on the role of instruments in meeting both specific and general CAP objectives. Eco-schemes have potential to address this hiatus in implementation, particularly where mismatches between high societal demands and priorities have occurred in the past.

When the priority for individual soil functions is compared with demand (Figures 2-6), different opportunities for better alignment emerge. A high relative demand associated with a low relative budgetary prioritisation (bottom-right quadrant in Figure 2-6_, indicates scope to increase the budgetary priority of that soil function for better alignment. In these instances, scope for targeting could exist through the Pillar 2 framework. However, this requires that the importance of other Pillar 2 targets have been considered, which varies by MS. For example, farm viability and competitiveness are a high budgetary priority in Croatia, France, Portugal and Romania, while high support for social inclusion and economic development is observed in Spain (figure 1). Greater targeting within Pillar 2 towards climate and environment objectives implies a reduction in budget allocation for other objectives and therefore requires consideration on a case-by-case basis. Comparing across functions, the PP, WPR and the NC functions are most frequently associated with high societal demands yet less-than-average prioritisations. A high demand for the PP function was found in the UK, Denmark, Belgium and the Netherlands and for the WPR function in France and Spain. Related to the latter, the introduction under Pillar 1 of proposed Good Agricultural and Environmental Condition (GAEC) 4 to support the establishment of buffer strips along watercourses and the use of a Farm Sustainability Tool (FaST) under proposed GAEC 5, foresee improvements under the Water Framework and Nitrates Directives. Such ambitions of enhanced conditionality can go some way to support a transition towards meeting societal demands and should provide for a more sustainable agriculture. In MSs where the demand for a soil function is particularly high, tailored eco-schemes could be selectively deployed to bridge the gap between functional and societal demands. For example, related to WPR, an eco-scheme that supports the establishment of green cover crops ahead of spring crops could reduce nutrient leakage to groundwater (EC, 2021b). In this way, Pillar 1 eco-schemes offer scope to be tailored to the contextual needs of MS.

In Hungary, and to a lesser extent Lithuania and Bulgaria, an additional demand for the HB soil function is associated with a less-than-average budgetary prioritisation. In these instances, in addition to enhanced conditionality and Pillar 2 environmental commitments, targeted eco-schemes could support an additional density of landscape elements in favour of biodiversity in alignment with the biodiversity strategy. Under the EU Biodiversity Strategy, at least 10% of agricultural area must be under high-diversity landscape features, which must be translated to smaller geographical scales to support habitat connectivity; this will require alignment of the SPs with F2F and the Habitats Directive (EC, 2020c). This implies greater horizontal integration of policy objectives to ensure that trade-offs between competing objectives are limited. It is important to note that where a trade-off between lands for productivity versus lands for biodiversity emerges, farmers are likely to require lucrative compensation schemes to progressively dedicate more land to biodiversity-friendly features.

At the opposite end of the spectrum, we find examples of above-average budgetary allocation targeted towards soil functions with a relatively low societal demand(upper left quadrants of Figures 2-6). This is most commonly found for the PP and NC functions.

When we compare the total magnitude of demand and total budget support for each MS, a high variability is found in relation to the demand and relative priority placed on climate and environment objectives between MS. It is important to reiterate that the societal demands, when presented as z-scores, are reflective of the relative demands for soil functions between member states. Where demands and priorities align, e.g. a high demand and a high prioritisation, this does not equate to objectives being satisfied. Rather, the patterns observed in Figure 7 highlight which soil functions are needed where and how they have been prioritised thus far. It self-evidently makes sense to align budgetary priorities with societal demands, in particular where a high societal demand is coupled with a less than average budget. In cases where both societal demand and budget priority are both above average, this may indicate a need for additional targeting (upper right quadrants in Figures 2-6). For example, in the Netherlands, above-average budgetary prioritisations and societal demands are aligned for CS (Fig. 4), NC (Fig. 6), and to a lesser extent WRP (Fig. 3). Several similar examples emerge, whereby MS are already assigning above average budget towards existing climate or environmental demands. Examples include NC in Belgium (Fig. 6) or in the case of Ireland for CS, NC with a marginal additional demand for PP (figures 4, 6, 2, respectively). The latter country already has the highest Pillar 2 budgetary allocation of any MS towards soil functions and so meeting demand for CS and NC could require additional prioritisation of these specific soil functions under Pillar 1 eco-schemes. In addition to agricultural mitigation associated with reducing GHGs and energy mitigation related to fossil fuel displacement, the opportunity to reduce emissions can now also include the protection of organic soils proposed under GAEC 2, while options for water table manipulation could be supported under Pillar 1 eco-schemes (EC, 2021b). While maintenance of SOC stocks might have scope to meet societal demand in the context of Ireland or Denmark, alternative eco-scheme designs cognisant of local conditions would be required elsewhere, as the promotion of re-wetting organic soils is likely to have limited impact, for example, in the Mediterranean agro-climatic zone.

Anecdotally, low demands for soil functions may be indication that investments in climate and environment objectives have already yielded relatively positive outcomes; however, no causal relationship could be established here and this is not consistently found, as instances also exist where below-average demand is aligned with below-average budgetary allocation (bottom-left quadrants in Figure 2-6).The role of institutional support in supporting a low societal demand should be explored where a less than average demand is associated with above-average budget. Also, opportunities to achieve greater efficiencies through improved targeting may have evolved over time. Equally, whether the high prevalence of MS with low demands associated with below-average expenditure may provide insights into benefits of Pillar 1 cross compliance measures towards meeting societal expectations for specific soil functions should be established.

Urgency for alignment

A new EU soil strategy outlining an overarching policy framework for soil health has been launched that envisions more resilient, healthy soil ecosystems achieved through concrete measures that protect, restore and promote sustainable use of soils (EC, 2021a). Central to all of these ambitions is sustainable land management. Sustainable soil management will be critical for many actions within the EGD with the role of soil considered in emerging agricultural policy (Farm to Fork (F2F) strategy), environmental protection (Biodiversity strategy) and climate change (Climate Law) (Montanarella and Panganos, 2021). The central role of soil in relation to food production has not changed except for a societal requirement to produce more food to support an increasing world population. At the same time, environmental expectations on soil and land have expanded massively which creates a significant challenge in terms of managing soils optimally to meet the demands of all stakeholders. By now, it is accepted that different soils have variable capacity to deliver particular soil functions or suites of soil functions and that a spatially tailored proactive management is needed to optimise the delivery of such services (Schulte et al., 2014; 2016). While farmers understand and appreciate the functionality of soils and the services provided to humankind, such as food production, it is considered that the broader multifunctional nature of soils and land use is not self-evident for European farmers (Schröder et al., 2020). In part, it is proposed that this can be overcome through more specific environmental goal setting and appropriate payment procedures for ecosystem services (Bouma, 2021).

Limitations and further research

The indicators selected to reflect demands for each of the soil functions were derived from an assessment of relevant EU policies and the related policy objectives that are considered to represent societal demand for soil functions at MS scale (Schulte et al., 2015, 2019; Vrebos et al., 2017). The limits of singular or few indicators for soil functions must be borne in mind when assessing these results, as in some instances the indicator may only reflect the partial demand for a soil function, or may otherwise be constrained based upon the availability of existing datasets.

While it is recommended to align priorities with demand, further investigation into the limits of budgetary support within the current framework is required. Although beyond the scope of this assessment, evidence of efficacy of interventions over time is necessary, in particular to pinpoint successful measures with a view to exploring their scaling potential at EU scale. In some cases high public support has translated to a high uptake on the ground but in other instances high public support is not sufficient. Furthermore, while fiscal supports are important, it is also just one consideration within a multitude of factors that can influence the uptake of instruments at farm scale.

Conclusions

In this paper, we conceptualised the delivery of EU climate and environment objectives through the lens of five land-based soil functions. We propose that meeting higher ambitions on climate and environment objectives in the future will require a targeted approach that can better align budgetary allocation for incentivisation to meet societal demands. This work offers insights into how soil functions could be prioritised within and between member states, and has identified where such incentivisation efforts could be targeted for MS, based upon the current societal demands, with the following conclusions:

- One-size targeting does not fit all, with the heterogeneity of demands requiring a nuanced approach towards targeting for climate and environment objectives in the post-2020 CAP period.
- Already, many MS already prioritise selective soil functions reflected by an above-average budget allocation that are coupled with a high demand. In such cases, additional targeting may be exploited through new opportunities afforded in the proposed eco-schemes under Pillar 1 where these high demands are indicative of a pressure point.
- Options for better alignment in the existing framework should be explored, particularly

where a high relative priority in Pillar 2 is targeted toward a soil function for which the relative demand is low.

- Beyond this assessment, it should be explored whether low demands represent a positive outcome of investments in climate and environment and if so, what lessons can be shared and leveraged at EU scale.

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CHAPTER 8

Trust versus content in multifunctional land management: Assessing soil function messaging in agricultural networks

Putting the people into Functional Land Management

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Abstract

Growing sustainability demands on land have a high knowledge requirement across multiple scientific domains. Exploring networks can expose opportunities for targeting. Using mixed-methods combining social network analysis (SNA) and surveys, networks for key soil functions in case studies in Germany, Ireland and the Netherlands are explored. We find a diversity of contrasting networks that reflect local conditions, sustainability challenges and governance structure. Farmers were found to occupy a central role in the agri-environmental governance network. A comparison of the SNA and survey results indicate low acceptance of messages from many central actors indicating scope to better harness the network for sustainable land management. The source of the messages was important when it came to the implementation of farm management actions. Two pathways for enhanced farmer uptake of multi-functionality are proposed that have wider application are; to increase trust between farmers and actors that are agents of multi-functional messages and/or to increase the bundling or multi-functionality of messages (mandate) of actors trusted by farmers.

Introduction

Policy context

Within the European Union (EU), the Common Agricultural Policy (CAP) is the key agri-environmental instrument and represents the largest agricultural support system in the world (Pe'er et al., 2014). The early decades of the CAP have played a critical role in shaping land management in favour of food production. By the 1980s, guaranteed commodity prices had generated an over-supply of food products and an intensification of agriculture that aligned with environmental deterioration (Pe'er et al., 2014). To address this, successive CAP reforms have expanded agricultural policy to incorporate environmental concerns and the sustainability of rural ecosystems. Although the CAP is now recognised as the largest funding source for nature conservation in Europe (Keenleyside and Tucker, 2010; Herzon et al., 2018) a review of the CAP 2014-2020 period indicated that green payments for sustainable agriculture have neither met the environment and climate needs of Member States (MS) nor wider CAP objectives (Meredith and Hart, 2019). In 2018, the European Commission (EC) published a legislative proposal on the CAP period 2021-2027. Key elements of this proposal include: 1) better targeting of funding towards small and medium sized farms; 2) guaranteeing a higher ambition on environmental and climate action; 3) putting agriculture at the heart of European society and 4) making greater use of knowledge and innovation (EC, 2018). As anticipated, the proposal makes significant contributions to the EC Green Deal and the Farm to Fork and Biodiversity Strategies (EC, 2020). A new delivery model based upon strategic plans (SP) that reflect MS needs, is expected to facilitate more context-specific policies (EC, 2018).

The challenge

Agricultural policy reforms increasingly link agriculture to the delivery of public goods and services. Farmers receive policy support as producers and increasingly as natural resource managers in recognition of the more diverse role of agriculture from an ecosystem perspective. An abundance of policy instruments relevant to land management at farm and national scale have emerged under environmental directives that have largely been formulated independently of each other (Schulte et al., 2015; 2019). Historically, agri-environmental sustainability has been steered by direct regulatory processes focused on mandatory operating requirements targeted towards solving environmental problems (Taylor et al., 2012). However, since the 1990s, there has been a shift from government-based to multi-actor governance due to the failure of traditional policies to address the challenges of environmental degradation and biodiversity loss (Loft et al., 2015). This multi-actor governance refers to an expansion of the decision-making process on the provision and use of public goods to a much wider range of stakeholders (Maury et al., 2013). This implies that sustainability depends also on the role of different actors. Faced with a growing suite of competing societal demands on land (Schulte et al., 2019), farmers and stakeholders have to absorb and consider increasingly complex knowledge regarding both global and local processes to achieve sustainability (Leeuwis, 2004). This complexity presents particular challenges for farmers and other land managers with direct responsibility for land use and soil management decisions. The point of obligation of territorial agri-environmental policies typically applies at farm scale, meaning that farmers are assigned a key role with respect to the practical implementation of practices and measures for sustainable land management. European policies have fostered the model of family-operated farms, typically led and managed by one or two people. Within the context of increasing societal expectations, a high knowledge requirement across multiple scientific domains is now imposed on individual farmers. In the context of a network, knowledge (and information linked to other policy instruments) is communicated to farmers by means of messages that originate from different sources in the network. This can results in information overload. As the demands for sustainability are increasing, this can be associated with an implicit expansion of the amount of messaging and information from science, policy, markets and value chains that farmers receive, which may increase the potential for information overload at farm scale.

Theoretical framework

Functional Land Management (FLM) is an integrated approach that aims to optimise the delivery of land-based ecosystem services (Schulte et al., 2014). Five ubiquitous agricultural land-based ecosystem services, or soil functions, have been identified by Schulte et al. (2014), based on Haygarth and Ritz (2009): 1) primary production of food, feed, fuel and fibre; 2) water purification and regulation; 3) carbon storage, sequestration and climate regulation; 4) provision of habitats for biodiversity and 5) provision and cycling of nutrients. These five key soil functions represent a large portion of societal demand for land based ecosystem services with pertinence for agri-environmental governance within the EU (Schulte et al., 2015; 2019). Accordingly, the FLM framework offers a mechanism by which networks for sustainable land management can be framed. Already an EU level assessment of the societal demand (reflected by policy indicators) for multi-functionality based upon FLM was found to differ between MS indicating that SP represent an opportunity for more effective and targeted incentivisation of sustainable land management (Schulte et al., 2019). While that work provides insights into which soil functions should be prioritised where, further questions emerge, including who and how to target messages for FLM. The goal of this work therefore is to address this knowledge gap and to explore networks for multi-functionality using the five soil functions in the FLM framework to understand whether similarities or differences exist between networks in different contexts for the same key soil functions from which high-level conclusions can be drawn.

In relation to multifunctional social networks for FLM, the following are important considerations outlined in brief below; 1) the potential of particular actors to bundle messages, 2) the coherence of messages that actors receive and 3) the role of trust and message acceptance.

The expanded governance context gives rise to potentially alternative points of entry for agri-environmental sustainability, for example through targeting different actors who communicate messages in the network. Targeting "higher" entry points could potentially address the complexity of messages through bundling. Bundling refers to messages that address multiple soil functions simultaneously. Actors that bundle could be targeted to align messages in favour of fostering sustainable land management. Actors who transmit messages related to multiple soil functions (bundle) may have a particular role to streamline messaging for multiple functions. Off-farm organisations may employ more people and so scope to bundle and align messages could be leveraged.

Coherence can be defined as a lack of contradiction or the degree of agreement between different elements in a set (Toro-Alvarez, 2020). Cognitions refer to the opinions, knowledge and beliefs about oneself and their environment and when two cognitions are inconsistent this can generate dissonance (Festinger, 1975). This cognitive dissonance, also called incoherence, creates a state of discomfort and can promote a search for coherence (Toro-Alvarez, 2020). Within a network, messages are communicated to farmers from multiple different sources. The messages related to soil functions are likely to come from multiple sources but refer to the same resource and could therefore result in incoherence for message recipients. At an applied level, coherence has been linked to several criteria of success (see Toro-Alvarez, 2020 for overview). Understanding the level of coherence that farmers associate with messages related to sustainable land management could provide insight into whether a need for greater coherence exists. In turn, this could help inform needs and mechanisms to support sustainable land management at a practical level.

According to Social Judgement Theory, the messages that people receive are compared to their current point of view, upon which different attitudes are formed that fall into different zones of acceptance (Sherif and Hovland, 1961; Sherif et al., 1965; Mallard, 2010). The level of involvement, or how important an issue is to the person's life will affect where on the scale the individual will position the message received, which may fall into the latitudes of acceptance, rejection or non-commitment (Sherif and Hovland, 1961). Although individuals judge messages according to their own so-called anchor or standpoint, it is important that this anchor is movable. If messages fall within the latitude of acceptance, it is perceived as closer to their viewpoint and the anchor is moved closer to the message, however if outside the latitude of acceptance, the message is perceived as further away (Griffin, 2012). Acceptance is multi-faceted, and can be linked to different layers including acceptance of the underlying problem, acceptance of the solutions, credibility and trust in the change agent and acceptance of the consequences of the innovation (Leeuwis, 2005). Based upon the adoption and diffusion research, Leeuwis (2005) indicate that increasing acceptance, and ultimately adoption of sustainability innovations, a number of different stages occur including awareness, interest, evaluation, trialling of the proposed innovation and adoption/acceptance each with different information requirements. To transition towards a more sustainable agriculture, inclusive educational programmes are important (Maini et al., 2021) and the knowledge intensive nature of addressing the challenges of food security, climate change and biodiversity means that education will play a critical role (Carlisle et al., 2019). Furthermore, the acceptance of the message is influenced by the relationship between the sender and receiver with acceptance increased where a favourable relationship exists (see S1 Figure S1). As networks play a role in informing shared norms, values and understanding they can inform in part the attitudes towards messages received at an individual level. Whether messages are translated into actions is embedded in a complexity of factors encompassing aspects such as identify, knowledge, risk perceptions, belief, experience and aspirations (Leeuwis, 2004).

Considering these dimensions and exploring networks, such as how information diffuses in the network could help to identify the opportunities for targeting. Networks with shared norms, values and understanding can facilitate cooperation and can generate bonding social capital between individuals and bridging capital, between groups or wider networks (de Krom, 2017). In this sense, the role of social capital in social networks that farmers are associated with may be important for spreading information about practices and providing role models or generating norms of participation. Trust is an implicit feature of social capital (Coleman, 1990; Putnam, 1993) with the magnitude of network potential governed in part by the levels of trust between actors. Acknowledging the need to adjust approaches to knowledge exchange, learning and innovation in agriculture, already the EU EIP-AGRI interactive innovation model fosters a network-based approach to information exchange for competitive and sustainable farming and forestry across all actors in the agricultural knowledge innovation system (EC, 2020a). Competitive and sustainable farming refers to a primary sector that can secure global food availability, provide a diversity of products and production, with greater farm profitability with supply efficiency and natural resource management reflective of environmental sustainability (EC, 2012). In this regard, better understanding of the network of actors in the AKIS can help to identify actors to target with respect to specific agri-environmental objectives through incentives or other mechanisms.

Aims and objectives

In this research, we hypothesise that governance messages for soil functions converge at farm scale, which can result in overload of messages, making decisions related to sustainability challenging. The aim of this study was to increase understanding of messaging for soil functions in the network and the extent to which messages are accepted at farm scale. The major objective, using SNA and survey analysis data, was to expose opportunities to harness the potential of the network based upon network characteristics and farmer acceptance. The following research questions were addressed:

- What is the composition of current networks for soil functions in terms of context, diversity and scaling?
- What coverage of different soil functions is found in existing networks and to what extent are messages related to soil functions bundled, i.e. multifunctional?
- To what extent are messages related to soil functions coherent?
- To what extent are messages accepted by farmers?
- How can messaging for soil functions support sustainable land management?

Materials and methods

Research design

A mixed-method comparative case-study design was used in this research. This included social network analysis techniques. A social network is the structure of the interacting elements based upon a set of interconnected actors (nodes) and the connections (edges/arcs/ties/links) between them. Social network participatory mapping techniques in tandem with social network analysis (SNA) were used to investigate the social structure of these interactions. In addition to social network data, participants each completed an individual survey to ascertain the degree of coherence and the acceptance or non-acceptance of messages. These data were compared with network data to reveal opportunities for targeting within the wider networks of the individual case studies.

Selection and overview of case studies

Three local case studies in three EU Member States were included in this research and were participants in an EU project exploring soil functions and the FLM framework. Lower Saxony in Germany; the south-west of Ireland and the Western Peat Meadows in the Netherlands. Case studies were selected based on several similarities and differences in relation to the agri-environmental governance systems. As EU Member States, these countries have shared priorities in relation to achieving EU agri-environmental targets but exhibit different levels of implementation and AKIS integration (Knierim and Prager, 2015). The context specific nature of networks means that the social networks are reflective of these local networks but not necessarily representative of the national pictures.

Farmland in the Dümmer-Lake region in Lower Saxony, Germany is used mostly for tillage (86%) with some grassland (13%) with 1% special cultivars. Many farms are mixed livestock and arable with one-third dairy or beef enterprises. Almost one-quarter do not have livestock and another quarter are pig or poultry enterprises. The Dümmer Lake is sensitive to phosphorus (P) eutrophication, so water quality is an important consideration in this area. The case study region in the south-west of Ireland is predominantly an intensive dairy catchment representative of the most intensively farmed dairying areas in Ireland. Most land is in grass and the area is characterised by herds producing milk under an intensive grass-based system. Nitrogen (N) loss via well-drained soils is the main threat to water quality in this area. The Western Peat Meadow Area is a typical Dutch landscape occupying large areas of the province of Utrecht, South Holland and the province of North Holland (Henkens, 2013). Although a long history of dairy grazing farming exists, agricultural drainage and subsidence due to oxidation of the soil layer is a key concern in this landscape (Henkens, 2013).

Methods of data collection

Social network participatory mapping

Actor network data were collected between April and November 2017-2019 (Germany, n=17; Ireland, n=41 and Netherlands, n=20). Social network maps representing the FLM governance network were constructed in participatory workshops. To understand the structural and functional aspects of how different actors conceptualise the governance network for soil functions, actors constructed network maps of the flow of messages related to soil functions. The main elements captured were nodes, which represent actors or organisations in the network with capacity (agency) to influence soil functions by sharing messages with other organisations; ties representing the links between nodes and messages for the five soil functions. During the mapping exercise, actors assigned probabilistic centrality tie weights calculated as the frequency (f) of a message multiplied by the likelihood to act (a) using the weight loadings shown in Table 1.

Table 1 Weight loadings for actor ties associated with frequency and action

Weight loadings (zero-order reciprocal approximation)			
Frequency (f)		Action (a)	
Daily	1	High potential- will transmit / act	1
Weekly	.5	Med-High potential -should transmit / act	0.5
Monthly	0.25	Medium - may transmit / act	0.25
Annually	0.125	Low potential – unlikely to transmit / act	0.125
Less than annually	0.0625	Very low potential	0.0625

To complete the mapping exercise, participants were given an A0 sheet and sticky notes to populate the network. Following Burt (1983) and Reagans and McEvily (2003), respondents were asked a series of questions/prompts to generate nodes. To overcome issues of recall, a roster of 'typical' contacts was also provided (Reagans and McEvily, 2003). The five soil functions were used as a formal criterion to boundary the network with analytical significance to the current research after Laumann et al. (1989). Prompt questions included:

Please compose a list of names of all the 'organisations' with which you share information in relation to your organisation (as information receiver or information supplier) for the soil function XXX ?

Please consider all sources of information and knowledge – these can include your informal network – such as other farmers, family, social media, industry representatives, advisory etc.

Please also consider your formal contacts – such as the department of agriculture.

Prompts for individual soil functions were tailored to account for differences between actors in the network - so whether you are a farmer, or another actor. For example, in relation to water purification function, N,P and K application rates might be more pertinent for farmers, versus a prompt in relation to the Nitrates Directive when talking with policy makers. .All participants, along with those identified by respondents as message senders were included as actors and represent network nodes. Saturation was determined when all key actors listed prior to the sampling process based on literature and discussions with key-informants appeared in the network. Previously, the Pro-AKIS project had visualised the main actors in the AKIS that link people and organisations at MS level, providing an overview framework (Pro-AKIS, 2014). While that work provided an AKIS overview, ties were not specifically in relation to soil functions. While the earlier work provided insight into the AKIS in general, in this research we distil the networks out of our analysis of who is sending messages to whom in three case studies in relation to five soil functions.

In addition to relational data, respondents were also asked to fill in node attribute data to describe the type of organisation (farm, business, government, NGO, R&D, other, unknown) and the scale of the node (local, county, regional, national, international or unknown). To eliminate bias associated with power relations, the egocentric data for key actors were collected and combined to produce egocentric networks by actor type, e.g. farmer network. These were subsequently combined into a single data matrix to visualise the whole sociocentric network. Where repeat ties occurred between nodes, these were merged in Gephi © 9.2 software and reflected by the average tie weight. This meant that actor types were provided equal weighting when ties were subsequently generalised to reflect the whole network to avoid an actor bias. Network statistics were calculated for the whole network based upon the combined SNA maps within case studies. Two facilitators completed the data collection following a guide for data collection to ensure consistency. Two preparatory meetings prior to data collection took place in the Netherlands in 2018 to ensure facilitators were prepared to engage in a consistent, accepted, productive and neutral way.

Survey data

Respondents answered questions to characterise the messages they receive on the basis of consistency and coherence. They were also asked about how to improve coherence in the messaging they receive. Farmer respondents indicated which actions they have implemented on farm, structured along mandatory, market or voluntary measures to provide insight into sustainability actions at farm scale and the key message source for measures implemented. This represents the operationalisation of message (non-)acceptance. The source of messaging for measure implemented was recorded also to understand who the key brokers were and to allow for a comparison between them and those identified as the most central actors in the whole network.

Methods of data analysis

Social network analysis

Gephi © 9.2 software was used to visualise and analyse the networks using exploratory SNA techniques. Exploratory network analysis methods are based upon graph theory whereby maps are transformed into adjacency matrices with nodes listed on the horizontal and vertical axes. A weight is coded in the matrix where a tie is observed between two nodes (Scott, 2017); in this instance weighted ties were used. The metrics used to analyse network position and for network structure are shown in Table 2.

Table 2 Numerical expressions used to assess and compare the social networks of each case study region and structural properties

Node Properties			
Node position	Numerical Expression	Definition	Node characteristic(s)
Out-degree (OD)	$ODi = \Sigma\lvert a_{ij}\rvert$ k=1	The cumulative strength of connections with which a node influences others	Driver
Weighted out-degree (WOD)	$ODw = \Sigma\lvert a_{ij}\rvert * \Sigma\, Wa_{ij}$ k=1	The out-degree of a node considered by the total weight of its outward edges	Influencer
In-degree (ID)	$IDi = \Sigma\lvert a_{ij}\rvert$ k=1	The cumulative strength by which a node is influenced by others	Receiver
Weighted in-degree (WID)	$IDiw = \Sigma\lvert a_{ij}\rvert * \Sigma\, Wa_{ji}$ k=1	The in-degree of a node determined by the total weight of its incoming edges	Affected
Centrality Degree (D)	$DoC_i = OD_i + ID_i$	The cumulative strength of connections of a node (in and out ties)	Central
Weighted degree of centrality	$DoC_{i\,w} = OD_{iw} + ID_{iw}$	The degree of centrality of a node determined by the total weight of all its edges	Dominant centrality
Betweenness Centrality	$C_B(n_i) = \Sigma\ g_{jk}\,(n_i)/g_{jk}$ j<k	The fraction of shortest paths that go through a node divided by the total number of shortest paths between nodes	Broker/Bridge

Closeness Centrality	$CC(i) = \frac{N-1}{\Sigma d(i,j)}$ j	Average length of the shortest path between node and all other nodes.	Diffusion
Network Structure			
Number of nodes	N	The number of components in the map	
Number of edges	E	The total number of linkages between components	
Diameter	$D = \max_{st}\{a(s,t)\}$	The shortest path length in the network (the shortest distance between the most distant nodes in the network).	Indicates how long it would take (or how many intermediary nodes it will take) for messages to circulate between the two most distant nodes.
Density	$Dn = E/N(n\text{-}1)$	Indicates how densely nodes are connected	

In table 2, *a* represents each edge, *i* is the transmitter node of edge *a, j* is the receiving node of edge *a* and *W* is the weight of edge a (example source calculation references see e.g. Özesmi and Özesmi, 2004; Micha et al., 2020). For betweenness centrality, *gjk* represents the number of geodesics or shortest paths connecting *jk*, and *gnk (ni*) = the number that node *i* is on (based on Derrible and Holme, 2012). For closeness centrality, where I≠j and dij is the length of the shortest path between nodes i and j in the network, N is the number of nodes following Sabidussi (1966). Diameter $a(s,t)$ indicates the number of edges in the shortest path from a node *s* to a node *t*. Density represents the number of edges (E) divided by actors times actors minus 1.

In addition to network properties and structure, ties were analysed in terms of the soil functions that they applied to so that the coverage of different soil functions in the network could be established along with the bundling capacity of network actors.

Survey data were analysed using Microsoft excel 2016 to determine acceptance of messages based upon the translation of messages received into action. Survey data were compared with network analysis results in terms of similarities or divergences. This comparison exposed opportunities for future targeting of actors in the wider network described in the SNA.

Results and discussion

Social network analysis

Network compositions and characteristics – context, diversity and scale

Data collected through the participatory mapping exercises are used to describe the composition and characteristics of the network and are presented in tables 3, 4 and 5. Table 3 shows the global structure of each network such as size, diameter and density. Table 4 shows the types of actors in the networks while table 5 shows the scale of actors.

Table 3 Global network context of the case studies

Network	Germany	Ireland	Netherlands
Nodes (actors)	52	110	73
Edges (ties)	130	259	213
Diameter	4	5	4
Path length (average)	2.37	3.278	2.605
Clustering Coefficient (average)	0.175	0.07	0.142
Graph density	0.049	0.02	0.041

In relation to messages for soil functions, the largest sustainability network was identified for Ireland (110 nodes and 259 edges) compared to the German case study, which had the fewest nodes and ties (52 nodes and 130 edges) (Table 3). Having a larger network can foster innovation but this also relies on the diversity of these actors (Hermans et al., 2017). Graph diameter is a measure of the shortest distance between the two furthest actors. Graph diameters of four, five and four were found for Germany, Ireland and the Netherlands respectively. In practice, this means that for messages related to soil functions to be transmitted between the two most distant actors the messages would need to transit between three, or four in the case of Ireland, other actors. This is an indication of small but highly connected networks (Iijima and Kamada, 2017). Average path lengths of ~40% less than graph diameter indicates a relatively high network efficiency. While most nodes are not directly connected, only a few intermediary steps exist between any two nodes. A relatively low diameter, coupled with a power law distribution (meaning the presence of a few dominant hubs with very high degree representing a high number of messages) (S1, Figure S2) are characteristics consistent with the presence of ‘small worlds’ (Travers and Milgram, 1969; Watts and Strogatz, 1998) and were found in all case studies. The emergence of some actors with high clustering coefficients further suggests cliques whereby these particular nodes have dense networks with friends who tend to be friends with one another. In Germany, examples include a hunting organisation or the dung board. In Ireland, the food marketing board and soil analysis contractors have these characteristics while in the Netherlands it includes the young farmers lobby group. These may be effective actors for relaying information while keeping the number of links to connect the network to a minimum. However, this must be considered within the global network context, whereby low average global clustering coefficients indicate a relatively low cohesion in the networks overall with only about 15% of possible triads (triangles between three nodes) completed (Table 3). Furthermore, graph densities < 1 were found in each of the case studies (all < 1 where 1 indicates all nodes are connected to each other), indicating network vulnerability and that potential for increased connectivity in the networks exists.

Table 4 show how diverse the networks are, based upon the types of actors represented. Diversity in networks is an important indication of the potential for innovation as different actors bring different understandings into the biophysical, technological and institutional dimensions of the problem with capacity to innovate benefitting from interactions between a diversity of actors (Hermans et al., 2017).

Table 4 Soil function sustainability network diversity - actor type

	Type												
Case study	Farm Org	Business	Gov.	Semi-state	NGO	Research	Advisory	Info	Lobby	Multi-actor	Other	Total nodes	Total ties
Germany	5 (10%)	17 (33%)	10 (19%)	2 (4%)	5 (10%)	1(2%)	7 (13%)	2(4%)	2(4%)	1(2%)	-	52	130
Ireland	3 (3%)	30 (27%)	45 (41%)	2 (2%)	3(3%)	6(5%)	7(6%)	2(2%)	1(1%)	3(3%)	8 (7%)	110	259
Netherlands	5 (7%)	14 (19%)	12 (16%)	1(1%)	7(10%)	11(15%)	2(3%)	2(3%)	5(7%)	4(5%)	10 (14%)	73	218

The networks analysed here reflected a broad mix of different actor types with private business and public governmental actors the most prevalent types of actors across all networks. Thereafter, actors described as research or advisory were the most identified actor types in these networks (Table 4). In this regard, each of the networks reflects a diversity of actors with no noticeable absences of a particular actor type observed.

The spatial scale at which actors operate provides insight into the scaling potential of networks. Table 5 shows the proportionality of organisations per network scale. Actors at different scales typically have access to different resources such as knowledge or power. Networks with connected actors operational at different administrative scales are relevant so that information or other resources can flow between different levels (up-scaling) (Hermans et al., 2017).

Table 5 Number and percentage of organisations per scale in the network – scaling potential

	Local	County	Regional	National	International	Multi-scale
Germany	11 (21%)	7 (13%)	13 (25%)	9 (17%)	4 (8%)	8 (15%)
Ireland	13 (12%)	1 (1%)	14 (13%)	67 (60%)	15 (14%)	-
Netherlands	14 (19%)	1 (1%)	14 (19%)	38 (53%)	3 (4%)	2 (3%)

The German network unveiled a more even distribution of actors at different scales (Table 5). Regional scale actors accounted for one-quarter of nodes, followed by local scale actors (21%). In relation to the political geography, the networks highlight two main differences. In Germany, a much higher proportion of the network is assigned to 'county' scale while the 'national' scale is far higher in the other case studies. The much larger geographic spatial scale is likely a driver of the key differences between Germany and the other case studies. In part, this may be due to the respective EU institutional frameworks of the case studies, administered at regional scale in Germany due to federal governance potentially more efficient, compared to the national scale in Ireland and the Netherlands where much higher proportions of national scale actors are reported. Even though all countries are within EU MS implying a similarity in agri-environmental governance, the island nature of Ireland may be important with the high proportion of national scale actors linked with a greater need for connectivity at wider geographical scales. Beyond actors at different scales, the presence of multi-scale actors represents added opportunity to connect administrative scales. Actors described as 'multi-scale'', such as the dairy industry or a farmer association were recorded in Germany (15%) but were not described in the Irish network with a low proportion identified in the Dutch case study (2.7%).

While there is no one optimal network configuration, in relation to scaling and innovation potential as per Hermans et al., (2017) the German network theoretically reflected greater scaling potential based on the network configuration whilst the larger network found in Ireland may have greater scope for innovation due to the larger network of actors reported.

Who's who? Actor prominence

Different measures of centrality are useful for understanding the role of different actors in the network. Within networks, different actors occupy different positions with respect to the level of prominence that they hold associated with the volume of messages that they both receive and emit (degree) or that they receive (in-degree) or emit (out-degree). A high degree centrality means that an actor receives and emits a high number of message making then central to the network. Table 6 provides an overview of the position of the top ten actors in the networks based upon centrality measures allowing the most important actors in the network based upon the number of connections to be identified. Those with a high weighted in degree (WID) receive a lot of messages whereas those with a high weighted out degree (WOD) emit a lot of messages and are also referred to as influencers. Actors with high out degree can exchange with many others and can make people aware of their views, which increases the capacity of these actors to be influencers in the network.

Table 6 Whole network centrality results for case studies

Germany									
Actor	Degree	Actor	WID	Scake	Type	Actor	WOD	Scale	Type
NGO (SustAg)	51	NGO (SustAg)	7.61	R	NGO	NGO (SustAg)	7.66	R	NGO
Farmer	47	Farmer	7.21	L	F	Farmer	7.59	L	F
Advisory (CALS)	35	Advisory (CALS)	3.78	MS	A	Advisory (CALS)	2.35	MS	A
Agricultural Contractor	6	Advisory (LWK)	1	MS	A	Natural Resource Management	1.1	R	G
County Council	6	Natural Resource Management	1	R	G	Advisory (LWK)	1	MS	A
Advisory (BRS)	6	Research (University)	1	N	R	Research (University)	1	N	R
Environment Association	6	Family	1	L	F	Family	1	L	F
Advisory (LWK)	6	Other Farmers	1	L	F	Other Farmers	1	L	F
Environment (NLWRN)	5	Inputs (seed)	1	L	B	Inputs (seed)	1	L	B
Water Supply (WSV)	4	Agriculture Ministry	0.75	MS	G	Weather	1	N	I
Ireland									
Actor	Degree	Actor	WID	Scale	Type	Actor	WOD	Scale	Type

Farmer	52	Farmer	5.70	L	F	Fertiliser Industry	6.13	R	B
Fertiliser Industry	36	Fertiliser Industry	5.07	R	B	Farmer	4.71	L	F
EPA (Catchments)	31	Environment Agency (EA) (Licensing)	4.69	N	G	EPA (Licensing)	4.44	N	G
EPA (Licensing)	30	Advisor (Teagasc Specialist)	3.98	N	A	EPA (SEA)	3.39	N	G
DAFM Climate	30	EPA (Catchments)	3.18	N	G	EPA (Catchments)	2.78	N	G
EPA (SEA)	25	DAFM (Climate)	2.52	N	G	DCCAE – Climate and Environment	2.46	N	G
Dairy co-operative	22	Dairy co-operative	2.23	L	B	Research (Teagasc)	2.39	N	R
Research (Teagasc)	22	Research (Teagasc)	1.57	N	R	Advisor	2.37	N	A
EPA (SOE)	20	DAFM	1.48	N	G	Dairy Co-op	1.81	L	B
DAFM	17	Media (online)	1.21	N	I	DAFM	1.72	N	G
Netherlands									
Actor	Degree	Actor	WID	Scale	Type	Actor	WOD	Scale	Type
Farmer	72	Farmer	9.19	L	F	Farmer	7.42	L	F
Nature Board	46	Nature Board	6.27	N	MA	Nature Board	6.36	N	MA
Research	43	Research	5.96	N	R	Research	4.46	N	R
Gov (Reg)	35	Agriculture & Nature Collective	3.02	P	MA	Agriculture and Nature Collective	3.57	P	MA
NGO (SustAg)	22	Regional Government	2.39	P	G	Regional Government	2.31	P	G

Agriculture & Nature Collective	16	NGO (Sustainable Agriculture)	2.23	N	NGO	NGO (Sustainable Agriculture)	2.23	N	NGO
Water Board (Regional)	12	Water Board (Regional)	1.57	P	G	Nature Lobby	1.55	N	L
Nature Lobby	10	Local Dwellers	1.50	L	O	Local Dwellers	1.5	L	O
Advisor (P)	7	Nature Lobby	1.32	N	L	Media	1.33	N	I
University	7	Services – AI	1	L	B	Farm workers	1	L	F

The farmer represented the most central actor in Ireland and the Netherlands, with the highest degree centrality based upon the number of messages (received and emitted) (Table 6). This confirms that most messages converge at farm scale. As more farmers completed the network data collection exercises, this plausibly increases scope to identify more actors and in turn can increase centrality scores even if ties were averaged for all farmers in a given network. However, this result is still consistent with previous findings in relation to farmer stakeholders who are considered to have a high degree of centrality for agricultural biodiversity governance (Hauck et al., 2016). However, as more farmers completed the network data collection exercise, it is plausible that scope to increase the number of nodes identified exists and so this In Germany, an NGO on sustainable agriculture had the highest overall degree (received and emitted). The farmer was the second most central actor in the German network, still indicating the prominence of farmers in the network for agri-environmental messages related to soil functions with a high message load converging at farm scale. In the Netherlands, the farmer represents the actor who both receives the most messages but also has the highest Weighted Out Degree (WOD) indicative of high capacity to influence. In Ireland, the fertiliser industry emerge as having high potential to influence and in Germany the NGO working in sustainable agriculture held this position. These actors are important given their potential to influence the network, however it must be borne in mind that the extent to which this potential is utilised will rely on the extent to which messages might be congruent with the central objectives of these actors.

In addition to degree centrality, betweenness centrality was analysed (Figure 1). Betweenness is important to identify the bridging actors in the network as they can influence flow around the network. Betweenness centrality is based upon the number of shortest paths that pass through an actor (Freeman, 1977) and is a critical measure to assess which actors could act as bridging agents in the network. In the absence of these actors, different actors in the network would be disconnected so these actors are important brokers to reach certain actors.

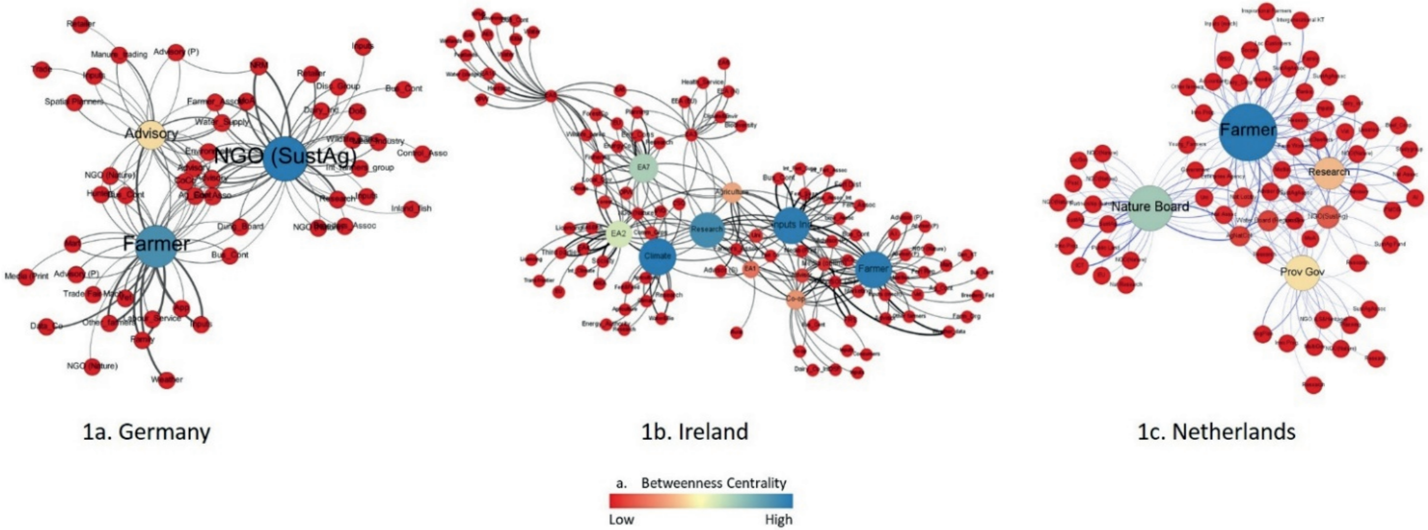

Figure 1. Betweenness centrality indicative of key bridging actors in the network. The most important bridging actors are shown in blue.

Across the networks, farmers are a top bridging actor (Figure 1). Consistent with previous findings, sustainability organisations/collectives are important in the Netherlands and Germany (Prager, 2015) whereas governmental bodies and industry partners represent the key brokers in the Irish network. While having the potential to act as a bridge or knowledge broker, these actors may also be gatekeepers of information. The power of this role may give rise to a service charge. Maury et al. (2013) emphasise attention for actors who bridge gaps between environment, agriculture and territory that through their presence, may have potential to mobilise resources particularly in relation to coordination. This may be particularly important going forward as there is heightened demand to validate the sustainability credentials of agricultural production. Meeting targets outlined under emerging policies, for example a 20% reduction in fertiliser (EC, 2020), is likely to require many actors across the whole chain, who may evolve as having a role in coordination, for example, industry partners. In some instances, additional bureaucracy could be potentially off-set where such coordination could accrue benefit via marketed goods that could be linked to a reduced footprint in relation to environmental outcomes.

Closeness of a node represents the shortest distance between a node and all other nodes. Closeness highlights those actors that can readily influence the network quickly and are useful for information diffusion based upon their proximity to other actors, as shown in Figure 2. Closeness centrality is important as these actors can perform a role in information diffusion in the network due to their capacity to reach actors more readily than actors that are further away.

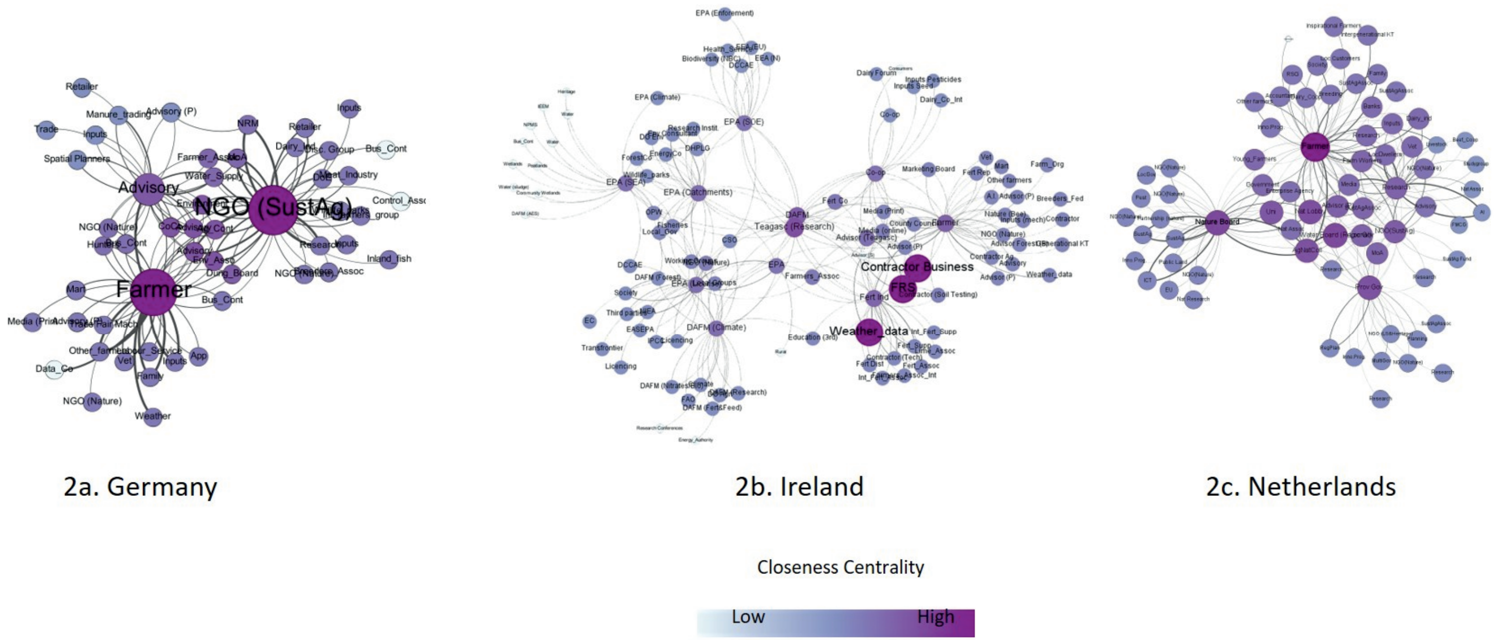

Figure 2. Closeness centrality whereby actors with highest closeness centrality (darkest colour) have potential for message diffusion in the network.

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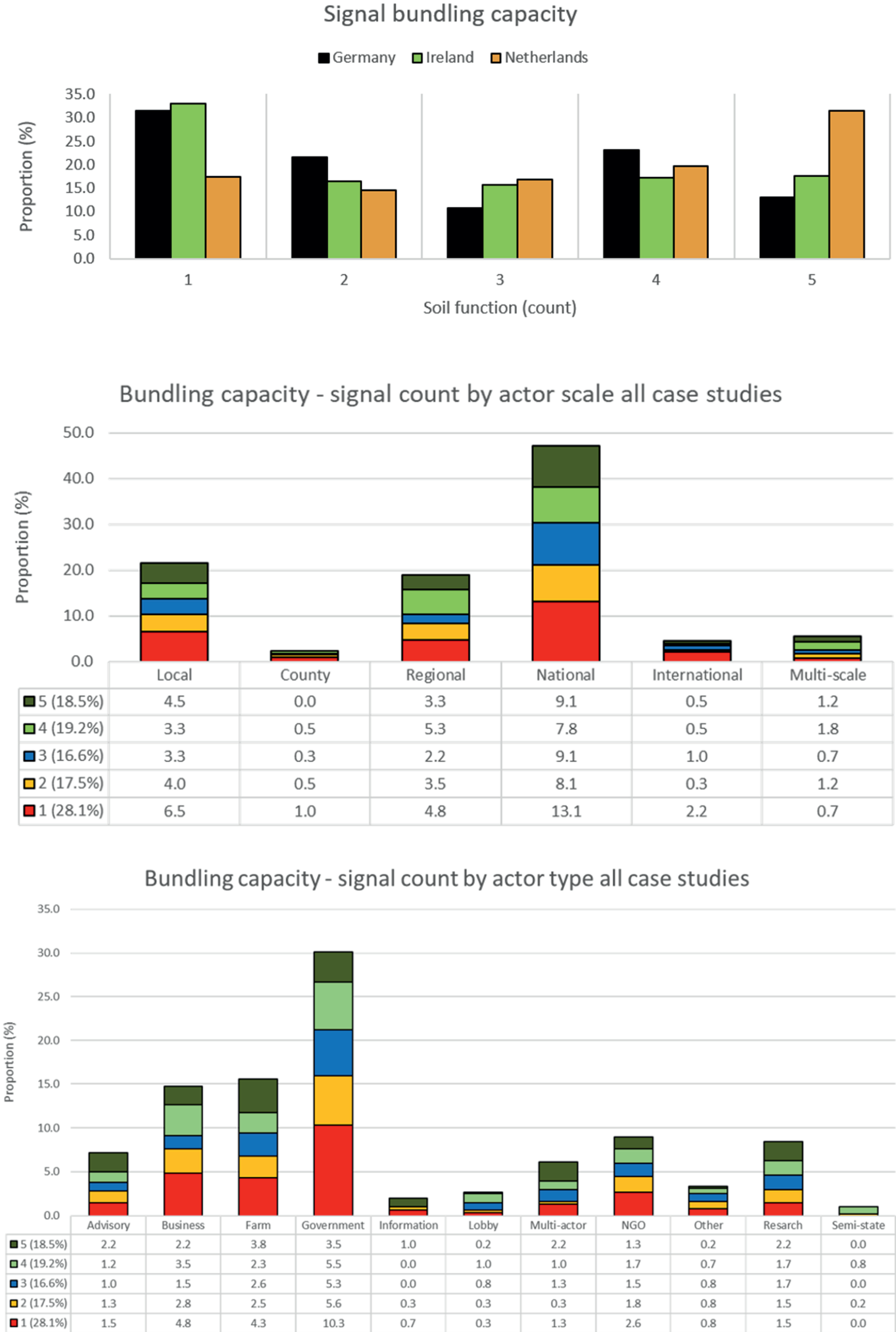
In general, those actors that had high betweenness, were also characterised by high closeness centrality (Fig. 2). In Germany, the NGO, the farmer and the advisor had high closeness centrality (Fig. 2a). This was similarly the case in the Netherlands (Fig. 2c) where farmers and the nature and sustainable agriculture organisations emerged as close. The closest actors in the Irish case study were mainly government or national bodies such as the Ministry for Agriculture or the public agricultural research authority (Fig. 2b). Where this value is zero is indicative of a node that is disconnected and infinitely far from some nodes. Some of these actors were found in Germany (n=3 e.g. data company) and the Netherlands (n=1 e.g. mechanical inputs supplier), however, there were several found in Ireland (n=17) and examples included the energy authority or international conference fora.

Targeting messages

The nature of bundling – who and at what scale

At a practical level, farmers occupy a key role in the implementation of practices and measures for sustainable land management. As the suite of competing demands on land is growing, other actors who communicate messages related to soil functions could be targeted to bundle and align messages to help reduce the complexity at farm scale. This requires in the first instance understanding of the extent to which different network actors are already bundling messages. Figure 3 shows the current extent of bundling or multi-functionality within the networks by country, by scale and by actor type.



	Local	County	Regional	National	International	Multi-scale
5 (18.5%)	4.5	0.0	3.3	9.1	0.5	1.2
4 (19.2%)	3.3	0.5	5.3	7.8	0.5	1.8
3 (16.6%)	3.3	0.3	2.2	9.1	1.0	0.7
2 (17.5%)	4.0	0.5	3.5	8.1	0.3	1.2
1 (28.1%)	6.5	1.0	4.8	13.1	2.2	0.7

	Advisory	Business	Farm	Government	Information	Lobby	Multi-actor	NGO	Other	Resarch	Semi-state
5 (18.5%)	2.2	2.2	3.8	3.5	1.0	0.2	2.2	1.3	0.2	2.2	0.0
4 (19.2%)	1.2	3.5	2.3	5.5	0.0	1.0	1.0	1.7	0.7	1.7	0.8
3 (16.6%)	1.0	1.5	2.6	5.3	0.0	0.8	1.3	1.5	0.8	1.7	0.0
2 (17.5%)	1.3	2.8	2.5	5.6	0.3	0.3	0.3	1.8	0.8	1.5	0.2
1 (28.1%)	1.5	4.8	4.3	10.3	0.7	0.3	1.3	2.6	0.8	1.5	0.0

Figure 3. Message bundling graph showing the distribution of ties and the respective number of soil functions captured by country (top), by scale (middle) and actor type (bottom) across all case studies.

A greater proportion of actors in Dutch network transmitted messages that encompassed all soil functions (fig. 3, top). This indicates that multi-functionality and more holistic approaches to sustainable land management are more prevalent within the Dutch social network. In contrast, the German and Irish networks had a similarly high proportion of messages wherein messages related to just one dimension of soil functionality. These network compositions include higher proportions of business and governmental actors and messages exchanged thus reflect the more specialist nature of business exchanges or policies that promote certain business exchanges or a lack of horizontal integration with respect to policies related to soil functions. However, these networks did have actors whose messages were more multi-functional. In Ireland, the public agricultural research authority showed to be a key actor for messages that related to all soil functions reaching multiple other network actors such as industry partners (dairy co-operative, fertiliser industry), farmers and advisory services (public, specialist and private). In Germany, farmer ties with other farmers, family, advisory, along with ties between the sustainable agriculture NGO and advisory captured the full suite of soil functions.

Collectively, with respect to scale, a mixed pattern emerges whereby actors at all scales reflect varying degrees of bundling capacity (figure 3, middle). While the largest proportion of messages emitted by national and local scale actors are only in relation to one function (28.1%), the next largest proportion of messages at the same scales relate to all five soil functions. Despite this mixed outcome, while some national scale actors have a key role for bundling, as they are highlighted as key message emitters in general, it means that overall they can have a disproportionately large role with respect to bundling of messages to reduce message complexity and overload at farm scale. As for the bundling capacity of particular actors, farmers emerge as the number one actor that transmits messages related to all soil functions (fig. 3, bottom). However, as a proportion of the messages by actor type, advisory, information and research actors along with actors defined as multi-actor are indicated as having the highest bundling capacity with respect to the messages that they emit. As the demand for multi-functionality grows, actors with information across multiple domains may have growing importance as brokers in future.

Tie strength

While it is important that while a tie between actors might be multi-functional, the message strength (based upon weighted influence) of that tie provides insight into whether actors are more or less likely to use that information.

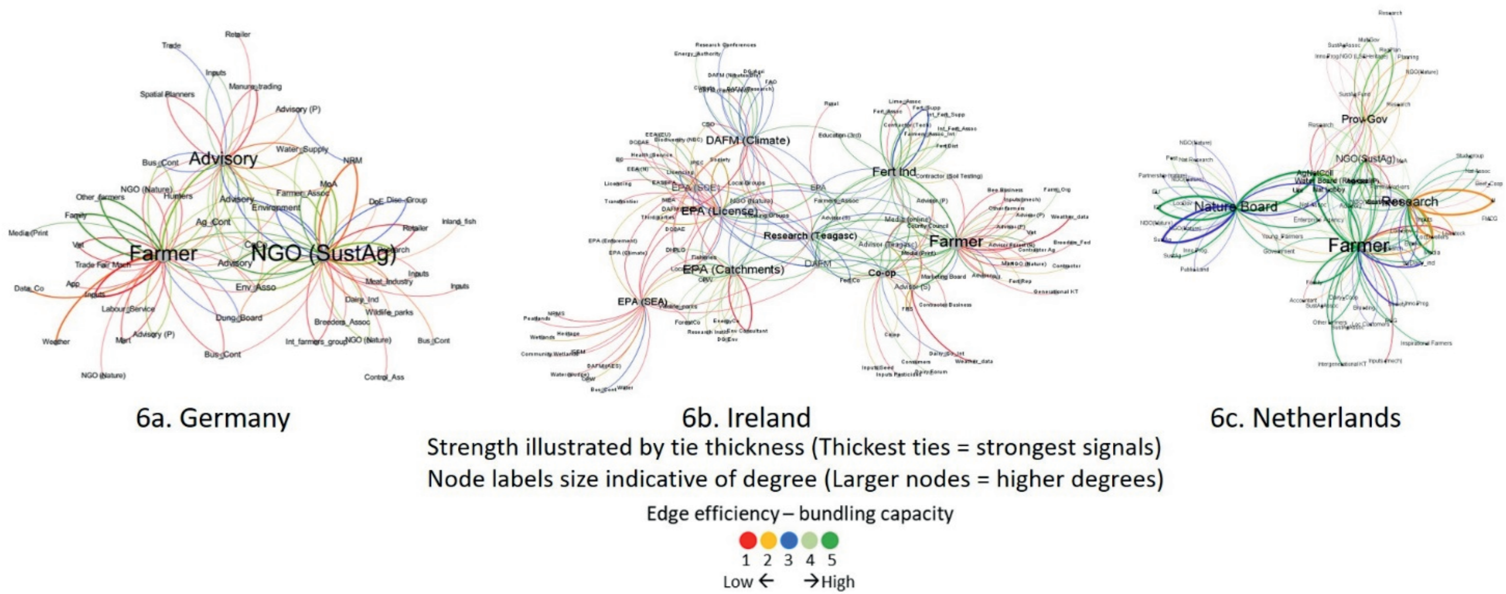


Figure 4. Tie strength indicated by width of tie between actors with widest ties representing the strongest ties. Bundling shown by tie colour from 1 soil function (in red) to 5 soil functions (in green).

In Germany, other farmers and family are the key actors with whom farmers exchange the strongest messages related to all soil functions (Fig. 4). This is consistent with homophily whereby actors preferentially identify with actors having the same traits and are more likely to form ties (Rogers, 1983; Newman, 2003). Strong ties between actors that are similar in a sociodemographic sense are characteristics associated with trust and bonding social capital (Szreter and Woolcock, 2004; Klerkx and Proctor, 2013). Where homophily exists, the likelihood of more rewarding communication increases due to shared common meanings (Rogers, 1983) but the limitation with respect to innovation potential that this might represent must be borne in mind as greater heterophily typically adds more capacity for innovation. In the Irish network, strong ties are reported for inter-agency actors in the environment sector, but also, with environmental consultants. Strong ties also occur between actors who are less similar, for example between an input provider and the farmer with the message specific to only one function (Fig. 4). This tie represents a formal collaboration with a brokerage function that is important to the farmer but only addresses a singular aspect of soil functioning. In Ireland, the use of weather apps for weather information was amongst the strongest message for farmers that influenced their decisions related to primary productivity. However, for all soil functions, the fertiliser industry relayed strong messages to farmers with other strong messages between public advisory and farm relief services, or farmers and public specialist advisors. In the Netherlands, strong ties occur between actors engaged in conservation and sustainable agriculture (e.g. nature board, sustainable agriculture NGO, agriculture nature collective). Farmers also have strong messages with the same collective while research actors are strongly connected with business actors (artificial Insemination), media actors and local dwellers.

Targeting soil functions in favour of sustainable land management

Coherence requirement and needs

Our results confirm that a large number of messages converge at farm scale which can result in overload and difficulty for decision making related to sustainability. To validate the latter, survey respondents were asked whether decision-making related to sustainability is difficult, whether messages come from multiple sources and to what extent messages are conflicting or coherent. This allowed for the establishment of a composite indicator to highlight to what extent a need for greater coherence within messaging exists. In general, across all case studies farmers indicated a need for greater coherence (Germany 66%, Ireland 56% and Netherlands 52%). While 20% of farmers neither agree nor disagree on a need for more coherent messaging, one-quarter indicated a low requirement for greater coherence in the Irish case study, which increased to 28% and 39% in Germany and the Netherlands respectively. The latter result coincides with the greater multi-functionality of messages observed in the Dutch network analysis even if a sizeable gap still exists. As to how to increase coherence, more face-to-face interaction and discussion groups emerged as important and while more advisory was indicated for the Irish case study, the existing level of advisory was considered sufficient in the other case studies. Online platforms and group apps were proposed as potential support tools in the Netherlands. The highest demand overall was for more discussion groups endorsing the importance of peer-to-peer interactions and the high value placed on connections associated with trust and bonding.

Action implementation and message acceptance

Figure 5 shows the proportional uptake of measures grouped according to their nature, whether mandatory, market or voluntary to provide insights into actions taken at farm scale. This insight into sustainability actions at farm scale helps to better understand which messages farmers are more responsive to. It also operationalises the non-acceptance of messages in the network, which may be particularly relevant for emerging policies that may or may not may not resonate with farmers, falling inside or outside their latitudes of acceptance.

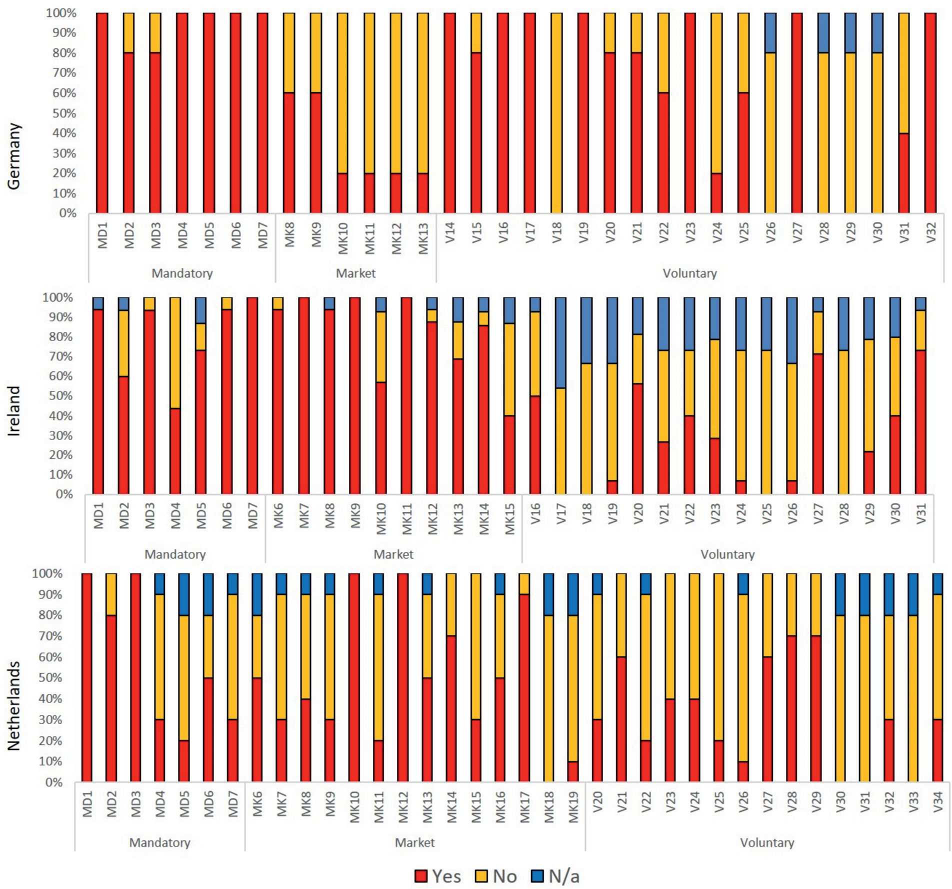


Figure 5. Proportional uptake of measures at farm scale structured along mandatory (MD), market (MK) or voluntary (V) instruments for case studies as indicated by farmers. For a full list of measures, see Supplementary Information S1, T1.

The measures or actions implemented by farmers in the German and Irish case studies are orientated in favour of compliance requirements (Fig. 5). Thereafter, in Germany a prioritisation of soil protection and management in terms of the uptake of voluntary actions by farmers is reflected in the results (V14 soil testing, V16 and V19 erosion related measures, and V17 fertiliser training and V23 use of low emission slurry spreading) and is consistent with regional objectives to support water quality in Lower Saxony. In Ireland, selected voluntary measures included the use of low emission slurry spreading (V27), fencing off watercourses (V20) and integrated pest management (V31). The farmers in the Irish case study were a group of intensive dairy producers and measures selected more directly related to agricultural practices and a need to support the sustainability of their enterprise. Land management in favour of farmland birds is a high priority for Dutch agriculture (EC, 2020b) and was reflected in market and voluntary measures (MK10 Conservation of meadow birds, V27 Management of breeding primary meadow birds and V28 Management for other birds) that had a high uptake at farm scale. The implementation of buffer strips (MD4) had a low uptake but reasons for this have been described previously, including the high productivity of agricultural field margins, the potential increased need to export manure and loss of eligible land under CAP area based payments (Dworak et al., 2009). With respect to the voluntary measures, implementation reflected the particular challenges specific to the case studies. Awareness of the context-specific environmental challenges in their areas may have prompted farmers to act, as greater environmental awareness has previously been found to support the uptake of agri-environmental schemes in the UK (Beedell and Rehman, 2000; Wynn et al., 2001; Baumgart-Getz, 2012).

Overall, there is a high proportion of measures that were not implemented or were considered as not applicable. Reasonably, capacity and resources to implement all measures everywhere is not plausible. In general, farmers that are more commercially orientated may require larger economic incentives to switch from more intensive production systems that benefit from higher economies of scale from food production versus the return on environmental services (Gailhard and Bojnec, 2015). For example, the Irish farmers who participated in the survey are more intensive producers and engendering a shift towards voluntary schemes would require sufficiently competitive schemes relative to market or compliance requirements for these farmers. Although financial incentives are important in relation to uptake of schemes and practices (Posthumus and Morris, 2010), alone they overlook intrinsic motivations which may diverge from incentive objectives resulting in low adoption of proposed measures, irrespective of financial rewards (e.g. Duesberg et al., 2014; Greiner and Gregg, 2011). It is also important that existing lock-ins be considered. Farmers in the Dutch case study indicated diverse system lock-ins that impede sustainable management practices that were not only motivated by profit maximisation objectives, even if they are willing to implement them (de Vries et al., 2019).

Although awareness has been associated with the enhanced uptake of measures, it may not necessarily increase the acceptance of messages in favour of action. For example, the Dutch and Irish case studies reported a lack of recognition of existing sustainable land management practices. In both case studies, actors indicated that society attributes a disproportionate responsibility on agriculture for environmental challenges compared to other actors and sectors, indicating an awareness of the need for sustainable land management. At the same time, this had resulted in a polarisation of ‘them’ and ‘us’ occurring, which could reduce acceptance of messages (de Vries et al., 2019). Expanding market-based initiatives (MBI) to incorporate a wider range of targeted public goods for which consumers are willing to pay may be another pathway that could share responsibility more widely however, with respect to the case study network for soil functions, there was limited reference to consumers and their role in these networks. Market instruments act to correct market failure associated with negative externalities and are designed to address some form of pricing signal (Cocklin et al., 2007) and can include negative (e.g. tax) or positive (e.g. subside) incentives (Pannell, 2008). The high cost of regulations makes MBIs an attractive way to reach conservation objectives more cheaply as they use market forces to pass on incentives while also have potential to generate revenue that can be funnelled towards conservation management, acting as a complementary approach rather than an alternative (Bräuer et al., 2006). This could offer a compromise between intensive production and environmental services making the latter a more attractive alternative.

In general, messages that fall outside the latitude of acceptance that are too far from farmers' internal logic or aspirations are more likely to be rejected or filtered with a multitude of socio-economic and cultural factors impacting the acceptance of a message (Leeuwis, 2004. These findings highlight important considerations, particularly for those measures that were rejected or considered 'not applicable', for example organic farming which is becoming a heightened priority in the emerging policy landscape under the EU Green Deal (EC, 2020). Increasing uptake would require combined policy mixes that in addition to incentives or market signals would require education and information tools and potential re-framing to increase the acceptability requiring participation of actors all across the agri-food chain. A deeper assessment into the acceptance of messages in the Dutch case study found that the relationship between the farmers and their network was important for acceptance of messages and recommended placing effort towards establishing relationships between farmers and their network (de Vries et al., 2019). Multi-actor approaches, such as operational groups are an opportunity for AKIS actors to work together to find solutions to overcome gaps and bottlenecks that draw on tacit knowledge and participation that in principle could also serve to increase acceptability.

A comparative analysis for targeting opportunities

A comparison between survey results and the SNA allowed us to see to what extent influential network actors in the global networks were consistent with the key actors that farmers engage with for the implementation of measures on farm (shown collectively for some common measures Fig. 6). From this, we can identify opportunities or challenges that exist within the current network for targeting or bundling of messages.

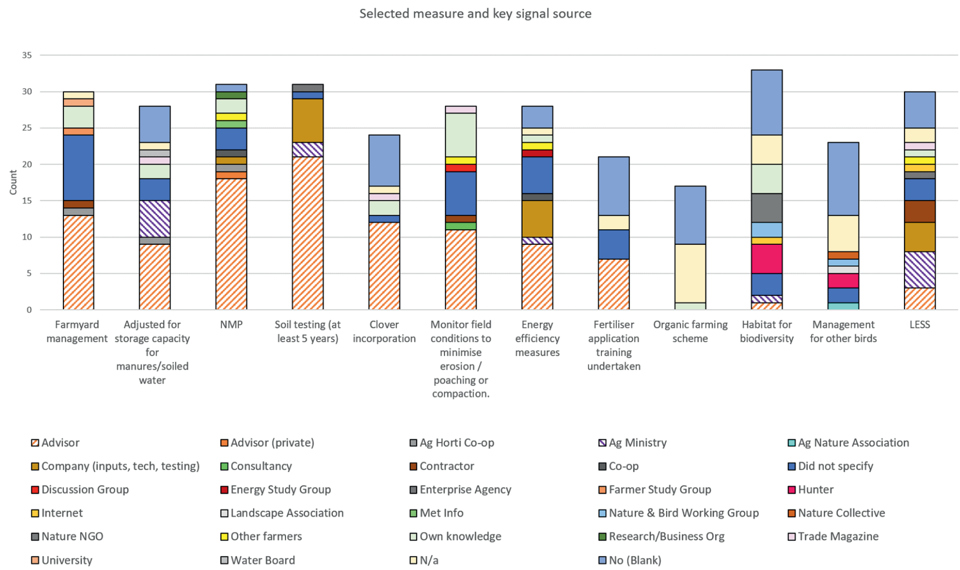


Figure 6 Selective universal measures and the main message source as identified by farmers for all case studies

Despite the assigned influence of certain actors in the SNA, their influence did not always translate into action at farm scale. In Germany, advisory emerged as the key signal emitter with respect to actions implemented on farm (50%), followed by messages from other farmers (21%) the latter consistent with the SNA. The SNA indicated weak messages from advisory, but in practice, these emerge as the most important broker at farm scale with farmers most likely to act on a signal received from an advisor over other actors. So, while an NGO on sustainable agriculture had high prominence in the SNA their signal ties with farmers were not strong and only 3% of signals associated with implementation were from a nature NGO. These results are consistent with other research whereby the message origin may be more decisive than the information itself (e.g. Ulrich-Schad et al., 2017). This is also found in the Irish network, whereby the fertiliser industry emerged as having high bundling capacity with potential to influence, but were not highlighted as a key message source for the implementation of measures at farm scale with survey results highlighted that advisory occupyied that role. This result is consistent with very high levels of trust indicated by farmers in their advisor, even at the early stages of the relationship due to trust in the organisation (Teagasc) (Gorman et al., 2019). Altogether, the results point to message overload with many messages in network not translating into action. They also highlight the complexity of decision-making at farm scale. In the case of the fertiliser industry in Ireland or the German NGO who have high bundling capacity, messages were not prioritised by farmers and may be filtered or lost or are simply superseded by messages from more established trusted brokers. The nature of the relationship between actors has an important role in the receptivity of messages exchanged. As a need for coherence was indicated, this can also explain why messages of some actors are filtered where an already large message load converges at farm scale. In many instances, key brokers already have a high bundling capacity but this is not always the case. From this, we can determine different potential pathways for targeting. On the one hand, actors whose ties have high bundling capacity or network influence could be targeted by strengthening such relationships and building trust through greater collaboration. Alternatively, the remit for actors whose ties have high weight that have shown to inform implementation but only refer to one aspect of soil functioning could be expanded. For example, weather apps are an important information source for farmers to support their decisions around primary productivity but could potentially integrate other information that is of relevance for farmers for sustainability. The use of a farm sustainability tool (FaST) for nutrients under new good agri-environmental condition (GAEC) requirements was proposed at EU level, and is consistent with the Dutch case study who indicated a demand for more online/app tools. Business partners often have these characteristics also as they are providing a paid service demanded by farmers usually with respect to a particular topic. Fundamentally, targeting existing relationships that show a high level of trust exhibited through current implementation practices may have more immediate potential than building new relationships.

Limitations and further research

This work has looked at three key studies. As such, networks are context specific and therefore not generalizable. This has not been the purpose of this work but rather to see what insights can be garnered that have wider relevance that could support greater sustainability in the future. In this regard, we have tested our hypothesis in three different contexts that highlight both commonalities and differences and we have advanced our understanding of messaging, and opportunities to effect change towards sustainable land management. Future research should consider different farm typologies as different farming systems and intensities are likely to require differentiated targeting of messaging. Furthermore, the similarity of message content between entities as this was not explored here and may have importance to increase coherence and efficiency within the networks if better understood. As shown here and consistent with other research, awareness, acceptance and ultimate adoption have a high dependency on multiple factors such as farm and farmer characteristics, value and belief systems, and economics.

Conclusions

SNA techniques revealed a diversity of actors in the AKIS with actors forming network links with different types of organisations and at multiple scales in each of the three case studies. The larger network in the Irish case study suggests potentially greater capacity for innovation while the regional configuration generated greater scaling potential in the German case study. Farmers showed to occupy a central role in the agri-environmental governance, as evidenced by the convergence of messages at farm scale. This in turn can increase the complexity for making decisions for sustainability with respect to the implementation of actions and measures on farm. A greater level of multi-functionality in the Dutch case study coincided with a reduced requirement for coherence within messages. This indicates that greater attention to increase multi-functionality across actors within the AKIS can help to support enhanced acceptance, which could in turn support greater sustainability. Awareness and acceptance of messages showed to be important. Particularly important, was the reliance of farmers on trusted brokers. In this regard, the amount of information became less relevant than how information was received. This was further endorsed with respect to the coherence requirements specified, with a preference for peer-to-peer interactions rooted in trust and bonding. The main lessons learnt are as follows:

- Farmers indeed receive an overload of information; this results in low acceptance of messages in the network.
- The signals that are acted upon and translated into farm management actions depends in the first instance on the source of the message, rather than their content *per se*.
- Two potential pathways for enhanced farmer uptake of multi-functionality:
    a. Increase trust between farmers and actors that are currently agents of multifunctional messages;
    b. Increase the multifunctional breadth of messages (mandate) of actors that are already trusted by farmers.

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CHAPTER 9

General Discussion

Introduction

The demise of once great civilisations is a topic that inspires fascination amongst scholars and society alike particularly, as the reasons for these demographic shocks are often not fully understood. Soil is the basis for all terrestrial life with natural resource endowments and productive soils fostering the development of such civilisations. Mesopotamia, located in the northern part of the fertile crescent was home to the planting of the first cereal crops, but it and other cultures such as the Indus, survived only for as long as soil had capacity to support them (Lal and Stewart, 2016). With respect to the Maya civilisation, researchers often hypothesize the intensification of agriculture as a driver for soil erosion that precipitated a decline in agricultural output. In his thesis "*The role of soils in the development and collapse of Classic Maya civilization at Copan, Honduras*", Wingard (1992) presents the explicit relationship between productivity and population declines at Copan, Honduras. A management shift towards a shortened fallow period prompted a drop in production due to nutrient depletion and erosion that aligned with a population decline (Wingard, 1992). Several other similar examples exist, such as the Asian civilisations of the Akkadian Empire and the Indus Valley Civilisation or the Rapa Nui people who inhabited the Polynesian island of Easter Island. While demise of a civilisation might be due to a number of factors, environmental changes and shocks perpetuated by a growing population driving resource depletion or degradation typically had a role to play.

More recently, the severe drought of the Plains of 1930s America and the associated destitution of the Dust Bowl was a seminal moment in American history, immortalised in well-known cultural works such as "The Grapes of Wrath" by American realist writer John Steinbeck. The failure to apply appropriate dryland agricultural management practices resulted in huge losses of topsoil that were simply blown away by the end of the 1930s. The subsequent failure to adapt to more appropriate crops for eroded areas induced a legacy of economic deprivation that persisted for decades. Importantly, this gave rise to the notion that soils are a finite resource and that rates of regeneration cannot match depletion (EC, 2006; FAO, 2015). It also highlighted the intimate link between agricultural practices and land degradation and that farming practices must be sustainable but also sensitive and adapted for the environmental context in which they exist.

If we fast-forward to the present day, with respect to sustainable land management, hindsight and decadal investments in science and technology have yielded little gains, as indicator data on the status of soils and land attest that more than half of agricultural land worldwide is severely impacted by soil degradation (ELD Initiative, 2015). Rockström et al. (2009) propose planetary boundaries as a precondition for human development. In their framework, human actions are the driver of global environmental change and three of the nine interlinked boundaries have already been crossed (Figure 1). Agriculture is one of the key drivers of exceedance cited. With potentially catastrophic consequences foreseen for large parts of the world (Rockström et al., 2009), the challenge facing society is critical at a global scale as biodiversity loss, climate change, land degradation and more threaten life on the planet in ways previously unseen.

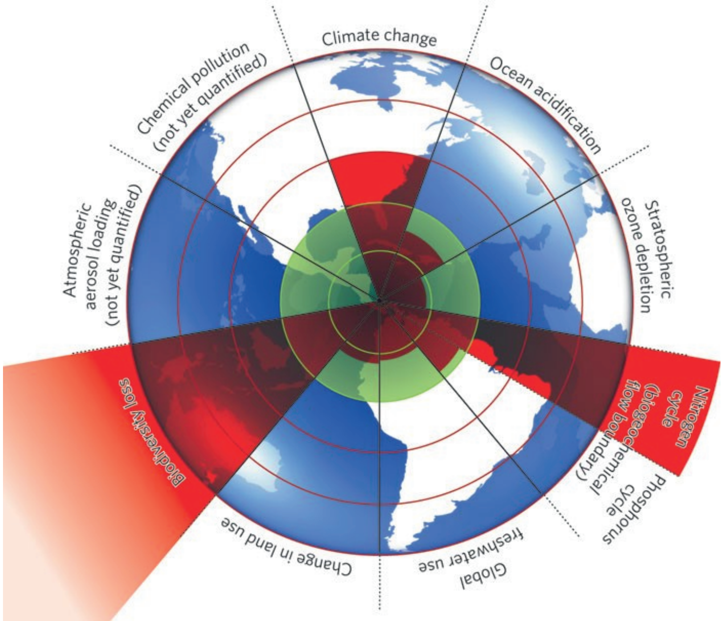

Figure 1: Beyond Planetary Boundary originally published in Rockström et al., (2009). Reproduced with permission

The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded.

Soil in an undulating policy landscape

Prior to delving into the specific objectives of this thesis, it is important to revisit the European policy landscape that was presented in Chapters 1 and 2. At the start of this PhD journey, the high level policy discourse on soil was weighed down by a sense of stalemate with discussions on soil policy firmly framed by the Thematic Strategy for Soil Protection (COM (2006) 231 final), a heavy emphasis on threats to soil quality and a failed proposal for a Soil Framework Directive (Chapter 2). Different EU policies consider and contribute to soil protection and health (Glæsner et al, 2014; Vrebos et al., 2017; O'Sullivan et al., 2018; Schulte et al., 2019), primarily environmental (water and air such as the Nitrates Directive (2000/60/EC), and the Air Quality Framework Directive (2008/50/EC)) and agricultural (cross-compliance) policies. The lack of a dedicated Union law within the European environmental policy framework for soils diminishes their importance compared to other natural resources (Heuser, 2022). In principle, the Single European Act of 1987 offers the theoretical scope to address soil threats that could be targeted under the objectives to preserve, protect and improve the quality of the environment along with prudent and rational use of natural resources under Article 191 of the Treaty on Functioning of the European Union (TFEU) (EU, 2012). A 2006 Soil Thematic Strategy put forth objectives for the sustainable use, protection and restoration of soils (EC, 2006). With respect to soil degradation and restoration costs, the Strategy emphasised the polluter pays principle (EC, 2006). The introduction of a common Soil Framework Directive envisaged legislation for the sustainable use and protection of soils that would equally address legacy issues of land degradation. With more than three million contaminated sites across Europe and the cost of historical contamination to be borne under national liability regimes, several member states (MS) were confronted with high remediation costs (EC, 2006). This was amongst the issues that ultimately resulted in the failure to ratify the proposed Soil Framework Directive in 2014. In addition, the nature of private land ownership, making soils an issue of private rather than public governance and the fact that they are not movable and thus do not require transnational policies were amongst the primary reasons cited for this rejection (Montanarella, 2015). In many way, the seven years of indeterminate action prior to the rejection of the proposed Soil Framework Directive, positioned soil in the awkward juxtaposition of perceived action at EU level but with limited tangible progress in real terms. All the while, an estimated 75 billion tonnes of crop soil continued to be lost worldwide annually to erosion and through agriculture with estimated annual costs of ~US$400 billion (ELD Initiative, 2015). Within Europe, it is considered that 60-70% of soils are unhealthy due to current management practices (Veerman et al., 2020).

Post 2014, a marked scientific and political shift started to happen both at a global scale but very strongly in Europe. The United Nations set their Sustainable Development Goals (SDGs) to be implemented by all countries by 2030 (UN, 2015). As described in Chapter 3, four targets specifically cite soil (2.4, 3.9, 12.4 and 15.3), with other targets that consider land and soil functions (UN, 2015). A land degradation neutrality target for 2030 was set. This represented a higher ambition than that outlined in the 2006 Thematic Strategy for Soil Protection (Heuser, 2021). Thereafter, the European Green Deal (EGD) framework (outlined in Chapter 7) put forth ambitious measures to make Europe the first climate neutral continent by 2050 (EC, 2019). Within the EDG framework, soil is targeted under the Zero Pollution Strategy, the EU Climate Law, the Farm to Fork strategy, the Biodiversity Strategy and most recently the new EU Soil Strategy. Heuser (2021) succinctly outlines the role of soil in relation to each of these strategies but concludes that although these developments lean towards sustainable agriculture and contribute to increased soil protection, they may not be enough. Instead, a comprehensive performance-based system with coherent and coordinated policies that directly address soil-related issues may be required (European Court of Auditors, 2018).

EU Missions represent highly ambitious and coordinated efforts to address the greatest challenges facing society. In 2021, the European Commission commenced a ‘mission’ on soil health and food, one of only five missions, equating to a high-level commitment to support soil by way of funding through the Horizon Europe framework. The goal of the mission proposed by the Soil Health and Food Mission Board aims to “ensure that 75% of soils are healthy by 2030 and are able to provide essential ecosystem services” (Veerman et al., 2020) This high level commitment places soil as a core focus in relation to research, innovation and policy. The Horizon Europe Mission ‘A Soil Deal for Europe’ provides a research and innovation framework towards the creation of harmonised monitoring and reporting with an emphasis on research-policy and research-practice (EC, 2021). A network of ‘living labs’ experimenting on the ground complemented by ‘lighthouses’ that showcase best practices will deploy solutions for soil health (EC, 2021). The Soil Mission Board report outlines an ambition to “ensure that 75% of soils are healthy by 2030 and are able to provide essential ecosystem services”

(Veerman et al., 2020). In parallel, the European Joint Programme (EJP) on soil was established to focus on the role of agricultural soil management to contribute to the key societal challenges including climate change, water and future food security (EJP Soil, 2022). Following the Mission, a new EU Soil Strategy was launched later that year – *Reaping the benefits of healthy soils for people, food, nature and climate* that envisions a 2030 whereby all EU soil ecosystems are healthy and more resilient and where protection, sustainable use and restoration is the norm (EC, 2021). It is anticipated that it will align with other initiatives (Figure 2). This strategy acknowledges that although soil does not have the same protection level as other resources such as water or air, this need has become more pressing recently as recognition of the value of soil has increased as have the pressures and expectations and claims on soil (EC, 2021). Altogether, there has been a dramatic shift in terms of the importance of soil at EU scale with concerted efforts now aiming to radically overhaul the approach to fostering soil health across Europe, targeting action across actors and scales.

Figure 2. Links between the EU Soil Strategy and other EU initiatives from EC, 2021.

Given this context, this thesis explored the potential of Functional Land Management for a sustainable land base in the EU. As outlined in the introduction, a key challenge for multifunctionality rests in the policies that lack horizontal integration. This can result in blind spots from maximisation approaches that fail to acknowledge that not all soil functions can be maximised in all locations owing to the intrinsic trade-offs between soil functions (O'Sullivan et al., 2015; Zwetsloot et al., 2021). The objective of the thesis was to understand and frame modern day multifunctionality, develop tools to explore the divergent expectations of stakeholders for land. Also, how trade-offs might be accounted for and what gaps and solutions can be proposed. The work was structured around the following three objectives:

- Objective 1 - Understanding and managing divergent expectations from land
- Objective 2 - The challenge of trade-offs
- Objective 3 – Implementation gaps and solution spaces.

Objective 1 - Understanding and managing expectations from land

To understand and manage what we expect from the land, we must first frame the 'demands' on land. In the introduction of this thesis, I presented the traditional perspective of land as an agricultural resource farmed for food, fuel, fodder and fibre. In this thesis, we have highlighted how societal expectations have evolved in relation to land-based ecosystems services. Unlike earlier framing of multifunctionality that linked environmental public goods to agricultural production (Burrell, 2011), the supply of multiple soil functions is by now an accepted definition of 'multifunctionality' (Giuffré et al., 2021). Originally proposed by Doran and Zeiss (2000), Bünemann et al. (2018) refer to soil functions as soil based ecosystem services made by soil processes mediated by the interaction of physical, chemical and biological properties of the soil (Vogel et al., 2018). In 2014, Schulte et al. (2014) proposed the Functional Land Management (FLM) framework that is underpinned by soil functions. This framework is expanded upon in chapter 2 and focuses FLM to five key soil functions that are delivered across all agricultural landscapes. Moreover, these functions are delivered simultaneously to a greater or lesser extent, determined not only by intrinsic soil properties but also by the interaction of environment and management (Coyle et al., 2016). Although Creamer et al. (2022) highlight some ambiguity related to 'multifunctionality', by now the concept of soil functions underpinning multifunctionality, has gained traction at EU scale with the FLM concept by Schulte et al. (2014) referenced in the foresight report on soils (Giuffré et al., 2021). Having participated as part of a pan-European project that engaged with stakeholders across all scales, from local to European and beyond, the work in this thesis has engaged in and played a role in the discourse to frame what we expect from a multifunctional land base in Europe.

In Chapters 3 and 4, we explore the demands for soil functions at two different scales. Earlier concepts to define soil quality were unbounded and failed to take into account the quality of soil for what. For example, a farmer may be most concerned with the quality of soil for producing food. In contrast, a climate policy maker might be more interested in the quality of the soil to regulate climate through storage of organic matter in soil. Unlike earlier unbounded concepts, the FLM concept introduced the notion of 'demand' for soil functions (Schulte et al., 2015). As different stakeholders have divergent demands on the land, FLM enables us to consider soil quality in relation to different outputs for the divergent demands of different stakeholders. In chapter 3, we develop the Catchment Challenge methodology that allows an optimised landscape for the delivery of soil functions to be co-designed by different stakeholders. In the introduction of this thesis, I touched on the emotional nature of place-based attachment, which is particularly strong for farmers who not only work their land but also live, socialise and more on the land (Hildenbrand & Hennon, 2005). The Catchment Challenge methodology has capacity to transcend place-based attachment by detaching stakeholders from the emotion of their own setting. This creates space for stakeholders to co-design mutually acceptable solutions, while simultaneously defining transition pathways. It can enhance innovative capacity allowing for different knowledge domains and expertise to connect, be that cultural farming to high-tech industry or European policy makers enabling deeper understanding of what will or will not work and why. The absence of this understanding is often a reason as to why so many initiatives do not work. The Catchment Challenge has enjoyed success as a learning tool. In education, the method has been deployed as part of Farming Systems Ecology modules in Wageningen University and Research (WUR). In science, it has been well received, for example as an interactive session in conferences including the International Union of Soil Sciences conference in Rio in 2018 or Catchment Science Week in Ireland on several occasion. It has also been used across Europe as part of the LANDMARK project to harvest stakeholders knowledge published in Bampa et al., (2019). Industry partners, in private and (public) advisory and businesses in the AKIS have repeatedly requested workshops with some industry partners such as Glanbia incorporating the method into their toolkit to communicate with their stakeholders about sustainable land management. A limitation in the past has been the inability to model feedback in real time the outcome of the decisions that stakeholders implement as part of the landscape design process. Although beyond the scope of this PhD, the modelling group in Farming Systems Ecology (FSE), WUR have been building models, complemented with augmented reality technology to overcome this limitation.

While the Catchment Challenge has universal applicability if adapted to a familiar context for users, we also wanted to explore the wider societal expectations on land. In its origins, FLM pitched policies as a means to frame societal expectations (Schulte et al., 2014). In chapter 4, we explore the demands for soil functions based upon high-level EU policies. Across Europe, soils differ dramatically in relation to physical, chemical and biological properties which translates to a high variability with respect to the supply and demand for selective soil functions. In chapter 4, this is borne out whereby the demand for soil functions varies markedly between MS due to population, farming systems, livestock densities, geo-environmental conditions and landscape configuration (Schulte et al., 2019). Very often, EU agri-environmental policies have been deemed ineffectual, failing to meet the environment and climate needs of MS or policy objectives (Meredith and Hart, 2019). In chapter 4, we highlight which soil functions are needed most where. Historically, EU agri-environmental policies have been indiscriminate, lacking differentiation on the basis of demand. Here, we show that not all soil functions are required in all EU locations to the same extent. Greater targeting could increase the efficacy of policies in the future where a discrepancy between policy objectives and the supply of soil functions is found.

Objective 2 - The challenge of trade-offs

The FLM concept supersedes traditional approaches that aim to maximise the delivery of one or all functions everywhere at all times (Schulte et al., 2015). As the augmentation of one soil function can lead to an increase or a trade-off of other soil functions (Power, 2010), a key consideration is how to limit trade-offs between functions. Prior to the EU LANDMARK project, the extent of synergies and trade-offs between soil functions was unknown. Utilising soil, management and climate data from 94 sites and 13 countries, five climatic zones and two land-use types (arable and grassland) data Zwetsloot et al. (2021) used a multi-criteria decision support system to answer this question. They found an optimal co-occurrence of three soil functions indicating that multifunctionality is possible but local constraints and trade-offs exist (Zwetsloot et al., 2021). Trade-offs are particularly relevant in the discourse in relation to the EU Soil Health Law related to sustainable use to be developed by 2023. This law aims to protect and sustainably manage soils that would in-turn support a zero decline in ecosystem functioning. Chapter 2 outlined three pathways by which the supply of soil functions could be altered to meet demand namely; alter a dynamic property such as soil fertility, alter a static property such as drainage capacity or through land use change. In chapter 5, we explore the second option whereby in an Irish case study we use a process-based model (DNDC) to simulate land drainage of imperfectly and poorly draining grassland soils to assess the trade-off between primary productivity and the carbon cycling and storage functions and interpolate this across Ireland. As the first policy relevant FLM paper, this clearly reflected the divergence between stakeholder priorities, those that are responsible for the supply of soil functions, usually farmers and other land managers and those who frame demand, policy makers. We found a gap in relation to the prioritisation of the production and climate regulation soil functions (O'Sullivan et al., 2015). The agronomic benefit outweighed the monetised environmental cost; the value of CO_2 loss would only exceed productivity gains at a higher CO_2 price. That paper represented the first of a number of works where we highlighted how spatially tailored approaches to land management that take into account the differences between soil types could be more effective than blanket policies. Prompted by strongly increased default CO_2 emission factors for organic soils (IPCC, 2014) we assessed the role of artificially drained carbon rich (histic and humic) agricultural land for climate change mitigation in Ireland (Paul et al., 2018). As with Chapter 5, we utilised a modelling and mapping approach to estimate annual drainage emissions of ~10 Tg CO_2 equivalent for these drained soils. An estimated annual saving of 3.2 Tg CO_2 equivalent was estimated if half the area of histic soils were rewetted (Fig. 3). The FLM concept emphasises the utilisation of land to make best use of its capabilities to deliver ecosystem services. This concept is expanded upon in Schulte et al. (2016) were we propose the proactive management of soil organic carbon according to soil type as an opportunity for climate smart agricultural soils (Fig. 4). Teagasc are the Irish Agriculture and Food Development Authority for Ireland with responsibility to provide research, advisory and education to the agri-food sector. Teagasc routinely publish a 'Marginal Abatement Cost Curve' (MACC) to show the cost and mitigation benefit of selected agricultural and land use measures to mitigate climate change. A spatially differentiated approach to organic soils has since been included in the Teagasc land use MACC (Lanigan & Donnellan (Eds.), 2018). Practices in relation to organic soils now no longer recommend drainage of peat soils and the potential of rewetting peats is being explored. We see this evolution happening too at EU scale as new Good Agriculture and Environmental Conditions (GAECs) include the protection of peatland and wetland being implemented across Europe.

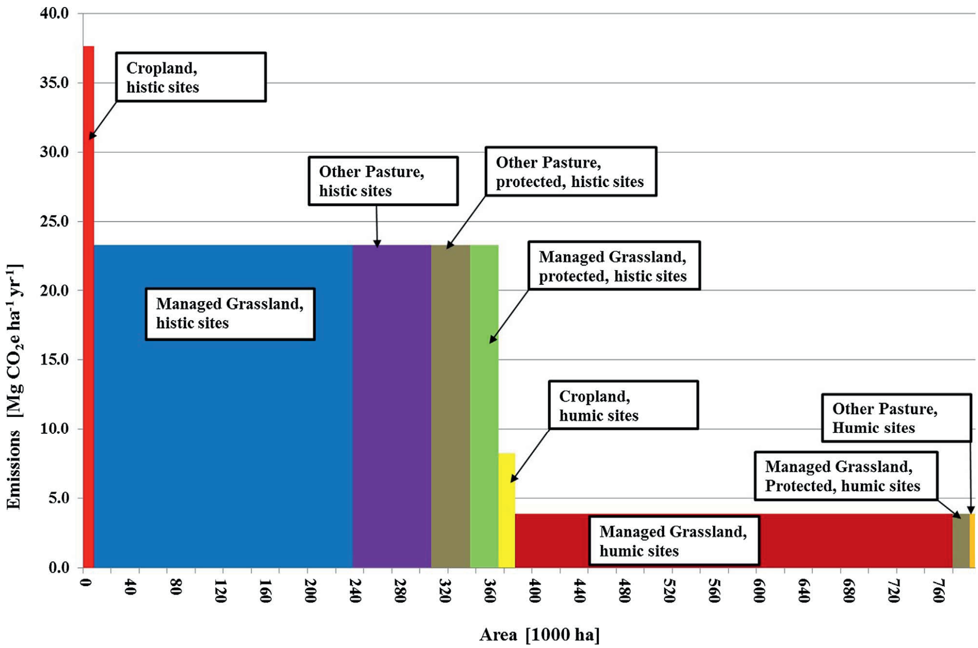

Fig. 3. Area of and GHG gas emissions from of carbon rich soils in Ireland drained for agriculture. The size of each coloured area corresponds to total emissions from the respective land use/soil combination from Paul et al. (2018).

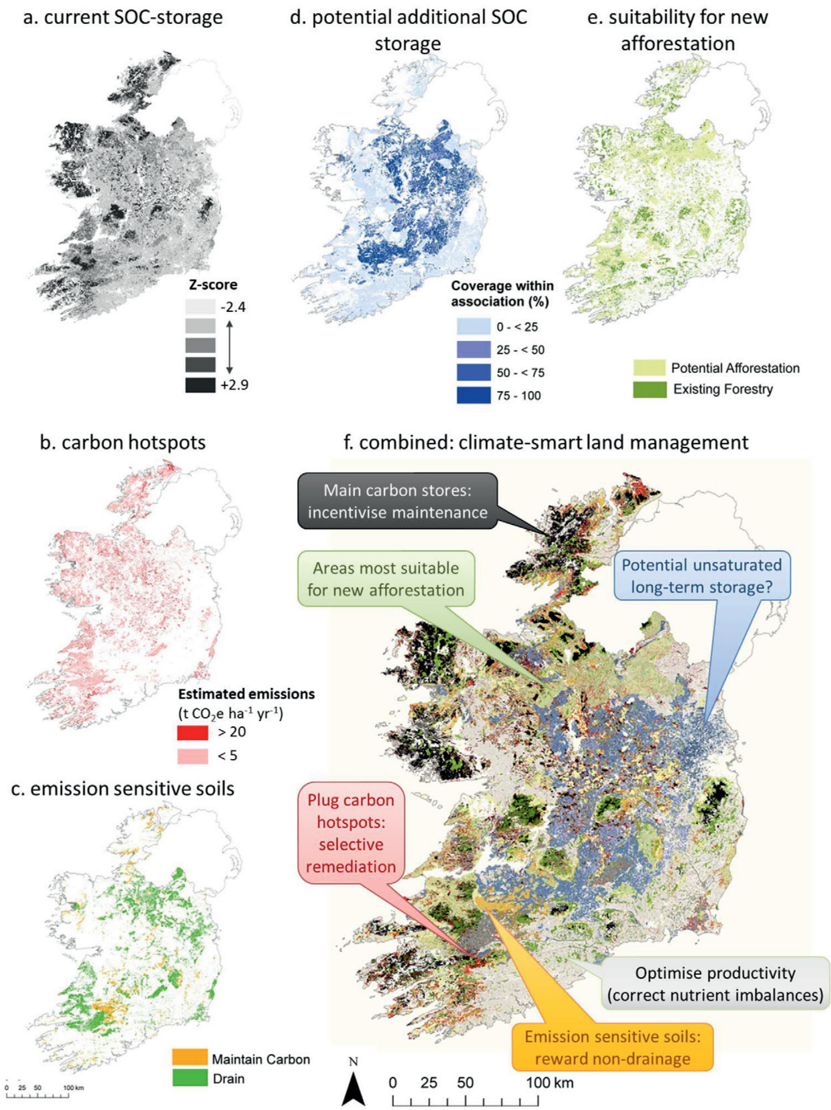

Fig. 4 Indicative maps showing the geographical distribution of soil organic carbon (SOC) stock and fluxes of relevance to climate smart land management in Ireland. (a) Current SOC stocks: relative carbon storage capacity (z-scores) of soil × land use combinations. (b) "Emission hotspots" associated with drained organic soils: estimated annual loss of CO2 per hectare. (c) "Emission sensitive soils" indicating soils that would release CO2 in response to drainage works: modelled annual loss of CO2 per hectare following drainage. (d) Soils subject to clay illuviation, which store stable carbon at depth: percentage of area within the soil association covered by soils with argic properties. (e) Existing forestry and soils most suitable for new afforestation: marginal soils not subject to environmental legislation. (f) Map combing the five aspects of SOC dynamics (a–e). From: Schulte et al. (2016).

Of course trade-offs are not only confined to local catchment scale, national or even EU scale. This thesis has focused primarily on FLM within the EU context however, in Chapter 7 we delve into the external dimensions of the European Green Deal. The EU has set sights on becoming the first climate neutral continent by 2050, anticipating high standard for European food to be *the* standard as it relates to sustainability (EC, 2019). Strategic Plans (SPs) in the post-2020 CAP give MS scope to look inward to devise context appropriate plans and implement policies to reach ambitious targets in the areas of climate and environment. European farmers often put forth carbon leakage and the lack of an even playing field for their produce with respect to the high standards they are required to meet, when at the same time, for example the so-called *lungs of world* are being deforested in Brazil for commodity production with lower environmental standards. As part of this thesis and the EU LANDMARK project, I had the opportunity to spend time and collaborate with Brazilian researchers in CENA, University of São Paulo, Piracicaba campus to consider the carbon leakage and environmental impacts in the Upper Xingu River Basin in Brazil. In chapter 7, we show the strong connections at global scale via the soybean trade networks that have intensified over time. We also found that the external dimensions of EU policies have not sufficiently accounted for leakage or environmental impacts vis-à-vis the other soil functions. These issues are of global relevance. Hence, multilateral agreements are best placed to target and mitigate leakage effects at the global scale. Instead of multilateral agreements, an increase in bilateral trade arrangements can be found, with exporting markets shifting increasingly in towards markets with less stringent standards than those at EU scale. Multilateral governance has greatest capacity to mitigate global challenges in a collective way but mitigating leakage effects at the global scale will be particularly challenging as nations seek to supersede multilateralism in favour of unilateral objectives.

Objective 3 – Implementation gaps and solution spaces.

In chapters 7 and 8 of this thesis we lean into the solution space further as we derive more specific pathways to create a more enabling context for the deployment of sustainable land management as visualised through FLM. Policy is iterative, changing to meet the pressing challenges of the day. By now it is accepted that blanket approaches in the policy space have not generated the types of results intended, borne out by results on the ground. In a bid to overcome blanketed targeting, in chapter 4 we show how the demands vary across MS. We see that this demand is highly variable across MS and we show where the greatest discrepancies between policy objectives and actual supply of individual soil functions can be found (Schulte et al., 2019). A pertinent outcome from this research is that the divergent demands of stakeholders must somehow be reconciled. This divergence can arise because society may require the delivery of a soil function to a much greater extent than that which is required to satisfy the functional ambitions on farm. Cross-compliance represents the minimum sustainability criteria with universal relevance for all farmers and farms. Typically, these standards can achieve the functional objectives at farm scale. However, sometimes, what is required a farm scale differs to the societal demand for a soil function. For example, soil organic carbon for soil fertility at farm scale required by farmers compared to the additional sequestration of soil carbon to meet societal climate targets. If the societal demand for a soil function exceeds the functional objectives and thresholds, Pillar 2 agri-environmental schemes, or the more recently introduced eco-schemes under Pillar 1 are key levers for policy makers to bridge this gap. In chapter 4, we highlighted that MS have varying demands for selective functions. In a bid to better reconcile those demand with the governance framework, in chapter 7, we assess to what extent soil functions have been prioritised in the last funding period of the EU CAP (2014-2020). This is compared with demands highlighted in chapter 4 to expose opportunities for greater targeting in the post-2020 CAP as MS now have greater potential to target measures and support towards objectives that are needed most.

So far in this thesis, we have used FLM as a framework to support greater multifunctionality of the land base. We have emphasised the need for spatial and institutional fitting and we have shown how the discourse on soils has changed so much over the journey of this PhD. Developing solutions to enhance the sustainability of agriculture have little impact unless those solutions are translated to action on the ground. Solutions must represent social sustainability and be acceptable to stakeholders. Farmers and land managers have a defining role in sustainable land management but many factors govern decision making on land. Networks are proposed as an emerging solution to accelerate best practice for sustainability and the EU already has a European Innovation Platform for Agriculture (EIP-AGRI) to foster a network-based approach to information across the agriculture, knowledge and innovation system (AKIS) (EC, 2020). Beyond facilitated networks such as EIP-AGRI, farmers have social networks that can inform their acceptance and implementation of practices for sustainable land management.

In chapter 8, we explore the networks for soil functions for case studies in three different EU countries. As expected, networks were context specific reflective of local sustainability challenges and governance structures (OSullivan et al., 2022). It also confirmed that farmers have a central role in agri-environmental governance but that they receive an overload of messages in relation to sustainability. Sometimes these messages were considered incoherent or contradictory. Information source is very important for farmers who rely on actors that they trust thus, there is a need for a more integrated knowledge infrastructure across all actors in the AKIS. As societal expectations on land continue to evolve it is necessary that the messages are coherent and integrated. Historically, the messages that farmers received have been fragmented or may have generated an unintended consequence.

Culturally, for the first time in the mid-00s more people are living in cities than in rural areas. Thus, more people are disconnected from the source of their food but at the same have growing expectations on the land. Through the course of this work, discussions with farmers highlighted a growing sense of polarisation between the farming community and wider society. Impacts of farming are felt beyond the farm gate and the consequences of poor practice can be felt at wider scales, such as at catchment scale. At the same time, through the course of this work, farmers indicated that they felt a disproportionate burden to address the complex challenges facing society. Moreover, they indicated that they apply recommended best practices on farm and that they do not receive recognition or credit for their efforts that do contribute to societal well-being. We have shown in this PhD that farmers receive incoherent messages. Therefore, it is often the responsibility of individual farmers to translate divergent messages into one coherent farm management plan. It is essential that there is a sufficient supporting knowledge system for farmers. In practice, the fragmentation in science, policy and communication can generate an unintended consequence. There is a need to match the new societal expectation being placed on farmers with support structures that include better knowledge information systems in addition to financial incentivisation. One example of such a knowledge support system is the Soil Navigator, developed as part of the LANDMARK project, but beyond the scope of this PhD. The Soil Navigator is an integrated decision support tool (DST) for soil functions. End-users select the soil functions that are most important for them to optimise and the tool will provide a suite of potential management options that they could deploy on farm to move towards their selected targets.

Research shows that land is more than a place to produce food for those who live and work on the land. Farmers have shown their ability to adapt and respond to changes in the external environment. Farming has focused on production as its primary motivation for millennia. Now, the remit of farming is expanding. Engendering such a shift at farm scale will require a strong AKIS and appropriate reward mechanisms to support this transition. To harness the potential of sustainable land management to address the challenges of the day, mutually acceptable solutions supported by enabling transition pathways that capture the nuance of biophysical, economic and social diversity must be developed.

Final reflections and take home messages

Functional and societal demands - As to the demands of different stakeholders, particularly relevant is the gap between local stakeholder needs that might centre on functional objectives at farm scale, versus societal needs. Fulfilling a functional objective at local scale can represent a sustainable investment as farmers will accrue benefit at that scale but additional management options for which the demand and return on investment is at societal rather than local scale will require market or policy incentives. This is a particularly important entry space to be explored for transition pathways to enable sustainable land management. Farmers must fulfil their mandatory requirements but beyond that, they have autonomy through their property rights to choose the management of their enterprise. Thus, if society requires additional services, then options to incentivise or valorise services must be explored.

Multifunctionality and multilateralism - multifunctionality is now accepted in European policy circles as the different soil based ecosystem services/functions delivered through agricultural landscapes. While there may be on-going clarity sought with respect to how to assess and manage the bundles of soil functions as context relevant indicators, thresholds and ranges are not yet defined (Creamer et al., 2022) the concept of considering land for its productive function alone is insufficient. Science has developed technical solutions to overcome declining yields and to support intensification. Often, these solutions mask the on-going degradation of the land base. This calls for greater ambition in the areas of research and development that can find solutions that are integrative in nature addressing multiple functions. As there is greater acceptance of multifunctionality a new challenge is coming to the fore. With multifunctionality there is anticipation of increased sustainability in European agriculture, a shift that has mobilised policy support in recent years. The full extent to which the external dimensions of more stringent EU policies impact producers and importers/exporters is unclear. The European Green Deal has proposed the economic weight of the EU to shape standards in line with EU environment and climate ambitions (EC, 2019). However, exporters can selectively export into markets for which the policy requirements are less stringent. This creates a challenge when addressing issues, such as climate change, that are transnational in scale and global in their reach and require a concerted effort at all scales, including the global. For multifunctionality to work, without leakage, a multilateral agreement is necessary. It is important that the absence of multilateral agreements does not prompt a race to the bottom. One mechanism proposed for reciprocity in relation to environmental and health standards is the so called 'mirror clause'. Such clauses aim to apply similar production standards as in the EU to "ensure that imported products are subject to the manufacturing standards in force within the EU, whenever this is necessary, to heighten protection of health and the environment, in compliance with WTO rules ("mirror measures")" (French Government, 2022). Matthews (2022) explores the use of 'mirror clauses' as a unilateral measure and highlights six principles to be considered that relate to justification, costs, evaluation and risks of retaliation. The relevance of a mirror clause should therefore be considered on a case-by-case basis (Matthews, 2022). While a prohibition on imports that are not in-line with EU standards is not desirable (Matthews, 2022) it is important to consider that countries may forego the EU market diverting to a market with lesser standards.

Mixed messages – them and us – in some ways polarisation between stakeholders presents a distraction that can fuel more procrastination, which is a luxury that our planet cannot afford. In relation to addressing societal challenges, there is a need to recognise that all actors in the food system have a responsibility to take action in enabling the other actors to turn their responsibility into action. This requires all actors to be part of the solution. This implies agreement on shared responsibilities and for a process of distributed responsibility to be orchestrated in a coherent mechanism. Advisory and all actors in the AKIS will increasingly need to take a more integrated approach with respect to the information and messages that are shared. Science requires greater integration between disciplines and co-construction of solutions in consultation with stakeholders to allow for the wider incorporation of different knowledge sources. Policies must have greater horizontal integration between policy objectives and there is a need for greater recognition that the farm is not the only place where targets related to sustainable land management can be set or deployed. Markets have their role to play to ensure the credentials of their products and consumers who place demands in relation to food should be willing to recognise the value of ecosystem services provided.

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Summary

Sustainable land management requires approaches that reconcile agricultural production with the sustainable use of natural resources. Globally, land and land-based ecosystems are being degraded or lost, driven by the pressures of population increases, climate change, biodiversity loss and consumer demands. Agricultural land is the primary interface between the global food system and the global environment, which means that it can impact on and be impacted by the environment. Farming in Europe has undergone significant changes in the latter half of the last century. In the post-World War II period, European ambitions for food security translated into a strong shift in farming towards productivist methods on the ground. Production linked agricultural policies that guaranteed prices meant that European farmers could embrace technologies to intensify with minimal risk. Such policies generated surplus production and overtime, intensive agriculture gave rise to negative environmental impacts. By the 1990s, awareness of the environmental consequences of intensive agriculture had begun to increase and prompted society to impose different expectations from farming and the land. In addition to food production, the societal expectations on land have increased and expanded beyond food production towards the delivery of multiple land-based goods rooted in sustainability and ecosystem science.

The extent to which agricultural land can co-exist with environmental sustainability and the delivery of environmental goods while increasing food outputs represents an enormous challenge. An integrated approach that simultaneously considers both the agronomic and the environmental goods delivered through agricultural landscapes is urgently required. The complexity of demands on land today is giving rise to conflicts between farmers and wider society across Europe. This PhD aimed to contribute to this societal debate through the provision of science-based input with a view to providing guidance for all actors involved, from farmers to advisors to policymakers. I used an interdisciplinary approach to embrace the complexity and many dimensions of multifunctional land management to explore pathways in favour of a more sustainable land base in the EU utilising the Functional Land Management (FLM) framework. The common theme throughout this PhD to navigate the complexity of multifunctional land management is rooted in the sustainable management of soils.

In Chapter 2, I introduced the policy context and found that there are few examples of legal protection of soils with international binding legal agreements for soils having failed thus far. At a policy level, when compared to other resources land and soils are treated differently. Water and air resources have dedicated legislation whereas the proposed Soil Framework Directive (2006/0086/COD) was withdrawn after a lengthy debate that lasted seven years. The emphasis on threats and issues related to ownership were key factors in its withdrawal. The literature review showed that several policies indirectly offer soil protection but in the absence of a unifying framework or body with responsibility for soils, protection for soils tends to be fragmented with different agencies and bodies with different objectives having responsibility for different soil related issues. It was around the time of the proposed Soil Framework Directive withdrawal in 2014, that the FLM concept was proposed. In Chapter 2, I described the FLM framework. FLM is underpinned by the multifunctionality of soil, which is that soils perform multiple functions simultaneously to deliver land based ecosystem services. Soils provide a wide range of goods and services to society and several studies have categorised these services but often the number of services is too many for practical application or utility to guide policy development. The FLM framework distils the multitude of soil-based ecosystem services to five key land based functions delivered across all agricultural soils, namely primary productivity, water regulation and purification, carbon and climate regulation, nutrient cycling, and habitat for biodiversity. These functions are supplied to a greater or lesser extent owing to the intrinsic soil properties interacting with environment and management factors. FLM, rather than maximising selective soil functions, focuses on optimising the delivery of the suite of soil functions for meeting societal expectations and demands on land. Historically, research and policy had fostered the maximisation of individual soil based ecosystem services, typically in favour of maximising production. I found that the compartmentalised nature of research and policy has failed to acknowledge that all soil functions cannot be maximised in all locations due to the intrinsic trade-offs that occur between soil functions. Drawing on the existing knowledge and literature presented in Chapters 1 and 2, I identified three knowledge gaps around which this thesis is structured: understanding and managing expectations for soil functions (Chapters 3 & 4), trade-offs (Chapter 5 & 6) and finally, implementations gaps and solutions spaces (Chapters 7 & 8).

Different stakeholders have different expectations on land for the delivery of the five key soil functions. Gaps that arise between farmers/land managers and other stakeholders for the delivery of soil functions must be identified as these gaps may need to be reconciled. To address this knowledge gap, in Chapter 3, I developed, piloted, refined and published the *Catchment Challenge* methodology as a tool to understand stakeholder demands for soil functions. This method provides stakeholders with an opportunity to develop a landscape management plan that considers the variable capacity of the soil to supply soil functions across a landscape setting. The method was designed to be flexible with scope for adaptation to localised conditions anywhere in the world. This provides stakeholders the opportunity to work in a neutral space, but also one that is familiar to their frame of reference. As part of the exercise, in addition to an optimised integrated land management plan, stakeholders also identified transition pathways to transition towards this idealised plan. I found a high level of consensus between stakeholders in the design of the optimised catchment. In relation to addressing transition gaps, there was a greater degree of divergence between stakeholders as to requirements for the implementation of the optimised plan. In addition to knowledge gaps, a mix of market and mandatory measures were proposed along with voluntary incentives. This methodology can enhance innovative capacity by allowing for different knowledge domains and expertise to connect, from cultural farming practices, to industry or European policy makers. This can readily provide a deeper understanding of what will or will not work and why.

To crystallise the wider societal demands of EU stakeholders, in chapter 4 we explored the demands for soil functions based on high-level EU policies. Soils are highly variable across Europe and this translates to a high variability with respect to the supply and demand for selected functions. Common Agricultural Policy (CAP) reforms have translated into a myriad of EU and national policies over time intended to ensure the sustainability and multifunctionality of agriculture. This has resulted in a highly complex regulatory environment for farmers and land managers. At the time of this work, which was completed as part of the

EU H2020 LANDMARK project, the EU CAP reform in support of the development of Strategic Plans (SP) was on going. This work contributed to the knowledge base for the development of the SP by mapping the variation in the societal demands for soil functions across EU Member States (MS). Taking EU policy metrics as indicative of societal demands we showed that the demands for soil functions are determined by population, farming systems and livestock densities, geo-environmental conditions and landscape configuration. We concluded that greater subsidiarity through SP offers opportunity for more effective and targeted incentivisation of sustainable land management once the variation in demand for soil functions, as well as the capacity of contrasting soil to deliver on this multifunctionality have been taken into account.

Not all soil functions can be maximised in all locations simultaneously. The augmentation of one soil function can result in the increase or the suppression in the supply of other soil functions. The delivery of soil functions can be managed by altering a dynamic property such as soil fertility, or by altering a static property such as drainage or through land use change. In chapter 5, I demonstrated the trade-off between the soil functions 'primary productivity' and 'carbon cycling and storage' in response to the intervention of land drainage. I applied this to 'poorly' and 'imperfectly' draining managed grasslands in Ireland. I combined a series of national scale spatial datasets in ArcGIS 10.2.2 using overlay analysis. I explored the trade-off between these two soil functions using the nominal price of carbon credits. Drainage was simulated using a process-based DNDC model and data from the Irish Soil Information System. I characterised the results spatially in ArcGIS to account for the variability in the supply of soil functions. I completed a sensitivity analysis in relation to the CO_2 price and the discount rate over which the loss of soil organic carbon (SOC) was applied. I found a high degree of sensitivity to the discount period. When a 10-year rate is applied, the value of increased productivity associated with drainage is outstripped by the environmental value of CO_2 loss at a price of €40 per tonne. A longer discount period of 40 years at the same price showed that the productivity gains exceeded CO_2 value in almost all areas. In this paper, I showed a clear divergence between stakeholder priorities of those that are responsible for farm management and policy makers who frame demand.

Trade-offs between soil functions can occur at multiple scales, from local to the global scale. In Chapter 7, I explored the global flows of soil functions to the Netherlands and China from the Upper Xingu Rivers Basin (UPXR) in Brazil. The EU has put forth ambitions for Europe to be the first climate neutral continent by 2050 and to adhere to the highest standards as it relates to sustainability in the agri-food sector. In this work, utilising land use change data and soybean export data, I quantified the regional exports of soil functions to the Netherlands and to China. I found that the UXRB is highly connected at the global scale via the soybean trade network and that these connections have intensified over time. I found that EU policies have insufficiently addressed the external dimensions of carbon leakage or environmental impact. I also found an increase in bilateral trade arrangements in favour of markets with less stringent standards than those at EU scale. Multilateral agreements have the most potential to address the global challenges of climate and environment however mitigating leakage effects at that

scale will be particularly difficult as nations supersede multilateralism in favour of unilateral objectives.

In Chapters 7 and 8, I concentrated on identifying tailored opportunities for FLM. In Chapter 4, the demands for soil functions showed to be highly variable across Europe. To further contribute to the discourse on the development of SP, I explored how soil functions were prioritised in the 2014-2020 period based upon Pillar 2 budgetary allocation. I found that there are opportunities for greater targeting of incentives in line with societal demands. I also highlighted where additional targeting could be exploited through the Pillar 1 eco-schemes. Beyond instruments such as incentives, FLM has a high knowledge requirement. This knowledge requirement is boundary spanning and requires actors across the whole agriculture, knowledge and innovation system (AKIS) to work together to realise greater agri-environmental sustainability. In Chapter 8, I took a mixed-method approach and combined social network analysis with surveys to explore the networks for FLM soil functions in case studies in Germany, Ireland and the Netherlands. Unsurprisingly, I found that farmers are at the heart of agri-environmental governance networks. The networks were diverse and reflective of local conditions, sustainability challenges, historic trajectories and governance structures. I showed that the amount of information was less important for farmers than the source of their messages. From this analysis, I identified two main pathways to enhance farmer uptake of multifunctionality. I proposed to increase trust between farmers and actors that emit multifunctional messages or to increase the bundling capacity of actors trusted by farmers.

Altogether, my research endorses the need for multifunctional land management. Implementation in real terms remains a complex challenge however; I have demonstrated the utility of the FLM framework and I have developed and tested a suite of methodological approaches and considerations that are highly relevant to the rapidly evolving policy discourse of the day. In addition to advancement of the FLM framework, the results of my thesis can inform current policy and governance developments in the EU where soil is increasingly taking a central role in the discussion to develop pathways for multifunctionality and greater sustainability with a view towards meeting the growing demands on land. Indeed, this thesis delivered on the policy pillar of the LANDMARK project which in turn has contributed directly to the establishment of the EU Mission on Soil Health and Food, one of the key mega-missions for Europe's Research and Innovation framework.

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Life is unpredictable. Ten or 15 years ago, I could never have imagined that I could or would aspire to complete a PhD. Indeed, thinking about a career in research was not something that had even occurred to me. People don't always see their own potential. Sometimes this takes meeting the right people at the right time who also create the right environment and opportunity for you to embrace and succeed. In this regard, I have been lucky.

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About the author

Lilian O'Sullivan was born on 15th August 1977 in Bantry, Co. Cork, Ireland. She graduated from secondary school at Ard Scoil Phobail, Bantry, Co. Cork in 1994. After a period of working overseas, she returned to education and graduated with a BSc International Development and Food Policy from University College Cork in 2013. This was followed by an MSc in Soils and Sustainability from the School of Geosciences at University of Edinburgh, Scotland. She completed her MSc research with Teagasc Agriculture and Food Development Authority in Ireland at the Johnstown Castle Environmental Research Centre in Wexford, Ireland. Subsequently, she was awarded a Research Fellowship by the Environmental Protection Agency Ireland to co-edit the Soils of Ireland book, the Irish contribution to the Springer World Soil Series books published in 2018. Having worked as a contract research officer with Teagasc on a number of national and EU projects, she is now employed by Teagasc as a permanent research officer in Johnstown Castle, Co. Wexford, Ireland working on sustainable soils and land use.

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)

Review of literature (6 ECTS)

- Sustainable soil and land management using functional land management

Writing of Project proposal (4.5 ECTS)

- Sustainable soil and land management using functional land management

Post-graduate courses (8.9 ECTS)

- ArcGIS Spatial analysis unit; Teagasc (2015)
- Advanced access training; e-Bridge (2017)
- Q-Methodology; WUR (2018)
- Introduction to statistics in R; Teagasc (2018)
- Sustainable food security; WUR (2022)

Deficiency, refresh, brush-up courses (0.3 ECTS)

- GDPR Data management and compliance; Dillon Academy (2018)

Laboratory training and working visits (7.5 ECTS)

- Intercontinental implications of functional land management; CENA Lab, University of Sao Paulo, Piracicaba, Brazil (2017, 2018)
- Functional land management; Landwirstkammer Neidersacchen, Oldenburg, Germany (2018)

Invited review of (unpublished) journal manuscript (3 ECTS)

- Soil Use and Management: quantifying the interactions of land management practices and agricultural productivity using a soil quality index,(2017)
- Journal of Human Environment: wetland recreational agriculture: a potential mode to balance wetland conservation and agricultural development (2017)
- Journal of Human Environment: effect of the thermal growing season on farmers’ practice and nitrogen concentrations in Norwegian agricultural catchments (2020)

Competence strengthening / skills courses (4.7 ECTS)

- Interviewer training for research roles for managers; Teagasc (2018, 2019)
- Health and safety training; Teagasc (2018/2020)
- Presentation skills; BBC World News; BBC Communication Training (2020)
- PhD Supervisor training; Thinkwell (2020)
- Internet security training, phishing training; Teagasc ICT (2021)
- GenderSmart training; Teagasc UCD (2021)
- Management development programme FETAC; Beacon Training (2021)

- Grant writing and successful coordination of horizon Europe research project; Teagasc (2022)

Scientific integrity / ethics in science activity (0.3 ECTS)

- Research integrity certified training; Epigeum (2018)

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

- PE&RC First years weekend (2017)
- Knowledge discovery and data mining in soil science (2019)
- Applying a participatory approach in understanding soil functions (2019)
- Interactive augmented reality workshop for managing soil functions (2019)

Discussion groups / local seminars or scientific meetings (4.8 ECTS)

- Farmer discussion groups in Co. Cork (2017)
- Soil conference; WUR (2019)
- Industry catchment challenge Glanbia (2019)
- ASSAP Catchment challenge (2020)
- Teagasc research insights September series on soil carbon (2020)
- Research insights seminar series on land use (2020/2021)
- Signpost farms advisory training group Johnstown (2021)
- Teagasc work programme overview visits (2021)
- Farmer discussion group in Co. Kerry (2021)
- The Irish Land Evidence Review Forum (2021/2022)

International symposia, workshops and conferences (25.3 ECTS)

- EU INTERREG FLM meeting; oral presentation; Latvia (2017)
- EU/China FAB meeting; oral presentation; China (2017)
- EU FLM Workshop; Belgium (2018)
- IUSS Conference; Belgium (2018)
- WUR soil conference; poster presentation; Brazil (2018)
- Soil conference; oral presentation; the Netherlands (2019)
- HORIZONS Workshop; the Netherlands (2019)
- EU Final Landmark policy workshop; Belgium (2019)
- EUROSOIL; online (2021)
- Conference abstracts; online
- LANDMARK Scientific meetings; Italy, Romania, Belgium, Germany, Denmark, Austria (2017-2019)

Societally relevant exposure (3.6 ECTS)

- Technical reports (2017-2021)
- Teagasc daily articles (2020)
- Science week contribution video (2020)
- Farmers journal feature article (2021)

Committee work (2 ECTS)

- Teagasc sustainability committee (2018/2019)

Lecturing / supervision of practicals / tutorials (1.8 ECTS)

- Reading sustainable foodscapes (2018, 2019)
- Sustainable soils and land use for multifunctionality; University College Cork (2021, 2022)
- Sustainable foodscapes (2020, 2021)

BSc/MSc thesis supervision (12 ECTS)

- Effective communication for disseminating soil water management practices to bring about sustainable smallholder agriculture in Tanzania: case study of Dodoma and Manyara regions
- Evaluating farmer decision-making support towards more regenerative dairy farming
- Message acceptance and actor trust amongst Irish dairy farmers: a cross-sectional case study concerning communication about sustainable land management practices
- 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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