TOWARDS REGENERATIVE AGRICULTURE

The case of dairy and arable farming in the Netherlands

LOEKIE SCHREEFEL

Propositions

1. Soil conservation is the sole entry point for regenerative agriculture.
   (this thesis)
2. A shift towards regenerative agriculture is only possible when we valorize regenerative objectives beyond primary productivity.
   (this thesis)
3. Participatory processes are essential for every complex societal transition.
4. Birth control is the most effective strategy to respect planetary boundaries.
5. Universities should boycott journals that do not allow open access publishing.
6. Every thesis should have a layman summary describing how the main findings are relevant to society.

Propositions belonging to the thesis, entitled

'Towards regenerative agriculture: the case of dairy and arable farming in the Netherlands'

Loekie Schreefel

Wageningen, 7 March 2023

Towards regenerative agriculture:
the case of dairy and arable farming in the Netherlands

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Towards regenerative agriculture: the case of dairy and arable farming in the Netherlands

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Abstract

The global food system causes severe pressures on the environment. In response, farming approaches, such as regenerative agriculture, are heralded by industries and governments as mainstream solutions to keep the global food system within planetary boundaries. However, the absence of a clear scientific definition and the low level of consensus on science-based approaches to the monitoring and verification of regenerative agriculture has left many initiatives vulnerable to evidence-based allegations of greenwashing. Therefore, we first aimed to determine what is meant with regenerative agriculture. By conducting a global literature review we analyzed the level of convergence and divergence between definitions which resulted in the core themes of regenerative agriculture. From these core themes, we found that that soil conservation forms the basis of regenerative agriculture to regenerate and contribute to multiple ecosystem services. The core themes of regenerative agriculture, however, were found to be not equally relevant for every farming system and local context. For example, a dairy farmer on peat soil faces very different challenges compared to an arable farmer on a clay soil. Subsequently to a general definition, we aimed to make regenerative agriculture meaningful at the farm-level. We did this by creating a modelling framework that combines a soil model with a bio-economic farm model that quantifies the themes of regenerative agriculture and shows which regenrative objectives and practices are most relevant for farming systems in their local context. This modelling framework was applied to three contrasting farming systems in the Netherlands to determine if we can create tailor-made solutions for conventional farming systems towards regenerative agriculture. For these farming systems we showed that using regenerative practices improves environmental performance, but reduces farm profitability when using current business models. In order to further monitor the efficacy of implementing regenerative practices a comprehensive perspective on the role of metrics for regenerative agriculture is given. Here, we propose a flexible yet coherent framework for the transparent, temporal, and context-sensitive selection of metrics for monitoring the extent to which regenerative initiatives lead to verifiable changes in land management, and as such the degree to which they achieve regenerative goals. Overall, it is concluded that regenerative management can contribute positively to the transition towards sustainable food systems, however, an enabling environment for practitioners has yet to be established. This coming decade, we find ourselves at a unique crossroad where regenerative agriculture has the attention of farmers, citizens, industry, and policy makers alike. As such, we believe that this thesis contributes to the challenge of mainstreaming regenerative agriculture, thus securing a sustainable future for the land that humanity relies on for tomorrow’s food and wellbeing.

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Chapter 1

General introduction

1. “Our global food system is broken”

The global human population has increased from about three billion people in 1960 to almost eight billion in 2022 and is expected to reach over 10 billion by 2060 (United Nations, 2021). A growing and wealthier population demands among other things an increase in or a better distribution of housing, infrastructure, energy, and food (Nooghabi et al., 2018; Thornton, 2010). However, increasing the demand of, for example, food causes severe pressures on the environment and our planetary boundaries (Rockström et al., 2009). More specifically, the global food system releases about one third of annual anthropogenic greenhouse gas (GHG) emissions, causes about one-third of terrestrial acidification and is responsible for the majority of global eutrophication of surface waters (Crippa et al., 2021; Poore and Nemecek, 2018). These deteriorating environmental impacts threaten global food security by, among others, land degradation. One third of our global land is degraded as a result of erosion, salinization, compaction, acidification, and chemical pollution (United Nations, 2022). Land degradation hampers soils to fulfill their functions to simultaneously produce food, feed, fuel, and fiber; regulate our climate, recycle nutrients, purify and regulate fresh water, and provide biodiversity and habitats for species (IPCC, 2020; Schulte et al., 2014). Hence, five of the nine planetary boundaries are crossed: climate change, loss of biosphere integrity, land-system change, and altered biogeochemical cycles (phosphorus and nitrogen), and more recently green water as part of freshwater use (Steffen et al., 2015; Wang-Erlandsson et al., 2022).

Although the urgency to overcome these food system challenges were already acknowledged in early scientific literature (see for example Arrhenius, 1896; Revelle and Suess, 1957; Wilson, 1985), the popular media is increasingly showcasing the urgency as well. Headlines such as “the global food system is broken” (Carrington, 2018) or “a final call to save the world from climate catastrophe” (McGrath, 2018) are increasingly common, stressing the urgency to move towards healthy food systems. Besides attention in the popular media, the need for healthier food systems is also progressively acknowledged in international agreements and policy frameworks such as the Common Agricultural Policy (European Commission, 2019a), the Farm to Fork strategy (European Union, 2020), and the Agriculture Innovation Strategy (USDA, 2021). However, at present only a few countries world-wide have effective policies to deal with the addressed challenges and protect the health of soils (FAO and ITPS, 2015).

Agriculture, as the basis of the global food system, has achieved great successes such as high production levels per unit of input, and low resource use and emissions to the environment per kilogram of food produced (FAO, 2017; Pingali, 2012). Moreover, the production of grain, rice, and maize has increased at a greater rate than human population growth, which decreased global malnutrition (Tilman, 1999). Despite these agricultural successes, the cumulative impact of agriculture is environmentally problematic. Global agriculture is responsible for about 20% of total net anthropogenic greenhouse gas emissions (IPCC, 2022) and is the leading source of environmental pollution through the use of pesticides, fertilizers, and other toxic farm chemicals that leach into water, air, and soil (Aktar et al., 2009; Sharma et al., 2019; Wang et al., 2019). Nowadays, agriculture's key challenge is to produce enough safe and nutritious food for a growing and wealthier population within the carrying capacity of the planet, while respecting the welfare of both humans and animals.

2. Regenerative agriculture at the forefront

As a response, farming approaches that were promoted by farmers, however, thus far considered as niches are now heralded by industries (e.g. Danone, 2021; Unilever, 2021) and governments (e.g. EIT Food, 2021; NSW DPI, 2021) as mainstream solutions to keep our global food system within planetary boundaries. Regenerative agriculture is one of such approaches and is receiving a lot of attention from actors in the food system (Giller et al., 2021). As an indication of the increased attention, the number of peer-reviewed articles and citations including the word "regenerative" and "farm" or "agri" over time is shown in Figure 1. Regenerative agriculture was mentioned in early scientific and popular publications by, for example, Gabel (1979) and Francis et al. (1986). They wrote about more sustainable agricultural production systems as a response to the foreseen world food shortages and excessive use of non-renewable resources. Regenerative agriculture was further articulated by Rodale (1987, 1984) who carried out long-term experiments to show the effect of regenerative practices at farm-level (e.g. Delate et al., 2017). Throughout the past few decades, many actors have been increasing the body of knowledge about regenerative agriculture.

In 2018 (at the start of this PhD), regenerative agriculture was just beginning to flourish in attention. At that time, a comprehensively described scientific definition was still missing (Elevitch et al., 2018). In absence of such a scientific definition, a variety of actors may foster diverging perceptions of regenerative agriculture. For example, Malik and Verma (2014) describe regenerative agriculture as "dynamically advanced modified techniques involving the use of organic farming methods", while Elevitch et al. (2018) describe regenerative agriculture as "a farming approach that has the capacity for self-renewal and resiliency, contributes to soil health, increases water percolation and retention, enhances and conserves biodiversity, and sequesters carbon".

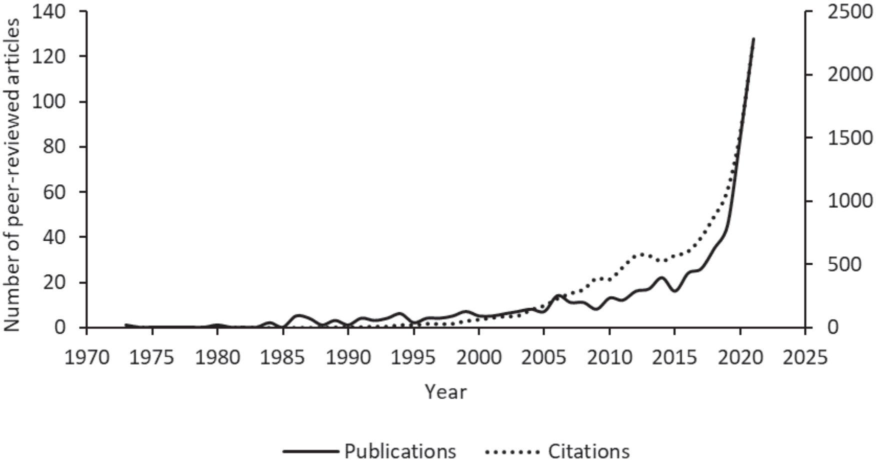
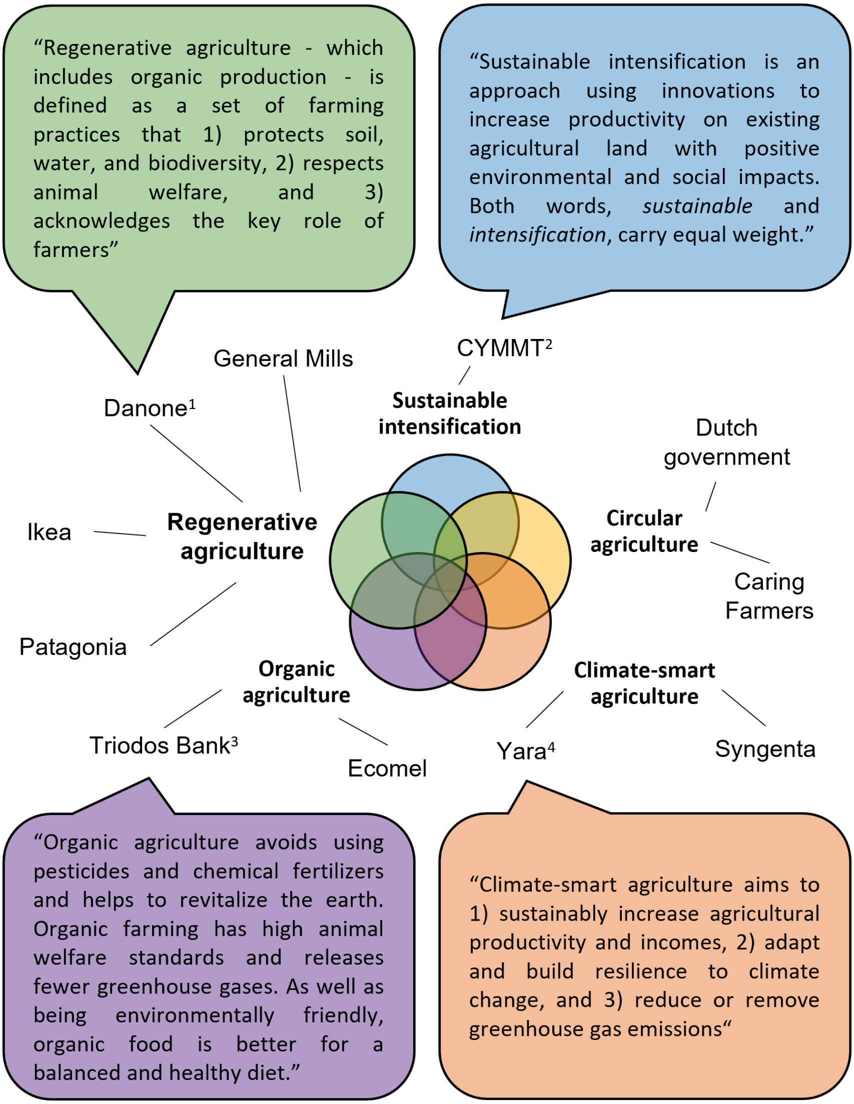


Figure 1. *Number of peer-reviewed articles published and citations in English with the words "regenerative" and "farm*" or "agri*" in the title, abstract, or keywords, based on the Scopus database, in June 2022.*

Besides, divergent definitions of regenerative agriculture, other emerging approaches to sustainable farming often have similar objectives and practices. Some of these farming approaches have definitions that are regulated, such as organic agriculture (European Commission, 2019b; IFOAM, 2019), while others remain yet unregulated, such as circular agriculture (Fan et al., 2020), regenerative agriculture (Chapter 2), climate-smart agriculture (FAO, 2018), and sustainable intensification (FAO, 2013). While all these emerging farming approaches aim to be future proof and contribute to keeping our global food system within planetary boundaries, they originate from different narratives to sustainable agriculture. Some of these farming approaches come from a production-orientated narrative such as sustainable intensification, which explores increased production yields to reduce environmental impacts (Garnett et al., 2013). While, other farming approaches originate from broader theoretical narratives such as circular agriculture, which originates from the circular economy using the 4R-framework (reuse, repair, refurbish and recycle) as a baseline (Jurgilevich et al., 2016; Van Zanten et al., 2018). Again other farming approaches, such as regenerative agriculture, emerged from practitioner experiences rather than an un up-front theoretical framework (Giller et al., 2021).

As regenerative agriculture is currently in a pioneering phase, there is merit in building on the learnings of similar farming approaches (and vice versa) to avoid and leapfrog similar pitfalls that may arise. Figure 2 shows the potential overlap between some emerging farming approaches which are supported and defined differently by actors in the food system. Although each of these farming approaches can be a solution to a specific farming problem, the overlap within farming approaches can be confusing and elusive for actors (e.g. farmers, industries, governments) trying to identify themselves with a particular farming approach. Therefore, it is of utmost importance to understand why approaches to sustainable farming are needed and have a common understanding about farming approaches before working towards their implementation. The **first** objective of this PhD thesis, therefore, is to determine what is meant with regenerative agriculture by reviewing scientific definitions and giving a comprehensive overview about the level of convergence and divergence between definitions.



"Regenerative agriculture - which includes organic production - is defined as a set of farming practices that 1) protects soil, water, and biodiversity, 2) respects animal welfare, and 3) acknowledges the key role of farmers"

"Sustainable intensification is an approach using innovations to increase productivity on existing agricultural land with positive environmental and social impacts. Both words, *sustainable* and *intensification*, carry equal weight."

"Organic agriculture avoids using pesticides and chemical fertilizers and helps to revitalize the earth. Organic farming has high animal welfare standards and releases fewer greenhouse gases. As well as being environmentally friendly, organic food is better for a balanced and healthy diet."

"Climate-smart agriculture aims to 1) sustainably increase agricultural productivity and incomes, 2) adapt and build resilience to climate change, and 3) reduce or remove greenhouse gas emissions"

***Figure 2**. Potential overlap within definitions of emerging farming approaches which are supported by different actors in the food system. The four examples refer to Danone (2021), Triodos Bank (2022), CIMMYT (2020), and Yara (2015).*

3. Making regenerative agriculture meaningful at the farm-level

Farming systems are highly heterogeneous and face diverse challenges (Giller et al., 2021). They differ in farm archetype (e.g. arable or dairy), pedo-climatic conditions (e.g. climate and soil type), socio-economic situations (e.g. access to markets), all of which result in variability of farming systems. Therefore, regenerative objectives and practices are not equally relevant, applicable, or effective for all farming systems (Giller et al., 2021; Luján Soto et al., 2021). For example, a dairy farmer on peat soil faces very different challenges compared to an arable farmer on clay soil. A typical challenge for dairy farmers on peat soil is to improve climate regulation (Jong et al., 2021), while arable farmers on a clay soil may face challenges with the enhancement of soil biodiversity or handling drought (Bockstaller et al., 2011). Even when the challenge of different farming systems is the same (e.g. improve climate regulation), the most effective practices can be completely different (Stringer et al., 2020). Dairy farmers on peat soils may focus on reducing carbon dioxide (CO_2) emissions by avoiding drainage (Jong et al., 2021), while arable farmers on clay soils aim to improve carbon sequestration by implementing solid manure instead of artificial fertilizers or incorporating crop residues into the soil. These examples highlight that, besides a common understanding, we need to make specific what regenerative objectives and practices are to be meaningful in local contexts (Giller et al., 2021). Building on the first objective, the **second** objective of this PhD thesis, therefore, is to make regenerative agriculture meaningful at the farm-level and use ex-ante design to demonstrate which objectives and what practices are relevant for farmers in their local context.

4. The Netherlands as case-study

The Netherlands (Figure 3) is used as case-study to illustrate the applicability and effects of regenerative agriculture (in Chapter 3 and 4). The Netherlands was selected because of its large contribution to global food supply, their intensive agricultural landscape, and having the ability and societal willingness to change (Erisman, 2021; Schulte et al., 2019). Furthermore, the Netherlands includes very contrasting farming systems and soil types which is of interest to the overarching project (Box 1.), as the aim is to look for multidisciplinary transition processes for a diversity of food systems actors.

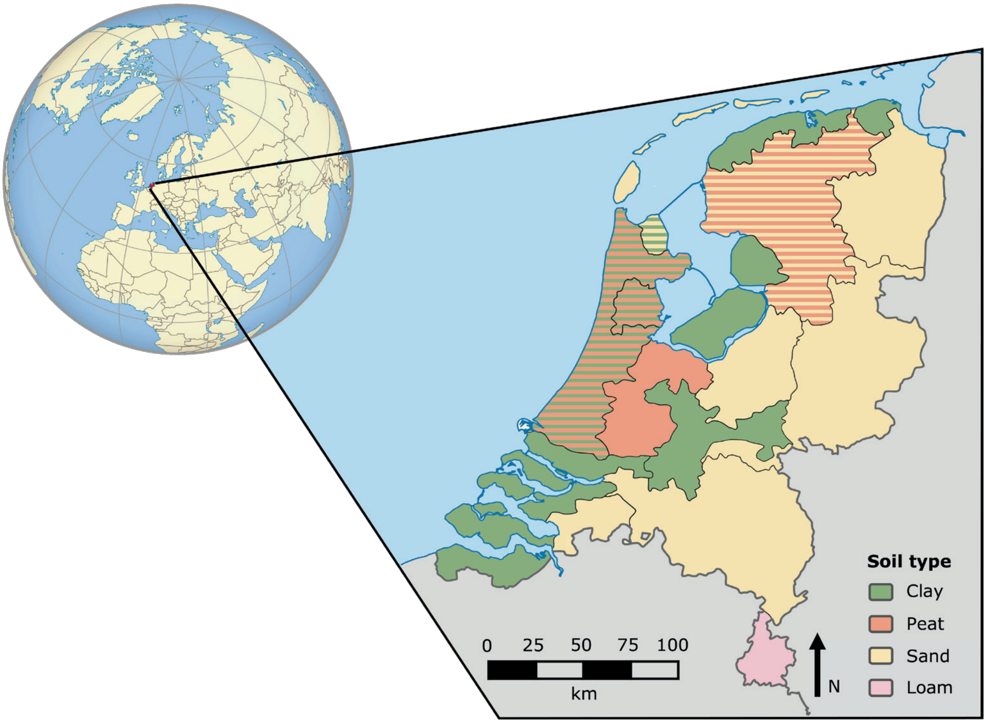


***Figure 3**. Map of the Netherlands divided in 14 agricultural regions according to the Central Bureau of Statistics (CBS, 2022).*

Box 1. TiFN Regenerative Farming Project

This PhD-project was commissioned as part of the TiFN (Top institute Food and Nutrition) Regenerative Farming project. This four-year project aims to bring scientists, sector organizations, farmers, and food chain companies together to identify characteristics of regenerative agriculture in the Netherlands and work towards its implementation by 2050. The research in this project focusses on biophysical aspects of transitioning towards regenerative agriculture (this thesis) as well as socio-cultural aspects (thesis of Niko Wojtynia). Together with a team of researchers, we created a community of practice of 20 Dutch farmers transitioning towards regenerative agriculture. We cooperated with this community to share best practices between farmers, to measure the impact of best practices, and help researchers to learn from systemic changes of farmers enabling the wider implementation of regenerative agriculture.

For more information, see project website: www.regenerativefarming.nl

Although the Netherlands is a tiny country, it comes with big agriculture. Currently, 54% of the surface area in the Netherlands is used for agriculture, dominated by dairy and arable farming (CBS, 2020; CLO, 2020). Although agriculture is economically important in the Netherlands, it is also environmentally problematic. The dairy sector contributes significantly national emissions, for example, producing 11% of the domestic GHG emissions (van Eerdt and Westhoek, 2019). Dairy farmers rely heavily on imports of concentrate feed: 40% of the cow's protein intake is derived from imported feed (van der Meulen, 2021). Furthermore, about 60% of the dairy farmers export part of their manure from the farm (Luesink, 2021), while arable farmers use relatively large amounts of inorganic nitrogen fertilizers (106 kg N ha^{-1} yr^{-1}) (Leeuwen, 2021). This intensive agricultural landscape has resulted in the Netherlands being the European nitrogen hotspot since the 1980s, and recently led to a national nitrogen crisis (Erisman, 2021).

As a response the Dutch agricultural ministry has drawn up proposals with radical changes to limit nitrogen deposition (e.g. slashing livestock numbers with 30%). Farmers, however, show to be economically vulnerable for these changes leading to national farmers protests (Boztas, 2021). It is these farmers that currently face the challenge to maintain a sound farm profitability, while producing enough food; reduce GHG emissions; reduce their nitrogen deposition. If that is not challenging enough, they are also requested to improve their water regulation and purification (e.g. droughts are recently reoccurring events) (Slob, 2022), and to invest in below and above ground biodiversity (Huizen, 2018). To embrace the challenge to contribute to multiple objectives simultaneously, farmers and industries might benefit from tools that can help on-farm decision making and show the consequence of implementing combination of practices on multiple farm objectives. The **third** objective of this thesis, therefore, is to use the ex-ante redesign approach developed as a second objective and determine how tailor-made solutions towards regenerative agriculture can be identified as such that they result in meaning-full advice for farmers.

5. Monitoring the success of regenerative agriculture

After deciding what objectives and practices are relevant for farming systems, a next step for governments and industries is to monitor the success of farmers contributing to regenerative agriculture. There is a significant body of literature on monitoring the impact of farming systems (e.g. Bockstaller et al., 2011; de Olde et al., 2017a; FAO, 2014) and there are even scientific journals completely dedicated to approaches of monitoring, such as Ecological Indicators (2022) and Environmental and Sustainability Indicators (2022). However, the low level of consensus on science-based approaches to monitoring and verification is restricting the efficacy and transparency of implementation (de Olde et al., 2017b), and has left many initiatives vulnerable to evidence-based allegations of greenwashing (Diab, 2022). A particular challenge in monitoring the effectiveness of farming practices is the diversity of agronomic, bio-physical, and socio-cultural contexts between, and even within, individual value chains within the food system (Gasparatos et al., 2008; van Oudenhoven et al., 2012). There is an urgent need to match the zest with which regenerative initiatives are pursued and promoted by farmers, industries, and governments with a robust framework for assessing the effectiveness of regenerative agriculture in delivering its objectives (European Commission, 2022a). The **fourth** objective of this PhD thesis is, therefore, to discuss the role of metrics for regenerative agriculture and present a framework that can be used to monitor the success of farming systems that transition towards regenerative agriculture.

6. Objectives and outline of this thesis

In summary, a transition towards sustainable food systems is needed to produce enough food for a growing and wealthier population, while at the same time staying within the biophysical boundaries of the planet and respecting the welfare of humans and animals. Regenerative agriculture is increasingly seen as a solution but a common understanding about what it is and how to apply it is currently lacking. The main objective of this thesis is to better understand practices that contribute towards regenerative agriculture with a focus on dairy and arable farming in the Netherlands. To this end, the objectives of this PhD project are to understand what is meant with regenerative agriculture, to explore how farmers can contribute to regenerative dairy and arable farming, and to determine how success of farming systems towards regenerative agriculture can be monitored.

These objectives are answered in four different chapters in this thesis. As can be seen in Figure 4, some of these chapters (Chapter 2) are more practically orientated and discuss the framing of regenerative agriculture, while other chapters (Chapter 3 and 5) are more theoretical-orientated and discuss conceptual frameworks. The remaining Chapter 4 is in between and shows the (modelled) performance of future regenerative farming systems.

More specifically, **Chapter 2** describes what is meant with regenerative agriculture by reviewing scientific definitions. This study discusses the level of convergence and divergence between definitions and provides a provisional definition for regenerative agriculture. To illustrate the convergence of regenerative agriculture with other sustainable farming approaches, regenerative agriculture is related to organic agriculture as an example of a regulated farming approach and circular agriculture which remains yet unregulated concept. In **Chapter 3**, regenerative agriculture is made meaningful at the farm-level. This study demonstrates a modelling framework for an *ex-ante* design and assessment of farming systems on multiple regenerative objectives. The modelling framework takes context-specific soil management practices center-stage to optimize overall farm sustainability. **Chapter 4** showcases the applicability of this modelling framework on three contrasting farming systems in the Netherlands (i.e. dairy farming on peat soil, arable farming on clay soil, and mixed farming on sand soil). This study shows that our modelling framework can be used to explore a multitude of tailor-made solutions for diverse farming systems. **Chapter 5**, discusses the role of metrics for regenerative agriculture and present a framework which can be used to select metrics to monitor the success of farming systems that transition towards regenerative agriculture. In **Chapter 6**, the relevance and implications of transitioning towards regenerative agriculture are discussed.

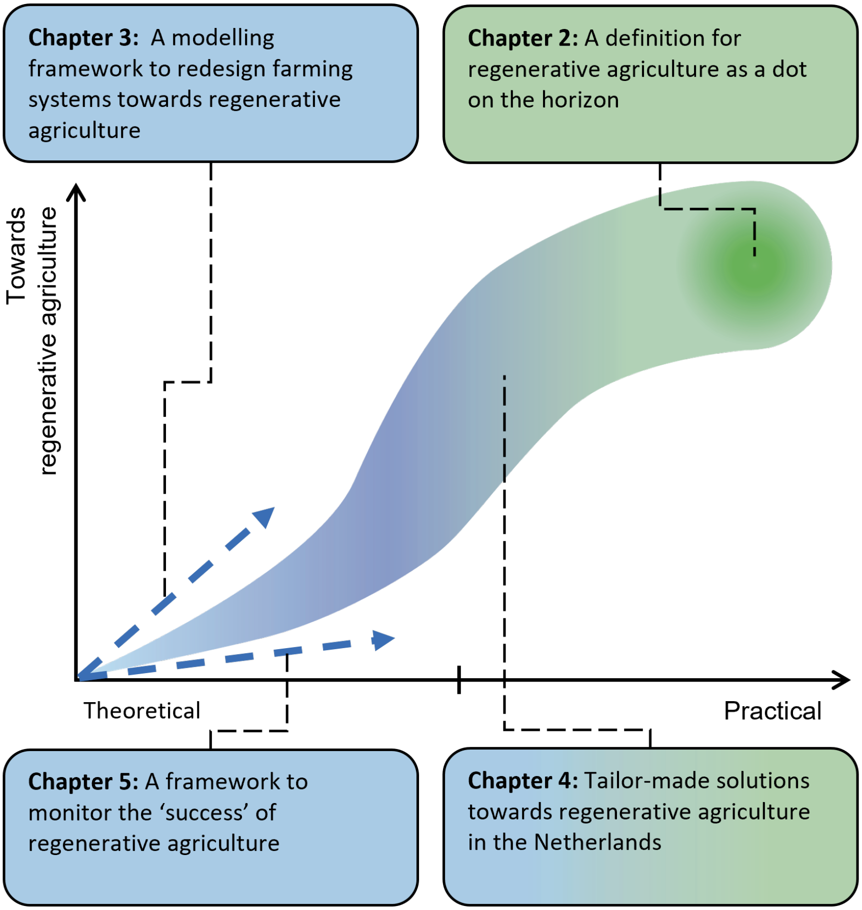


Figure 4. *Structure of the chapters of this thesis, in which the chapters colored blue indicate theoretical-orientated studies and chapters colored green indicate practically-orientated studies.*

Chapter 2

A definition for regenerative agriculture as a dot on the horizon

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Abstract

Regenerative agriculture is proposed as a solution towards sustainable food systems. A variety of actors perceive regenerative agriculture differently, and a clear scientific definition is lacking. We reviewed 28 studies to find convergence and divergence between objectives and activities that define regenerative agriculture. Our results show convergence related to objectives that enhance the environment and stress the importance of socio-economic dimensions that contribute to food security. The objectives of regenerative agriculture in relation to socio-economic dimensions, however, are general and lack a framework for implementation. From our analysis, we propose a provisional definition of regenerative agriculture as an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services.

1. Introduction

The global food system currently releases about 25% of annual anthropogenic greenhouse gas (GHG) emissions, causes about one-third of terrestrial acidification and is responsible for the majority of global eutrophication of surface waters (Poore and Nemecek, 2018). If our food system continues with current practices, using synthetic pesticides, artificial fertilizers, fossil fuels and producing food waste, the carrying capacity of the planet is likely to be surpassed (Campbell et al., 2017). Therefore, the key challenge for humanity is to produce enough safe and nutritious food for a growing and wealthier population within the carrying capacity of the planet (Willett et al., 2019). The importance of producing food within the carrying capacity of the planet is also increasingly acknowledged in policies - for example, the EU Circular Economy Action Plan (European Commission, 2015), the Paris Climate Agreement (United Nations, 2015) and the Common Agricultural Policy (European Commission, 2019a).

This challenge has led to new narratives for sustainable agriculture. Some of these narratives are production-oriented and find their solutions in approaches such as sustainable intensification, which explores increased production yields to reduce the environmental impact (Cole and McCoskey, 2013; Garnett et al., 2013). Another narrative argues that the production-oriented approach is not sufficient to deal with the key challenge for humanity and that consumption patterns should be adjusted for the global food system to function within the boundaries of our planet (Garnett et al., 2013; Stehfest et al., 2009; The Eat-Lancet Commission, 2019; Tilman and Clark, 2014). Building on both the production and consumption-oriented approaches for example Van Zanten *et al.* (2018) argues that production and consumption-oriented approaches are needed together and should be in balance with their ecological environment. Their narrative takes a food systems perspective and aims at safeguarding natural resources by closing of nutrients and carbon cycles in the food system as far as possible, also referred to as a circular food system (de Boer and van Ittersum, 2018).

Farming approaches within these narratives often share similar desires to reach an objective, such as achieve global food security, reduced use of external inputs and reduced environmental damage. Some of these farming approaches have definitions that are comprehensively described in the scientific literature and regulated, for example, organic agriculture (European Commission, 2019b; IFOAM, 2019), climate-smart agriculture (FAO, 2018) and sustainable intensification (FAO, 2013), while others remain yet as unregulated and mainly scientific concepts such as circular agriculture. An approach that recently gained attention in the literature as a solution for sustainable food systems is regenerative agriculture (LaCanne and Lundgren, 2018; Shelef et al., 2017). Currently, regenerative agriculture does not have a comprehensively described scientific definition (Elevitch et al., 2018).

In absence of such a scientific definition, a variety of researchers may foster diverging perceptions of regenerative agriculture. For example, Malik and Verma (2014) describe regenerative agriculture as dynamically advanced modified technique involving the use of organic farming methods, while Elevitch et al. (2018) describe regenerative agriculture as a farming approach that has the capacity for self-renewal and resiliency, contributes to soil health, increases water percolation and retention, enhances and conserves biodiversity, and sequesters carbon. Therefore, in this review, we assess the background and core themes of regenerative agriculture by examining the convergence and divergence between definitions in peer-reviewed articles. An assessment of the background and core themes of regenerative agriculture allows the establishment of an evidence-based provisional definition. Such a definition forms a basis for further discussion not only within science but also among a large group of actors (e.g. governmental agencies, sector organisations, industries and farmers). This large group of actors may foster different definitions dependent on their particular interests. A provisional definition is, therefore, essential to establish a common definition in which more views are included and indicators that enables actors to assess their performance towards a sustainable food system. Indicators, for example, enables governments and industries to monitor their performance towards the Sustainable Development Goals (SDG's), it enables policymakers to create supporting policies for actors in the field, it enables researchers to have a scientific basis to accumulate knowledge and it enables farmers to assess which activities to adjust. To illustrate the convergence between sustainable farming approaches we relate regenerative agriculture to organic agriculture as an example of a regulated farming approach and circular agriculture which remains yet an unregulated concept.

2. Materials and methods

We systematically studied peer-reviewed articles to find definitions of regenerative agriculture using the methodological framework PRISMA-P (Preferred Reporting Items for Systematic Reviews) (Shamseer et al., 2015). A checklist of the suggested items reported in PRISMA-P is given in supplementary materials S1 and a detailed overview of the review and analytical process is presented in supplementary materials S2. Five journal databases (Scopus, Web of Science, Agricola, CAB Abstracts and Medline) were searched for definitions of regenerative agriculture in December 2019. Keywords used to create a search string to find articles that include a definition for regenerative agriculture build upon the words 'regenerative' and 'farming' (see supplementary materials B10). For 'farming' different synonyms were used, including agriculture, agronomy and food system. Search terms such as 'agronomy' and 'food system' were included to capture definitions for regenerative agriculture embedded in the transition towards a regenerative food system.

The database search yielded 279 articles mentioning 'regenerative' and 'farming' (see Figure 1). These 279 articles were screened on their abstract and titles and narrowed down to 43 articles. The eligibility criteria to narrow down articles based on their titles and abstracts were to exclude: duplicates, unavailable articles within the selected databases, articles which were not peer-reviewed and articles unrelated to agriculture. After excluding fifteen articles which did not contain a definition of regenerative agriculture, 28 articles (Supplementary materials S3) remained for further synthesis. Reference checking using the snowballing technique (Jalali and Wohlin, 2012) did not yield more articles. No articles were excluded based on the year of publication. The PRISMA workflow in the supplementary materials S4 provides a more extensive overview of the methodical process of inclusion and exclusion of articles.

We analysed the background (e.g. actor and scale to which the definition applies) and different definitions of regenerative agriculture in the reviewed articles using a cultural domain analysis and inductive coding. A cultural domain analysis (Borgatti, 1994) and inductive coding (Thomas, 2006) are both synthesis methods to cluster segments of text, based on their coherence. Following these methods, the definitions were split-up into text segments called *issues* (e.g. improve soil carbon, minimize tillage). These issues were categorised into *objectives* (e.g. improve soil carbon, interspecies equity) and *activities* (e.g. minimize tillage, use natural pest control). In this review, objectives capture the desire of researchers to achieve a certain goal, whereas activities capture operationalizations, for example, suggested farm practices. If these objectives or activities were mentioned at least five times in the literature, then we grouped them into themes (e.g. improve soil physical quality, improve human health). The criterion to have at least five convergent objectives or activities to form a theme was based on a sensitivity analysis (see supplementary materials S5.15c, in which different numbers (3 till 7) of convergent issues were assessed on their inclusiveness of specific themes. The allocation process of issues was done by all co-authors independently to reduce interpretation bias, and any disagreement on the allocation of issues was solved by discussion. Supplementary materials S6 shows the allocation framework used. All the different themes together form the core of regenerative agriculture. The following four aspects were analysed to determine the themes of regenerative agriculture: i) the number of articles referring to the themes, ii) the number of converging and diverging interpretations of nomenclature within themes, iii) the classifications of themes among objectives or activities and iv) the relation of themes with the three dimensions of sustainability, i.e. people, planet and profit (Elkington, 1997). Converging themes indicate that authors of different articles present similar objectives within their definitions. Diverging themes present contradictions or issues which are unclear.

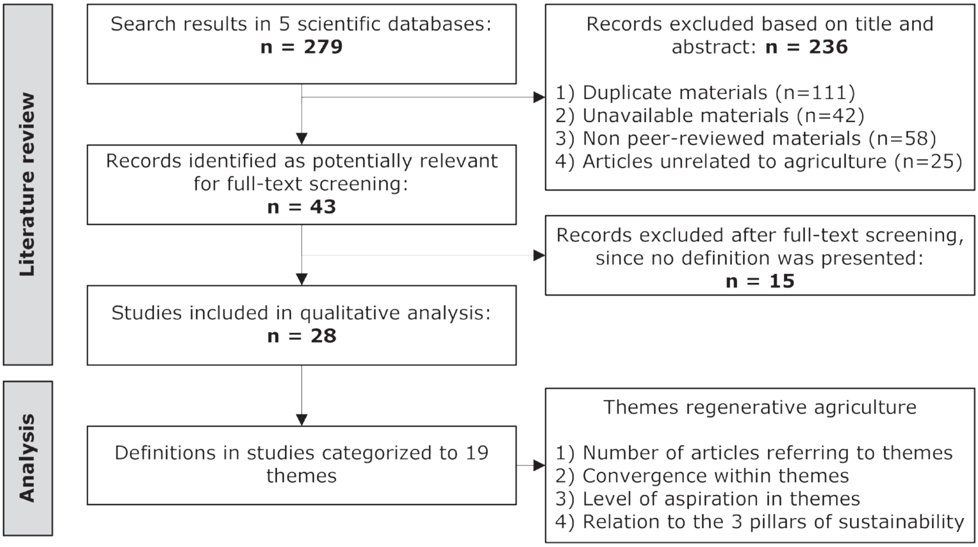

Figure 1. *Illustration of the research methodology to analyse existing definitions of regenerative agriculture, in which 'n' represents the number of search records.*

The triple bottom line approach (people, planet and profit) was used to categorize themes among social (e.g. maintain cultural diversity), environmental (e.g. improve soil structure) and economic (e.g. create long-term economic sustainability) aspects (Elkington, 1997; Slingerland et al., 2003). Furthermore, we analysed whether definitions were based on the objectives of researchers or farmers and to which scale (farm, regional or systems-level) they relate. Figure 1 illustrates the steps required to analyse the existing definitions of regenerative agriculture.

3. Results and analysis

3.1 The core themes of regenerative agriculture

In the 28 peer-reviewed articles we found that definitions addressed different issues (e.g. soil health, climate change) and scales (e.g. farm, food systems-level), resulting in different levels of implementation. Our review yielded 214 objectives and 77 activities. The assessment of the convergence among objectives and activities, which was based on the underlying issues, resulted in thirteen themes for objectives and seven themes for activities (Figure 2).

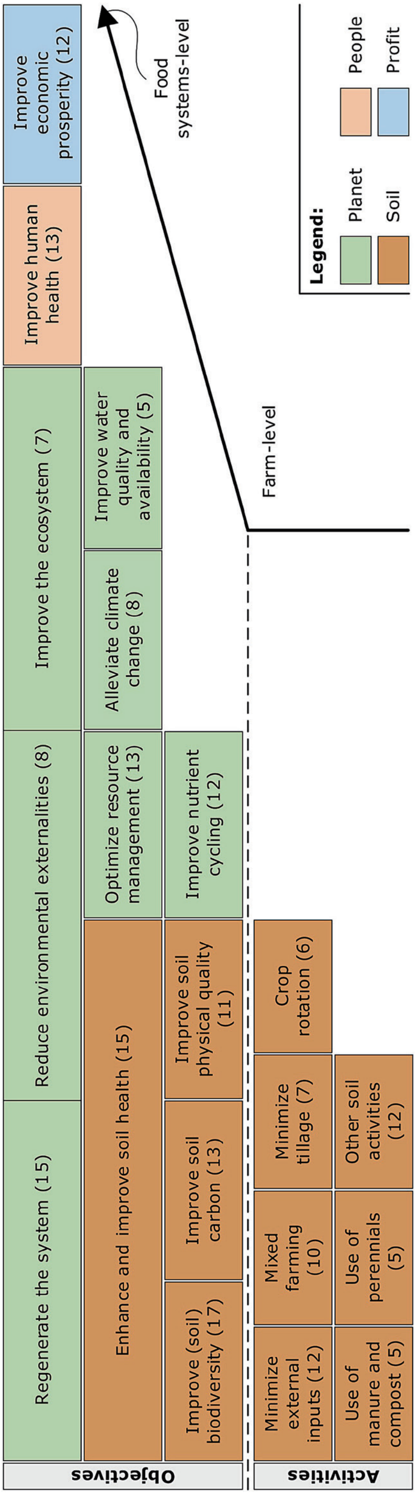

Figure 2. *The core themes of regenerative agriculture, in which 'the number between brackets' represents the number of search records*

These twenty themes referred mostly to the environmental dimension of sustainability (seventeen out of nineteen). Environmental issues were addressed from farm to food systems-levels (Figure 2). Of these, all activities and four objectives specifically focussed on soil issues: *enhance and improve soil health*, *improve soil carbon*, *improve soil physical quality* and *improve (soil) biodiversity*. The multiple aggregation levels and quantity of articles referring to environmental issues indicated that regenerative agriculture focusses specifically on environmental issues, and in particular soil issues.

We will first discuss the environmental themes that show most convergence among definitions (see section 3.2), followed by themes with divergence (see section 3.3). The specific issues among the themes can be found in supplementary materials S6.

3.2 Themes in regenerative agriculture showing convergence

All reviewed articles related regenerative agriculture with the environment (planet) and mainly with improving environmental issues, which is referred to as *regenerate the system*, *reduce environmental externalities* and *improve the ecosystem*. Convergent objectives were mentioned regarding reducing environmental externalities e.g. ‘reduce environmental damage’ (Teague, 2018, P.1520) and ‘reduce environmental pollution’ (Rhodes, 2012, P.345). Similarly, there was convergence about the improvement of the ecosystem. A healthy agroecosystem was referred to as a resilient ecosystem that enables the provision of ecosystems services, such as provisioning, regulating, habitat and supporting services (e.g. Gosnell et al., 2019; Rhodes, 2017; Teague, 2017). These three environmental themes were further articulated by four themes that refer to the improvement of the food system: *enhance and improve soil health* (n=15), *optimize resource management* (n=13), *alleviate climate change* (n=8) and *improve water quality and availability* (n=5).

The theme *enhance and improve soil health* received most attention; seventeen of 28 articles explicitly mentioned improving soil quality in a variety of synonymous objectives, such as ‘improve soil quality’ (Mahtab and Karim, 1992, P.54), ‘contribute to soil fertility’ (Elevitch et al., 2018, P.2), ‘enhance soil health’ (Sherwood and Uphoff, 2000, P.86) and ‘improve their soils’ (White and Andrew, 2019, P.2). A synthesis of the issues among the objective to improve soil quality is that a healthy soil is the basis for regenerative agriculture and therefore degraded agricultural soils should be restored to healthy soils. This is expressed by, for example, Rhodes (2012, P.380) who mentioned that regenerative agriculture ‘regenerates the soil’ and by Diop (1999, P.296) who mentioned that regenerative agriculture ‘gives the soil as a resource the first priority’.

Thirteen out of 28 studies mentioned objectives to *optimize resource management*. Reviewed articles highlight objectives towards recusing waste and optimal nutrient availability. They indicated regenerative agriculture as a system which has the objective to regenerate resources in an integrated manner for sustained soil fertility and desired crop and animal productivity. They mentioned, for example, issues as ‘minimize waste’ (Teague, 2015, P.5), ‘synergisms in different combinations and methods of management’ (Teague and Barnes, 2017, P.80), ‘regeneration of natural resources’ (Teague, 2015, P.5), ‘improve nutrient retention and availability’ (Diop, 1999, P.295) and ‘encompass solid-waste management’ (Mahtab and Karim, 1992, P.54).

Themes *alleviate climate change* and *improve water quality and availability* received less attention compared to other themes with objectives. Moreover, eight of 28 articles have the objective to *alleviate climate change*. Studies mentioned for example to ‘reduce GHG emissions’ (Teague, 2018, P.1520), ‘invert carbon emissions of our current agriculture’ (Elevitch et al., 2018, P.2) and ‘mitigate climate change’ (Rhodes, 2012, P.434). Similarly, five of the 28 studies mentioned issues supporting the theme of *improve water quality and availability*. For example, to ‘improve water quality’ (Elevitch et al., 2018, P.4), ‘achieve clean and safe water runoff’ (Elevitch et al., 2018, P.2), ‘reduce water shortages’ (Rhodes, 2012, P.380) and ‘protect freshwater supply’ (Rhodes, 2017, P.95). Other studies did not mention such objectives about the alleviation of climate change or the improvement of water quality and availability.

The objectives *enhance and improve soil health* that received most attention were further articulated by more specific objectives which include *improve (soil) biodiversity* (n=17), *improvement of soil carbon* (n=13) and *soil physical quality* (n=11). An objective frequently mentioned (13 out of 28) is to *improve (soil) biodiversity* for improved soil functioning, which relates to above and below ground biodiversity. The issues among this theme showed convergence, although different issues are mentioned in the reviewed articles: the improvement of soil biodiversity by ‘promoting soil biology’ (LaCanne and Lundgren, 2018, P.7) or more general statements such as ‘increase the biodiversity’ (de Haas et al., 2019, P.548). Although biodiversity is clearly an important theme, it remains unspecified what is meant with the improvement of biodiversity (below or above-ground biodiversity, to which scale does it relate). Most studies expect or assume, however, that regenerative agriculture will improve biodiversity, which in general is seen as a precondition for sustainable food systems.

Another objective which shows convergence and is frequently mentioned (13 out of 28) is to *improve soil carbon*, articulated in the reviewed article as for example ‘build soil organic matter’ (e.g. Diop, 1999, P.290; Rhodes, 2017, P.100), and ‘increasing carbon sequestration’ (e.g. Elevitch et al., 2018, P.2; Provenza et al., 2019, P.3; Sambell et al., 2019, P.3). The improvement of soil carbon is considered a cross-cutting issue across the three spheres of soil science (soil chemistry, soil physics and soil biology) since it affects all three aspects (Ontl, 2018). Improving soil carbon levels affects, for example, soil structure and porosity; water infiltration rate and moisture holding capacity of soils; biodiversity and activity of soil organisms; and plant nutrient availability (Bot and Benites, 2005).

The last objective related to *enhance and improve soil health* is to *improve soil physical quality*. Similarly, to the previous theme, eleven of 28 articles mentioned improving soil physical characteristics and reducing threats to soil quality. Examples of improvements in soil physical characteristics include ‘improvement of water infiltration’ (Teague, 2017, P.348), ‘improvement of water holding capacity’ (Diop, 1999, P.290) and ‘improvement of soil aeration’ (Teague, 2018, P.1528). Mitigation of soil threats included ‘minimizing erosion’ (Francis et al., 1986, P.70), ‘improving soil structure’ (Rhodes, 2017, P.123) and ‘reducing soil degradation’ (Rhodes, 2012, P.345).

An underlying theme of *optimize resource management* is to *improve nutrient cycling*. Twelve out of 28 articles mentioned convergent issues regarding nutrient cycling and these articles share the ambition to work towards closed nutrient loops. Examples are ‘improve nutrient cycling’ (Teague and Barnes, 2017, P.1527), ‘tendencies towards closed nutrient loops’ (Mitchell et al., 2019, P.7) and ‘more on-farm recycling’ (Teague, 2015, P.5).

In addition to objectives, most of the reviewed articles (20 of 28) also mentioned activities to define regenerative agriculture (Figure 2). Activities showing convergence in the literature are for example *minimizing external inputs* (e.g. Lockeretz, 1988; Rhodes, 2017), *minimizing tillage* (e.g. Francis et al., 1986; LaCanne and Lundgren, 2018), *using mixed farming* (Diop, 1999; LaCanne and Lundgren, 2018), *improving crop rotations* (e.g. Francis et al., 1986; Rhodes, 2012), and using *manure and compost* (Diop, 1999; Rhodes, 2017). These activities direct towards a food system that builds on its ecological cycles and as a co-benefit reduces environmental externalities. The suggested activities promote the integration of crop-livestock operations (e.g. Dahlberg, 1994; Diop, 1999), in which animals are primarily valued for their capabilities to build soil, besides their role in producing food and fibre (Teague et al., 2016). Livestock breeds are, therefore, chosen for their compatibility with their local environment (Gosnell et al., 2019; Steenwerth et al., 2014). The suggested activities also shift from single to multi-cropping systems (Francis et al., 1986), in which the use of perennials is favoured over annuals (Elevitch et al., 2018; LaCanne and Lundgren 2018), because perennials have more extensive and deeper root systems and don’t leave fields fallow in between growing seasons. Therefore, perennials are more resilient to weather extremes (LaCanne and Lundgren, 2018), soil erosion (Pimentel et al., 1997), reduce nutrient runoff (Teague, 2018), improve water conservation (Glover et al., 2010) and carbon sequestration (Elevitch et al., 2018). Relying on ecological cycles also resulted in a preference for animal manures over artificial fertilizers (Pearson, 2007), and for the use of natural pest control over synthetic pesticides (Rhodes, 2017). Minimizing tillage is a specific crop management technique valued to reduce soil disturbance, due to the absence of heavy tillage machinery, allowing earthworms to aerate the soil and increase nutrient distribution (Shah et al., 2017). Activities among the theme ‘other soil conservation practices’ did not necessarily represent divergence, however they presented various activities that were not clustered as a separate theme, such as the use of windbreaks (Diop, 1999), silvopasture (Elevitch et al., 2018), and managed grazing (Provenza et al., 2019). These activities are in line with the objectives of regenerative agriculture, without being clustered into separate themes.

3.3 Themes in regenerative agriculture showing divergence

Although the reviewed articles may show convergence upon most of the themes, we can discern three themes showing a degree of divergence: *regenerate the system*, *improve human health* and *improve economic prosperity*. These themes show divergence because they embrace a sum of issues which do not meet the requirement of at least five convergent issues to form a separate theme.

One of the key objectives of regenerative agriculture is that it is part of a regenerative system. A large number of articles (15 out of 28) referred to environmental objectives regarding the theme *regenerate the system*. A total of fourteen environmental objectives showed that regenerative agriculture is aimed towards productive agriculture that focusses on the health of nature through the regeneration of the resources the system requires (e.g. energy, water, nutrients and carbon). The objectives within this theme remain rather vague because the reviewed articles did not define what is meant by objectives such as regenerative agriculture: should be able to ‘restore earth’ (Shelef et al., 2017, P.2), ‘regenerates the natural system’ (Dahlberg, 1994, P.173) and creates a ‘long-term rehabilitative strategy’ (Diop, 1999, P.296). Such objectives may require a more elaborate description of, for example, the capture of socio-economic aspects and how such objectives can be implemented.

The theme *improve human health* relates to the objectives to provide goods and services for human health to ensure global food security through regenerative agriculture. The quantity of studies (13 out of 28) mentioning social issues is large, however, no themes could be formed with lower levels of aggregation due to a lack of studies mentioning convergent issues. This theme, therefore, showed high variability between issues. A total number of 27 issues was related to this theme and based on the issues we can express that regenerative agriculture aims for sustainable food production which should be in balance with both environmental and social issues. The reviewed articles highlight the quality of human life emphasizing the need to invest in ‘regenerating the social system’ (Dahlberg, 1994, P.173), ‘restoring human health’ (Shelef et al., 2017, P.2), ‘interspecies equity’ (Dahlberg, 1994, P.173), ‘social justice’ (Dahlberg, 1994, P.173), ‘regenerating farm families’ (Dahlberg, 1991, P.2), ‘supporting local populations’ (Teague, 2017, P.348), ‘sustainable food supply’ (Francis et al., 1986, P.68) and ‘reducing food shortages’ (Rhodes, 2012, P.345). Other issues mentioned were *fitting social costs* (Dahlberg, 1994, P.174), ‘improvements in animal welfare’ (Colleya et al., 2019, P.3), ‘cultural re-appreciation’ (Berg et al., 2018, P.314) and ‘social diversity, with a variety of knowledge and diverse economies’ (Zazo-Moratalla et al., 2019, P.16). This theme presents different issues in which we can discriminate human health and wellbeing issues relating to different scales (e.g. farm families, local populations). For example, some articles mentioned human health issues (e.g. physical conditions) and other human wellbeing issues (e.g. happiness of the farmer). An issue which is recognized by only one author is that regenerative agriculture values spirituality in their holistic approach of farming (Dahlberg, 1994).

The theme of *improve economic prosperity* refers to the economic sustainability of farmers: twelve out of 28 studies mentioned a total number of fifteen issues regarding economic prosperity. Issues among this theme showed some divergence but lacked operationalisation. Studies presenting economic issues mentioned that regenerative agriculture creates e.g. 'long-term economic sustainability' (Teague and Barnes, 2017, P.83), 'improves crop yields' (Rhodes, 2017, P.80), 'improves soil productivity' (Francis et al., 1986, P.68) and 'political-economic repositioning' (Berg et al., 2018, P.315). Although these issues present various diverging objectives, they all reflect that regenerative economics work towards a sustained farm income providing goods and services that contribute to human well-being and global food security. From the objectives within this theme, it remains unclear what activities are involved to reach for example long-term economic sustainability.

4. General discussion

This study is the first to systematically review the background and core themes of regenerative agriculture based on peer-reviewed articles. Analysis of the 28 included articles showed that there is currently no uniform scientific definition. Instead, multiple combinations and variations of objectives and activities together define regenerative agriculture. The convergence within these definitions resulted in the core themes of regenerative agriculture. These core themes are compatible with the ecosystem services described by TEEB (2010). Themes such as *enhance and improve soil health*, *optimize resource management*, *alleviate climate change and water quality and availability* are contributing to multiple provisioning and regulating ecosystem services. These provisioning and regulating ecosystem services described by TEEB (2010) contribute to food security and relate to the core themes of regenerative agriculture by for example regulating climate, soil erosion and water purification to provide i.e. food, feed and fuel. Themes such as *improve soil physical quality* and *improve nutrient cycling* are aspects that come back as supporting ecosystem services. The socio-economic dimension we found in regenerative agriculture, *improve human health* and *improve economic prosperity* relates, furthermore, to some components of cultural ecosystems services. From our review we, therefore, propose a provisional definition in which regenerative agriculture is defined as: *an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions* *of sustainable food production*. We acknowledge that regenerative agriculture is a rapidly evolving farming approach in which more views and studies could allow further refinement of the proposed definition. Although for example, Diop (1999) and LaCanne and Lundgren (2018) based their study on farmers perception in relation to regenerative agriculture, we used peer-reviewed articles including opinion, review and research articles mainly focusing on environmental aspects of regenerative agriculture. These peer-reviewed articles articulated insights of natural scientists rather than other actors such as farmers and policy makers.

Related to this description, we will further discuss 1) the core themes of regenerative agriculture, 2) the relation of regenerative agriculture with circular and organic agriculture to show their convergence and 3) the next step in fostering the transition towards regenerative agriculture.

4.1 The core themes of regenerative agriculture

In this study we reviewed 28 peer-reviewed articles which enabled us to describe themes that together characterize regenerative agriculture. These peer-reviewed articles mentioned in general convergent objectives related to environmental themes such as resource management, water quality and availability, alleviate climate change, with a strong focus on improving soil quality (Figure 2). This shows that the soil is the base of regenerative agriculture and that regenerative agriculture strongly focusses on the environmental dimension of sustainability. Although socio-economic objectives are mentioned in reviewed articles, the issues raised did not result in underlying themes (issues needed to be mentioned five times to become a theme).

The themes are, however, sensitive to the amount of convergent issues appropriate to form a theme. From the sensitivity analysis, we learnt that, had we chosen three convergent issues to form a theme, then *cultural diversity* would have been underlying to the theme *improve human health.* In addition, eight other themes could then have been formed as well, which include *minimize waste* underlying to *optimize resource management*; *minimize erosion, improve water holding capacity and improve water infiltration* underlying to *improve soil physical quality*; *intercropping, the use of windbreaks, forest farming, riparian buffers, silvopasture and managed grazing* in addition to *minimize fertilizer and pesticide use* among activities.

4.2 The relation of regenerative agriculture with circular and organic agriculture

In order to illustrate the convergence between sustainable farming approaches, we relate the themes of regenerative agriculture to circular agriculture (CA) which remains yet a unregulated concept and organic agriculture (OA) as an example of a regulated farming approach. CA originates from a much broader concept than regenerative agriculture, the circular economy (CE) using the 4R-framework (reuse, repair, refurbish and recycle) as a base-line (Fan et al., 2020; Jurgilevich et al., 2016). CA uses the themes of industrial ecology as it promotes the circular utilization of agricultural resources and waste products (Fan et al., 2020; Kusano et al., 2019; Zhu et al., 2019). The entry point in CA is, therefore, to keep flows of mass and energy of products at their highest utility through a positive developing cycle (Blau et al., 2018; van Zanten et al., 2018). Regenerative agriculture has a different entry point namely healthy soils and environmental issues which should be in balance with social values (Diop, 1999). While, regenerative agriculture and CA may have different entry points in their approaches, both rely strongly on the environmental dimension of sustainability, since they share similar objectives regarding e.g. reducing environmental externalities and optimizing resource management. Nevertheless, regenerative agriculture also shows to relate to a social dimension. By contrast, it is unclear to which extent CA also relates to this social dimension, since the current reviewed articles about CA did not mentioned social issues within their definitions. The different entry points of regenerative agriculture and CA may lead to a different focus in their farming approach, in which CA focuses on topics such as avoidance of waste and the reuse of resources. Recently, this 4R framework from CE is translated to themes related to circularity in agricultural production – referred to as circular food systems (de Boer and van Ittersum, 2018; van Zanten et al., 2019). The themes of circular food systems go beyond agriculture production and also take into account consumption, therefore circular food systems work on a larger scale compared to regenerative agriculture and also includes issues such as reuse of by-products and feed-food competition (van Zanten et al., 2019).

OA is an example of a farming approach that has a comprehensively described scientific definition and is regulated by different authorities worldwide, e.g. European Commission (2019b) and USDA (2019). The timeline of organic agriculture is described by Arbenz et al. (Arbenz et al., 2016) in which OA started very similar to regenerative agriculture, with a pioneering phase (known as Organic 1.0). In this pioneering phase objectives where used to define OA as a farming approach that contribute to sustainable global food security while respecting all dimensions of sustainability. Regenerative agriculture, as shown in this paper, is currently in this pioneering phase and the regenerative themes defined in this paper are to varying extents convergent with aspects mentioned in OA as IFOAM – Organics International (2019) focuses on the health of soils, ecosystems, people and their management which relies on ecological processes (e.g. nutrient cycling, biodiversity). The objectives in the pioneering phase, evolved into Organic 2.0 in which OA was regulated by certification of standards (Arbenz et al., 2016). These standards presented as a set of technical checklists (USDA, 2019), described mostly what ‘not to do’, for example, ‘Do not use synthetic pesticides’. Synthetic pesticides are replaced by ‘natural inputs’ such as organic pesticides (zinc and copper oxide) which, however, still have a damaging effect on the environment (e.g. loss of biodiversity) (Kuehne et al., 2017). These standards, therefore, often fail to entirely capture the aspects that are at the core of the organic philosophy (Arbenz et al., 2016) and it may be that some organic farmers are 'locked' into organic regulations to guarantee the delivery of products that conform to organic standards. The Organic 3.0 strategy recognizes this and aims to change this by becoming less prescriptive and more descriptive, working towards the replacement of the list of 'do's and don'ts', with a mode of outcome-based regulations which should continuously be adaptable to local contexts (Arbenz et al., 2016). This requires a systemic shift towards an integrative farming approach like regenerative agriculture (LaCanne and Lundgren, 2018). Such an integrative farming approach does not focus on individual (pre-decided) sustainable activities, but on improving ecological and social processes and observable outcomes which enable a larger solution space for implementing sustainable activities. Some authors, therefore, mention that regenerative activities are organic, however, other reviewed articles showed that not all organic activities are regenerative (e.g. Pearson, 2007; Rhodes, 2017) for example the use of organic pesticides and raw minerals. Not all objectives of OA however are centre-stage in regenerative agriculture, with one difference being the objective to promote animal welfare (European Commission, 2019b). Improvement of animal welfare is mentioned in one peer-reviewed article defining regenerative agriculture, although certification frameworks for regenerative agriculture such as Regenerative Organic Certification do put animal welfare centre-stage. As regenerative agriculture is currently in the pioneering phase, there is merit in building on the learnings from the evaluation of OA through the last hundred years, to avoid and leapfrog similar pitfalls that may arise.

4.3 The next step in fostering the transition towards regenerative agriculture

This review showed the core themes of regenerative agriculture from the many definitions that are presented in peer-reviewed articles. These core themes of regenerative agriculture, enable to define indicators to allow actors to regulate and control their activities to foster the transition towards regenerative agriculture. The reviewed articles do show indicators on some specific practices of regenerative agriculture, for example, Elevitch et al. (2018) provide regenerative agroforestry standards. They present a measure which should increase biodiversity throughout the life of the agroforest: at least eight plant families, genera, species, and/or varieties of woody perennials per 100 m^2. It is, however, unclear if this measure refers to each category (e.g. families, genera, species) individually or whether it refers to the sum of the individual categories. Furthermore, the applicability of these standards to other farming practices is limited. Based on the current reviewed articles we were therefore unable to identify specific indicators which allow for a generic assessment of regenerative agriculture. Other research, however, shows a wide range of indicators are already available for sustainability assessments (De Olde et al., 2016) which can be related to each of the themes underpinning regenerative agriculture. Having derived a clear provisional definition, our next step is to link these indicators to the themes of regenerative agriculture described in this paper, in order to facilitate a comprehensive assessment of regenerative agriculture and potentially refine the definition.

5. Conclusion

This review has systematically assessed definitions of regenerative agriculture in 28 peer-reviewed articles. Our analysis has shown that such definitions are based on several combinations and variations of recurring objectives and activities from scientists. The convergence within these definitions allowed us to formulate core themes of regenerative agriculture. Our findings show that regenerative agriculture focuses strongly on the environmental dimension of sustainability, which includes themes such as *enhance and improve soil health*, *optimize resource management*, *alleviate climate change, improve nutrient cycling* and *water quality and availability*, articulated by both objectives (e.g. improve soil quality) and activities (e.g. use perennials). These themes enhance food security by contributing to provisioning (e.g. food, feed and fibre), regulating (e.g. climate regulation, soil erosion and water purification) and supporting (e.g. nutrient cycling and soil formation) ecosystem services. We also found a socio-economic dimension in regenerative agriculture, *improve human health* and *improve economic prosperity,* which relate to aspects of cultural ecosystem services. This socio-economic dimension, however, relies currently on divergent objectives and lacks a framework for implementation. Therefore, we propose a provisional definition which defines regenerative agriculture as an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production. To foster the transition towards regenerative agriculture, this review contributes to establishing a uniform definition; subsequently, indicators and benchmarks should be created to assess regenerative agriculture.

Acknowledgements

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Supplementary materials

S1: PRISMA-P 2015 checklist

This checklist has been adapted for use with protocol submissions to reviews from Table 3 in Moher D et al: Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Systematic Reviews 2015 4:1.

Section/topic	#	Checklist item	Stated
ADMINISTRATIVE INFORMATION			
Title			
Identification	1a	Identify the report as a protocol of a systematic review	No
Update	1b	If the protocol is for an update of a previous systematic review, identify as such	No
Registration	2	If registered, provide the name of the registry (e.g., PROSPERO) and registration number in the Abstract	No
Authors			
Contact	3a	Provide name, institutional affiliation, and e-mail address of all protocol authors; provide physical mailing address of corresponding author	Yes
Contributions	3b	Describe contributions of protocol authors and identify the guarantor of the review	Yes
Amendments	4	If the protocol represents an amendment of a previously completed or published protocol, identify as such and list changes; otherwise, state plan for documenting important protocol amendments	No
Support			
Sources	5a	Indicate sources of financial or other support for the review	Yes
Sponsor	5b	Provide name for the review funder and/or sponsor	Yes
Role of sponsor/funder	5c	Describe roles of funder(s), sponsor(s), and/or institution(s), if any, in developing the protocol	Yes
INTRODUCTION			
Rationale	6	Describe the rationale for the review in the context of what is already known	Yes
Objectives	7	Provide an explicit statement of the question(s) the review will address with reference to participants, interventions, comparators, and outcomes (PICO)	Yes
METHODS			
Eligibility criteria	8	Specify the study characteristics (e.g., PICO, study design, setting, time frame) and report characteristics (e.g., years considered, language, publication status) to be used as criteria for eligibility for the review	Yes

Section/topic	#	Checklist item	Stated
Information sources	9	Describe all intended information sources (e.g., electronic databases, contact with study authors, trial registers, or other grey literature sources) with planned dates of coverage	Yes
Search strategy	10	Present draft of search strategy to be used for at least one electronic database, including planned limits, such that it could be repeated	Yes
STUDY RECORDS			
Data management	11a	Describe the mechanism(s) that will be used to manage records and data throughout the review	Yes
Selection process	11b	State the process that will be used for selecting studies (e.g., two independent reviewers) through each phase of the review (i.e., screening, eligibility, and inclusion in meta-analysis)	Yes
Data collection process	11c	Describe planned method of extracting data from reports (e.g., piloting forms, done independently, in duplicate), any processes for obtaining and confirming data from investigators	Yes
Data items	12	List and define all variables for which data will be sought (e.g., PICO items, funding sources), any pre-planned data assumptions and simplifications	Yes
Outcomes and prioritization	13	List and define all outcomes for which data will be sought, including prioritization of main and additional outcomes, with rationale	Yes
Risk of bias in individual studies	14	Describe anticipated methods for assessing risk of bias of individual studies, including whether this will be done at the outcome or study level, or both; state how this information will be used in data synthesis	Yes
DATA			
Synthesis	15a	Describe criteria under which study data will be quantitatively synthesized	Yes
	15b	If data are appropriate for quantitative synthesis, describe planned summary measures, methods of handling data, and methods of combining data from studies, including any planned exploration of consistency (e.g., I^2, Kendall's tau)	Yes
	15c	Describe any proposed additional analyses (e.g., sensitivity or subgroup analyses, meta-regression)	Yes
	15d	If quantitative synthesis is not appropriate, describe the type of summary planned	No
Meta-bias(es)	16	Specify any planned assessment of meta-bias(es) (e.g., publication bias across studies, selective reporting within studies)	Yes
Confidence in cumulative evidence	17	Describe how the strength of the body of evidence will be assessed (e.g., GRADE)	Yes

S2: PRISMA-P 2015: response on protocol

3a. Provide name, institutional affiliation, and e-mail address of all protocol authors; provide physical mailing address of corresponding author:

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3b. Describe contributions of protocol authors and identify the guarantor of the review:
LS, RS, IB, APS and HZ conceived this paper. LS was the guarantor. LS drafted the manuscript and conducted initial screening of articles. All authors contributed to the development of the selection criteria, the risk of bias assessment strategy and data extraction criteria. All authors critically evaluated the review process, individually allocated issues among themes, read, provided feedback and approved the final manuscript. The evaluation steps involved structuring the review and manuscript, developing the search query, the selection of databases, analysis of the definitions in articles and the categorization of definitions among themes.

5a. Indicate sources of financial or other support for the review:
The work presented in this paper is part of TiFN's Regenerative Farming project, a public - private partnership on precompetitive research in food and nutrition.

5b. Provide name for the review funder and/or sponsor:
Funding for this research was obtained from FrieslandCampina, Cosun, BO Akkerbouw, TKI Agri & Food and TiFN.

5c. Describe roles of funder(s), sponsor(s), and/or institution(s), if any, in developing the protocol:
The funders were not involved in the design of the protocol, data collection or analysis. The funder will have no input on the interpretation or publication of the study result.

6. Describe the rationale for the review in the context of what is already known:
[Review title: Regenerative agriculture – the soil is the base]

Regenerative agriculture is recently gaining attention in the literature as a solution for sustainable food systems (LaCanne and Lundgren, 2018; Shelef et al., 2017). Currently, regenerative agriculture does not have a widely acknowledged scientific definition (Elevitch et al., 2018). In absence of such a widely acknowledged scientific definition a variety of researchers may foster diverging perceptions of regenerative agriculture. For example, Malik and Verma (2014) describe regenerative agriculture as dynamically advanced modified technique involving the use of organic farming methods, while Elevitch et al. (2018) describe regenerative agriculture as a farming approach that has the capacity for self-renewal and resiliency, contributes to soil health, increases water percolation and retention, enhances and conserves biodiversity, and sequesters carbon.

7. Provide an explicit statement of the question(s) the review will address with reference to participants, interventions, comparators, and outcomes (PICO):
In this review, we will assess the background and core themes of regenerative agriculture by examining the convergence and divergence between definitions in peer-reviewed articles. An assessment about the background and core themes of regenerative agriculture allows the establishment of a clear but 'provisional' definition. A 'provisional' definition of a farming approach enables a basis for further discussion about refining the definition and the creation of indicators for actors to assess their performance towards sustainable food systems.

8. Specify the study characteristics (e.g., PICO, study design, setting, time frame) and report characteristics (e.g., years considered, language, publication status) to be used as criteria for eligibility for the review:
Studies were selected according to the criteria outlined below.
Screening of title, abstract and keywords:

- Articles were available within Scopus, Web of Science, CAB Abstracts, Agricola, Medline
- Duplicate materials: duplicates were removed in the review process
- Unavailable materials: materials which were unavailable or inaccessible using reviewed databases were removed from the review
- Non peer-reviewed materials: editorials, conference papers, books, letters and all other non-scientific material were removed from the review process
- Articles unrelated to agriculture: materials unrelated to agriculture were removed from the review process
- Articles are written in English

Full-text screening:

- Articles contained a definition for regenerative agriculture

9. Describe all intended information sources (e.g., electronic databases, contact with study authors, trial registers, or other grey literature sources) with planned dates of coverage:
We searched five journal databases: Scopus, Web of Science, Agricola (via Ovid), CAB Abstracts (via Ovid) and Medline (via Ovid). To ensure literature saturation, we screened the reference lists of included studies using the snowballing technique (Jalali and Wohlin, 2012). Finally, the bibliography of the included articles was circulated to the reviewing team.

10. Present draft of search strategy to be used for at least one electronic database, including planned limits, such that it could be repeated:
No study design or date limits were imposed on the search, although only studies in English language will be included. Scopus, Web of Science, Agricola (via Ovid), CAB Abstracts (via Ovid) and Medline (via Ovid). The specific search strategy was created by the corresponding author and evaluated by the review team who have expertise in review searching. The search strategy used to create a search string to find articles which include a definition for regenerative agriculture builds upon the words, "regenerative" and "farming". The word "regenerative" was used as a label in which we want to find its meaning. For "farming" different synonyms were used including agriculture, agronomy, food and feed system, in which wildcards (*) were used to include the different forms of the word. Using search words such as agronomy and food system allowed to broaden the search, and capture more relevant articles. Broadening the scope for search words beyond food system did not yield in extra relevant articles for synthesis and were therefore neglected for the final search query. The table below shows the number of articles included additionally, after every step of broadening the search words.

Search words	**"regenera* farm*"**	**"regenera* agri*"**	**"regenera * agro*"**	**"regenera* food system"**	**"regenera * and feed system"**	**"regenera * system" AND agri***
Number of articles included for synthesis	1	22	2	3	0	0
Articles included for synthesis	(LaCanne and Lundgren, 2018)	(Sherwood and Uphoff, 2000)	(Pearson, 2007)	(Zazo-Moratalla et al., 2019)		
		(Diop, 1999)	(Berg et al., 2018)	(DeLind, 2011)		
		(Elevitch et al., 2018)		(Dahlberg, 1994)		
		(Francis et al., 1986)				
		(Lockeretz, 1988)				
		(Malik and Verma, 2014)				
		(Rhodes, 2012)				
		(Rhodes, 2017)				
		(Shelef et al., 2017)				
		(Teague and Barnes, 2017)				
		(Teague, 2017)				
		(Teague, 2018)				
		(Mahtab and Karim, 1992)				
		(Provenza et al., 2019)				
		(Dahlberg, 1991)				
		(Teague, 2015)				
		(de Haas et al., 2019)				
		(Mitchell et al., 2019)				
		(Colleya et al., 2019)				
		(Sambell et al., 2019)				
		(White and Andrew, 2019)				
		(Gosnell et al., 2019)				

The final search query used was *"regenera* farm*" OR "regenera* agri*" OR "regenera* agro*" OR "regenera* food system".* The search query was adapted to the syntax and subject headings of the other databases. As relevant studies were identified, the corresponding author will check for additional relevant cited articles using snowballing. The search was updated toward the end of the review (December 2019), after being validated to ensure that the search strategy retrieved a high proportion of eligible studies.

11a. Describe the mechanism(s) that will be used to manage records and data throughout the review:

Literature search results were listed in MS Excel spreadsheets and Mendeley reference management software. A framework with an overview of all issues mentioned was presented to the review team, so they could independently allocate the issues among themes. The reviewing team had discussion rounds to evaluate each process step of the review. Citations of included articles for title and abstract screening were saved in Mendeley. All articles included for full-text screening were downloaded and saved in Mendeley.

11b. State the process that will be used for selecting studies (e.g., two independent reviewers) through each phase of the review (i.e., screening, eligibility, and inclusion in meta-analysis):

The corresponding author independently screened through titles and abstracts yielded by the search against the inclusion criteria. Articles were obtained if they appeared to meet the inclusion criteria or where there is any uncertainty. The corresponding author screened the full-text reports and decided whether these met the inclusion criteria. Additional information was sought from articles where it was necessary to resolve questions about eligibility. Any disagreement was resolved through discussion and the reasons for excluding trials was recorded.

11c. Describe planned method of extracting data from reports (e.g., piloting forms, done independently, in duplicate), any processes for obtaining and confirming data from investigators:

The peer-reviewed articles were screened for definitions of regenerative agriculture by the corresponding author. The definitions were marked within the articles and copied to an a MS Excel spreadsheet. Than a cultural domain analysis (Borgatti, 1994) and inductive coding (Thomas, 2006) was used to cluster definitions. Within such frameworks the definitions from the reviewed articles are taken apart into text segments referred to as 'issues' (e.g. improve soil carbon or minimize tillage). These issues were marked and ordered iteratively on their coherence. After some iteration clusters arise which were named based on their coherence. All authors independently allocated issues to themes. Any disagreements about allocation of issues were solved by discussion.

The following four aspects were analysed to determine the themes of regenerative agriculture: i) the number of articles referring to the themes, ii) the number of converging and diverging interpretations of nomenclature within themes, iii) the classifications of themes among objectives or activities and iv) the relation of themes with the three dimensions of sustainability, i.e. people, planet and profit (Elkington, 1997).

12. List and define all variables for which data will be sought (e.g., PICO items, funding sources), any pre-planned data assumptions and simplifications:

We extracted indexing information (e.g. authors, year of publication, journal, type of document) of all documents in the review. For articles selected for full-text-screening the articles were downloaded.

13. List and define all outcomes for which data will be sought, including prioritization of main and additional outcomes, with rationale:
The primary outcome of this study was to define regenerative agriculture based on the definitions in peer-reviewed articles. Therefore, this review gave an overview and synthesis of existing definitions in peer-reviewed articles, in which it is essential to determine the core themes of regenerative agriculture: i) the number of articles referring to the themes, ii) the number of converging and diverging interpretations of nomenclature within themes, iii) the classifications of themes among objectives or activities and iv) the relation of themes with the three dimensions of sustainability, i.e. people, planet and profit (Elkington, 1997).
Secondary this study illustrated the convergence between sustainable farming approaches, in which we relate the themes of regenerative agriculture to circular agriculture (CA) which remains yet a unregulated concept and organic agriculture (OA) as an example of a regulated farming approach.

14. Describe anticipated methods for assessing risk of bias of individual studies, including whether this will be done at the outcome or study level, or both; state how this information will be used in data synthesis:
To facilitate the assessment of possible risk of bias for this study we chose to systematically review articles in scientific journal databases. This was done independently, however, under supervision of experts in conducting reviews. During the formation of themes all co-authors were involved in evaluating each step within the analysis process. The discrimination of issues among themes was therefore done independently by each co-author and supported by a sensitivity analysis. Any disagreements about allocation of issues was solved by discussion, however did not change the formation of themes.

15a. Describe criteria under which study data will be quantitatively synthesized:
Studies were analysed if peer-reviewed and the inclusion of a definition for regenerative agriculture. The analysis consisted of a cultural domain analysis (Borgatti, 1994) and inductive coding (Thomas, 2006), these are both synthesis methods to cluster segments of text (called *issues*) to themes, based on their coherence. Cultural domain analyses are widely used in research in the study of sensemaking of subjects, an example is a study of Bieling et al., (Bieling et al., 2014) which clusters values of human wellbeing to landscapes. Another example is a study of D'Ambrosio and Puri (Ambrosio and Puri, 2016) using a cultural domain analysis to categorize the perceptions of change in local foodways.

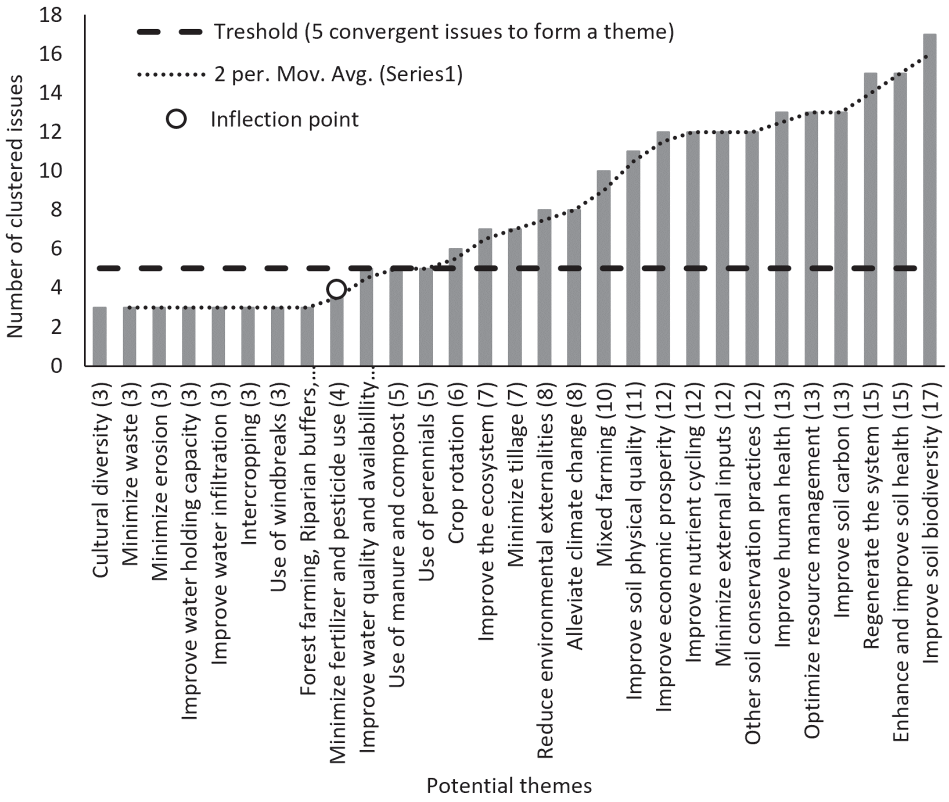
15b. If data are appropriate for quantitative synthesis, describe planned summary measures, methods of handling data, and methods of combining data from studies, including any planned exploration of consistency (e.g., I 2, Kendall's tau):
Typically, a cultural domain analysis starts with a frequency distribution in which a small core set of issues are mentioned in multiple definitions, followed by a very long list of

idiosyncratic issues mentioned once in the definitions (Borgatti, 1994). These issues will all be marked and ordered iteratively based on their coherence in a MS Excel spreadsheet. After iteration clusters may arise which can be named based on their coherence. These clusters do not necessarily represent cultural domains. Since a cultural domain is a set of issues which represent, according to the author, of a kind. Hence, determining which items are salient is not standardized and drawing a boundary will be a matter of judgment by expert opinion because salience is relative (Quinlan, 2017). The emergence of themes was, therefore, based on expert opinion from co-authors as well as discussions during Expert Meetings. In Expert Meetings preliminary results were discussed with other actors in the field. The emergence of themes was, furthermore, correlated to the first inflection point in which we see the number of convergent issues rise (see 15c). A sensitivity analysis shows how much themes would evolve if less issues were chosen to form a theme (15c). The following points will be quantified: total number of issues, the number issues among a theme, number of themes, number issues presented as vision, number of issues presented as practice. We will use sensitivity analysis to assess the impact on the overall formation of themes.

15c. Describe any proposed additional analyses (e.g., sensitivity or subgroup analyses, meta-regression):
A sensitivity analysis showed the emergence of themes based on the clustering of convergent issues. A theme was considered at the first inflection point in which we see a rise in the number of issues convergent. The first inflection point corresponds to clusters of issues which represent at least 2% of the total amount of issues (290). This matches to 5 issues representing a theme, which captures more than 70% of the total amount of issues. The sensitivity analysis shows how much themes would arise if less issues were chosen to form a theme.

16. Specify any planned assessment of meta-bias(es) (e.g., publication bias across studies, selective reporting within studies):
In order to limit reporting bias within the clustering of issues to themes all co-authors individually allocated issues to themes. Any disagreement about allocation of issues was solved by discussion. Furthermore each step of the reviewing process was discussed and evaluated by all co-authors.

17. Describe how the strength of the body of evidence will be assessed (e.g., GRADE):
The quality of evidence was assessed across the process by the co-authors which are experts in the field of reviews, and have profound track records in conducting reviews (Schulte et al., 2012; van der Linden et al., 2020; van Zanten et al., 2018; Van Zanten et al., 2019).

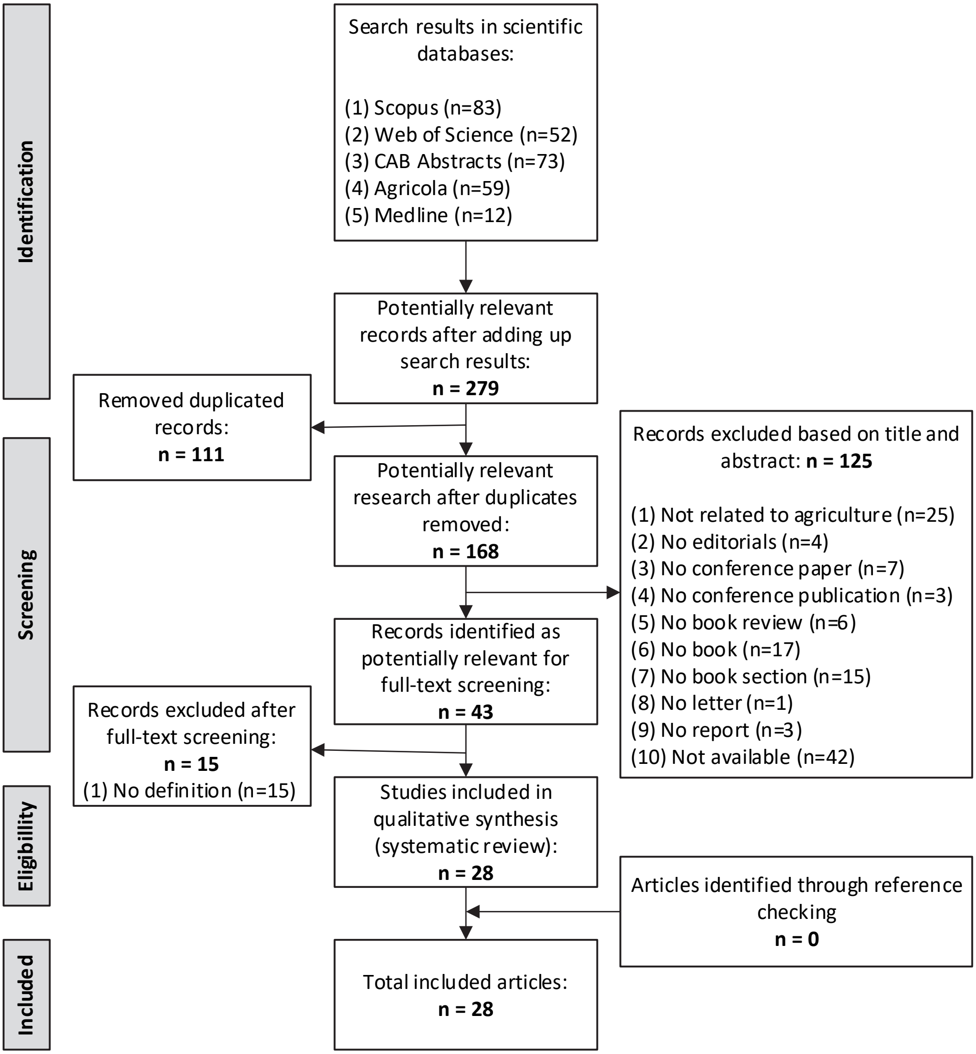


S3: overview of key literature

1. (Berg et al., 2018)
2. (Colleya et al., 2019)
3. (Dahlberg, 1991)
4. (Dahlberg, 1994)
5. (de Haas et al., 2019)
6. (DeLind, 2011)
7. (Diop, 1999)
8. (Elevitch et al., 2018)
9. (Francis et al., 1986)
10. (Gosnell et al., 2019)
11. (LaCanne and Lundgren, 2018)
12. (Lockeretz, 1988)
13. (Mahtab and Karim, 1992)
14. (Malik and Verma, 2014)
15. (Mitchell et al., 2019)
16. (Pearson, 2007)
17. (Provenza et al., 2019)
18. (Rhodes, 2012)
19. (Rhodes, 2017)
20. (Sambell et al., 2019)
21. (Shelef et al., 2017)
22. (Sherwood and Uphoff, 2000)
23. (Teague and Barnes, 2017)
24. (Teague, 2015)
25. (Teague, 2017)
26. (Teague, 2018)
27. (White and Andrew, 2019)
28. (Zazo-Moratalla et al., 2019)

S4: PRISMA flow diagram

PRISMA workflow which presents the steps of inclusion and exclusion during the systematic literature review.



S5: Overview of issues mentioned in scientific literature

Description:

The purpose of this spreadsheet is to assign issues to different themes (objective or activity). Assigning an issue to a theme can be done by filling a '1' in the column. If the author is not confident in assigning an issue to a theme, it can be marked yellow and a description of the issue can be given.

Terminology:

Issue: a text segment which is mentioned in a definition.
Theme: a term which is used as a denominator/cluster for a series of issues.
n: amount of scientific publication mentioning the issue.
Objective: an objective presents a qualitative mid,- or long-term future goal (e.g. improve soil quality).
Activity: a management method (practice) performed to work towards a vision (e.g. tillage).
Objective or activity*n: an objective or activity which is multiplied with the amount (n) of publication mentioning the issue.

Issue	**n**	**Vision**	**Farm practice**	**Vision*n**	**Practice*n**
TOTAL	**290**	**166**	**40**	**214**	**77**
Regenerate the system	20			0	0
regenerative capacity of food system	3	1		3	0
semi-closed system	2	1		2	0
regenerate natural system	1	1		1	0
regenerative capacity fiber system	1	1		1	0
long term rehabilitative strategy	1	1		1	0
recreate the resources that the system requires	1	1		1	0
self-regeneration of land	1	1		1	0
Regenerate landscapes	1	1		1	0
‘the capacity to bring into existence again’	1	1		1	0
re-grounding in natural resources	1	1		1	0
restore earth health	1	1		1	0
relies on natural processes	1	1		1	0
to increase the resilience of farming systems	1	1		1	0
harnessing of the dynamic, natural relationships that exist between all the organisms in the ecosystem and the environment itself	1	1		1	0
make their farming enterprises more sustainable	1	1		1	0
alternative form of food and fiber production	1	1		1	0
enhancing and restoring resilient system	1	1		1	0
Improve the ecosystem	8			0	0
regenerate ecosystem functions	2	1		2	0

Issue	n	Vision	Farm practice	Vision*n	Practice*n
improve soil ecosystem	1	1		1	0
increase ecosystem health	1	1		1	0
ensure long-term ecological resilience	1	1		1	0
restore ecological services	1	1		1	0
provision ecosystem services	1	1		1	0
Enhance ecological functions	1	1		1	0
supported by functional ecosystem processes	1	1		1	0
Reduce environmental externalities	8			0	0
less damage to the environment	2	1		2	0
healthy environment	1	1		1	0
reduce environmental damage	1	1		1	0
reduce environmental pollution	1	1		1	0
improve environmental conditions	1	1		1	0
enhances environmental management	1	1		1	0
fitting environmental costs	1	1		1	0
Enhance and Improve soil quality	22			0	0
improve soil fertility	4	1		4	0
stable soil	3	1		3	0
regenerate the soil	3	1		3	0
improve soil quality	2	1		2	0
improve soil health	2	1		2	0
increase soil quality	1	1		1	0
improve their soils	1	1		1	0
promote soil health	1	1		1	0
maintain healthy soil	1	1		1	0
enhance soil health	1	1		1	0
enhance soil fertility	1	1		1	0
soil resource first priority	1	1		1	0
better protection of the soil	1	1		1	0
Improve soil carbon	14			0	0
carbon sequestration	3	1		3	0
increases in soil carbon	2	1		2	0
improve carbon sequestration	2	1		2	0
improve soil organic matter	1	1		1	0
rebuild organic matter	1	1		1	0
soil organic matter more importer driver for profit than yield	1	1		1	0
high soil organic matter	1	1		1	0
increase soil organic matter	1	1		1	0
improve soil carbon stocks	1	1		1	0
increase soil carbon sequestration	1	1		1	0
Improve soil physical quality	23			0	0
minimize erosion	3	1		3	0
improve soil structure	2	1		2	0
improve water holding capacity	2	1		2	0
improve water retention	2	1		2	0

Issue	n	Vision	Farm practice	Vision*n	Practice*n
reduce soil crusting	1	1		1	0
reduce soil degradation	1	1		1	0
improving soil aggregation	1	1		1	0
improve soil formation	1	1		1	0
Improve water infiltration	1	1		1	0
increase water infiltration	1	1		1	0
moisture availability	1	1		1	0
improving soil aeration	1	1		1	0
moisture retention	1	1		1	0
decrease evaporative water loss	1	1		1	0
reducing surface runoff	1	1		1	0
increase moisture infiltration	1	1		1	0
increase water retention	1	1		1	0
increase water percolation	1	1		1	0
Improve soil biodiversity	17			0	0
increase biodiversity	3	1		3	0
improve biodiversity	2	1		2	0
promote biodiversity	1	1		1	0
increases soil biodiversity	1	1		1	0
maintain biological diversity	1	1		1	0
Enhance biodiversity	1	1		1	0
reservoir for biodiversity	1	1		1	0
high ecosystem biodiversity	1	1		1	0
diverse biology	1	1		1	0
greater diversity in the biological community	1	1		1	0
increases in the levels of biodiversity	1	1		1	0
stable productive biological integrity	1	1		1	0
diversity in the field and in border strips	1	1		1	0
diversity in the system	1	1		1	0
Improve water quality and availability	7			0	0
improve water quality	1	1		1	0
clean and safe water runoff	1	1		1	0
stable and productive clean water	1	1		1	0
better protection of water	1	1		1	0
reduce water shortages	1	1		1	0
protect fresh water supply	1	1		1	0
improve aquifer recharge	1	1		1	0
Alleviate climate change	8			0	0
reduce GHG emissions	2	1		2	0
copes with climate change	2	1		2	0
decreased greenhouse gas emissions	1	1		1	0
invert carbon emissions	1	1		1	0
climate change mitigation	1	1		1	0
alleviate climate change	1	1		1	0
Optimize resource management	19			0	0
Minimize waste	2		1	0	2

Issue	n	Vision	Farm practice	Vision*n	Practice*n
Integrated nutrient management	2		1	0	2
nutrient retention	1	1		1	0
nutrient availability	1	1		1	0
improving nutrient acquisition and retention	1	1		1	0
synergies in management practices	1	1		1	0
regenerative use of natural resources	1	1		1	0
reduce resource shortages	1	1		1	0
prevention of natural-resource degradation;	1	1		1	0
minimize nutrient runoff	1	1		1	0
synchronize mineralization and nutrient crop uptake	1	1		1	0
more efficient use of energy and other inputs	1	1		1	0
encompassing solid-waste management	1	1		1	0
encompassing organic recycling	1	1		1	0
environmentally-sound management practices	1	1		1	0
use of highly soluble nutrient sources must be avoided	1	1		1	0
nutrient amendments	1		1	0	1
Nutrient cycling	13			0	0
nutrient cycling	6	1		6	0
recycles far as possible	3	1		3	0
closed nutrient loops	3	1		3	0
more on-farm recycling	1	1		1	0
Minimize external inputs	18			0	0
rely on internal resources	6		1	0	6
minimize import of fertilizers and pesticides	4		1	0	4
use of internal resources	1		1	0	1
no external resources	1		1	0	1
minimizing external inputs	1		1	0	1
low-input practices without significantly reducing production	1		1	0	1
decreasing the need for inputs like pesticides and fertilizers	1		1	0	1
reduces or eliminates pesticide and herbicide use	1		1	0	1
reduce or eliminate the use of chemical inputs such as synthetic fertilizer, herbicides, and pesticides	1		1	0	1
natural pest control	1	1		1	0
Minimize tillage	8			0	0
minimum tillage	3		1	0	3
abandoning tillage	2		1	0	2
uses no-tillage	2		1	0	2
limited tillage	1		1	0	1
Crop rotation	8			0	0
crop rotation	5		1	0	5
varying use of land	1		1	0	1
No crop species in the same plot more than every 5 years	1		1	0	1
variate summer - winter species	1		1	0	1
Use perennials	5			0	0

Issue	n	Vision	Farm practice	Vision*n	Practice*n
fewer annuals more perennials	4		1	0	4
annual / perennial	1		1	0	1
Manure / compost	5			0	0
use of manure and compost	5		1	0	5
Mixed farming	14			0	0
integrate livestock and crop operations	9	1		9	0
uses high intensity, short duration time-controlled grazing with frequent rotation of livestock between small paddocks with perennial native grasses and long rest	1		1		1
intercropping	3		1	0	3
multiple cropping	1		1	0	1
Other soil conservation practices	31			0	0
RF is organic	3		1	0	3
windbreaks	3		1	0	3
Forest farming / Riparian buffers / Silvopasture / managed grazing	3		1	0	3
eliminating spatio-temporal events of bare soil	2		1	0	2
soil cover	2		1	0	2
cover crops	2		1	0	2
legumes trees and crops	2		1	0	2
soil management	1	1		1	0
prevention of damage by pests and diseases	1	1		1	0
Improve wildlife habitat	1	1		1	0
Better protection of wildlife	1	1		1	0
protection of wetlands, forested lands,	1	1		1	0
conservation agriculture	1	1		1	0
emphasis on biological nitrogen fixation programs	1	1		1	0
recuperative periods	1		1	0	1
use of deep rooted crops	1		1	0	1
filter strips around contaminated water	1		1	0	1
Use of a disk or chisel plow	1		1	0	1
installing energy efficient technology in buildings	1		1	0	1
maintain substantial amounts of N and nutrients in organic form when crops are not grown	1		1	0	1
increases and subsequently maintains the proportion of land with native vegetation	1		1	0	1
Improve social equity	27			0	0
regenerate social systems	1	1		1	0
improves social aspects	1	1		1	0
recognize the importance of social cultural aspect	1	1		1	0
intergenerational equity	1	1		1	0
interspecies equity	1	1		1	0
sustainable food supply	1	1		1	0
enhance power	1	1		1	0
social justice	1	1		1	0
enhance justice	1	1		1	0

Issue	n	Vision	Farm practice	Vision*n	Practice*n
restore human health	1	1		1	0
regenerate farm families	1	1		1	0
regenerate rural communities	1	1		1	0
support local populations	1	1		1	0
sustained production	1	1		1	0
reduce food shortages	1	1		1	0
provide food and material on the small-scale	1	1		1	0
fitting social costs	1	1		1	0
fitting policies	1	1		1	0
Cultural re-appreciation	1	1		1	0
enhance spirituality	1	1		1	0
maintain cultural diversity	1	1		1	0
reservoir for cultural diversity	1	1		1	0
balance between environmental goods and services and the output of food	1	1		1	0
improvements in animal welfare	1	1		1	0
enhancing a substantial interconnection between nature and society	1	1		1	0
when food is the main axis of this restoration, people, spaces, and resources coalesce, forming a Regenerative Food System (RFS) with healthy, natural, and social systems that are both responsive and responsible	1	1		1	0
social diversity, with a variety of knowledge and diverse economies	1	1		1	0
Improve economic prosperity	15			0	0
economic profitability	2	1		2	0
stable yields	2	1		2	0
increased crop yield	2	1		2	0
to ensure long-term economic sustainability	1	1		1	0
production long-term economic returns	1	1		1	0
sustainable farm income	1	1		1	0
producing nutrient-dense farm products profitably	1	1		1	0
improve crop yields	1	1		1	0
improve soil productivity	1	1		1	0
increases productivity	1	1		1	0
make their farming enterprises more profitable	1	1		1	0
political-economic repositioning	1	1		1	0

Chapter 3

A modelling framework to redesign farming systems towards regenerative agriculture

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Abstract

Regenerative agriculture is defined in Chapter 2 as an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services, with the aspiration that this will enhance not only environmental, but also social and economic dimensions of food production. The core objectives and practices associated with regenerative agriculture, however, were found not equally relevant or applicable for every farming system and local context. For example, a dairy farmer on peat soil faces very different challenges and enhances very different practices compared to an arable farmer on a clay soil. Subsequently to a more general definition, we aimed to make regenerative agriculture meaningful at the farm-level. We did this by creating a modelling framework that combines a soil model with a bio-economic model which can quantify the objectives of regenerative agriculture and show which regenrative objectives and what practices are most relevant for farming systems in their local context. In this chapter we showcase the mode of operation of this modeling framework by using a dairy case-study farm.

1. Introduction

The global food system has a detrimental impact on the environment and currently releases about 25% of annual anthropogenic greenhouse gas (GHG) emissions, causes about one-third of terrestrial acidification and is responsible for the majority of global eutrophication of surface waters (Poore and Nemecek, 2018). For the agricultural sector, as part of this global food system, a wide variety of sustainable farming approaches that aim to limit detrimental environmental impacts are gaining both public and academic attention. Farmers using these approaches show that while agriculture has detrimental impacts on the environment, well-managed agricultural land can also provide ecosystem services and contribute positively to the environment (FAO and ITPS, 2021). One of these farming approaches is regenerative agriculture, which takes the soil as the entry point (Chapter 2) and hence, is most relevant to areas where environmental stresses result in soil degradation or poor soil health (FAO and ITPS, 2015; Stolte et al., 2016). On agricultural land, many of these ecosystem services are mediated through the soil. The capacity of the soil to support these services can be summarized into five soil functions: primary productivity, climate regulation, nutrient cycling, water purification and regulation, biodiversity and habitat provision (Bünemann et al., 2018; Haygarth and Ritz, 2009; Schulte et al., 2014). These five soil functions, supplied by agricultural land, meet societal demands for soil multifunctionality (e.g. to produce food but also biodiversity). These societal demands for soil multifunctionality are currently center-stage in international agreements such as the Paris Climate Agreement (United Nations, 2015), the Common Agricultural Policy (European Commission, 2019a), the Biodiversity Strategy (European Commission, 2021) and the European Green Deal (European Commission, 2019c).

The review in Chapter 2, defined regenerative agriculture as "*a mode of agriculture that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the aspiration that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production*". From Chapter 2 regenerative agriculture seems to be a goal-orientated approach, the objectives for regenerative agriculture described in Chapter 2 are, however, broad. The extent to which these objectives can be achieved, depends on their local context (e.g. management and pedoclimatic conditions). Moreover, regenerative practices are not equally relevant, applicable or effective for all farming systems (Giller et al., 2021; Luján Soto et al., 2021). For regenerative agriculture to be meaningful for diverse farming systems, a variety of actors (e.g. governmental agencies, sector organizations, industries and farmers) need methods that can give them insight in the efficacy of regenerative practices which influence the services ecosystems can deliver to meet multiple regenerative objectives within local contexts (Giller et al., 2021). These methods should not only give insight into which practices contribute to the transition towards regenerative agriculture, but also show farmers on which objectives they can focus within their local context. The feasibility of regenerative practices is, therefore, not only dependent on their efficacy to contribute for example to soil health, but also on their effect on other sustainability aspects (e.g., farm profitability and human wellbeing). If we are not able to show actors which objectives and practices contribute to a healthier soil and other sustainability aspects, it will hinder the transition towards regenerative agriculture.

The ex-ante redesign of diverse farming systems and assessment of regenerative objectives in pedo-climatic conditions requires a modelling framework that links regenerative farm management practices at field-scale to environmental and socio-economic outcomes at farm-scale. In agricultural system research, biophysical models are used for the ex-ante redesign of faming systems and assessment of associated farm practices to meet specific objectives. Despite their proven usefulness (Pannell, 1996; Reidsma et al., 2018), many of these models do not address the full complexity of farming systems (Silva and Giller, 2021; van der Linden et al., 2020). Silva and Giller (2021), for example, argue that attention needs to be given in biophysical models to show the interactions between the different farm components. These interactions between farm components occur between hierarchical levels (e.g. between field and farm-level), between components within each level (e.g. multiple fields within a farm), and between the biophysical and socio-economic dimensions (van der Linden et al., 2020; van Ittersum et al., 2008). Most biophysical processes are measured at field-level, where for example carbon is sequestered and nutrients are utilized for crop production. However, decision-making processes at the farm-level are also guided by socio-economic factors. Although, farmers may consider both biophysical processes and socio-economic factors within decision-making processes, models are often oversimplified and therefore focus on one scale. Up-scaling biophysical processes from field to farm-level requires information transfer within each component (e.g. soil organic matter input effects on different environmental aspects) and across components (e.g. environment, social and economic aspects) (Ewert et al., 2011). The ex-ante redesign of farming systems and assessment of ecosystem services associated with regenerative agriculture, therefore, requires a link between models which can assess soil health at the field-scale with models which consider broader systems objectives at the farm-scale.

The complexity and performance of farm practices within the context of broader sets of environmental and socio-economic objectives can already be modelled by individual integrative farm models, e.g. FarmDESIGN and LiGAPS (Groot et al., 2012; van der Linden et al., 2020). These models allow actors to evaluate trade-offs and synergies between different farm management decisions and outcomes (Janssen and van Ittersum, 2007; Thornton and Herrero, 2001). However, most of these farm models make only tenuous references to soil health, and often assume a homogeneous soil type for the whole farm. As such, these models are limited in their capacity to optimize or assess the effectiveness of soil based regenerative practices in real-farm scenarios. Contrastingly, models that are specifically focused on the assessment of soil multi-functionality (e.g. Soil Navigator and Open Soil Index) operate at a field-level and acknowledge the diversity of soil properties within farms (Debeljak et al., 2019; Ros and Fujita, 2019). These soil assessment models, however, commonly lack an assessment of the environmental and socio-economic impacts of soil management practices at farm-level. In this paper, we demonstrate a modelling framework for the ex-ante redesign for diverse farming systems and assessment of ecosystem services associated with regenerative agriculture in pedo-climatic conditions that link soil management practices at field scale to environmental and socio-economic outcomes at farm scale. As such, we link two models: Soil Navigator (Debeljak et al., 2019) and FarmDESIGN (Groot et al., 2012) and evaluate the efficacy of this framework in exploring and optimizing the selection of regenerative objectives and soil management practices for diverse farming systems using a Dutch dairy-farm as a case study. Our aim is that this framework can be used by researchers as a tool to help various stakeholders to assess and redesign farms to transition towards regenerative agriculture.

2. Materials & Methods

2.1 Relation of the selected models with regenerative agriculture and their mode of operation

We selected two innovative models used by researchers: Soil Navigator (SN) (e.g. Vazquez et al., 2020; Zwetsloot et al., 2020) and FarmDESIGN (FD) (e.g. Adelhart Toorop et al., 2020; Timler et al., 2020), to assess a broad range of indicators that relate to all objectives of regenerative agriculture (described in Chapter 2), see Figure 1. SN is a soil assessment tool developed to qualitatively assess simultaneously five soil functions at field-level (Debeljak et al., 2019): primary productivity (Sandén et al., 2019), nutrient cycling (Schröder et al., 2016), water purification and regulation (Wall et al., 2020), climate regulation (van de Broek et al., 2019), and biodiversity and habitat provision (van Leeuwen et al., 2019). These five soil functions considered play a key-role in the supply and demand for soil-based ecosystem services (Schulte et al., 2014), and are largely congruent with the objectives of regenerative agriculture at farm-level, as defined in Chapter 2. The objectives from Chapter 2 relevant at the farm-level are to "*enhance and improve soil health*", "*alleviate climate change*", "*improve nutrient cycling*", "*improve water quality and availability*", "*improve economic prosperity*" and "*improve human health*". The congruence between the objectives of regenerative agriculture and the different soil functions are shown in Figure 1 and summarized by the following bullet points:

- Improve economic prosperity is reflected by the soil function primary productivity which is the economic foundation for farmers and a prerequisite for agricultural sustainability (Sandén et al., 2019). Primary productivity is determined by the capacity of a soil to supply nutrients and water to produce plant biomass for human use, providing food, feed, fiber, and fuel within natural or managed ecosystem boundaries.

- The objective of regenerative agriculture to improve nutrient cycling is reflected in the soil function nutrient cycling, which indicates the capacity of the soil to receive nutrients, to make and keep nutrients available to crops, to support the uptake of nutrients by crops and to support their successful removal in harvested crops (Schröder et al., 2016).
- The objective of regenerative agriculture to improve water quality and availability is reflected in the soil function water purification and regulation which assesses the capacity of the soil to remove harmful compounds and to receive, store and conduct water for subsequent use (Wall et al., 2020).
- The objective to alleviate climate change is reflected by the soil function climate regulation which is determined by the magnitude of N_2O and CH_4 emissions and carbon sequestration (van de Broek et al., 2019).
- The objective of regenerative agriculture to enhance and improve soil health is reflected by the soil function biodiversity and habitat provision. Soil health is more than soil biodiversity alone, it is also the functional capacity of the soil to deliver on for example above ground biodiversity (Bünemann et al., 2018), which is not addressed in this function model. Biodiversity and habitat provision is described as the multitude of soil organisms and processes, interacting in an ecosystem, providing society with a rich biodiversity source and contributing to a habitat for aboveground organisms (van Leeuwen et al., 2019).

SN captures the synergies (positive relationships between soil functions) and tradeoffs (negative relationships between soil functions) between soil functions and the effects of management practices on the five soil functions in the form of decision rules (Zwetsloot et al., 2020). These decision rules determine if soil functions are delivered at low, medium or high capacity. The required model input data include farm management attributes (i.e. tillage and the amount of N fertilizer applied to the field), environmental attributes (i.e. average temperature and precipitation) and soil attributes (i.e. clay content and soil organic matter). The capacity to supply the five soil functions were defined in SN by qualitative scores resulting from integrated hierarchical decision-support models which were structured, calibrated and validated for crop and grassland using datasets collected across Europe (Sandén et al., 2019; Schröder et al., 2016; van de Broek et al., 2019; van Leeuwen et al., 2019; Wall et al., 2020). In addition to the assessment of soil functions, SN offers the possibility to optimize soil functions to meet user-set objectives: it will propose directions for change and farm management practices, needed to meet these objectives. More details about the construction of SN are described in supplementary materials S1 and by Debeljak et al. (2019).

FD is a static bio-economic whole-farm model which consists of a large array of interrelated farm components developed for the analysis and redesign of mixed crop-livestock systems (Groot et al., 2012). The model consists of flows that are quantified to calculate material balances, a feed balance, a labor balance and an economic balance on an annual basis. The flows can be used to assess the environmental performance of a farm (i.e. land use diversity, nutrient losses and soil organic matter accumulation) as well as the capacity to sustain socio-economic prosperity (i.e. farm profitability and labor requirements). FD also enables the exploration of optimized farm configurations, which are generated by a multi-objective optimization based on one or multiple user-defined objectives (e.g. minimize nutrient losses or maximize farm profitability), set constraints (e.g. upper and lower limits on animals' energy and protein requirements) and a variety of decision variables (e.g. upper and lower limits on crop areas or animal numbers). The new farm configurations can include optimized performance indicators and optimized field-use configurations. These optimized field-use configurations, for example, have optimized allocation of crop areas, new crop or animal products entering the farm, changes in herd size, animal type, fertilizers and feed use. More detail about the construction of FD are given in the supplementary materials S2 and described by Groot et al. (2012).

From the wide variety of indicators available in FD, a specific set of indicators shows overlap with the objectives of regenerative agriculture (Figure 1), specifically operating profit, farm labor, nitrogen (N) surplus, GHG emissions and the soil organic matter (SOM) balance. Operating profit is congruent with the objective of regenerative agriculture to improve economic prosperity and is calculated as the sum of total farm returns minus farm costs. Farm labor is the only indicator used in our framework to reflect the "people" dimension of regenerative agriculture – wellbeing of the farmer. Farm labor is calculated as the sum of labor requirements due to crop and livestock management minus the hired labor and the hours spend of the farmer. The N surplus corresponds to the objective of regenerative agriculture to improve nutrient cycling and is quantified by subtracting the N exports (animal and crop produce and manures) from the sum of N inputs onto the farm in the form of crop products (e.g. purchased or off-farm collected feeds), animal products, manures and fertilizers, deposition, symbiotic fixation by leguminous plants and non-symbiotic fixation by free-living soil biota. GHG emissions relate to the objective of regenerative agriculture to alleviate climate change, accounting for soil carbon sequestration and emissions at farm-scale, such as emissions from animals (enteric), manure (direct emissions and volatilization), fertilizers, as well as diesel consumption and pesticide and fertilizer production and usage. The SOM balance indicates changes in organic matter in response to changes in farm practices and relates to the objective of regenerative agriculture to enhance and improve soil health. As such, this balance is an overarching indicator encompassing the three spheres of soil health and relates to all sub-objectives of regenerative agriculture to improve soil health. It is calculated as the difference between inputs and outputs of organic matter into the soil (from crop roots and residues, mulch, and farm-produced and imported manures) on the one hand, and losses by degradation of active SOM, added manure and erosion on the other. Figure 1 illustrates the congruence between the objectives of regenerative agriculture, the model indicators used in this study and their relation to the three pillars of sustainability. An extended version of this figure is given in supplementary material S3.

Figure 1. *Congruence between the three pillars of sustainability (people, planet and profit), the core objectives of regenerative agriculture with underlying objectives (in the circles) and the indicators which can be assessed by the models (around the objectives). Indicators which are assessed by Soil Navigator are represented by "SN" and FarmDESIGN by "FD".*

2.2 Case-study farm

***Figure 2**. Map of the Netherlands divided into 12 provinces. The arrow locates the case-study farm in the province of Zuid-Holland (red).*

We used a conventional Dutch dairy farm on peat overlaying a clay soil to illustrate our framework for farm redesign. The use of a conventional farm allowed us to explore multiple permutations of regenerative farm practices that would contribute to meeting the objectives of regenerative agriculture. The case-study farm is located in the peat meadow area in the province of Zuid-Holland (Figure 2) and has 22 fields of permanent grassland with a total farm area of 40.4 ha, used to feed approximately 100 cows. Farm specific data was collected in semi-structured interviews in September 2020. This data covered parameters related to the farm environment (e.g. climate and soils), farm management (e.g. fertilizer use, grazing system), yields of crops and animals with their related products and economics (e.g. farm expenses and labor prices), crops and animals with their related products on an annual basis. The grassland close to the farm (16.9 ha) is used alternately for grazing and mowing. Grassland located further from the farmyard (23.5 ha) is used for mowing only. The cows are in the pasture for 4 hours a day, 150 days a year; they remain in the barn for the remainder of the time. In addition to grass, the diet of the cattle is sustained with purchased feed such as maize, wheat straw and concentrate feed. The average yearly milk production is 8720 liter per cow, equating to 21384 kg milk ha^{-1}. The grassland is fertilized using cow slurry (254 kg N ha^{-1}; 85 kg P ha^{-1}) and inorganic fertilizer (75 kg N ha^{-1}; 10 kg P ha^{-1}). No synthetic pesticides were used. Parameters not readily available on the farm, such as the effective organic matter of grassland, were estimated using secondary literature with references provided in-text.

2.3 The ex-ante redesign of farming systems towards regenerative agriculture

We designed context-specific optimized farm configurations of regenerative practices using two sequential steps. The first step was to upscale soil functions to the farm-scale. The second step was to link field and farm-scale models for the redesign of our case-study farm, tailored to its local conditions. In the following section (2.3.1) we will first illustrate how we upscaled soil functions to the farm-scale, followed by the steps needed to systematically redesign the farm, using a combination of SN and FD (section 2.3.2).

2.3.1 Upscaling soil functions to the farm-scale

SN assesses soil functions at field-scale to acknowledge the potential variation in biophysical properties within the farm. In order to relate the performance of individual soil functions to the other environmental and socio-economic indicators that operate at farm-scale (e.g. operating profit, N surplus), we aggregated the assessment of soil functions from field to farm-level using area weighted averages. For this aggregation, we applied SN to areas of land that were considered homogeneous in terms of soil attributes and farmer management; as such we created separate models for fields used for alternate grazing and mowing, and fields used for mowing only. This difference in field-use was reflected in management attributes such as the percentage of yield obtained by grazing and the livestock density. Most other management attributes, such as fertilizer use, drainage management and pesticide use, were found to be uniform for our specific case-study farm. For farms with more diverse management, further disaggregation may be required, for example on arable farms with multiple crops and associated management practices.

Besides the uniformity of management and land use among fields, further disaggregation was also based on the uniformity of soil attributes (e.g. SOM content and clay percentage). Determining the variation between soil attributes among fields is essential to the context-specific recommendations of practices for particular fields. Soil attributes that varied within the predetermined thresholds (categories) within SN were considered uniform. The clay content between fields ranged for our dairy farm between 34-40%, which is within one of the five predetermined thresholds of 25-40%. There are, however, five different thresholds in SN that indicate the percentage of clay in the top 25 cm of the soil, each threshold is associated with different scores. Soil attributes from different fields ranging across thresholds were, therefore, further examined on their influence on the final assessment of soil functions using their weighting factors. Weighting factors were used in the five function models of SN to indicate the importance of the soil attributes on the final assessment of soil functions (Supplementary materials S1). We conducted a sensitivity analysis to determine the boundary between low and high weighting factors. The sensitivity analysis included a calculation of the weighting factors of all input attributes on soil functions. This resulted in a sorted list with the number of input attributes with their associated weighting factor (see supplementary materials S4). The inflection point, supported by expert opinion, was used to classify low and high categories for the weighting factors. Soil attributes with low weighting factors (<8%) were deemed to have no or minimal effect on all scores of soil functions. Soil attributes with high weighting factors (≥8%) could lead to further disaggregation of model applications if the input attributes of fields varied among thresholds. The influence of further disaggregation based on the variability in soil types and land use will improve the context specific recommendation of soil management practices from SN. Ultimately, the variation within our case-study farm could be captured satisfactorily using two categories of land (i.e. land used for alternatingly mowing and grazing; mowing only) and hence two model applications, which were aggregated to the farm-level using area weighted averages. In the result section we will present error bars besides the aggregated scores. These bars represent diverging soil function scores from the area weighted averages.

2.3.2 Linking field and farm-scale models

We subsequently employed FD to assess the directions for change by SN in the context of the wider socio-economic and environmental performance at the level of the farming system. As FD facilitates multi-objective optimizations, the output does not consist of a single optimized farming system; rather it shows a multitude of optimized solutions in the form of solution clouds, plotted against the objectives. Following farming systems optimization, the output of FD was re-entered in SN for a re-evaluation of the performance of soil functions. SN needs farm-level input data to optimize management inputs in the different field-scale models. Optimized management inputs can be related to for example livestock density, grassland diversity, fertilization rates and crop yields. Figure 3 illustrates the farm optimization cycle between SN and FD. In the following section we will show how we aligned and coupled SN and FD to reconfigure our case-study dairy farm, as well as its management practices, for a context-specific operationalisation of regenerative agriculture.

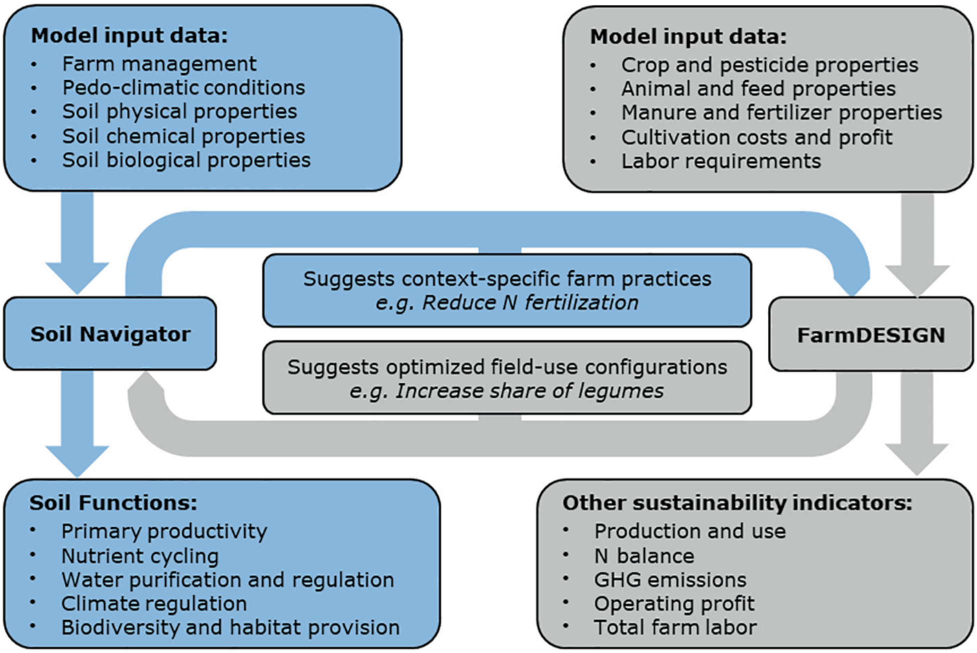

Figure 3. *Illustration of the farm optimization cycle between Soil Navigator (blue) and FarmDESIGN (gray).*

2.3.3 Obtaining improved farm practices from Soil Navigator

Current farm data was used to create an initial assessment of soil functions in SN and the other sustainability indicators in FD. After the initial assessment we employed the optimization of SN to obtain directions for change and farm practices which contribute to the improvement of soil functions. Previous studies, however, found that it is challenging to optimize all soil functions simultaneously to their maximum capacity (high) due to occurring trade-offs (Vazquez et al., 2020; Zwetsloot et al., 2020). Multiple iterations of optimization, with diverse objectives, may therefore be necessary to ensure all the soil functions individually reach a high capacity. Hence, to determine the optimal solutions and practices that contribute to all individual soil functions. For our case-study farm we needed one iteration to optimize all soil functions to their maximum capacity. Table 1 shows the suggested directions for change and farm practices from SN that we incorporated in FD at the farm-level.

2.3.4 Incorporating the improved soil management practices in FarmDESIGN

Besides the original land-use, management recommendation by SN were subsequently incorporated in FD as objectives, constraints and decision variables (Table 1). Where SN suggested to increase or reduce a certain practice or model input, this was included into FD as one of the objectives. For example, in our case-study farm SN recommended a reduction in total N fertilization; we reflected this in FD by including the objective to minimize available N from all fertilizers allocated to the soil. For some practices, constraints were added to avoid the use of, for example, mined N-fertilizers in the optimized scenario. Constraints were also set to maintain a realistic operating space for FD. For example, constraints were set for the feed balance to match animal requirements and availability of energy and protein and the dry matter intake capacity and saturation (digestibility of feed). Constraints can also be set to restrict the model to stay within national fertilization guidelines. This was, however, for our case-farm not needed because a fixed fertilization rate (94 kg N ha^{-1}) was used for the optimized scenario. More specifically, both SN and FD use the amount of N that is applied by the farmer to the fields (total N). In cases where SN introduced a new practice, a new form of dairy or grassland management was introduced, and the area allocated was modelled as a decision variable in FD. Decision variables allowed the model to allocate for example more area to grassland or herb-rich grassland based on set objectives and constraints. A complete list of conditions for FD is shown in supplementary materials S5.

The introduction of new practices or strategic adjustment required a degree of interpretation and parameterization using secondary data and expert opinion. For example, in our case-study farm, SN suggested the cultivation of crops with a high-water use, underlying soil functions indicated that this suggestion related to a low water storage

Table 1. *Directions for change suggested by Soil Navigator (SN) for integration in FarmDESIGN (FD). The directions for change and farm practices from SN are implemented in FD as constraints (a), objectives (b) and decision variables (c) in which a new form of dairy or grassland management was introduced.*

Suggested changes SN	To improve the soil function	Adjustments in FD
Reduce total N fertilization	Climate regulation	[b] Minimize available N fertilizers to soil (kg ha^{-1} yr^{-1}) [b] Minimize N balance (kg ha^{-1} yr^{-1})
Apply solid manure/compost	Biodiversity and habitat provision	[c] Introduce solid manure [b] Maximize C in manure to soil (kg ha^{-1} yr^{-1}) [a] Constrain mineral N fertilizer to 0 kg ha^{-1} yr^{-1}
Increase N offtake by grassland	Water purification and regulation	[c] Introduce herb-rich grassland [b] Maximize area with herb-rich grassland (ha) [b] Maximize N-fixation (kg ha^{-1} yr^{-1})
Increase share of crops with a higher water use		

capacity of the soil. SN gave examples of crops which could increase the water uptake and storage capacity using for example winter cereals, spring cereals with legumes or grass, grass with legumes or other crop mixtures with legumes. It remained, however, unclear how these crops contribute to improved water storage, if these crops could be used in the local-context or its share in the rotation. Peat soils are for example considered unsuitable for arable land (e.g. cereals and perennial crops) and are predominantly used for grassland (Verhagen et al., 2009). Based on secondary literature (e.g. Hayes et al., 2019; Mytton et al., 1993) and expert opinion (all co-authors and four grassland experts, see acknowledgements) we chose to implement this recommendation by introducing herb-rich grassland with ~30% white clover and reparameterized the input attributes for farm profitability, labor requirements, N surplus, GHG emissions and the SOM surplus accordingly (Table 2). The input attributes in Table can, therefore, be different for the reference and optimized scenario. For example, values for the effective organic matter rate of herb-rich grassland are lower compared to permanent grassland. The reason that the effective organic matter of herb-rich grassland is lower compared to permanent grassland relates to the inclusion of herbs (for the dominant part white clover). White clover, for example, has an effective organic matter value of 850 kg ha^{-1}, while permanent grassland has an effective organic matter value of 2000 kg ha^{-1} (Bosch and de Jonge, 1989). The effect of for example herbs does not only affect the effective organic matter rates but also values for N-fixation in both models. In FD we addressed specific N-fixation rates for specific legumes (e.g. clover) and adjusted appropriate fertilization rates accordingly. In SN specific N-fixation rates cannot be addressed, instead SN takes into account the number of years legumes are used and the share of legumes on the field as input attributes to determine scores for nutrient cycling and primary productivity. In this study we have used the Dutch feed evaluation system and units (i.e. VW, SW, VEM and DVE) (Tamminga et al., 1994; van Es, 1975). Table 2 shows some of these input attributes for grazed grass and silage obtained from mowing. The complete table of changed input attributes is provided in supplementary materials S6, this also includes a justification of the changes made. This also includes grass silage obtained from the fields which were used for alternately mowing and grazing.

Table 2. *A part of the composition table used to reparametrize the reference scenario in FarmDESIGN with optimized literature values based on the suggested directions for change and practices from SN.*

Input attribute	**Unit**	**Reference scenario**		**Optimized scenario**	
		Permanent grassland		Herb-rich grassland	
		Grazed grass	Grass silage	Grazed grass	Grass silage
Nitrogen fixation	kg ha^{-1}	0	0	172	172
Effective org. matter	kg ha^{-1}	2000	2000	1540	1540
Cultivation costs	€ ha^{-1}	988	988	988	988
Regular labor	h ha^{-1}	18	21	21	25
Price fresh matter	€ kg^{-1}	0	0.062	0	0.067
Dry matter yield	kg ha^{-1}	1969	11453	1969	11453
Feed saturation value (VW)	-	0.89	1.02	0.89	1.02
Feed structure value (SW)	-	1.88	3.02	1.88	3.02
Energy content (VEM)	-	960	888	979	906
Protein content (DVE)	g kg DM^{-1}	92	67	93	68

Values were based on farm interviews, expert opinion (all co-authors and three grassland experts, see acknowledgements) and the following secondary literature: Bosch and de Jonge (1989), CVB (2018), de Wit et al. (2004), Feedipedia (2020), van der Voort (2018), Blanken et al. 2018) and Goyens (2016).

2.3.5 Multi-objective optimization

The multi-objective optimization of FD allowed further exploration of optimized farm configurations using other regenerative objectives such as farm profitability, labor or GHG emissions. The multi-objective optimization uses a Pareto-based Differential Evolution algorithm in which alternative farm configurations were created which outperformed the reference scenario on at least one of the regenerative objectives (Groot et al., 2012). The model was allowed to select combinations of the reference and optimized land use to create a broad solution space of optimized farm configurations. We used a fixed seed for optimization to generate a solution space which remained constant when exploring optimized farm configurations with the same conditions. This was needed to ensure a stable output of FD ready for use in SN. We used 4000 iterations per model run to reveal a stable solution space of 2000 solutions. From the solution space, any farm configuration can be selected and viewed in the FD model, to further inspect the performance on a wide range of farm sustainability indicators. The solution space is normally used by farmers and stakeholders together to decide which configuration is most appropriate for a farming system. Instead, we used a multi-objective filtering approach to decide which of the 2000 configurations best reflected the recommendations of SN. We did this by ranking all farm configurations from 0 (best) to 2000 (worst) for each individual optimization objective. The solution with the lowest aggregate score was selected as the best overall solution and was re-entered into SN, in order to assess the improvement of soil functions that resulted from the optimization. Table 3 shows the seven input attributes that changed for this second iteration of SN, for both grassland dedicated to alternated grazing and mowing and grassland dedicated to mowing only. These seven input attributes changed were related to the inclusion of herbs in grassland and changes in manure management. It is important to highlight that the manure type in Table 3 does not only refer to the nitrogen and carbon contents as two independent attributes, but also to the relation between them such as the C:N ratio.

Table 3. *Input attributes for SN which changed between the reference and optimized scenario.*

Input	**Unit**	**Reference scenario**		**Optimized scenario**	
		Grazed and mowed grass	Grass silage	Grazed and mowed grass	Grass silage
Number of years with legumes	yr	0	0	5	5
Share of legumes on the field	%	<10	<10	>10	>10
Grassland diversity	N species	1	1	>2	>2
Application of mineral fertilizer	Yes/No	Yes	Yes	No	No
Mineral N fertilization	kg N ha^{-1}	75-100	75-100	0	0
Type of manure	-	Slurry	Slurry	Solid	Solid
Organic N fertilizer	kg N ha^{-1}	>200	>200	75-100	75-100

3. Results

3.1 Windows of optimized farm opportunities

The exploration of our dairy case-study farm resulted in an optimized solution space of 2000 alternative farm configurations. Figure 4 shows relationships between the farm-level objectives set based on the suggestions of SN (i.e. increase N-fixation, reduce fertilizer N supply, increase manure C supply and reduce the farm N surplus). The relationships show the existence of both synergies and trade-offs between optimization objectives. A synergy was found between the objective to reduce the N surplus and to reduce fertilizer N supply

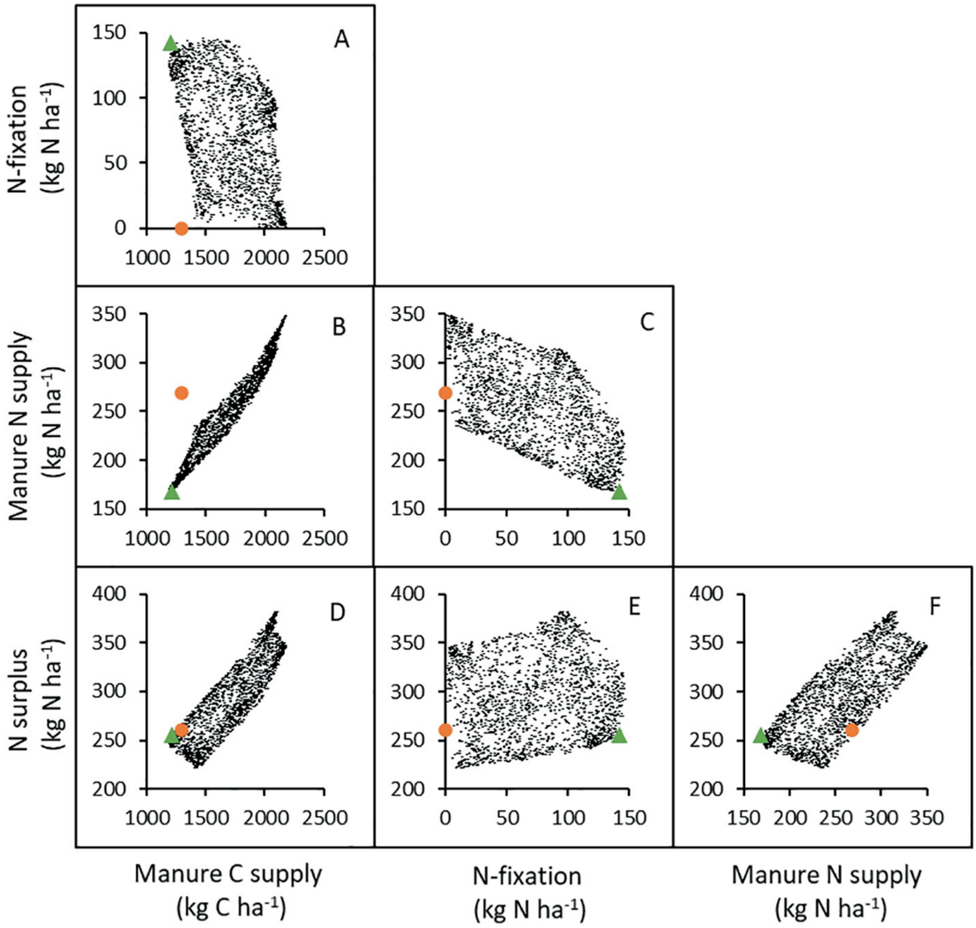

Figure 4. *Relationships between the objectives N fixation, N surplus, fertilizer N supply, and manure C supply for the dairy case-study farm. Each dot (black) indicates an alternative farm configuration, the orange dot and green triangle mark the performance of the reference and selected optimized farm configuration respectively.*

(Figure 4F), i.e. reducing fertilizer N supply also leads to a reduction in the N surplus. A trade-off was found trying to increase the manure C supply reflecting the use of solid manure while reducing the fertilizer N supply (Figure 4B), i.e. an increase in manure C supply is in this case also associated with a higher fertilizer N supply. This relationship is vary depending on the type of manure used. Another trade-off was found between the objective to increase manure C supply and the objective to reduce the N surplus (Figure 4D), i.e. a higher manure C supply increased the N surplus. The objective to maximize N-fixation did not result in synergies or trade-offs but showed a rather broad solution space (Figure 4A, C and E).

The exploration in FD yielded 2000 optimized farm configurations using the land use of the reference scenario and optimized scenario in different extents. Only ~14% of the optimized farm configurations were shown to have 75 to 100% of the total farm area allocated to the optimized scenario. Moreover, ~28%, ~29% and ~29% of the optimized farm configurations used the optimized scenario within the range of 50-75%, 25-50%, 0-25% of the total farm area, respectively. This indicates that using the current objectives in FD leads to a small set of optimized farm configuration which allocated most of the land to the optimized scenario. Moreover, none of the configurations had 100% of the land-use allocated to the optimized scenario. Using the multi-filtering approach, we selected the overall best performing farm configuration and reassessed the performance indicators in FD and the five soil functions SN.

3.2 Assessment on the themes of regenerative agriculture

In this study we modelled all five soil functions in SN (Figure 5a) and farm profitability, N surplus, labor requirements, SOM surplus and GHG emissions in FD (Figure 5b) to illustrate that the model output can help different stakeholders to assess and redesign farms based on the regenerative objectives. The error bars in Figure 5a represent model applications (models used for alternated mowing and grazing, and for mowing only) which showed diverging scores on soil functions from the calculated area weighted averages. The results show that the optimization resulted in four of the five soil functions performing at a 'high' level, at the expense of the function primary production, which dropped to 'medium'. The reason for this decline is that SN indicates that the implemented soil management practices (e.g. reduction in N-fertilization) are suboptimal for primary production. We, however, show that this decline in primary production leads to an increase in the supply of other soil functions (i.e. water purification and regulation, biodiversity and habitat provision and climate regulation). Figure 5 shows that this reduction in primary production was associated with a 27% decrease in farm profitability (from 55620 to 40720 € yr^{-1}), mainly as a result of an increase in the purchase of concentrate feed needed to satisfy animal nutrition requirements. Water purification and regulation increased from a low to a medium function score, due to the integration of herb-rich grassland and the lower N fertilization. The objective to reduce N-fertilization and reduce the N surplus did not result in a significant lower N surplus and stayed stable (from 258 to 256 kg N ha^{-1}). The decrease in N surplus was limited, mainly due to an increased uptake of concentrate feed and a higher N-fixation rate. Like the N surplus, the soil function nutrient cycling remained unchanged at high capacity in the optimized scenario. The functions biodiversity and habitat provision also remained high in the optimized scenario as a result of increased grassland diversity and the implementation of solid manure. The use of solid manure instead of slurry also increased the SOM balance by 7%. The use of solid manure instead of slurry and mineral fertilizers outweighed the difference in effective organic matter which is higher for permanent grassland compared to herb-rich grassland. Climate regulation improved to high, in response to the reduction in N fertilization of the soil.

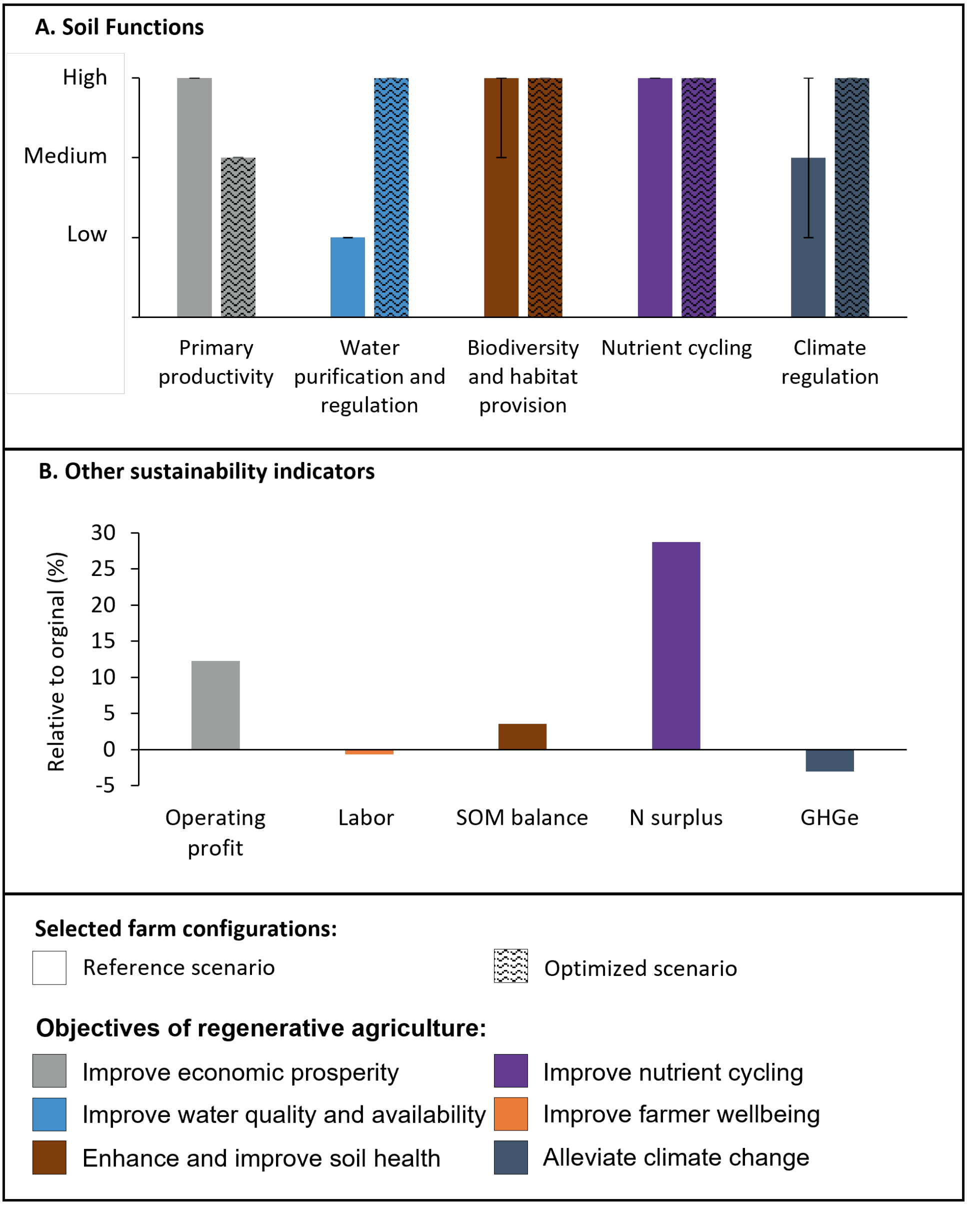

Figure 5. *The performance of soil functions (a) for the reference scenario and the optimized scenario of the case-study farm. Error bars represent function scores which were diverging from the calculated area weighted averages, indicating within-farm variability. The performance of other sustainability indicators (b) are shown relative to the reference scenario.*

Overall GHG emissions at the farm-level showed a small decline of 3% (from 30 to 29 Mg CO_2 eq. ha^{-1}) mainly due to a reduction in N-fertilization. Farm labor showed a small increase of 5% due to a higher labor requirement of the optimized scenario (from 2989 to 3147 h yr^{-}

[1]). A more extensive version of Figure 5 can be found in supplementary materials S7. The effect of farm configuration with diverging land use ratios for this case-farm on soil functions are shown in supplementary S8. Supplementary materials S8 for example shows that if less than 75% of the area of land was allocated to the optimized scenario, it would yield in a reduced performance of soil functions i.e. water purification and regulation. Land use with an area of less than 25% allocated to the optimized scenario would also yield in a reduced climate regulation score.

4. Discussion

4.1 Supporting tailor-made solutions in regenerative agriculture

The optimalisation of farming systems towards regenerative agriculture is complex and comes with a high knowledge requirement, as it requires detailed insights into soil multifunctionality at a field-level and knowledge about broader systems objectives at a farm-level. Jones et al. (2017) highlighted the lack of integrated models that can assist with such complex challenges that operate across multiple scales. Instead of creating a single model, our study showed that different models can be used together to address the complexity of the soil while at the same time addressing wider sustainability aspects (i.e. farm labor, GHG emissions). Specifically, we successfully combined and applied a field-scale model of soil functions, with a farm-scale model on environmental and socio-economic sustainability, to operationalize regenerative agriculture for the context-specific redesign and assessment of a Dutch dairy farm. By definition, regenerative agriculture uses soil conservation practices as the entry point for environmental and socio-economic sustainability (Chapter 2), and it is these practices that take center-stage in the recommendations of SN. At the same time, multi-objective optimization of FD showed that even for an individual farm there are multiple viable reconfigurations.

4.2 Reflection on the modelling of our case-study dairy farm

Peat soils are in the Netherlands considered unsuitable for arable agriculture and, are therefore, predominantly used as permanent grassland for grazing animals – typically dairy cattle. This traditional use of land has resulted in an open landscape with important cultural-historical features. Intensification has resulted in high productivity and resource use-efficiency. At the same time, resource losses are externalized, and other environmental indicators have deteriorated due to increased drainage, intensive grazing and fertilizer use, which have increased CO_2 emissions, and mineralization rates, with associated losses of SOM and nutrients (Schothorst, 1977). This is reflected in our assessment of the reference scenario in which SN presented high productivity and nutrient cycling in the soil, similar to SN results from 52 Dutch farms (Vazquez et al., 2020). Following SN, primary productivity decreased to a medium level due to a reduced use of nitrogen fertilization required to optimize other soil functions. FD showed that farm profitability was also reduced mainly due to an increased purchase of concentrate feed, to compliment the diet of the farm animals. A higher import of concentrate feed is not in-line with the objectives of regenerative agriculture, and reduced farm profitability could hinder the transition towards regenerative agriculture. In future studies it would therefore be of interest to also consider the objectives of regenerative agriculture in the optimization of FD.

Our study shows high scores for soil biodiversity for both the reference and the optimized scenario. While this result was unexpected in light of the reported declines in soil biodiversity in the Netherlands (Rutgers et al., 2019, 2010), the scores in SN are context specific (e.g. land use). This corresponds with the findings of Reidsma et al. (2006), who showed that levels of biodiversity are very dependent on land use, soil type and climatic regions. The decision rules in SN are currently set-up to evaluate biodiversity within an agricultural perspective. From an agricultural perspective, peat soils with permanent grassland and the use of herb-rich grass mixtures are associated with improvements in soil life and structure (van Eekeren et al., 2010). SN is, furthermore, sensitive to input attributes with a high weighting factor, such as the use of no-tillage and a high SOM. On peat soils no-tillage is a common practice and a high SOM is self-evident, which may lead to the overestimation of SN function score for biodiversity and habitat provision.

The score for climate regulation was medium for the reference scenario and this improved to high in the optimized scenario due to the reduction of N fertilization. Although this is a valid measure to reduce N_2O emissions, it is surprising that SN did not recommend an increase in groundwater levels or, concurrently, a reduction in artificial drainage. Peat soils in the Netherlands are associated with high CO_2 emissions due to peat oxidation from drainage to enable grazing of typically cattle (Schothorst, 1977). Currently the role of livestock on peat soils is under debate and increasing the water level is an oft-suggested measure to reduce CO_2 emissions from peat soils (Querner et al., 2008). A recent study of De Jong et al. (2021) shows that rewetting peatlands can reduce CO_2 emissions with more than 30%. This study evaluated the role of peatlands for paludiculture instead of dairy farming. Although SN is developed for pan-European coverage of soils with land use and climate, we found that calibration and validation of SN remains limited on peat soils. The five function models used 94 to 251 sites for calibration and validation across Europe (van de Broek et al., 2019; Wall et al., 2020), we found that only five of these sites were on peat soil. Vazquez et al. (2020) used 52 farms in the Netherlands for assessment on soil functions and did not include peat soils. We, therefore, recommend further calibration and validation of SN for peat soils in the Netherlands.

The low score for water regulation and purification improved to a high score, due to the integration of herbs in grassland which improved grassland diversity in the respective time horizon of five years. Including clover is a well-known practice to improve soil functions on sandy and clay soils. However, its role for peat soils is subject to debate: while our case-study farm has a soil pH (pH-KCl) of 5.5, the average pH of peat soils in the Netherlands is 4.7 (Rutgers et al., 2007), which is suboptimal for clover growth. The use of clover in grassland is recommended only for soils with a pH >5.2 (de Wit et al., 2004; van Eekeren, 2007). The reduction of N-fertilization also significantly contributed to improving the score of water purification and regulation, showing that some regenerative practices may contribute to multiple soil functions.

The social dimension of regenerative agriculture was in this study reflected by farm labor. We acknowledge that farm labor by itself is a suboptimal indicator to reflect the wellbeing of farmers and the objective of regenerative agriculture to "*improve human health*". We would, therefore, recommend in future studies to also take indicators into account which can reflect human wellbeing. Brown et al. (2021) for example suggests that even subjective wellbeing measures can be used to assess regenerative agriculture. Although, farm labor may not give insight in the wellbeing of a farmer, it does give context regarding the social dimension of regenerative agriculture. Moreover, increased labor requirements may result in for example increased job opportunities and reduced labor requirements may result in more leisure time for the farmer.

4.3 Recommendations and prospects for future modelling

Like most models, SN and FD are designed and parameterized to simulate common farming systems. In this study we modelled a dairy farm. This, however, could, also have been any other common farm type i.e. a conventional arable farm or mixed farm. Besides common farming systems, regenerative agriculture aspires to be equally relevant to, and in fact promote, the establishment of new farming systems, such as agroforestry or strip-cropping (e.g. Ditzler et al., 2021). These farming systems often yield their positive effect on a wide range of interrelated ecosystem services over a longer time period (Robertson et al., 2014; Teague and Kreuter, 2020). Neither SN, nor FD, are designed to simulate these emerging farming systems over a multi-year time period. While we have shown that linking FD and SN to be an effective first step to customize regenerative agriculture for diverse farming systems, we recommend to further develop SN to include a wider variety of farming and farm practices that could influence soil functions (e.g. grazing strategies, fixed traffic lanes).

5. Conclusion

This study demonstrated that we can use SN and FD together by researchers as a tool to help different stakeholders to assess and redesign farms based on regenerative objectives. Combining SN with FD allowed evaluating the impact of soil management practices as the basis for optimizing the overall socio-economic and environment sustainability of a farm, which is aligned with the definition of regenerative agriculture. The modelling framework we present in this paper gives therefore, not only new insights in the consequences of implementing different soil management practices on soil health, but also the consequences for other sustainability aspects such as labor requirements and farm profitability. For our case-study dairy farm, we found a set of practices that delivered four out of the five functions at high capacity. While this high performance came at a lower primary productivity score, it also reduced farm profitability. Reduced farm profitability could hinder the transition towards regenerative agriculture. While this study successfully demonstrated an initial combination of SN and FD models for the ex-ante design and assessment of farming systems towards regenerative agriculture, further model development is essential to widen the applicability of this study to include emerging farming systems and new indicators of sustainability that are measured over a longer time period. Furthermore, we would recommend to further calibrate and validate SN for peat soils across Europe.

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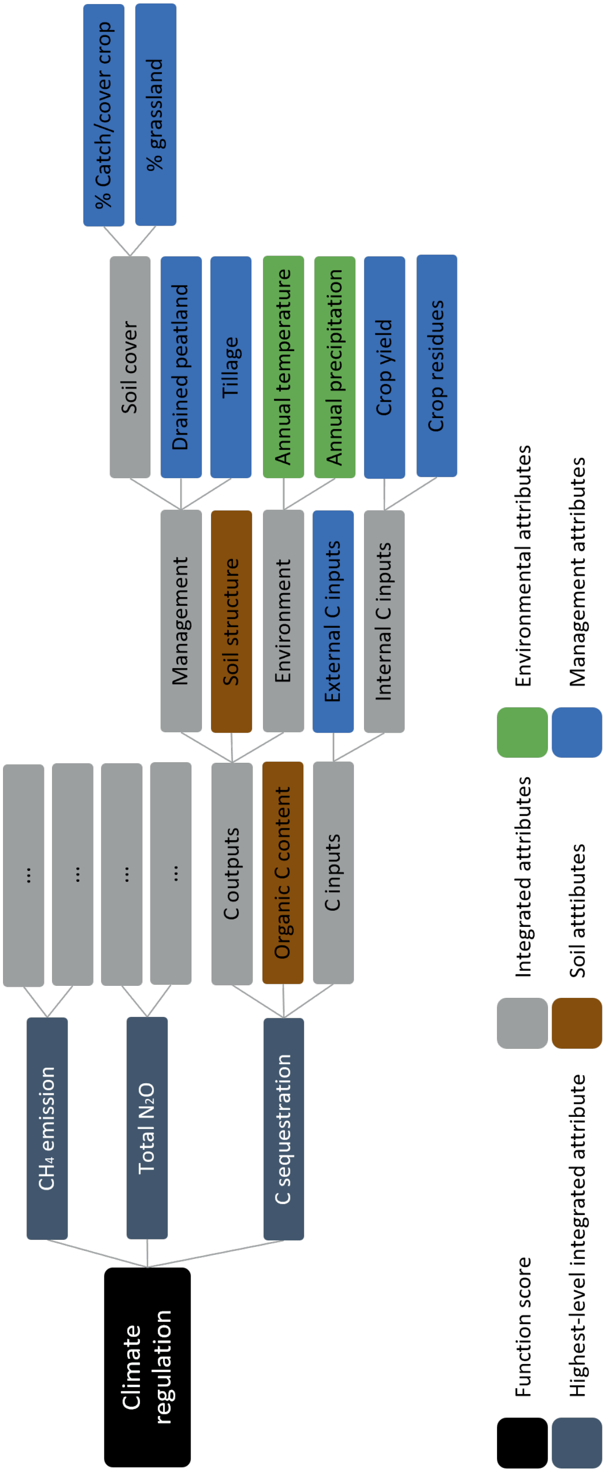
Supplementary materials

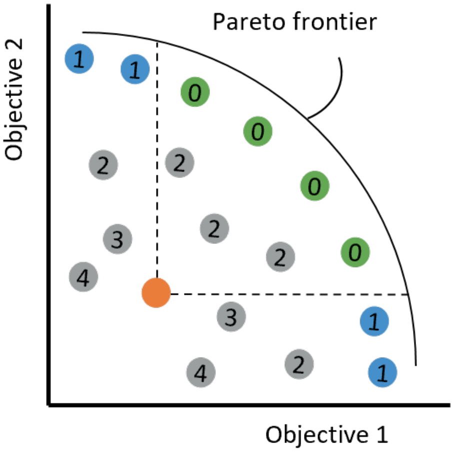
S1: Mode of operation of the Soil Navigator (SN)

The SN is an multi-criteria decision support model based on expert opinion that enables the assessment of five soil functions simultaneously at the field scale (Debeljak et al., 2019). The five soil functions are based on the Functional Land Management (FLM) framework proposed by Schulte et al. (2014). These five soil functions are articulated in the SN as different models and include primary productivity (Sandén et al., 2019), nutrient cycling (Schröder et al., 2016), water purification and regulation (Wall et al., 2020), climate regulation (van de Broek et al., 2019), and biodiversity and habitat provision (van Leeuwen et al., 2019). The input attributes (see adapted figure from Van de Broek et al., 2019; Zwetsloot et al., 2020) required for assessment of soil functions are based on farm management (i.e. land and fertilizer use), environment (i.e. average temperature and precipitation) and soil attributes (i.e. clay content and soil organic matter). Each model follows the hierarchical structure of a decision tree, in which input attributes are assigned qualitative scores (low, medium, high) based on pre-set thresholds. Using expert-based decision rules, the higher-level integrated attribute scores are derived from the input attributes or lower-level integrated attribute scores. Hence, the final soil function scores are determined by the scores of highest-level integrated attributes and associated decision rules. At each level of aggregation in the decision tree, weight factors determine the importance of the lower-level attributes to the calculation of the higher-level attribute. The input attributes for the five different soil functions can be used multiple times within a model and across models. The decision rules used to assess these input attributes are, however, unique for each function model. The five soil function models were structured, calibrated and validated for crop and grassland using information obtained by expert knowledge and with different datasets across Europe (Sandén et al., 2019; Schröder et al., 2016; van de Broek et al., 2019; van Leeuwen et al., 2019; Wall et al., 2020). The figure below shows part of the model structure of the climate regulation model to illustrate how the models in the Soil Navigator are organized to assess soil functions based on their input attributes. In addition, the SN offers the possibility to optimize soil functions based on user-determined objectives and indicates if certain objectives are achievable due to synergies and trade-offs between soil functions or local constraints. The SN will search all possible combinations of values of the input attributes in order to identify which input attributes need to be improved along with farm practices to establish this improvement. When a suitable combination is found, the SN will show the new potential capacity of the soil to deliver the five functions. Details about the construction of the SN are described in Debeljak et al. (2019).


Climate regulation
CH_4 emission
Total N_2O
C sequestration
...
...
...
...
C outputs
Organic C content
C inputs
Management
Soil structure
Environment
External C inputs
Internal C inputs
Soil cover
Drained peatland
Tillage
Annual temperature
Annual precipitation
Crop yield
Crop residues
% Catch/cover crop
% grassland
Function score
Highest-level integrated attribute
Integrated attributes
Soil attibutes
Environmental attributes
Management attributes

S2: Mode of operation of FarmDESIGN (FD)

FD is a bio-economic whole-farm model which consists of a large array of interrelated farm components developed for the analysis and redesign of mixed crop-livestock systems (Groot et al., 2012). The model was used within the framework of the DEED-cycle (Describe, Explain, Explore, Design) (Giller et al., 2011) and we present the model accordingly. The describe-phase describes the farm using various parameters related to crop and animal performance. The explain-phase explains the performance of the farm using a variety of indicators. A wide range of flows such as that of carbon and nitrogen are calculated at the farm level. The resulting material balances, the feed balance, the amount and composition of manure, labor balance and economic results are calculated on an annual basis. The explore-phase explores multiple optimized farm-configurations that are generated by a multi-objective optimization based on selected objectives (e.g. minimize N balance or maximize operating profit), set constraints (e.g. upper and lower limits on animal's energy and protein requirements) and a variety of decision variables (e.g. upper and lower limits on crop areas or animal numbers).



The objectives, constraints and decision variables are used to improve the environmental performance of a farm (i.e. land use diversity, nutrient losses and soil organic matter accumulation) as well as the capacity to improve socio-economic prosperity (i.e. profitability, household budgets and labor requirements). The multi-objective optimization uses a Pareto-based Differential Evolution algorithm to generate numerous alternative farm-configurations and the model displays them within a solution space (Radhika and Chaparala, 2018; Storn and Price, 1997). The figure here (modified from Groot et al. (2012), illustrates such a solution space in which the original farm configuration (orange) is optimized by maximizing Objective 1 and 2. The alternative farm configurations have different pareto ranks 0-4. Rank 0 (green) is given to farm configurations which outperform all objectives of the other farm configurations. Rank 1 (blue) is given to farm configurations which perform equal or outperform other farm configurations in at least one objective. The set of farm configurations with rank 0 and 1 is called the trade-off frontier and may be used to assess trade-offs and synergies between the objectives in the solution space. Farm configuration with ranks 2-4 (grey) form the rest of solution space and outperform the original farm configuration in different extents. In the design-phase new farm configurations can be selected from the solution space based upon user-determined criteria. The user may for example prefer solutions that are more aligned with Objective 1 than Objective 2, from the figure above. The new farm configurations can include optimized performance indicators and new land-use configurations. These new land-use configurations exist for example of optimized allocation of crop areas, new crops entering the farm, changes in herd size, animal type, fertilizers and feed use. The construction of FD and the corresponding farm balance equations are described by Groot et al. (2012).

The previous version of FD was equipped with a random seed, which means that reoptimizing a farm using the same conditions led to different solution spaces, hence farm-configurations. In our study we added the option to select a fixed seed, which allowed to generate a solution space which remained constant when optimizing a farm with the same conditions. This was needed to ensure a stable output of FD could be used in the SN. The solutions were generated using the Pareto-based Differential Evolution algorithm in FD with the exploration parameters set at values recommended by Groot et al. (2007), including a mutation probability of 0.85 and mutation amplitude of 0.15. To be able to view the selected farm-configuration we created a search function in FD to enable the end-user to search the farm-configuration using the farm-ID of the selected configuration (in our case farm-ID 9). In order to see if the farm practices suggested by the SN not only affected indicators in FD but also soil functions in the SN, we re-entered the optimized output of FD back into te SN. We, therefore, created an output folder in FD called “export to Soil Navigator” which exports a file that shows the required recalculated input data to reparametrize the different models in the SN. The attributes integrated in this folder include quantitative attributes which would change within the five year time-horizon of the SN such as the use of N-fertilizer and crop yield.

S3: Extended overview of the congruence between the three pillars of sustainability, the core objectives of regenerative agriculture and the model indicators

Congruence between the three pillars of sustainability (people, planet and profit), the core objectives of regenerative agriculture with underlying objectives (in the circles) and the indicators which can be assessed by the models (around the objectives). Indicators which are assessed by the Soil Navigator are represented by “SN” and FarmDESIGN by “FD”. The bolt indicators are used in this study.

S4: Weight factors of input attributes in the Soil Navigator

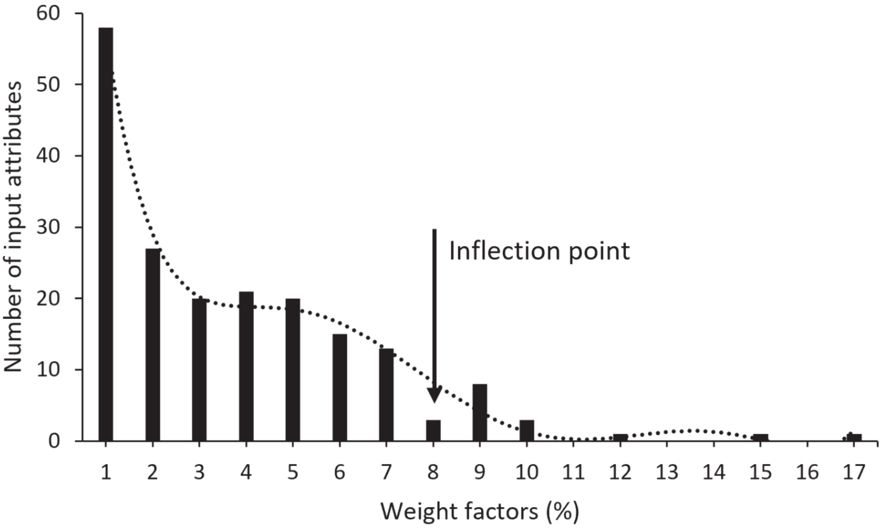
The table below shows the weighting factors of the input attributes used in the five soil function models. Some models use aggregated input attributes such the climate regulation model (CR) which sums the organic and inorganic N fertilizer applied on the field.

Model:	**PP**	**BD**	**CR**	**NC**	**WR**
Peer-reviewed model:	(Sandén et al., 2019)	(Leeuwen et al., 2019)	(van de Broek et al., 2019)	(Schröder et al., 2016)	(Wall et al., 2020)
Weighting obtained from:	Article	DEXi	DEXi	DEXi	DEXi
Total (%):	100	100	101	100	99
Management					
Farm management					
Land use		9			
Tillage		5			
Livestock management					
Stocking rate	5	1			2
Number of months in field		1			
Crop management					
Number of crops in rotation	6	2			
Crop type		2			5
Catch/cover crops/green manure	4	2	2	1	1
Share of crop residues left on the field			5	9	5
Intercrop cover					1
Grassland type			1		
Share of legumes	5	5		1	
Grassland diversity					
Grassland rotation					
N offtake by crop					7
Fertilization					
Mineral N fertilization	6	2	12	3	4
Organic N fertilization	6				2
Mineral P fertization					1
Organic P fertilization					1
Manure application			1	1	
Manure type		2			
Ammonia share of waste				1	
Other amendments					
Nitrification inhibitors			4		
Liming		4			
External C inputs			9		
Water management					
Irrigation	10	2	6	5	
Irrigation rate					1
Irrigation frequency					1
Irrigation type					1
Artificial drainage		3	9	4	8
Pest Management					
Chemical	2	6			

Model:	**PP**	**BD**	**CR**	**NC**	**WR**
Mechanical	2				
Biological	2				
Harvest					
Crop failure				9	
Net primary productivity			2		
Environment					
Climate					
Annual precipitation	10	5	9	7	4
Precipitation in 1st month of growing season				7	
Precipitation - cropping season					6
Precipitation - wet season					7
Annual temperature	5	1	5		
Average daily T in the first growing month				7	
Days with daily avarage T above 5 C				2	
Topography					
Altitude	6				
Slope Degree	9				
Soil					
Physical					
Soil type			9		
Soil texture		5	7	3	7
Clay content	1				
Soil crusting					4
Thickness of organic layer		2			
Plant rooting depth	1				8
Ground water table depth	4	3		7	7
SOC			17		1
SOM	2	2			7
Bulk density	2	5		7	3
Drainage class			1	3	5
Chemical					
PH	3	5		15	
CEC	1				
C:N ratio	1	1			
N:P ratio		1			
Plant available P (soil P status)	2			8	1
Plant available K	1				
Plant available Mg	1				
Salinity	3				
Biological					
Earthworm richness		1			
Earthworm abundance		1			
Nematode richness		1			
Nematode abundance		1			
Microarthropod richness		1			
Microarthropod abundance		1			
Enchytraeid richness		1			
Enchytraeid abundance		1			

Model:	PP	BD	CR	NC	WR
Bacterial biomass		2			
Fungal biomass		2			
Fungal: bacterial biomass ratio		1			
Additional					
Mollic/Chernic/Plaggic horizon		3			
Histic/Umbric horizon		1			
Vertic/fragic horizon		6			
Hydragric/Irragic horizon		1			
NH4 content in manure			1		
Drained peatland			3		

Weighting factors of the input attributes for all five function models. The orange arrow indicates the inflection point which determines in combination with expert opinion a low and a high weight factor. In total 9% of the input attributes had a high weighting factor and 91% of the input attributes had a low weighting factor.



S5: Overview of constrains, objectives and decision variables in FarmDESIGN

Farm-level indicators	Units	Min	Max
Objectives			
N balance	kg N ha^{-1}	x	
N fixation	kg N ha^{-1}		x
Total manure N supply to soil	kg N ha^{-1}	x	
Total manure C supply to soil	Kg C ha^{-1}		x
Area optimized scenario	ha		x
Decision variables			
Area permanent grassland (grazing/mowing)	ha	0	17
Area permanent grassland (mowing)	ha	0	24
Area herb-rich grassland (grazing/mowing)	ha	0	20
Area herb-rich grassland (mowing)	ha	0	40
Used as feed_maize silage	kg DM	0	100000
Used as feed_ wheat straw	kg DM	0	100000
Used as feed_concentrates	kg DM	0	300000
Used as feed_grass silage (grassland_mowing/grazing)	kg DM	0	160000
Used as feed_grass silage (grassland_mowing)	kg DM	0	260000
Used as feed_grass silage (herb-rich grassland_ mowing/grazing)	kg DM	0	200000
Used as feed_Grass silage (herb-rich grassland_mowing)	kg DM	0	300000
Fraction fed in non-grazing period_concentrates	-	0	1
Fraction fed in non-grazing period_wheat straw	-	0	1
Fraction fed in non-grazing period_maize silage	-	0	1
Fraction fed in non-grazing period_grass silage (grassland_mowing/grazing)	-	0	1
Fraction fed in non-grazing period_grass silage (grassland_mowing)	-	0	1
Fraction fed in non-grazing period_grass silage (herb-rich grassland_ mowing/grazing)	-	0	1
Fraction fed in non-grazing period_grass silage (herb-rich grassland_mowing)	-	0	0
Self reliance 1_grass silage (grassland_mowing/grazing)	-	1	99
Self reliance 1_grass silage (grassland_mowing)	-	1	99
Self reliance 2_grass silage (herb-rich grassland_ mowing/grazing)	-	1	99
Self reliance 2_grass silage (herb-rich grassland_mowing)	-	1	99
Fraction for fertilization_solid manure	-		0
Hired labor	h yr^{-1}	0	4000
Constraints			
Whole farm area	ha	38	42
Labour surplus	h yr^{-1}	0	9999
Farm profitability	€ yr^{-1}	30000	200000
N balance	Kg ha^{-1} yr^{-1}	0	999
P balance	Kg ha^{-1} yr^{-1}	0	999
K balance	Kg ha^{-1} yr^{-1}	0	999
Feed balance deviation/req.			
DM intake ≤100% % of saturation	%	-99999	0
Energy 95-105% of req.	%	-5	5
Protein 100-13-% of req.	%	0	30
Structure >100% of req.	%	0	99999

Farm-level indicators	Units	Min	Max
Exploration parameters			
Amplitude (F)	-	0,15	
Probability (CR)	-	0,85	
Fixed seed	-	300	
Number of solutions	-	2000	
Number of iterations	-	4000	

S6: Reparameterization of new animal and crop products in FarmDESIGN

Expert corrections were made based on suggestions by Pedro Janssen, Co Daatselaar, Alfons Beldman and Gertjan Holshof.

		Current management includes: Permanent grassland + pasture manure + slurry + art. fert. + no synthetic pesticide			
FD input variable	**Unit**	**Alternated grazing and mowing**		**Mowing only**	**Source**
		Grazed grass	**Grass silage**	**Grass silage**	
Grassland (area)	ha	16,9		23,5	1
Price fresh matter	€/kg	0,42		0,42	1
Production	kg/cow/day	23,9		23,9	1
Nitrogen fixation	kg N/ha/yr	0		0	2, 8
Effective org. Matter	kg/ha/yr	2000		2000	6
Diesel use	L/ha	150		178	4
Subsidies	€/ha	463		463	1
Cultivation costs (incl. labor)	€/ha	988		988	1
Total labor	h/ha/yr	18		21	1
Price fresh matter	€/kg	0	0,062	0,062	1, 15, 19
Fresh yield	kg FM/ha	12078	23652	28561	1
Dry matter yield	kg DM/ha	1969	9484	11453	1, 2
DM content	g/100g FM	16,3	40,1	40,1	1, 7, 10
Ash content	g/100g DM	10,60	11,13	11,13	7, 10
Nitrogen	g/100g DM	2,78	2,48	2,48	2, 7, 10
Phosphorus	g/100g DM	0,40	0,46	0,46	2, 7, 10
Potassium	g/100g DM	3,43	3,21	3,21	7, 10
Feed saturation value (VW)	-	0,89	1,02	1,02	1, 7
Feed structure value (SW)	-	1,88	3,02	3,02	1, 7
Energy content (VEM)	-/kg DM	960	888	888	1, 7
Protein content (DVE)	g/kg DM	92	67	67	1, 7

Values were based on farm interviews[1], expert opinion (all co-authors and three grassland experts, see acknowledgements)[2] and the following secondary literature: Abts et al., (2016)[3], Blanken et al. (2018)[4], Bom (1983)[5], Bosch and de Jonge (1989)[6], CVB (2018)[7], de Wit et al. (2004)[8] de Wolf et al. (2019)[9], Feedipedia (2020)[10], Geel and Brinks (2018)[11], Goyens (2016)[12], Gren (1994)[13], Hospers (2015)[14], Kadaster & WEcR (2017)[15], Scheepens (2001)[16], Schröder et al. (2003)[17], Starmans et al. (2015)[18], van der Voort (2018)[19], and van der Weide et al. (2008)[20].

		Optimized management includes: Herbrich grassland + pasture manure + farm yard manure + no synthetic pesticide			
FD input variable	**Unit**	**Alternated grazing and mowing**		**Mowing only**	**Source**
		Grazed grass	**Grass silage**	**Grass silage**	
Grassland (area)	ha	16,9		23,5	-
Price fresh matter	€/kg	0,42		0,44	-
Production	kg/cow/day	23,9		23,9	-
Nitrogen fixation	kg N/ha/yr	172		172	2, 8
Effective org. Matter	kg/ha/yr	1540		1540	6, 9
Diesel use	L/ha	143		169	4
Subsidies	€/ha	463		463	2, 12
Cultivation costs (incl. labor)	€/ha	988		988	2, 8, 13, 20
Total labor	h/ha/yr	21		25	2, 15, 16
Price fresh matter	€/kg	0	0,067	0,067	14, 15, 19
Fresh yield	kg FM/ha	12078	23652	28561	2, 5, 8, 11, 17, 18
Dry matter yield	kg DM/ha	1969	9484	11453	2, 3, 8
DM content	g/100g FM	16,3	40,10	40,10	8
Ash content	g/100g DM	11,88	12,24	12,24	2, 8
Nitrogen	g/100g DM	3,06	2,73	2,73	2, 10
Phosphorus	g/100g DM	0,45	0,46	0,46	2, 10
Potassium	g/100g DM	3,35	3,18	3,18	10
Feed saturation value (VW)	-	0,89	1,02	1,02	1, 2, 7
Feed structure value (SW)	-	1,88	3,02	3,02	1, 2, 7
Energy content (VEM)	-/kg DM	979	906	906	1, 2, 7
Protein content (DVE)	g/kg DM	93	68	68	1, 2, 7

Values were based on farm interviews[1], expert opinion (all co-authors and three grassland experts, see acknowledgements)[2] and the following secondary literature: Abts et al., (2016)[3], Blanken et al. (2018)[4], Bom (1983)[5], Bosch and de Jonge (1989)[6], CVB (2018)[7], de Wit et al. (2004)[8], de Wolf et al. (2019)[9], Feedipedia (2020)[10], Geel and Brinks (2018)[11], Goyens (2016)[12], Gren (1994)[13], Hospers (2015)[14], Kadaster & WEcR (2017)[15], Scheepens (2001)[16], Schröder et al. (2003)[17], Starmans et al. (2015)[18], van der Voort (2018)[19], and van der Weide et al. (2008)[20].

Justification of the input attributes

Milk price goes 2 cents up for the optimized situation based on different existing payment schemes. In this case we used the planet proof label (Baan, 2019). Fully organic, is 10 cents more to the conventional milk price (Bijttebier et al., 2016). It is from this modelling study, however, uncertain if all requirements for organic standards are met.

Milk production is kept the same because studies up to now are not clear if milk production increases or decreases using regenerative management.

Nitrogen fixation increases from 0 to 172 kg N/ha. Permanent grassland is adjusted to 0 in the model because N fixation of grassland is prevented from being accessible due to immobilization. The value of 172 kg N/ha is estimated based on the maximum share of legumes (clover) and the dry matter yield. The maximum share of clover is 30% on peat, on other soil types this may be up to 40-50% (based on expert opinion). Next, we used a rule of thumb which says that for every ton dry matter clover ±50 kg N/ha can be fixated (de Wit et al., 2004) p.13.

- **N mineralization** is normally equal to immobilization and therefore on mineral soils not taken into account. However, on peat soils there is extra N mineralization due to peat oxidation (very dependent on groundwater table). This extra N mineralization is in this study used as a fixed value (189 kg N/ha) obtained from the farmers Kringloopwijzer documentation. This value of the Kringloopwijzer is within the range of studies estimating this extra N mineralization of peat soil of for example van Kekem et al. (2004) and Kuikman et al. (2005), who estimated N mineralization rates between 160 and 250 kg N/ha.
- **Peat oxidation** consequences besides extra N mineralization also in extra CO_2 emissions, these extra emissions were obtained from the Kringloopwijzer and were 5125 kg CO_2/ha, almost 17% of total on-farm emissions. Very much in line which values found by Kuikman et al. (2005).

Effective organic matter (EOM) is based on values of Handboek voor de Akkerbouw en de Groenteteelt in de Vollegrond 1989 for grassland. For herb-rich grassland we recalculated with 20-30% white clover with an EOM of 850 kg OM/ha. More EOM was also allocated by changing from slurry to solid manure. This is in-line with literature values, showing that cattle slurry provides 48 g EOM/ kg FM, and solid cow manure 114 g EOM/kg FM (Veeken et al., 2017). This increase is, however, compensated by a higher aerobic degradation process of solid manure compared to the anaerobic degradation process of slurry. Although the effect on the SOM surplus may be limited by changing to solid manure, straw needs to be added which does increase SOM.

Diesel use for grassland was based on a farm survey. The lower diesel use for the optimized scenario was related to a reduction in N fertilization (no art. fertilizer and less manure) because of the use in legumes in the grassland. The reduction in diesel use was 34 l/ha, estimated by using KWIN-agv 2018 values (p. 116 and 191). The use of herbs in grassland on especially peat soils requires reseeding of the herbs which limits the reduction in diesel use. Based on expert opinion we, therefore, chose the estimated reduction 5%.

Subsidies for the reference scenario were based on farm surveys. For the optimized scenario we kept subsidies equal for the coming 5 years. Subsidies can be obtained by changing to organic standards or using single practices. Using for example herb-rich grassland can already lead to subsidies of 450 -600 euro/ha (Goyens, 2016; Vandepoel, 2015). Farmers from TiFN's (Top institute Food and Nutrition) Regenerative Farming project which already implementing these practices highlighted in farm surveys that subsidies can go up to 1750 euro/ha. Based on expert opinion and the uncertainty of subsidies we kept this parameter constant.

Cultivation costs were a sum of all costs including farm and hired labor regarding the production of the grassland. We kept this equal between the reference and optimized scenario. The reference scenario will require more external inputs like artificial fertilizer, however the optimized scenario requires reseeding of the herbs which requires the purchase of seeds and more labor. Following expert opinion and farm surveys with the CoP-farmers difference in costs were nihil.

Labor was determined by farm interviews for the reference scenario. We used KWIN-agv 2018 (p. 191) values and expert opinion to determine labor requirements for the optimized scenario. The increase in labor is justified by the resowing of herbs and harrowing to prepare the grass bed for the seeds. The reduction in fertilization does not lead to reduced labor since the frequency of fertilization remained the same. Reduced labor was also allocated to fields with grazing, due to less fertilization and grassland maintenance.

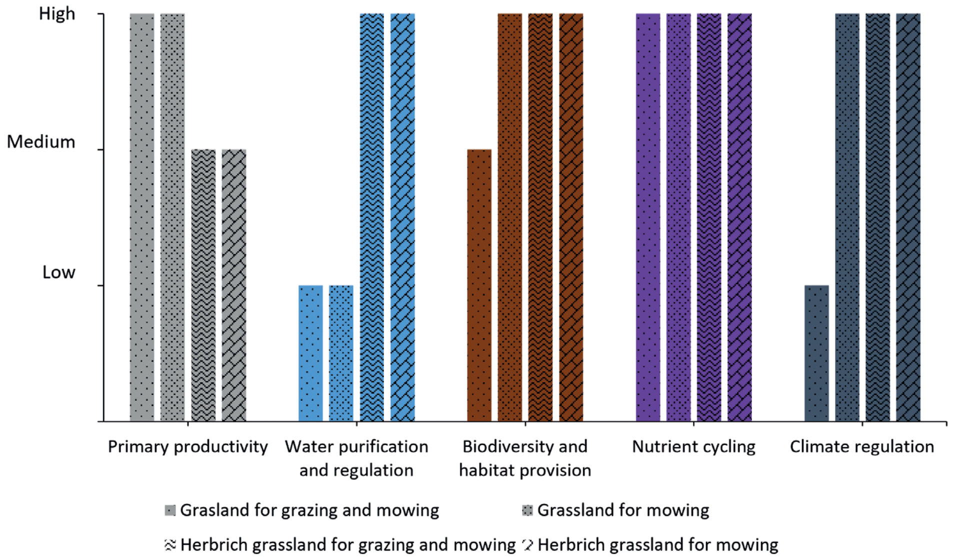
Fresh grass price was obtained from a farm survey for the reference scenario. For the optimized scenario we used expert opinion, KWIN-agv 2018 and Biokennis to determine the sales price of herb-rich grassland. The sales price is increasing due to for example a higher nitrogen content which results in higher feed values (VEM). Although the sales price is increasing, the effect on the model outcome will be limited because most grass will be used on-farm.

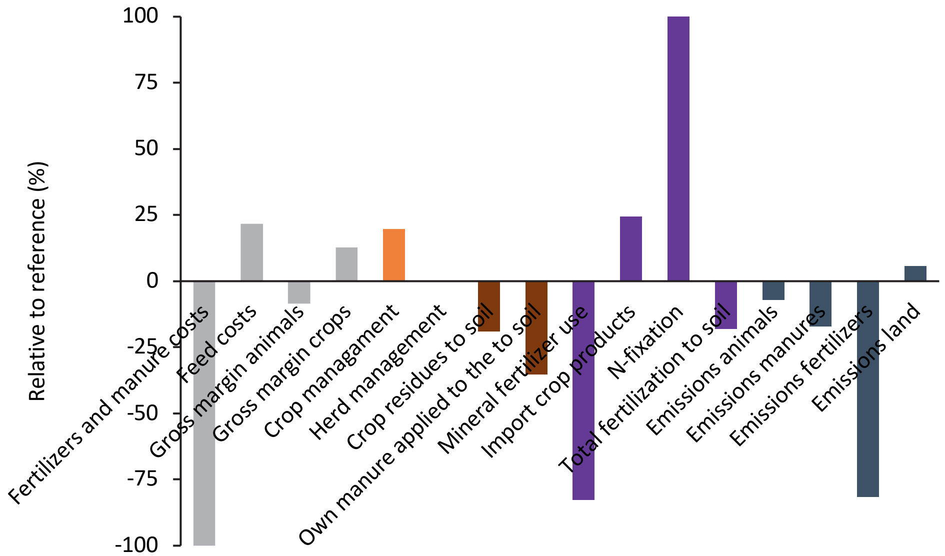
Dry matter yield values were obtained from a farm survey for the reference scenario. The yield of silage in alternated grazing and mowing was corrected with 0.95 due to an intensive system (low grazing). We kept yield values for the optimized scenario equal because literature does not show significant increases or decreases regarding yield. This was confirmed by expert opinion. Other yield parameters were obtained from CVB (2018) and Feedipedia (2020).

Feed values were obtained from a farm survey for the reference scenario. Based on data of CVB (2018) and Feedipedia (2020), farmers from TiFN's Regenerative Farming Project and expert opinion we estimated a slight increase in VEM and DVE due to a higher N content of the herbs.

S7: Details about the reference and optimized scenario

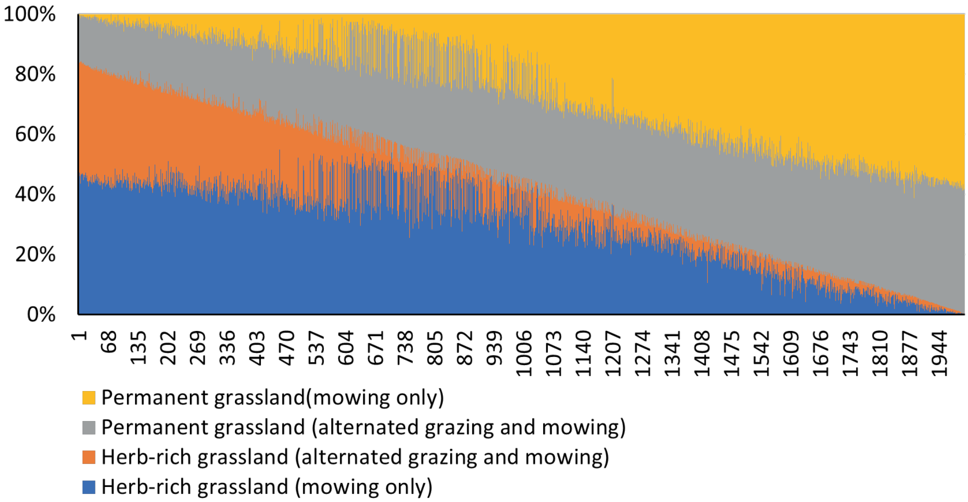
The five soil functions for the different land-uses of the dairy case-study farm, modelled with the Soil Navigator; underlying indicators with respect to the environmental and socio-economic farm sustainability, modelled with FarmDESGN.



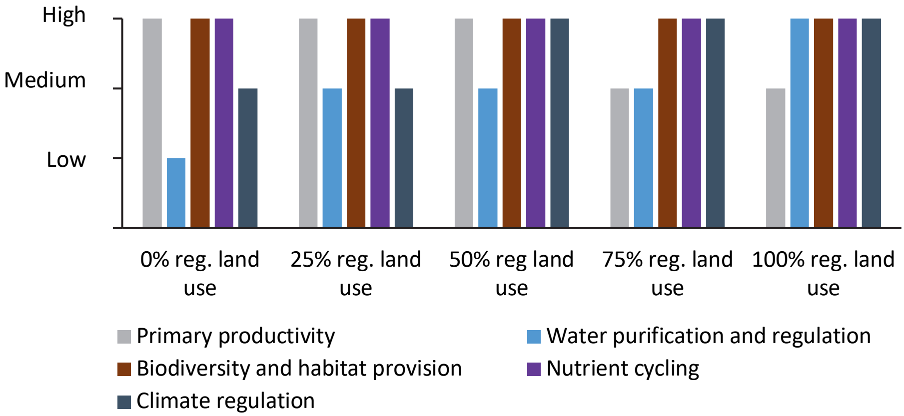


S8: The effect of different area allocated to the refence and optimized land use on soil functions

The figure here show the land use of 2000 optimized farm configurations calculated by FD. The farm configuration showed in this figure are ordered based on farms with a high to low sum of area allocated to the optimized scenario (herb-rich grassland with other associated practices). The area of land allocated to the reference and optimized scenario is a sensitive parameter for the final assessment of soil functions.



To showcase the effect of land use on the different soil functions the figure here shows how the performance of soil functions will change when selecting farm configurations with various land uses for our dairy case-study farm.



Chapter 4

Tailor-made solutions towards regenerative agriculture in the Netherlands

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Abstract

Regenerative agriculture is a farming approach that uses soil health as the entry point to regenerate and contribute to multiple objectives, such as improved nutrient cycling and climate regulation. To reach the multiple objectives farmers can apply different practices. The practices applied, however, are dependent on the relevant regenerative objectives and specific context of the farming system. In this chapter we applied the modelling framework from Chapter 3 on three contrasting farming systems in the Netherlands (an arable farm on clay soil, a dairy farm on peat soil, and a mixed farm on sand soil) to determine if we can create tailor-made solutions for conventional farming systems towards regenerative agriculture. In total, we created 4,000 tailor-made solutions per case-study farm tailored to their local context. For all farming systems, environmental performance was improved in the solutions dominated by the use of regenerative management practices. For example, for the arable, the dairy, and the mixed case-study farm, greenhouse gas emissions were reduced by 50% (from 4 to 2 Mg CO_2 eq. ha^{-1}), 6% (from 30 to 28 Mg CO_2 eq. ha^{-1}), and 23% (from 21 to 16 Mg CO_2 eq. ha^{-1}), respectively, while maintaining soil functionality at high capacity for four out of the five soil functions. This overall improvement in environmental performance due to the application of regenerative management practices, also resulted in reduced farm profitability for all case-study farms by on average 50%. Reduced farm profitability as a consequence of shifting towards regenerative management could halt the transition towards regenerative agriculture.

1. Introduction

The urgency to move towards healthy and regenerative food systems is increasingly acknowledged in international agreements such as the Common Agricultural Policy (European Commission, 2019a), the Biodiversity Strategy (European Commission, 2021), and the European Green Deal (European Commission, 2019c). For the agricultural sector, as part of our global food system, a wide variety of sustainable farming approaches aim to produce a sufficient amount of food, while respecting the boundaries of our planet (FAO and ITPS, 2021). Regenerative agriculture is one of these farming approaches and was defined in Chapter 2 as: *"an approach to farming that uses soil health as the entry point to regenerate and contribute to multiple ecosystem services, with the aspiration that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production"*. Although literature states that regenerative agriculture aims to be a farming approach with a positive impact on various dimensions of sustainable food production (Fenster et al., 2021a; LaCanne and Lundgren, 2018), it often remains unclear how farmers can contribute to the objectives of regenerative agriculture.

Recent critiques of regenerative agriculture state that the objectives of regenerative agriculture are broad and not specific for local contexts (Giller et al., 2021). The local contexts of farming systems can be very different indeed (climate, landscape, and management) and set the conditions to the objectives and solutions (e.g. tillage and fertilizer application). Therefore, tailor-made solutions are key to make regenerative agriculture a success. The body of scientific literature on the impacts of tailor-made solutions has increased recently, including studies on measurement schemes for regenerative agriculture (Brown et al., 2021; Elevitch et al., 2018; Luján Soto et al., 2020), the assessment of practices (Fenster et al., 2021; Kröbel et al., 2021), measurements of impacts (LaCanne and Lundgren, 2018; Luján Soto et al., 2021), and the institutional changes required (Gosnell et al., 2019; Vermunt et al., 2022). However, it remains unknown from these studies to what extent tailor-made solutions can contribute to the objectives of regenerative agriculture. To support farmers in their transitions towards regenerative agriculture, an approach is needed that shows which solutions could contribute to regenerative objectives relevant in their local contexts.

Farm focused models have proved to be effective tools for the assessment and *ex-ante* redesign of farming systems (Pannell, 1996; Reidsma et al., 2018). From the myriad of farm-models used by researchers, in Chapter 3 we developed a modelling framework specifically designed to explore the consequences of regenerative farming solutions, and design more sustainable future farming systems. More specifically, this framework uses soil management practices at field scale as the basis for optimizing the overall environmental and socio-economic sustainability of a farm. As such, this modelling framework is the first to combine assessments of soil health with assessments of the overall environmental and economic sustainability of farms. Soil health refers in this paper to the multifunctionality of the soil to support a vital living ecosystem (Creamer et al., 2022). To accumulate knowledge, support debates, and provide stakeholders with the knowledge needed to transition towards regenerative agriculture, we build upon the framework of Chapter 3 to explore tailor-made solutions for contrasting farming systems.

To do this, the Netherlands was selected as a suitable case study because of their intensive agricultural landscape. Currently, 54% of the surface area in the Netherlands is used for agriculture, dominated by dairy and arable farming (CBS, 2020; CLO, 2020). The dairy sector contributes significantly to national emissions, producing 85% of the ammonia (CBS, 2019) and 11% of the total GHG emissions (van Eerdt and Westhoek, 2019). Dairy farmers rely heavily on imports of concentrate feed: 40% of the cow's protein intake is derived from imported feed (van der Meulen, 2021). Furthermore, ~60% of the dairy farmers export parts of their manure from the farm (Luesink, 2021), while arable farmers use relatively large amounts of inorganic nitrogen fertilizers (106 kg N ha^{-1} yr^{-1}) (Leeuwen, 2021). We use three typical Dutch farming systems (i.e. arable farming on clay soil, dairy farming on peat soil, and mixed farming on sandy soil). These typical Dutch combinations of soil and farming systems each have their own challenges (e.g. soil compaction on clay soils, carbon emissions from drained peat soils, and nutrient leaching from sandy soils) and give ample opportunity for the exploration of tailor-made solutions towards regenerative agriculture for contrasting contexts.

2. Methods

Figure 1 illustrates our approach to explore tailor-made solutions. First, we selected typical Dutch farming systems and subsequently used *ex-ante* redesign for exploring a multitude of tailor-made solutions composed of combinations of practices. The *ex-ante* redesign procedure consisted of the following sub-steps: a) from field to farm-level assessment using the soil as the starting point, b) tailoring practices to local conditions, c) creating explorative regenerative scenarios, and d) exploring alternative farm configurations. The steps will be discussed in more detail below.

2.1 Selection of typical Dutch farming systems

In order to make this research widely interpretable, we aimed to find case-study farms representative of a larger group of similar Dutch farming systems. To select representative case-study farms we used the 14 different Dutch agricultural regions according to Central

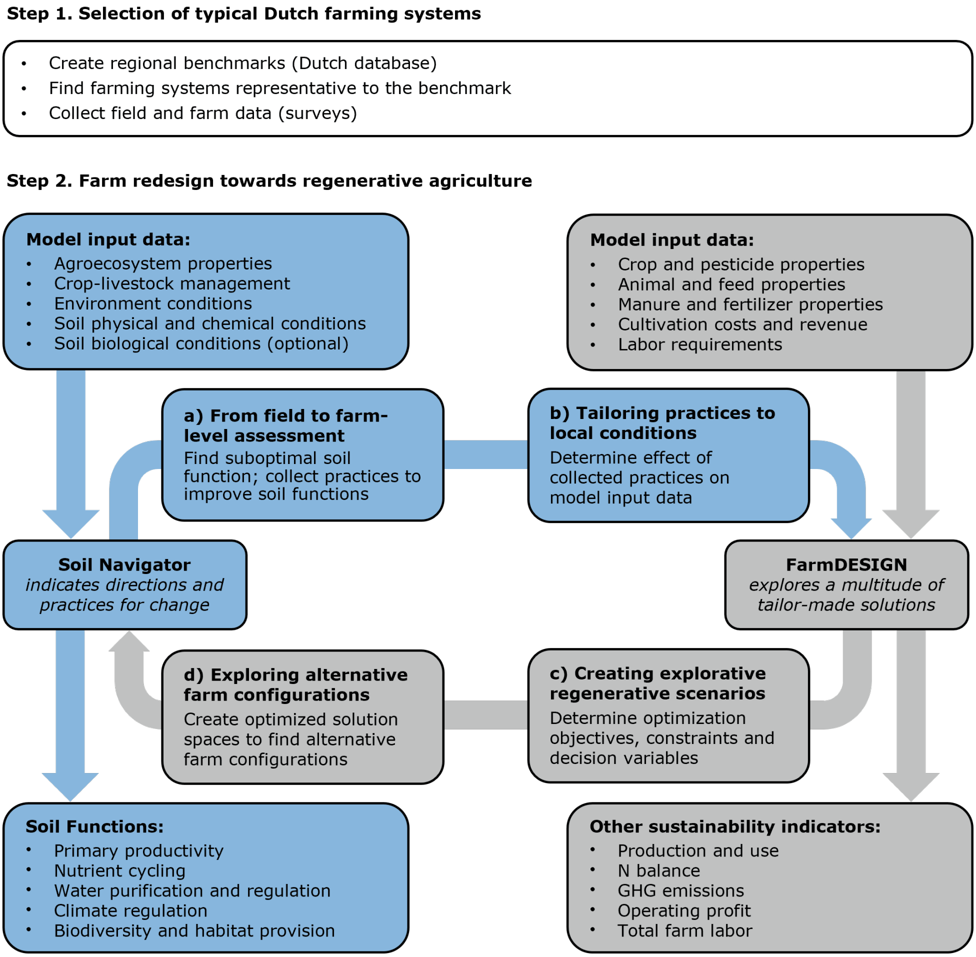

Figure 1. *Visualization of the methodology used to explore tailor-made solutions for typical Dutch farming systems towards regenerative agriculture, using the modelling framework of Chapter 3. In blue the steps in the farm redesign cycle associated with Soil Navigator and in grey with FarmDESIGN.*

Bureau of Statistics (CBS, 2022). The 14 agricultural regions and soil types in the Netherlands are shown in Figure 2. Data on farm characteristics for the regions were obtained from the main Dutch agricultural database: '*Bedrijveninformatienet*' (https://www.agrimatie.nl). To find regions typically known for dairy farming on peat soil, arable farming on clay soil, and mixed farming on sandy soil we assessed the homogeneity of the soil and the similarities in farm characteristics (e.g. farm type, farm layout, farm management, cropping patterns, primary cash crops, livestock holdings, and market orientation). The regions with the largest number of farming systems were used as a benchmark to further select case-study farms: the southern clay region for arable farming, the western peat meadow region for dairy farming, and the eastern sand region for mixed farming.

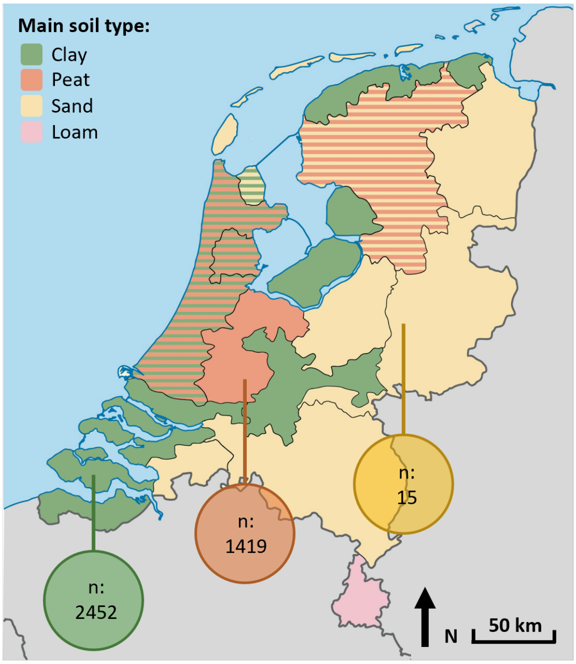

Figure 2. *Map of the Netherlands divided in 14 agricultural regions showing the selected benchmarks for different farm and main soil types, based on CBS (2022). The selected regions are indicated with a text-cloud that shows the number (n) of farming systems in the Dutch database used as benchmark.*

In order to select case-study farms, we approached representative farming systems from the selected regions to determine their willingness to participate in data collection. Farm specific data for the selected case-study farms were collected using a self-made survey tool containing semi-structured questions in September 2020. These data covered parameters related to the farm environment (e.g. pedoclimatic conditions), farm management (e.g. fertilizer use, cropping pattern), yields of crops and animal performance with related products, and economics (e.g. farm expenses and labor prices) on an annual basis. An overview of farm characteristics of the benchmark and case-study farms is shown in Table 1 (additional information is provided in supplementary materials S1). Parameters not readily available on the farm, such as the effective organic matter of grassland, were estimated using secondary literature.

The *arable case-study farm* on clay soil had 45 ha of cropland, which was divided in 16.3 ha to produce ware potatoes, 10.7 ha for sugar beet, 8.9 ha for winter wheat, 5.8 ha for chicory, 2.5 ha for kidney beans, and 0.7 ha for lucerne. Crop residues were removed from the land and the main source of fertilization was pig slurry (on average 107 kg N ha^{-1}; 35 kg P ha^{-1}) and inorganic fertilizers (on average 88 kg N ha^{-1}). A wide range of synthetic pesticides was applied for crop protection and disease suppression.

The *dairy case-study farm* on peat overlaying a clay soil had a total farm area of 40.4 ha, used to feed 99 dairy cows. The grassland close to the farm (16.9 ha) was used alternately for grazing and mowing. Grassland located further from the farmyard (23.5 ha) was used for mowing only. The cows were in the pasture for 4 hours a day, 150 days a year; for the remainder of the time the cows remained in the barn. In addition to grass, the diet of the cattle was supplemented with purchased maize, wheat straw, and concentrate feed. The grassland was fertilized using cow slurry (240 kg N ha^{-1}; 85 kg P ha^{-1}) and inorganic fertilizers (75 kg N ha^{-1}; 10 kg P ha^{-1}). No synthetic pesticides were used.

Table 1. *Overview of the farm characteristics of the benchmark with standard deviation and selected case-study farms.*

	Arable farms on clay		Dairy farms on peat		Mixed farms on sand	
Indicators	**Benchmark**	**Case-farm**	**Benchmark**	**Case-farm**	**Benchmark**	**Case-farm**
Farm area (ha)	44±51	45	48±30	40	92±64	54
Number of cows per farm	-	-	84±54	99	71±63	115
Livestock density (LU ha^{-1})*	-	-	2.0±1	3.3	2.2±1	2.8
Time grazing (d yr^{-1})	-	-	111±83	150	123±42	239
Time grazing (h day^{-1})	-	-	7±2	4	7±2	7
Milk yield (kg cow^{-1})	-	-	8422±1147	8720	9362±1151	8242
Milk yield (kg ha^{-1})	-	-	13304±4863	21384	16381±5510	16170
Concentrate use (kg DM cow^{-1})	-	-	2344±549	2687	2420±561	1940
Inorganic fertilizer use (kg N ha^{-1})	143±24	88	104±62	75	74±46	63
Pesticide use (kg AI ha^{-1})**	7±0	6.7	0±0	0	1±1	1.4

*LU = livestock units; **AI = Active Ingredients

The *mixed case-study farm* on sandy soil had both grassland and arable land to produce fodder crops. The grassland was separated in 23.6 ha grass used for alternated grazing and mowing and grasslands at a greater distance from the farmyard (10.4 ha) were used for mowing only. The cows were in the pasture for 7 hours a day, 239 days a year; they remained in the barn for the remainder of the time. In addition to grass, the diet of the cattle was supplemented with fodder crops produced on the farm and purchased concentrate feed. The area used to produce fodder crops was divided in 10.9 ha of maize, 5.6 ha of winter wheat, 1.7 ha of lucerne and peas (fed as whole plant silage), 2.5 ha of fodder beet, and 1.8 ha of summer barley (fed as whole plant silage). The grassland was fertilized using cow slurry (130 kg N ha^{-1}; 33 kg P ha^{-1}) and inorganic fertilizer (100 kg N ha^{-1}). The arable land was also fertilized with cow slurry (on average 116 kg N ha^{-1}; 35 kg P ha^{-1}) and inorganic fertilizer (48 kg N ha^{-1}). A limited amount of synthetic pesticides was used for crop protection and disease suppression.

2.2 Farm redesign towards regenerative agriculture

The *ex-ante* redesign process to explore tailor-made solutions towards regenerative agriculture used the modelling framework of Chapter 3. Chapter 3 determined that the objectives relevant at the farm-level were to “enhance and improve soil health”, thereby increasing the contribution of soil within the farming system to support multiple ecosystem services; “alleviation of climate change”, “improvement of nutrient cycling”, “improvement of water quality and availability”, “improvement in economic prosperity”, and “improvement in human health”. The modelling framework combines two models (see Figure 1 and the next two sections for a detailed explanation of each model):

1. Soil Navigator (SN): a decision support tool to assess and optimize five soil functions at the field-level (Debeljak et al., 2019).
2. FarmDESIGN (FD): a bio-economic model to explore and optimize overall farm sustainability (Groot et al., 2012).

The optimization of SN allowed for the recommendation of soil management practices that improve and optimize the five soil functions. These practices were subsequently incorporated in FD to identify potential synergies and trade-offs with other sustainability indicators.

2.2.1 Soil Navigator

SN was used to assess soil multifunctionality as the entry point for farm redesign, in line with the scientific definition of regenerative agriculture (Chapter 2). SN is a field-level decision support tool developed to qualitatively assess five soil functions simultaneously as low, medium, or high over a five-year period (Debeljak et al., 2019): primary productivity, nutrient cycling, water purification and regulation, climate regulation, and biodiversity and habitat provision. These five soil functions play a key-role in the supply and demand for soil-based ecosystem services (Schulte et al., 2014) and, therefore, were used in the modelling framework of Chapter 3. SN captures the synergies (positive relationships) and trade-offs (negative relationships) between these soil functions in response to changes in management (Zwetsloot et al., 2020). The input data required for SN include data on the environment (i.e. average air temperature and precipitation), farm management (i.e. tillage and the amount of N fertilizer applied to the field) and the soil (i.e. clay content and soil organic matter). The capacity of the soil to supply the five functions resulted from integrated hierarchical decision-support models. These models were structured, calibrated, and validated for grassland and cropland using datasets collected across Europe (Sandén et al., 2019; Schröder et al., 2016; van de Broek et al., 2019; van Leeuwen et al., 2019; Wall et al., 2020). Although SN was developed for pan-European coverage of soils, Chapter 3 highlighted that calibration and validation on peat soils has thus far remained limited. Besides the assessment of soil functions, SN offers the possibility to optimize soil functions based on user-set objectives (e.g. medium or high scores for any of the functions). SN shows if the objectives can be achieved; it proposes directions for change and farming practices (i.e. solutions) needed to meet the objectives (further details about the construction of SN are described in supplementary materials S2 and by Debeljak et al. (2019)).

2.2.2 FarmDESIGN

FD was used to show a multitude of different farm configurations (i.e. combinations of solutions) that each contribute in varying degrees to the objectives of regenerative agriculture. FD is a static, bio-economic whole-farm model consisting of a large array of interrelated farm components developed for the analysis and redesign of mixed crop-livestock systems (Groot et al., 2012). FD quantifies farm-level resource flows calculating annual balances for materials, animal feeds, economics and labor. The resource flows are grouped into modules and are used as proxy indicators to assess both the environmental and socio-economic performance of a farm. From the wide variety of indicators available in FD, a selected set of indicators showed to be congruent with the objectives of regenerative agriculture Chapter 3 and are used in this study: soil organic matter (SOM) balance, nitrogen (N) balance, GHG emissions, operating profit, and farm labor balance. Besides the quantification of flows, FD also enables the exploration of optimized farm configurations, which are generated by a Pareto multi-objective optimization, based on two or more user-defined objectives (e.g. minimize GHG emissions and maximize farm profitability), a set of decision variables (e.g. upper and lower limits on animal numbers or crop areas) and preset constraints (e.g. lower and upper limits on animal feed requirements). The new farm configurations are new land-use and resource allocation configurations that result in optimized performance indicators (e.g. reduced GHG emissions). These new configurations have, for example, new crop or animal products being introduced on the farm, different crop areas and allocation of crop products, and changes in herd size (more details about the construction of FD are given in the supplementary materials S3 and described by Groot et al. (2012).

2.2.3 From field to farm-level assessment using the soil as the starting point

SN is used as a starting point to assess the current status of the five soil functions for each field. However, in order to relate these functions to other farm sustainability indicators (e.g. GHG emissions and farm profitability) soil functionality must be expressed at farm-level. To aggregate the performance of each of the soil functions from field to farm-level, we first assessed the divergence between fields, based on agroecosystem conditions (e.g. land-use), management (e.g. tillage), environmental conditions (e.g. annual precipitation), and soil conditions (e.g. ground water table). Fields with the same conditions and management were merged into a single functional unit (one model application). Separate functional units (multiple model applications) were created for fields with diverging conditions or management. For example, for the dairy case-study farm most fields on the farm were grassland with the same agroecosystem, management practices, environment, and soil characteristics. The dairy case-study farm, therefore, resulted in two separate functional units, one that was dedicated to grassland used for alternately grazing and mowing; the other for mowing only. Due to more divergence in land-use (multiple crops) and related management practices, the arable and mixed case-study farms were captured using six and seven functional units, respectively. Supplementary materials S4 show the variation of soil attributes between fields, which did not lead to further disaggregation of functional units. The qualitative assessments of soil functions from the individual functional units were aggregated to the farm-level using area-weighted averages. Variation between functional units within the farm is presented in the result section using error bars.

After aggregation, we employed the optimization function of SN to determine how each soil function that currently performed at sub-optimal capacity could be improved. This resulted in an inventory (Table 2) of directions for change (e.g. reduce total N fertilization) along with suggested farming practices (e.g. use solid manure). Where these directions for change and suggested practices were congruent with the objectives of regenerative agriculture, they were used to create scenarios for regenerative soil management. For example, for the mixed case study farm SN suggested to increase inorganic N fertilizers to improve nutrient cycling and primary productivity. Although the use of inorganic fertilizers may indeed contribute to nutrient cycling and primary productivity in the soil, it is not in line with the overall objective of regenerative agriculture to reduce external inputs. For this reason we added two directions for change to the use of inorganic fertilizers and synthetic pest and weed control.

2.2.4 Tailoring practices to local conditions

SN provided directions for change along with farming practices applicable to the local context of the case-study farms. The effect of the suggested practices on the input attributes for SN and FD, however, was still unknown. Therefore, we tailored the suggested practices to local conditions within a five-year period. Tailoring of practices to local conditions to achieve the desired effect is currently an unautomated process and requires expert opinion. For example, for the dairy and mixed case-study farms, SN suggested to increase the share of legumes. The type of legumes to be used and their share in grasslands remained unclear. Based on secondary literature (e.g. Hayes et al., 2019; Mytton et al., 1993) and expert opinion (all co-authors and four experts per case-study farm, see acknowledgements) we chose to implement species-rich grassland and reparametrized the requirements accordingly. The selected mixture of forb species for the case-study farms, however, differed from each other. For example, for the dairy case-study farm on peat soil, we used white clover only, with a share of 30% in grassland. For the mixed case-study farm on sandy soil, conditions were more favorable (e.g. better pH) for a wider variation of forb species. This allowed the use of red clover which has deeper roots compared to white and clover, and hence made a larger contribution of effective organic matter. Part of the reparametrized input data is shown in Table 3 – 5, using the Dutch feed evaluation system and units (Tamminga et al., 1994; van Es, 1975). The complete table of changed input attributes and justification for all crops of the case-study farms is provided in supplementary materials S5.

Table 2. *Directions for change along with farming practices suggested by Soil Navigator for improving the three case-study farms. The asterisk (*) refers to additional practices included according to the review of Chapter 2. Soil functions were abbreviated: water purification and regulation (WR), biodiversity and habitat provision (BD), climate regulation (CR) and nutrient cycling (NC). Empty spaces indicate that the directions of change or farming practices were not suggested for the specific case-study farm.*

Soil function	**Directions for change**	**Suggested farming practices**			
		Arable farm	**Dairy farm**	**Mixed farm**	
				Grassland	**Cropland**
WR	Increase share of legumes	Increase area of lucerne	Introduce species-rich grassland	Introduce species-rich grassland	
	Reduce N application		Introduce species-rich grassland		
	Increase irrigation frequency/rate	Increase irrigation			
BD	Apply solid manure	Introduce solid manure	Introduce solid manure		Introduce solid manure
	Increase soil organic matter and soil C/N ratio	Reduce tillage frequency/intensity			
		Return crop residues to the soil			
		Introduce solid manure			
		Introduce cover crops			Introduce cover crops
	Increase grassland diversity			Introduce species-rich grassland	
	*Improve habitat for soil organisms and reduce pesticide leaching	Avoid synthetic pest and weed control			Avoid synthetic pest and weed control
CR	Reduce total N fertilization	Limit total N fertilization	Limit total N fertilization	Limit total N fertilization	Limit total N fertilization
	*Improve N fertilizer self-reliance	Avoid inorganic fertilizers	Avoid inorganic fertilizers	Avoid inorganic fertilizers	Avoid inorganic fertilizers
NC	Reduce soil bulk density				Introduce solid manure
					Return crop residues to the soil

***Table 3**. Part of the composition table of the arable case-study farm showing annual input data used in FarmDESIGN for reference and regenerative management.*

Reference management					
Input attribute	**Unit**	Lucerne	Sugar beet	Potato	Winter wheat
Nitrogen fixation	kg ha^{-1}	122	0	0	0
Effective org. matter	kg ha^{-1}	1550	375	875	2514
Cultivation costs	€ ha^{-1}	333	1300	3100	1071
Required labor	h ha^{-1}	5	25	30	17
Price fresh matter	€ kg^{-1}	0	0.04	0.14	0.16
Dry matter yield	kg ha^{-1}	10000	21800	7368	8680
Regenerative management					
Input attribute	**Unit**	Lucerne	Sugar beet	Potato	Winter wheat
Nitrogen fixation	kg ha^{-1}	122	0	0	0
Effective org. matter	kg ha^{-1}	1550	2149	1749	3504
Cultivation costs	€ ha^{-1}	281	1579	2657	621
Required labor	h ha^{-1}	5	75	34	19
Price fresh matter	€ kg^{-1}	0	0.04	0.14	0.16
Dry matter yield	kg ha^{-1}	8571	14497	5575	7315

Values were based on farm interviews, expert opinion (all co-authors and three grassland experts, see acknowledgements) and the following secondary literature: Bom (1983), Bosch and de Jonge (1989), de Wolf et al. (2019), Feedipedia (2020), Geel and Brinks (2018), Gren (1994), Scheepens (2001), Schröder et al. (2003), Starmans et al. (2015), van der Voort (2018), and van der Weide et al. (2008).

***Table 4**. Part of the composition table of the dairy case-study farm showing annual input data used in FarmDESIGN for reference and regenerative management.*

		Reference management		**Regenerative management**	
Input attribute	**Unit**	Grazed grass	Grass silage	Grazed grass-clover	Grass grass-clover
Nitrogen fixation	kg ha^{-1}	0	0	172	172
Effective org. matter	kg ha^{-1}	2000	2000	1540	1540
Cultivation costs	€ ha^{-1}	988	988	988	988
Required labor	h ha^{-1}	18	21	21	25
Price fresh matter	€ kg^{-1}	0	0.06	0	0.07
Dry matter yield	kg ha^{-1}	1969	28561	1969	28561
Feed saturation value (VW)	-	0.89	1.02	0.89	1.02
Feed structure value (SW)	-	1.88	3.02	1.88	3.02
Energy content (VEM)	-	960	888	979	906
Protein content (DVE)	g kg DM^{-1}	92	67	93	68

Values were based on farm interviews, expert opinion (all co-authors and three grassland experts, see acknowledgements) and the following secondary literature: Blanken et al. (2018), Bosch and de Jonge (1989), CVB (2018), de Wit et al. (2004), Feedipedia (2020), Goyens (2016), and van der Voort (2018).

Table 5. *Part of the composition table of the mixed case-study farm showing annual input data used in FarmDESIGN for reference and regenerative management.*

Reference management

Input attribute	**Unit**	Grazed grass	Grass silage	Fodder beet	Maize
Nitrogen fixation	kg ha^{-1}	0	0	0	0
Effective org. Matter	kg ha^{-1}	2000	2000	375	675
Cultivation costs	€ ha^{-1}	1200	1200	1621	1579
Regular labor	h ha^{-1}	25	30	31	37
Price fresh matter	€ kg^{-1}	0.00	0,06	0,05	0,06
Dry yield	kg ha^{-1}	5084	10219	15400	15567
Feed saturation value (VW)	-	0,89	1,01	0,69	0,79
Feed structure value (SW)	-	1,88	2,82	1,10	1,50
Energy content (VEM)	-	960	888	1079	1000
Protein content (DVE)	g kg DM^{-1}	92	67	104	70

Regenerative management

Input attribute	**Unit**	Species-rich grazed grass	Species-rich grass silage	Fodder beet	Maize
Nitrogen fixation	kg ha^{-1}	190	190	0	0
Effective org. Matter	kg ha^{-1}	2000	2000	1775	675
Cultivation costs	€ ha^{-1}	1200	1200	1946	1801
Regular labor	h ha^{-1}	30	35	91	107
Price fresh matter	€ kg^{-1}	0.00	0,07	0,05	0,06
Dry yield	kg ha^{-1}	5466	10985	13090	15567
Feed saturation value (VW)	-	0,90	1,02	0,69	0,79
Feed structure value (SW)	-	2,00	2,90	1,10	1,50
Energy content (VEM)	-	989	915	1079	1000
Protein content (DVE)	g kg DM^{-1}	95	69	104	70

Values were based on farm interviews, expert opinion (all co-authors and three grassland experts, see acknowledgements) and the following secondary literature: Blanken et al. (2018), Bom (1983), Bosch and de Jonge (1989), CVB (2018), de Wit et al. (2004), de Wolf et al. (2019), Feedipedia (2020), Geel and Brinks (2018), Goyens (2016), Gren (2018), Scheepens (2001), Schröder et al. (2003), Starmans et al. (2015), van der Voort (2018), and van der Weide et al. (2008).

2.2.5 Creating explorative regenerative scenarios

After tailoring the suggested practices to local conditions, we created two scenarios in FD for each case-study farm. The first scenario allowed the model to choose between combinations of reference and regenerative management (combined scenario). The second scenario allowed regenerative management only (regenerative scenario). Using these two scenarios increased the diversity of farm configurations towards regenerative agriculture. The scenarios in FD were further accompanied by constraints, decision variables and objectives. Constraints were set to maintain a realistic operating space. For example, constraints were set for the feed balance to match animal requirements and availability of energy, protein, dry matter intake capacity and saturation (to match animal intake capacity). Decision variables gave FD room for exploration as they allow the user to indicate in which range a variable can change. For example, in what range animal numbers or crop areas may increase or decrease. A complete list of parameter settings for the three case-study farms is shown in supplementary materials S6.

The objectives of regenerative agriculture were set in FD to give directions for optimization (e.g. reduce GHG emissions). The regenerative objectives were, however, not all equally relevant for the different case-study farms. In order to determine which regenerative objectives were most important at the farm-level a survey was conducted during a workshop, to demonstrate the working principle of the modelling framework to a wide variety of stakeholders (farmers, researchers, NGO's, government, and industries). The survey yielded 20 responses indicating the three most important objectives to be incorporated in FD for each case-study farm. The three most important objectives for arable farming on clay soil were deemed to be to maximize SOM (27%), minimize external inputs (26%), and maximize operating profit (18%). The most important objectives for dairy farming on peat soil were to minimize GHG emissions (29%), maximize profit (18%), and minimize external inputs (18%). The most important objectives for mixed farming on sandy soil were to minimize external inputs (27%), maximize operating profit (26%), and minimize the N balance (22%). Supplementary materials S7 shows more detail about the results of the survey.

2.2.6 Exploring alternative farm configurations

For each of the scenarios, we ran a multi-objective exploration in FD to create solution spaces which consist of alternative farm configurations (consisting of a combination of practices). The solution spaces can be used to find configurations most suitable to the individual farm, and to find relationships (e.g. synergies and trade-offs) between the optimization objectives. These relationships were found through visual inspection and regression analysis (supplementary materials S8). The multi-objective exploration was run separately for the combined and regenerative scenario, resulting in two solution spaces that each consisted of 2000 farm configurations. From the solution spaces, any farm configuration can be selected in the FD model, to further examine the performance for a wide range of farm sustainability indicators.

Three configurations were selected to be compared with the reference configuration. The first configuration (Configuration 1) was selected from the solution space of the combined scenario (combination of the reference and regenerative scenarios). We used a multi-objective filtering approach to decide which of the 2000 configurations best reflected the objectives obtained from the survey. We did this by ranking all configurations from 0 (best) to 2000 (worst) for each individual optimization objective. The configuration with the lowest aggregated score was selected and compared with the reference configuration. A second farm configuration (Configuration 2) was selected based on the largest area of land dedicated to regenerative management within the combined scenario. Through

Configuration 2, it was possible to show to what extent regenerative management was used. The last farm configuration (Configuration 3) was selected from the solution space created by running the regenerative scenario only. We used the multi-filtering approach again to find the overall best configuration. The selected farm configurations were re-entered into SN, in order to assess the improvement of soil functions that resulted from the explorations in FD. Table 6 – 8 show some of the input attributes that changed for this second iteration of assessment in SN for the different scenarios. Configurations 1 and 2 use both the reference and regenerative scenario (combined scenario) in different extents; Configuration 3 uses solely the regenerative scenario. The complete table of changed input attributes can be found in supplementary materials S9.

Table 6. *Input attributes for SN which changed between the reference and regenerative scenario of the arable case-study farm.*

Reference scenario					
Input	**Unit**	Sugar beet	Chicory	Potato	Winter wheat
Tillage	Yes/no	Yes	Yes	Yes	Yes
Use of catch crops and crop residues in the field	yr	0	0	0	5
Application of mineral fertilizer	Yes/no	yes	yes	yes	yes
Mineral N fertilization	kg N ha^{-1}	75-100	125-150	75-100	75-100
Mineral P fertilization	kg P ha^{-1}	<10	<10	<10	<10
Type of manure	-	No	No	Pig slurry	Pig slurry
Organic N fertilizer	kg N ha^{-1}	0	0	>200	>200
Chemical pest management	Yes/no	yes	yes	yes	yes
Irrigation rate	mm h^{-1}	0	0	6-12	0
Irrigation frequency	Days	0	0	<10	0
Regenerative scenario					
Input	**Unit**	Sugar beet	Chicory	Potato	Winter wheat
Tillage	Yes/no	No	No	No	No
Use of catch crops and crop residues in the field	yr	5	5	5	5
Application of mineral fertilizer	Yes/no	no	no	no	no
Mineral N fertilization	kg N ha^{-1}	0	0	0	0
Mineral P fertilization	kg P ha^{-1}	0	0	0	0
Type of manure	-	Solid manure	Solid manure	Solid manure	Solid manure
Organic N fertilizer	kg N ha^{-1}	75-100	50-75	125-150	100-125
Chemical pest management	Yes/no	no	no	no	no
Irrigation rate	mm h^{-1}	6-12	6-12	6-12	6-12
Irrigation frequency	Days	<10	<10	<10	<10

Table 7. *Input attributes for SN which changed between the reference and regenerative scenario of the dairy case-study farm.*

		Reference scenario		**Regenerative scenario**	
Input	**Unit**	**Alternated grazing and mowing**	**Mowing only**	**Alternated grazing and mowing**	**Mowing only**
Number of years with legumes	Yr	0	0	5	5
Share of legumes on the field	%	<10	<10	>10	>10
Grassland diversity	N species	1	1	2	2
Application of mineral fertilizer	Yes/No	Yes	Yes	No	No
Mineral N fertilization	kg N ha^{-1}	75-100	75-100	0	0
Type of manure	-	Cow slurry	Cow slurry	Solid manure	Solid manure
Organic N fertilizer	kg N ha^{-1}	>200	>200	75-100	75-100

Table 8. *Input attributes for SN which changed between the reference and regenerative scenario of the mixed case-study farm.*

Reference scenario						
Input	**Unit**	**Alternated grazing and mowing**	**Mowing only**	**Maize**	**Fodder beet**	**Winter wheat**
Tillage	Yes/no	No	No	Yes	Yes	No
Number of years with legumes	Yr	0	0	-	-	-
Grassland diversity	-	1	1	-	-	-
Use of catch crops and crop residues in the field	Yr	-	-	0	1	3
Application of mineral fertilizer	yes/no	yes	yes	yes	yes	yes
Mineral N fertilization	kg N ha^{-1}	75-100	75-100	<50	75-100	75-100
Mineral P fertilization	kg P ha^{-1}	<10	<10	<10	<10	<10
Type of manure	-	Cow slurry	Cow slurry	Cow slurry	Cow slurry	Cow slurry
Organic N fertilizer	kg N ha^{-1}	125-150	125-150	125-150	125-150	100-125
Chemical pest management	Yes/no	yes	yes	yes	yes	Yes

Regenerative scenario						
Input	**Unit**	**Alternated grazing and mowing**	**Mowing only**	**Maize**	**Fodder beet**	**Winter wheat**
Tillage	Yes/no	No	No	No	No	no
Number of years with legumes	Yr	5	5	-	-	-
Grassland diversity	-	>2	>2	-	-	-
Use of catch crops and crop residues in the field	Yr	-	-	5	5	5
Application of mineral fertilizer	yes/no	No	No	No	No	No
Mineral N fertilization	kg N ha^{-1}	-	-	-	-	-
Mineral P fertilization	kg P ha^{-1}	-	-	-	-	-
Type of manure	-	Solid manure	Solid manure	Solid manure	Solid manure	Solid manure
Organic N fertilizer	kg N ha^{-1}	75-100	75-100	100-125	125-150	125-150
Chemical pest management	Yes/no	no	no	no	no	no

3. Results

SN showed which soil functions could be improved using various farming practices for the different case-study farms (Section 2.2.3 and Table 2). Through FD we created in total 4000 solutions per farm consisting of solution spaces of 2000 farm configurations with a combination of reference and regenerative management practices and 2000 farm configurations with regenerative management practices only (Figure 3, Figure 5, and Figure 7). In the following sections we will show these solution spaces for the case-study farms and discuss the synergies and trade-offs between the optimization objectives. Furthermore, we will discuss the impact of the optimizations on soil functions, as well as the other sustainability indicators.

3.1 Arable case-study farm

3.1.1 Solution spaces of farm configurations

Figure 3 shows the solution spaces for the arable farm. The area of regenerative farmed land varied largely across alternative configurations (supplementary materials S11). For example, the majority (71%) of configurations used regenerative practices on 50 to 75% of their total farm area. The solution space of the combined scenario was larger than that of the regenerative scenario which accounts for all farms. The smaller solution space for the regenerative scenario resulted from additional constraints that for example did not allow

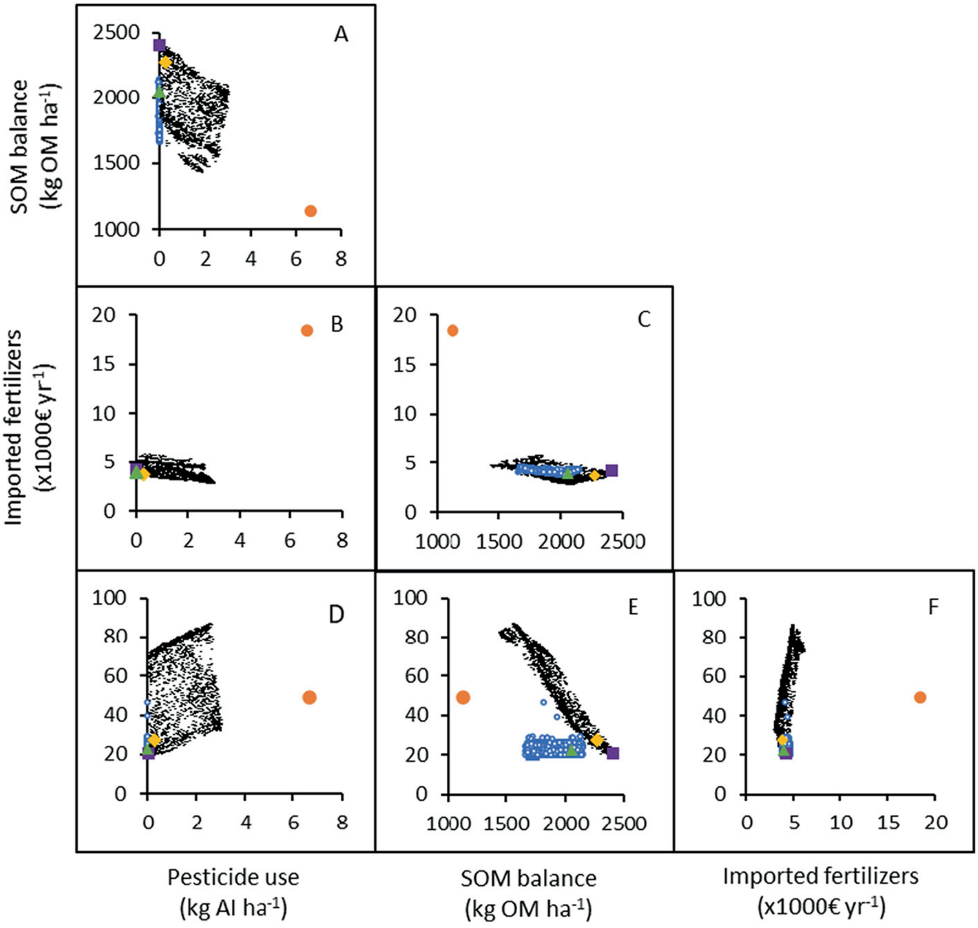

***Figure 3**. Solution spaces of alternative farm configurations in terms of imported fertilizers, pesticide use, SOM balance and operating profit for the arable case-study farm.*

the import of inorganic fertilizers and synthetic pesticides. The farm configurations outperformed the reference configuration on all objectives except for operating profit. Increasing operating profit has a trade-off with increasing the SOM balance (Figure 3D), reducing pesticide use (Figure 3E), and reducing imported fertilizers (Figure 3F). These relationships relate to larger areas in farm configurations with regenerative management yielding more effective organic matter due to, for example, returning crop residues to the soil and making use of cover crops. Avoiding the use of pesticides, reducing total N fertilization and fully substituting solid manure for additional inorganic N fertilizers would lead to lower crop production yields, and hence lower profits. The objective to increase the SOM balance had a synergy with reducing imported fertilizers (Figure 3C). Supplementary materials S8 gives quantification regarding synergies and trade-offs for all case-study farms. Supplementary material S10 shows a sensitivity analysis of the decision variables and their influence on the various objectives in the combined scenario. Reducing imported fertilizers showed a slight trade-off with reducing pesticide use (Figure 3B).

3.1.2 Assessment on the objectives of regenerative agriculture

Figure 4 shows the performance of the selected farm configurations (Configurations 1,2, and 3) from the solution spaces in Figure 3 (absolute values are presented in supplementary materials S11). Where the majority of land is managed under regenerative practices, four out of five soil functions can be achieved at high capacity at the farm-level (Configuration 3). Nutrient cycling, however, declined from high to medium, when changing to regenerative management. More specifically, the functional units for regenerative sugar beet, chicory, and potato showed reduced underlying scores for the nutrient harvest index (supplementary materials S11). Although soil nutrient cycling performed at medium capacity, the farm N balance was reduced by 60% for the three configurations (from 117 to ~40 kg N ha^{-1}) mainly due to a reduction of imported fertilizers (especially inorganic fertilizers). Soil conditions to enhance optimal primary production remained the same in SN and performed at high capacity. For the regenerative scenario in FD, reduced yield values were the main driver for a reduction in operating profit, despite a considerable reduction in external input costs was established (e.g. fertilizer costs were reduced on average from 18450 to 4050 € yr^{-1}). Reduced fertilization in combination with the use of cover crops led to improvements of the climate regulation scores among configurations. In addition, GHG emissions at the farm-level were reduced for all selected configurations by 50% (from 4 to 2 Mg CO_2 eq. ha^{-1}; from 172 to 94 Mg CO_2 eq.) mainly by reducing external inputs (inorganic fertilizers and synthetic pesticides). Diesel use, however, increased due to the seeding of cover crops, mechanical weeding, and the use of irrigation. These practices, in combination with reduced fertilization, improved the score for water purification and regulation from low to high for all selected configurations. The function biodiversity and habitat provision improved from medium to high as a result of better soil structure, hydrology, and nutrient supply due to reduced tillage, eliminating pesticides, using solid manure, and returning crop residues to the soil. The use of solid manure and returning crop residues to the soil also increased the SOM balance at the farm-level by on average 97%. Farm labor increased for all selected farm configurations by 30-48%, due to a considerable higher labor requirement associated with regenerative crop maintenance. The higher labor requirement is a result of a large demand for hand weeding as a consequence of the elimination of synthetic pesticides. For example, sugar beet requires 65 h ha^{-1} of hand weeding if no synthetic pesticides are used (Praktijkonderzoek Plant & Omgeving B.V., 2009).

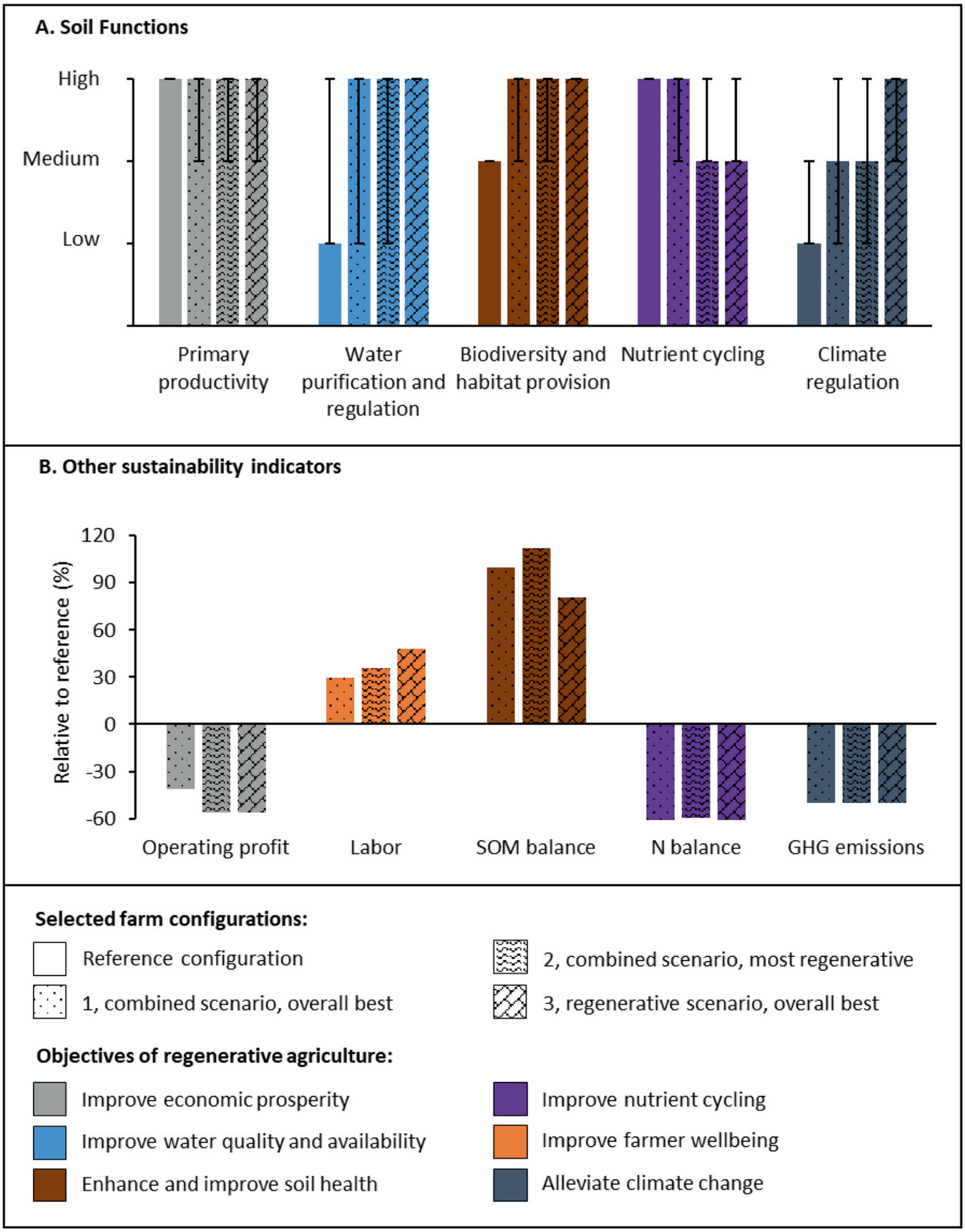

Figure 4. *The performance of farm configurations on the objectives of regenerative agriculture for the arable case-study farm, discriminated in soil functions (A) and other farm sustainability indicators (B). Error bars represent functional units with divergent scores from the area weighted averages, indicating within-farm variability. The performance of other sustainability indicators are shown relative to the reference scenario. The colors correspond to the objectives of regenerative agriculture.*

3.2 Dairy case-study farm

3.2.1 *Solution spaces of farm configurations*

Figure 5 shows the solution spaces for our dairy case-study farm. The solution space of the combined scenario has 52%, 37%, 11%, and 0% of the farm configurations within the range of 0-25%, 25%-50%, 50%-75%, and 75-100% of the total farm area used for regenerative management respectively (supplementary materials S11). The two scenarios resulted in two different solution spaces with the regenerative scenario showing a more condensed solution space compared to the combined scenario, similar to the results for the arable case-study farm. Among the solution spaces of both scenarios we found synergies and trade-offs.

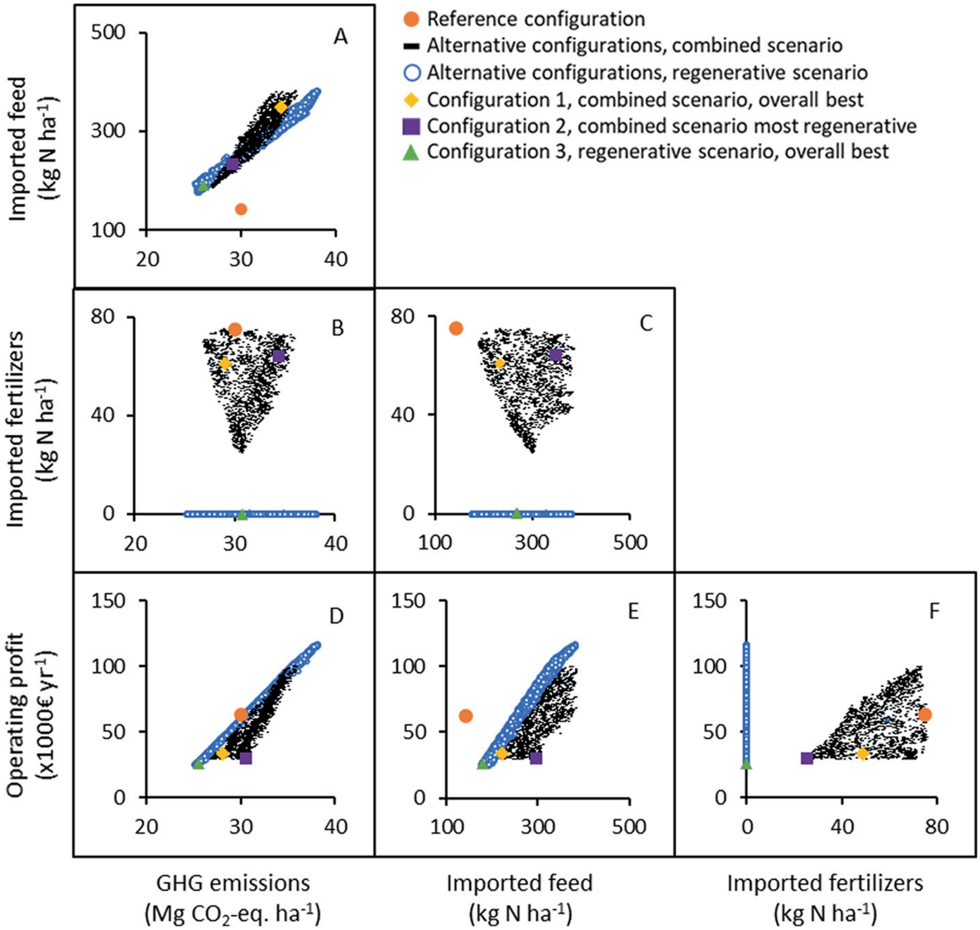

Figure 5. *Solution spaces of alternative farm configurations in terms of GHG emissions, imported fertilizers, imported feed and operating profit for the dairy case-study farm.*

The near-linear relationships in Figure 5A, 5D, and 5E share the same underlying drivers: Figure 5A shows a synergy between the objective to reduce imported feed and to reduce GHG emissions, i.e. reducing the import of concentrate feed leads to lower animal numbers and GHG emissions. Figure 5D shows a trade-off between increasing operating profit and reducing GHG emissions, i.e. an increase in operating profit also leads to an increase in GHG emissions. A trade-off was also found between reducing imported feed and increasing operating profit (Figure 5E). These relationships are a result of the increase in operating profit which relies on an increase in animal numbers and more milk production, and a higher external feed requirement, both resulting in increased GHG emissions. The objective to reduce external feed allowed the model to find solutions in which feed requirements match on-farm produced feed. Figure 5B, 5C, and 5F do not show a particular relationship for the combined scenario, rather a broad solution space. The regenerative scenarios of Figure 5B, 5C, and 5F clearly show that no imported fertilizers were used in these scenarios.

3.2.2 Assessment on the objectives of regenerative agriculture

Figure 6 shows the performance of the selected configurations from the solutions spaces (absolute values are presented in supplementary materials S11). It illustrates that four out of five soil functions can be achieved at high capacity if the majority of the land is used in a regenerative way. The selected configurations 1, 2, and 3 had various shares of land allocated to the regenerative scenario, i.e. 35%, 66%, and 100% respectively. The increase in land allocated to the regenerative scenario came at the expense of the soil function primary productivity, which declined from high to medium due to for example a reduction in N-fertilization rates. However, this decline in primary production was associated with an increase in the supply of other soil functions (i.e. water purification and regulation, nutrient cycling, and climate regulation). Figure 6 shows that compared to the baseline, farm profitability reduced by 40-60% (from 33412 to 26521 € yr^{-1}) for all selected configurations. The decrease in farm profitability was a result of lower animal numbers, hence less milk production. The reference and selected configurations 1, 2, and 3 included 99, 91, 93, and 87 dairy cows, respectively. Lower animal numbers were selected by the model to maintain animal nutrition requirements with lower quantities of imported feed and to reduce GHG emissions. Water purification and regulation increased from low to high capacity for the fully regenerative scenario only, with the integration of grass-clover and lower N fertilization. The objective to reduce quantities of imported fertilizers and feeds did not result in a significantly lower N balance, as it remained more or less stable for the selected configurations (from 258 to 274 kg N ha^{-1}). The decrease in farm N balance was limited, mainly due the increased N fixation which compensated for the reduction in total N fertilization (imported fertilizers and manure).

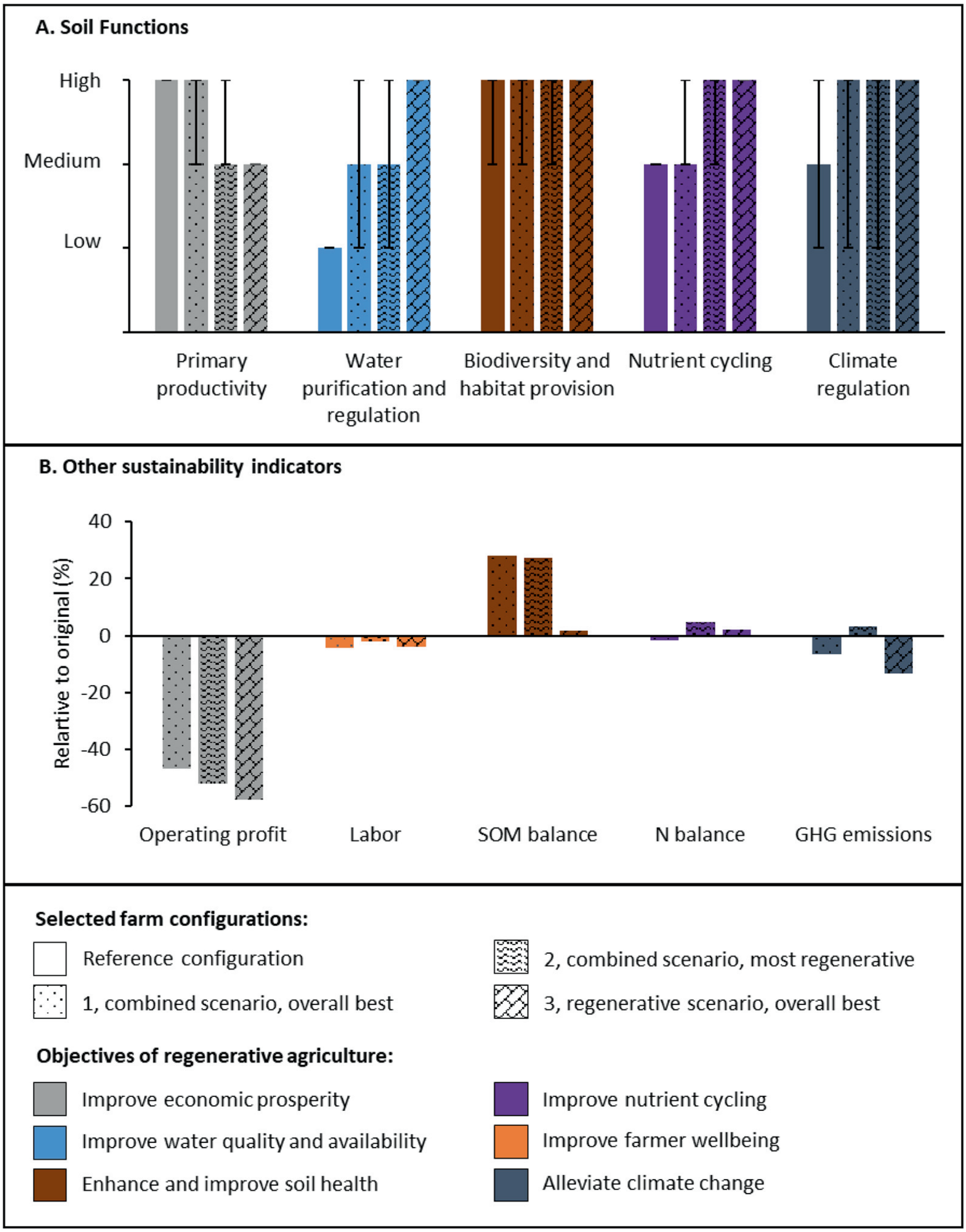

__Figure 6.__ The performance of farm configurations on the objectives of regenerative agriculture for the dairy case-study farm, discriminated in soil functions (A) and other farm sustainability indicators (B). Error bars represent functional units with divergent scores from the area weighted averages, indicating within-farm variability. The performance of other sustainability indicators are shown relative to the reference scenario. The colors correspond to the objectives of regenerative agriculture.

The soil function nutrient cycling improved from a medium to a high capacity for the selected configurations 2 and 3, due to including clover that improved nutrient recovery. The soil function biodiversity and habitat provision remained high for the selected farms as a result of increased grassland diversity and the application of solid manure. The farm SOM balance increased on average 28% for selected configurations 1 and 2. This indicates that the use of solid manure, which has a higher effective organic matter compared to slurry and inorganic fertilizers, outweighed the lower effective organic matter input from grass-clover compared to permanent grassland. In addition, lower animal numbers reduced the availability of manure, further reducing the SOM balance of configuration 1. Climate regulation improved from medium to high, in response to a reduction in total N fertilization, and hence N_2O emissions. The high score for climate regulation should be interpreted with caution, considering the limited calibration and validation of SN on peat soils Chapter 3. Decreases in overall GHG emissions (from 26 to 28 Mg CO_2 eq. ha^{-1}; from 1230 to 1050 Mg CO_2 eq.) reflected the improvements for climate regulation in configurations 1 and 3. However in configuration 2, a slight increase in GHG emissions was observed. This was due to a higher import of concentrate feed and slightly higher animal numbers. Farm labor decreased for the selected farms within the range of 2% to 4% (from 2863 to 2928 h yr^{-1}) due to lower animal numbers.

3.3 Mixed case-study farm

3.3.1 Solution spaces of farm configurations

Figure 7 shows the solution spaces for our mixed case-study farm, in which the combined scenario showed to have no alternative farm configurations dominated by regenerative management; in 84% of the farm configurations less than 25% of the land was managed regeneratively (supplementary materials S11). For the remainder of the farm configurations (16%), 25-50% of the land was managed regeneratively. Similar to the other case-study farms, the combined scenario resulted in a greater solution space in which farm configurations outperformed the reference configurations to different extents. Moreover, synthetic pesticides and inorganic fertilizer were reduced or even eliminated for all farm configurations (Figure 7B, 7C, 7G, 7H, 7I, and 7J). Furthermore, we observed a synergy between the objective to reduce pesticide use and imported fertilizers (Figure 7I), similar to the arable case-study farm. Another synergy was found between the objective to reduce imported feed and reduce the N balance, i.e. reducing imported feed leads to a reduced farm N balance. Trade-offs were found in the regenerative scenario for the objective to increase operating profit and reduce the farm N balance and imported feed (Figure 7D and E). Similar to the dairy case-study farm, this trade-off relates to higher feed imports required to maintain higher animal numbers and operating profits. Different from the dairy case-study farm, we found a clear inflection point in Figure 7E which indicates that operating profit can be increased until 70000 € yr^{-1} by using a limited amount of imported feed to support 80 cows. Moreover, the inflection point relates to the self-reliance of the farm. Supplementary material S11, specifically shows that when animal numbers increase above 80 cows, the farm is not self-sufficient in e.g. grass silage and concentrate feed needs to be imported to maintain animal requirements.

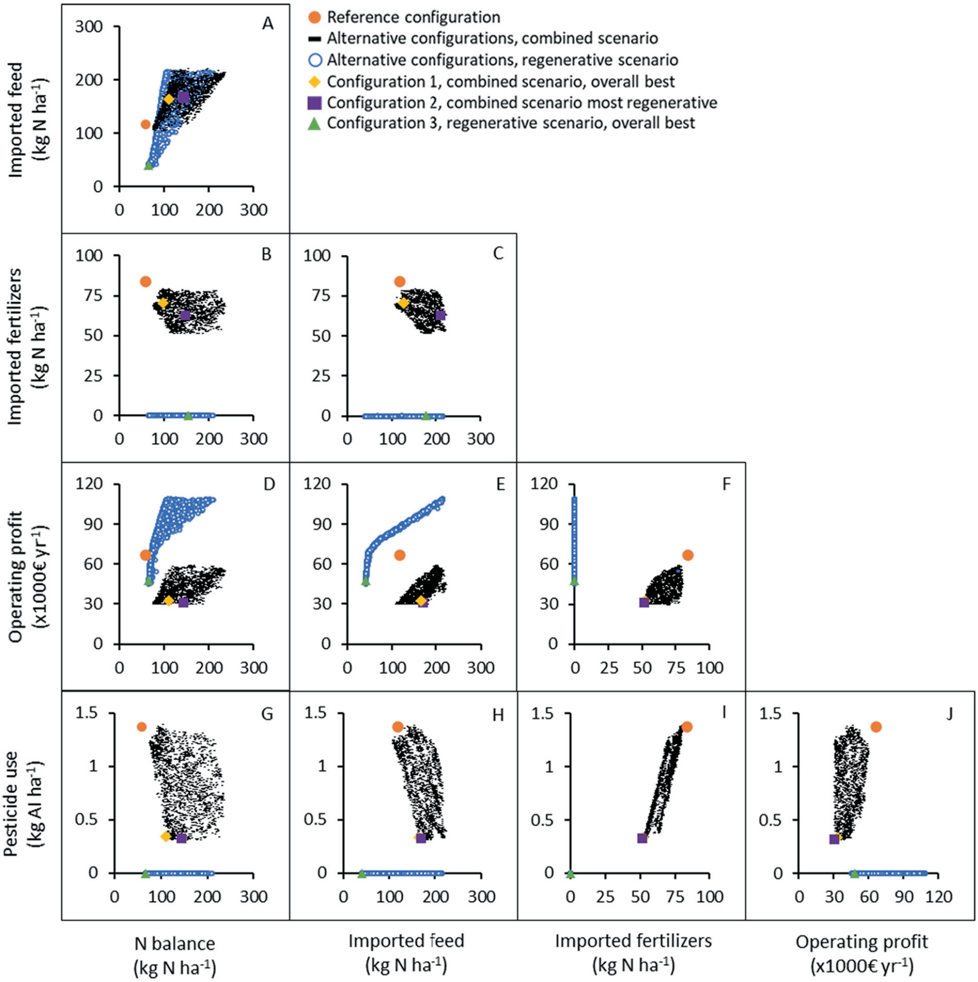

Figure 7. *Solution spaces of alternative farm configurations in terms of N balance, imported fertilizers, imported feed, pesticide use and operating profit for the mixed case-study farm.*

3.3.2 Assessment on the objectives of regenerative agriculture

Similar to the other case-study farms, the selected configurations of the mixed case-study farm show improvement in soil functions when moving towards regenerative management (Figure 8). For the mixed case-study farm specifically, four out of five soil functions can be achieved at high capacity when transitioning fully to regenerative management. Configurations 1, 2, and 3 allocated 31%, 32%, and 100% of their land to regenerative management. Primary productivity remained at high capacity, although farm profitability was reduced by on average 44% (from 66719 to 37122 € yr^{-1}), driven by lower animal numbers (to reduce feed imports and reduced crop yields) and increased crop cultivation costs related to increased labor requirements for hand weeding. Improved scores for water purification and regulation related to combinations of measures that affected grassland and cropland differently. Reducing N fertilization and using cover crops for example reduced N leakage for cropland. However, for grassland incorporating more species (e.g. clover) reduced total N fertilization and leakage, while the water storage capacity of the soil was improved from low to medium by applying solid manure which improved soil structure. Improved soil structure (from low to medium) and biology (from low to medium) also contributed to a high score for biodiversity and habitat provision; associated practices improved the average SOM balance by 119%. The amount of solid manure used was strongly related to animal numbers and the fixed demand for fertilization for the incorporated crops. Configurations with lower animal numbers, therefore, had a lower SOM balance. The N balance increased due to the higher N-fixation rates of species-rich grassland and greater import of animal feed, outweighing the reduction in N fertilization rates for grass- and cropland. The soil function nutrient cycling improved due to a higher nutrient recovery rate for grassland when including legumes. Incorporating cover crops, increasing the share of legumes and reducing total N fertilization did not improve the score for climate regulation which remained medium. If, however, we distinguish between grassland and cropland we see that grassland has a higher score for climate regulation, while cropland has on average, a medium score because of lower carbon sequestration (supplementary materials S11). In addition, farm-level GHG emissions declined by 17% compared to the reference (from 21 to 16 Mg CO_2 eq. ha^{-1}; from 1178 to 916 Mg CO_2 eq.) due to a reduction in animal numbers (supplementary materials S11 shows the absolute values for Figure 8).

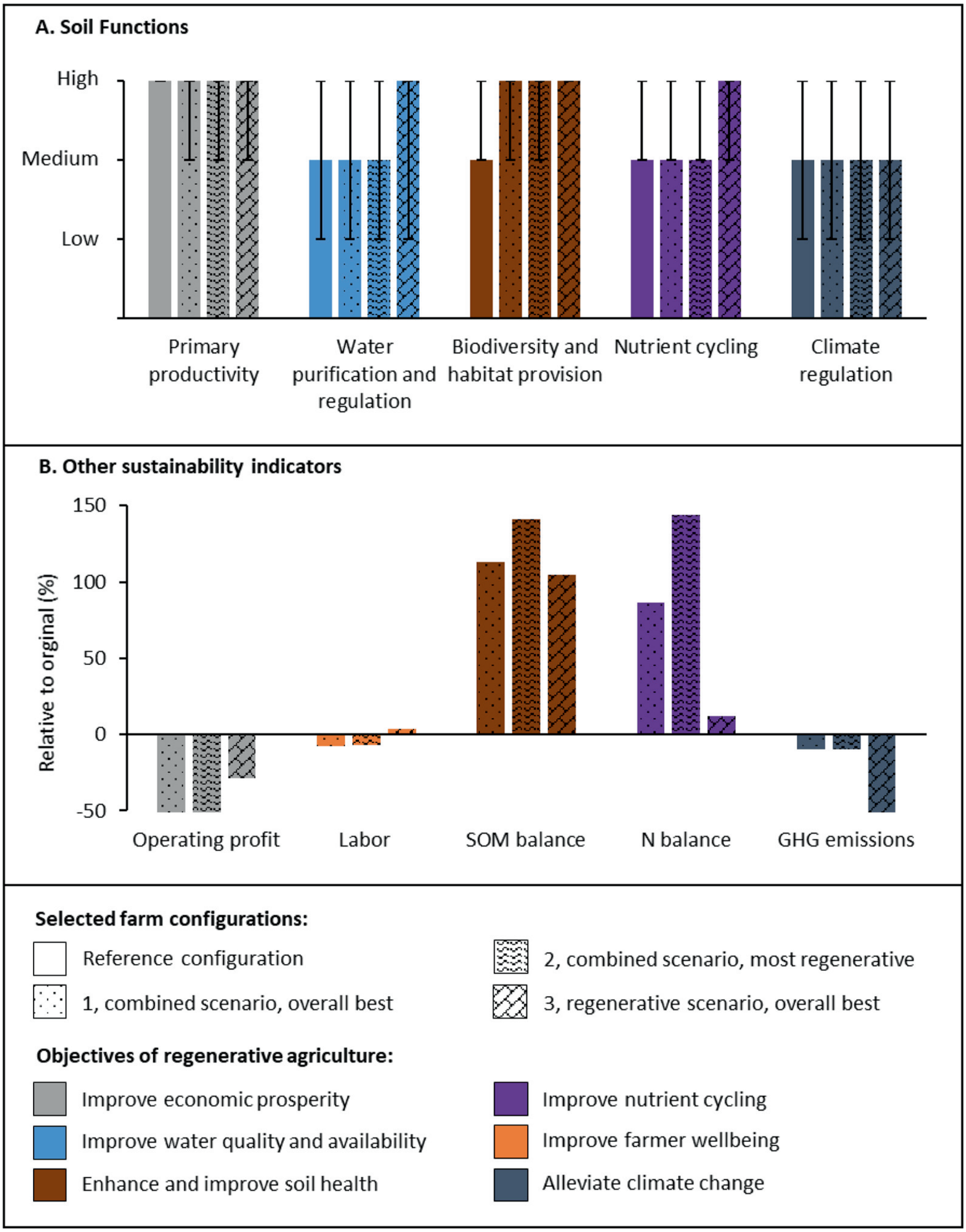

***Figure 8**. The performance of farm configurations on the objectives of regenerative agriculture for the mixed case-study farm, discriminated in soil functions (A) and other farm sustainability indicators (B). Error bars represent functional units with divergent scores from the area weighted averages, indicating within-farm variability. The performance of other sustainability indicators are shown relative to the reference scenario. The colors correspond to the objectives of regenerative agriculture.*

4. Discussion

4.1 A diversity of solutions

The common mode of Dutch farming has focused on increasing primary productivity, through the use of mined and synthetic fertilizers, concentrate feed, and synthetic pesticides, in order to meet the increased crop and livestock needs with great precision (Meerburg et al., 2009). These practices, however, are avoided in regenerative agriculture because they have strong trade-offs with regenerative objectives (e.g. the negative impacts of pesticide use on soil biodiversity (Oosthoek, 2013)) and are therefore not in line with the regenerative philosophy (Rhodes, 2017). Although regenerative agriculture has overarching objectives (e.g. improve soil health), Giller et al. (2021) felt that the concept of regenerative agriculture had little meaning at the individual farm-level. In our previous work Chapter 3, we created a framework that combined two models to explore alternative futures for individual farms, using soil health as the basis of a redesign of farming practices. This study has further explored this modelling framework and addressed the challenge set by Giller et al. (2021) by providing farm-level interpretations of regenerative agriculture. We assessed and redesigned diverse Dutch farming systems taking into account their contrasting pedo-climatic conditions, resulting in tailor-made solutions for individual farms. These tailor-made solutions differed between farms, both in terms of prioritized objectives, and the management practices associated with regenerative agriculture.

These tailor-made solutions improved regenerative objectives for all case-study farms, and more specifically, showed that four out of five soil functions can be achieved at high capacity. This was a stronger improvement than expected, since obtaining three out of five soil functions at high capacity is considered feasible for cropland farms, as a result of the occurrence of trade-offs between the soil functions (Zwetsloot et al., 2020). Showing synergies and trade-offs between soil functions, regenerative objectives, and farming practices is key for farmers to decide what management practices best suit their local conditions and individual preferences (Groot et al., 2012). Moreover, to support on-farm decision making we show solution spaces instead of single optimized solutions. Showing farmers solution spaces with a multitude of farm configurations gives farmers a negotiation perspective, in which they have the opportunity to select the solution that fits their intrinsic motivations the most (e.g. Groot and Rossing, 2011; Mandryk et al., 2014). Although, this framework was used in this study as a tool to support on-farm decision making, it might be used in participatory processes with farmers and other stakeholders; to consider both regenerative objectives and intrinsic motivations of the farmer that lead to the final selection of the farm redesign (see also Lacombe et al., 2018; López-García et al., 2021). Moreover, most models and tools to date have failed to be adopted by a wider audience (e.g. researchers and consultants) due to multiple reasons (e.g. complexity and availability) (de Olde et al., 2018). To increase user operability we selected two publicly available models with extensive user guides (Soil Navigator: http://www.soilnavigator.eu/; FarmDESIGN: https://fse.models.gitlab.io/COMPASS/FarmDESIGN/).

4.2 Profit more important than productivity

In this study we highlight that, for all case-study farms, environmental performance improved at the expense of farm profitability. The reduction in farm profitability was mainly associated with reductions in animal numbers to improve feed self-sufficiency, reductions in crop yields, and higher labor requirements. Declining crop yields within the first five years of regenerative management are a well-known symptom of transitions towards regenerative and organic management (LaCanne and Lundgren, 2018; Luján Soto et al., 2021; van der Voort, 2018). The reductions in yields are a result of, for example, the elimination of synthetic pesticides, which may result in an increased incidence of pests and diseases (Aktar et al., 2009), or a result of reduced tillage which can lead to weed infestations (Pittelkow et al., 2015). Under regenerative management as well as regenerative management, yield stability relies on the natural resilience of the farming system (Li et al., 2019). Various studies (e.g. Chee, 2004; Power, 2010), therefore, argue that primary productivity alone is a suboptimal indicator to evaluate the performance of a regenerative farming system, which besides productivity also contributes to the supply of other regenerative objectives (LaCanne and Lundgren, 2018). Yields may stabilize over a longer time span (>10 years) (Li et al., 2019; Schrama et al., 2018; Seufert et al., 2012). Increased labor will, however, remain a key driver for reduced farm profitability due to, for instance increased hand weeding in sugar beet or winter wheat production (van der Voort, 2018).

There are examples of regenerative farming systems around the globe that demonstrate that achieving multiple regenerative objectives and having viable business models is possible (e.g. Khumairoh et al., 2018; Koppelmäki et al., 2019). Currently the majority of Dutch farmers, however, prioritize economic profitability over environmental and social objectives of food production (Kik et al., 2021). Schulte et al. (2019) shows that Dutch citizens expect farmers to deliver on multiple regenerative objectives from their land. The disparity between the prioritization of farmers and the expectations of citizens can be solved by changing both policies and industries to valorize regenerative objectives (i.e. ecosystem services) in business models (Chee, 2004). These business models should not be built around single objectives such as carbon credits (Williams et al., 2005), but consider multiple regenerative objectives relevant to the local context. Furthermore, the valorization of regenerative objectives should not disadvantage farmers in the transition period in which yields may be reduced (Dabbert and Madden, 1986), while the positive effects in regenerative objectives are still increasing (Geisen et al., 2019). Ideas for such business models are already in existence (e.g. price premiums (Chee, 2004) and subsidies (Lotz et al., 2018)), however, it is currently unclear what role industries and policies could play in supporting such business models to support the valorization of regenerative objectives (Gosnell et al., 2019; Sivertsson and Tell, 2015). The European Union (European Commission, 2022a) is currently developing a Soil Health Law as part of the EU soil strategy for 2030, which highlights the multifunctional role that soils are expected to contribute to a range of ecosystem services. This law could provide an opportunity to stimulate a wider transition towards regenerative agriculture, highlighting soil health as the entry point for multifunctional agricultural systems and supporting farmers in this transition through subsidies.

4.3 The future of modelling: increasing complexity

In this study we selected case-study farms which represented typical but also conventional farming systems in the Netherlands. This allowed for the exploration of a wide range of regenerative farming practices such as the use of solid manure, the reduction in tillage, synthetic pesticides, and inorganic fertilizers. The farming practices suggested by SN were, however, limited to the inventory of practices available in SN. The full range of regenerative farming practices may include more practices than SN is able to assess, such as including additional regenerative crops, using multiple fertilizers on a field or farm, using fixed traffic lanes, using light-weight machinery, and differentiating between the impacts of synthetic pesticides (some are more harmful than others). Other practices will require radical changes within the model, such as improved spatial-temporal crop rotations (e.g. strip cropping). For the livestock sector, it requires more intensive integration of crop-livestock systems, which does not separate land for fodder production and grassland for grazing but integrates these systems such as agroforestry and silvopasture. It may be challenging to model practices that require such a radical systems change due to the intricate synergies and trade-offs occurring between the model components, which must then be captured and parameterized.

Besides increasing the complexity of models, attention should also be given to the modelled time horizon. A majority of modelling studies work on an annual basis or within a five-year crop rotation (e.g. Adelhart Toorop et al., 2020; Timler et al., 2020). Yet, many of the desired effects of regenerative agriculture only become visible over a longer time horizon. For example, increasing the SOM content on mineral soils can take more than five years (Powlson et al., 1998). Only after this period the positive effects on water and nutrient retention, and yields can be noticed (Menšík et al., 2018). At the same time, most of the costs associated with a transition to regenerative practices occur in the initial phase, while economic benefits to the farmer commonly accrued in the long term only. Therefore, we suggest that modelling studies extend their time horizon, to capture the benefits, economic as well as environmental, associated with regenerative management. Currently, this is challenging as data on the long-term effects of regenerative practices for different pedo-climatic conditions are largely lacking (Johnston and Poulton, 2018).

5. Conclusions

This study showed that transitions towards regenerative agriculture requires tailor-made solutions and management practices for individual farming systems. By building upon the modelling framework of Chapter 3, we made specific what regenerative agriculture means for individual farming systems, by showing which regenerative objectives and farming practices can contribute to the transition towards regenerative agriculture in contrasting contexts. Furthermore, we created a wide diversity of tailor-made solutions contributing in varying degrees towards the objectives of regenerative agriculture. We specifically showed for the case-study farms (arable farming on clay soil, dairy farming on peat soil and mixed farming on sandy soil) that overall environmental performance was improved (e.g. soil functions, GHG emissions, pesticide use and inorganic fertilizers). This improvement, however, came at the expense of farm profitability, which can hamper the wider implementation of regenerative agriculture. The modelling framework that is used, can underpin regenerative management for farmers and other stakeholders to help, for example, the valorization of multiple regenerative objectives in business models. To stimulate a wider transition towards regenerative agriculture we recommend that policies and industries find methods to support viable business models for regenerative agriculture.

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Supplementary materials

S1: Additional characteristics about the benchmark and case-study farm

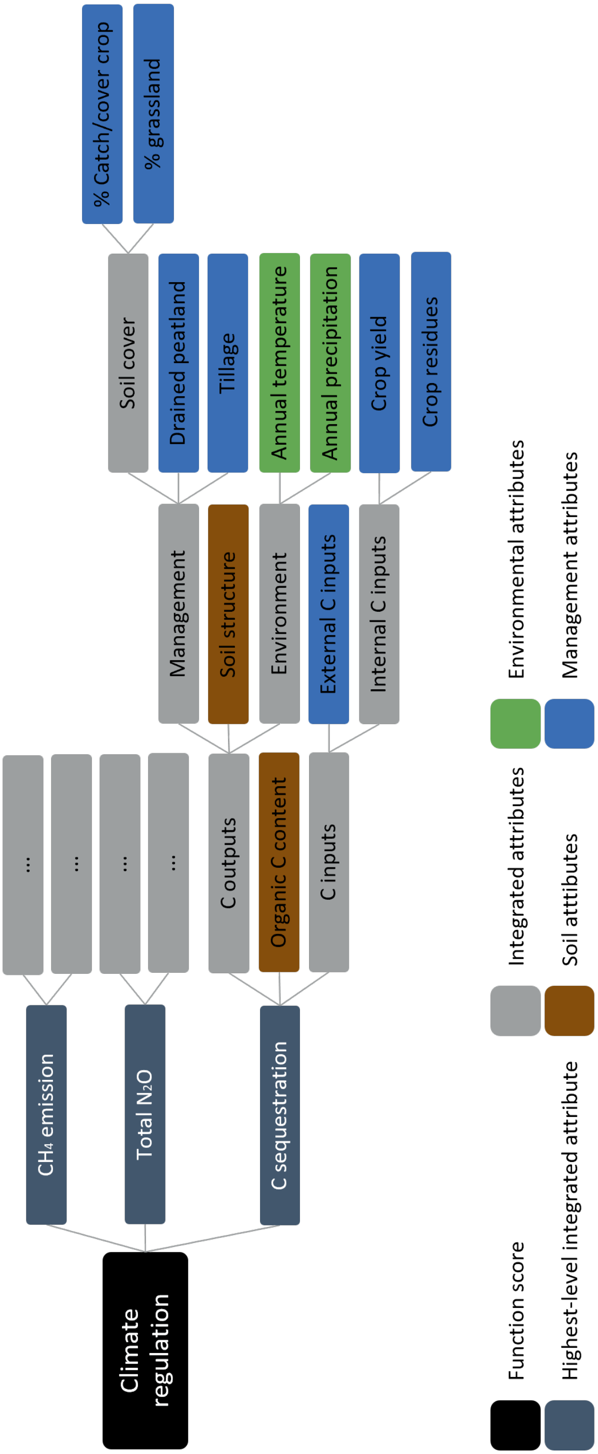
Values of the benchmark were obtained from the BIN-network. Values from the reference scenarios were obtained from farm surveys. The number of similar farming systems used as benchmark is small for the mixed case-study farm due to a limited number of mixed farming systems available in the BIN-database. A mixed farming system is in BIN defined as a farming system which has ≥ 66% of his primary productivity not allocated to a main farm production type (e.g. arable farming, dairy farming, horticulture). A farm with for example 65% dairy cattle and 35% arable production or vice versa is considered a mixed-farm.

		Dairy (peat)		**Arable (clay)**		**Mixed (sand)**	
Farm-level indicators	**Units**	**BM**	**Case-farm**	**BM**	**Case-farm**	**BM**	**Case-farm**
Benchmark	-	1419		2452		15	
Required labor	h yr^{-1}	4062 ±3145	2863	3034 ±2590	1096	4397 ±1706	3948
Operating profit	€ yr^{-1}	85862 ±202687	62876	69999 ±73926	46784	49259 ±76126	66719
GHG emissions	Mg CO$_2$-eq. ha^{-1}	25.5 ±8.5	30	3.8±2.2	4.0	24.8 ±7.6	21
N balance	kg N ha^{-1}	262±105	262	142±13	117	131±78	59
SOM balance	kg OM ha^{-1}	2475±1092	2741	n.a.	1136	n.a.	755
Pesticide use	kg AI ha^{-1}	0±0	0	7±0	6.7	1±1	1.4
Art. fertilizer use	kg N ha^{-1}	104±62	75	143±24	88	74±46	63
Concentrate use	kg DM cow^{-1}	2344 ±549	2687	-	-	2420 ±561	1940

BM = Benchmark; GHG = greenhouse gas; Art. = artificial

S2: Mode of operation of the Soil Navigator (SN)

The SN is an multi-criteria decision support model based on expert opinion that enables the assessment of five soil functions simultaneously at the field scale (Debeljak et al., 2019). The five soil functions are based on the Functional Land Management (FLM) framework proposed by Schulte et al. (2014) These five soil functions are articulated in the SN as different models and include primary productivity (Sandén et al., 2019), nutrient cycling (Schröder et al., 2016), water purification and regulation (Wall et al., 2020), climate regulation (van de Broek et al., 2019), and biodiversity and habitat provision (van Leeuwen et al., 2019). The input attributes required for assessment of soil functions are based on farm management (i.e. land and fertilizer use), environment (i.e. average temperature and precipitation) and soil attributes (i.e. clay content and soil organic matter). Each model follows the hierarchical structure of a decision tree, in which input attributes are assigned qualitative scores (low, medium, high) based on pre-set thresholds. Using expert-based decision rules, the higher-level integrated attribute scores are derived from the input attributes or lower-level integrated attribute scores. Hence, the final soil function scores are determined by the scores of highest-level integrated attributes and associated decision rules. At each level of aggregation in the decision tree, weight factors determine the importance of the lower-level attributes to the calculation of the higher-level attribute. The input attributes for the five different soil functions can be used multiple times within a model and across models. The decision rules used to assess these input attributes are, however, unique for each function model. The five soil function models were structured, calibrated and validated for crop and grassland using information obtained by expert knowledge and with different datasets across Europe (Sandén et al., 2019; Schröder et al., 2016; van de Broek et al., 2019; van Leeuwen et al., 2019; Wall et al., 2020). The figure below shows part of the model structure of the climate regulation model to illustrate how the models in the Soil Navigator are organized to assess soil functions based on their input attributes. In addition, the SN offers the possibility to optimize soil functions based on user-determined objectives and indicates if certain objectives are achievable due to synergies and trade-offs between soil functions or local constraints. The SN will search all possible combinations of values of the input attributes in order to identify which input attributes need to be improved along with farm practices to establish this improvement. When a suitable combination is found, the SN will show the new potential capacity of the soil to deliver the five functions. Details about the construction of the SN are described in Debeljak et al. (2019). A part of the structure of the climate regulation model to illustrate how the models in the Soil Navigator are organized to assess soil functions based on their input attributes (modified from van de Broek et al., 2019; Zwetsloot et al., 2020). Scores of input attributes are determined based on pre-decided thresholds. Scores of integrated attributes are determined by decision rules and scores of lower-level attributes. Function scores are determined by decision rules and scores of the highest-level integrated attributes.


Climate regulation
CH₄ emission
Total N₂O
C sequestration
…
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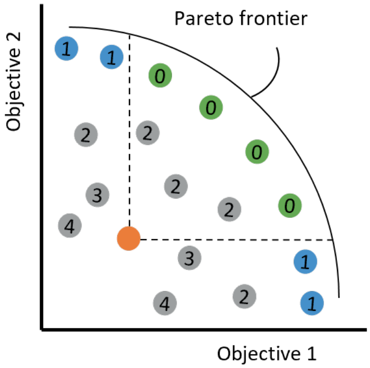
C outputs
Organic C content
C inputs
Management
Soil structure
Environment
External C inputs
Internal C inputs
Soil cover
Drained peatland
Tillage
Annual temperature
Annual precipitation
Crop yield
Crop residues
% Catch/cover crop
% grassland
Function score
Highest-level integrated attribute
Integrated attributes
Soil atttibutes
Environmental attributes
Management attributes

S3: Mode of operation of FarmDESIGN (FD)

FD is a bio-economic, whole-farm model which consists of a large array of interrelated farm components developed for the analysis and redesign of mixed crop-livestock systems (Groot et al., 2012). The model was used within the framework of the DEED-cycle (Describe, Explain, Explore, Design) (Giller et al., 2011) and we present the model accordingly. The describe-phase describes the farm using various parameters related to crop and animal performance. The explain-phase explains the performance of the farm using a variety of indicators. A wide range of flows such as that of carbon and nitrogen are calculated at the farm level. The resulting material balances, the feed balance, the amount and composition of manure, labor balance and economic results are calculated on an annual basis. From the wide variety of indicators available in FD, a selection of indicators showed convergence with the objectives of regenerative agriculture Chapter 3 and are used in this study: soil organic matter (SOM) balance, nitrogen (N) balance, GHG emissions, operating profit, and farm labor balance.

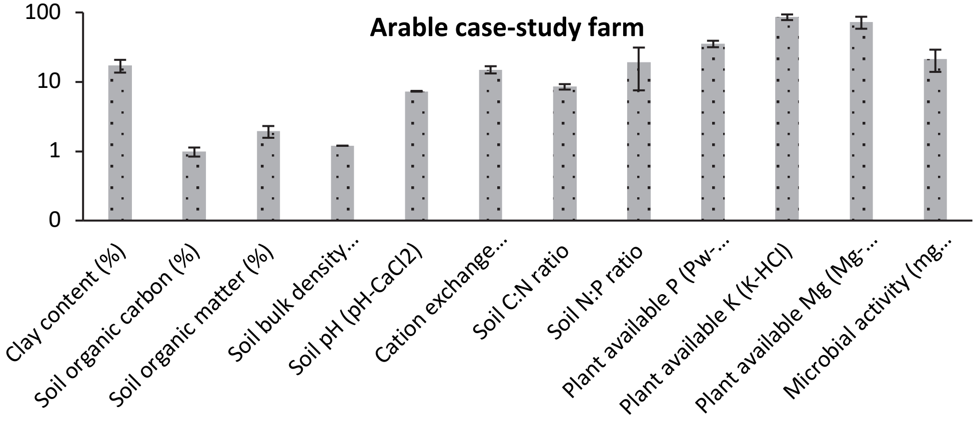
The SOM balance indicates changes in organic matter in response to changes in management and is calculated as the difference between inputs and outputs of organic matter into the soil (from crop roots and residues, mulch, farm-produce, and imported manures) on the one hand, and losses by degradation of active SOM, added manure, and erosion on the other. The N balance is calculated by subtracting the N exports (manures; crop and animal produce) from the sum of N inputs onto the farm in the form of animal products, crop products (e.g. purchased or off-farm collected feeds), manures and fertilizers, deposition, symbiotic fixation by leguminous plants, extra mineralization by peat oxidation, and non-symbiotic fixation by free-living soil biota. GHG emissions account for emissions and carbon sequestration at farm-scale, such as emissions from animals (enteric), manures (direct emissions and volatilization), the soil (peat oxidation); fertilizer, diesel, pesticide production and usage. Operating profit is calculated as the sum of total farm returns minus farm costs. Farm labor balance is calculated as the sum of labor requirements due to crop and livestock management minus the hired labor and the hours invested by the farmer.

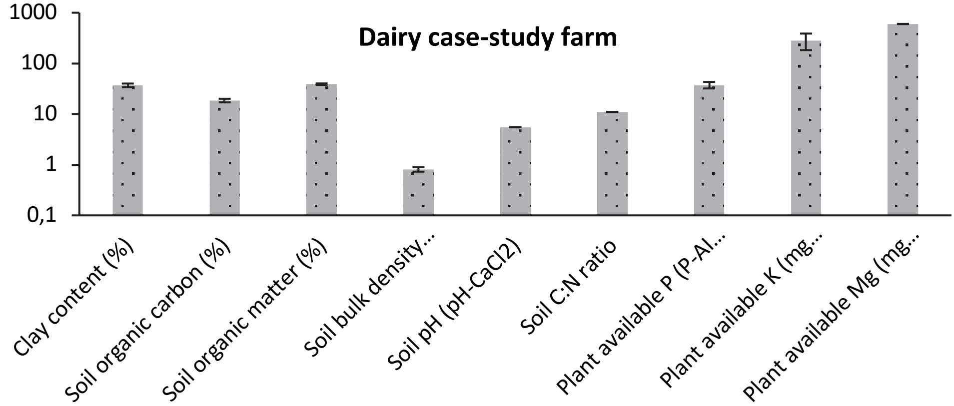
The explore-phase results in multiple optimized farm-configurations that are generated by a multi-objective optimization based on selected objectives (e.g. minimize N balance or maximize operating profit), set constraints (e.g. upper and lower limits on animal's energy and protein requirements) and a variety of decision variables (e.g. upper and lower limits on crop areas or animal numbers). The objectives, constraints and decision variables are used to improve the environmental performance of a farm (i.e. land use diversity, nutrient losses and soil organic matter accumulation) as well as the capacity to improve socio-economic prosperity (i.e. profitability, household budgets and labor requirements). The multi-objective optimization uses a Pareto-based Differential Evolution algorithm to generate numerous alternative farm-configurations and the model displays them within a solution space (Radhika and Chaparala, 2018; Storn and Price, 1997). The figure below, illustrates such a solution space in which the original farm configuration (orange) is optimized by maximizing Objective 1 and 2. The alternative farm configurations have different pareto ranks 0-4. Rank 0 (green) is given to farm configurations which outperform all objectives of the other farm configurations. Rank 1 (blue) is given to farm configurations which perform equal or outperform other farm configurations in at least one objective. The set of farm configurations with rank 0 and 1 is called the pareto frontier and may be used to assess trade-offs and synergies between the objectives in the solution space. Farm configuration with ranks 2-4 (grey) form the rest of solution space and outperform the original farm configuration to varying degrees. In the design-phase new farm configurations can be selected from the solution space based upon user's preferences. The user may for example prefer solutions that are more aligned with Objective 1 than Objective 2, c.f. figure on this page. The new farm configurations can include optimized performance indicators and new land-use configurations. These new land-use configurations consist of various configurations of the decision variables e.g. allocation of crop areas, new crops grown on the farm, changes in herd size, animal type, fertilizers and feed use. The construction of FD and the corresponding farm balance equations are described by Groot et al. (2012).

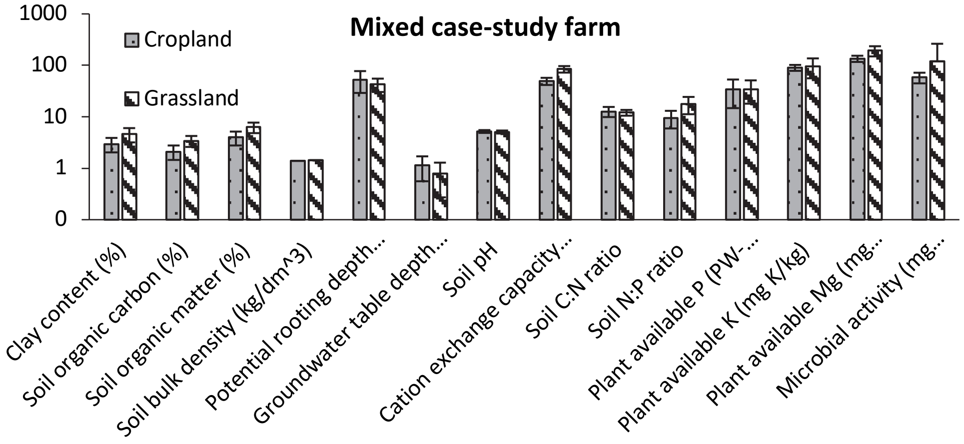


For the study, Chapter 3, added an option to select a fixed seed, which allowed to generate a solution set where ID's remained constant when optimizing a farm with the same exploration parameters. This was needed to ensure that the output of FD remained stable and could be used in the SN. The solutions were generated using the Pareto-based Differential Evolution algorithm in FD with the exploration parameters set at values recommended by Groot et al. (2007), including a mutation probability of 0.85 and mutation amplitude of 0.15. In this study we used 4000 iterations per model run to create a stable solutions space. To be able to view the selected farm-configuration we created a search function in FD to enable the user to search for a particular farm-configuration using the farm-ID of the selected configuration. In order to see if the farm practices suggested by the SN not only affected indicators in FD but also soil functions in the SN, we re-entered the optimized output of FD back into the SN. In Chapter 3, therefore, we created an output folder in FD called "export to Soil Navigator" which exports a file that shows the required recalculated input data to reparametrize the different models in the SN. The attributes integrated in this folder include quantitative attributes which would change within the five year time-horizon of the SN such as the use of N-fertilizer and crop yield.

S4: Average values of soil properties of the three case-study farms, the standard deviation represents variation between fields







S5: Reparameterization of new animal and crop products in the regenerative scenarios in FarmDESIGN

S5.1: Arable case-study farm

Overview of model inputs obtained from secondary literature. Expert corrections were made based on the suggestions of Bert Smit, Derk van Balen, Wijnand Sukkel and Koen Klompe. Below the table we justify the values used as input data.

Reference management includes:
Artificial fertilizers, pig slurry, synthetic pesticide use, tillage

FD input variable	Unit	Lucerne	Sugar beet	Kidney bean	Chicory	Potato	Winter wheat*	Source
Crop area	ha	0.65	10.72	2.50	5.80	16.30	8.95	1
Nitrogen fixation	kg N ha^{-1}	122	0	60	0	0	0	13
Effective org. Matter	kg EOM ha^{-1}	1550	600	170	700	875	2514	2, 4
Diesel use	L ha^{-1}	80	119	95	119	265	170	17
Cultivation costs	€ ha^{-1}	471	2015	1302	1955	3918	1010	1, 17
Subsidies	€ ha^{-1}	0	0	0	0	0	0	-
Total labor	h ha^{-1}	5.1	26	15	28	30	14	1, 17
Price fresh matter	€ kg^{-1}	0	0.04	1.3	0.07	0.14	0.16	1, 17
Fresh yield	kg FM ha^{-1}	50000	100000	2250	45000	40000	10000	1, 17
Dry matter yield	kg DM ha^{-1}	10000	21800	830	9000	7368	8680	1, 7
Dry matter content	g 100g FM^{-1}	20	22	88.25	20	18.42	86.8	1, 7

Regenerative management includes:
No synthetic pesticides, no mineral fertilizer, instead use solid manure, no/minimize tillage, catch crops (with*), crop residues, reduce total N fertilization, use sprinkler irrigation

FD input variable	Unit	Lucerne	Sugar beet*	Kidney bean*	Chicory	Potato*	Winter wheat*	Source
Crop area	ha	-	-	-	-	-	-	-
Nitrogen fixation	kg N ha^{-1}	122	0	60	0	0	0	13
Effective org. Matter	kg EOM ha^{-1}	1550	1406	868.5	700	1355	3504	2, 4, 6, 14
Diesel use	L ha^{-1}	81	145	155	151	231	135	16, 17
Cultivation costs	€ ha^{-1}	398	2003	1210	1493	3309	616	2, 9, 17
Subsidies	€ ha^{-1}	0	0	0	0	0	0	-
Total labor	h ha^{-1}	5	61	31	44	34	17	2, 11, 12, 17
Price fresh matter	€ kg^{-1}	0	0.04	1.3	0.07	0.14	0.16	2, 10, 17

FD input variable	Unit	Lucerne	Sugar beet*	Kidney bean*	Chicory	Potato*	Winter wheat*	Source
Fresh yield	kg FM ha^{-1}	42857	66500	2031	34200	30264	8427	3, 8, 10, 17
Dry matter yield	kg DM ha^{-1}	8571	14497	1792	6840	5575	7315	15
Dry matter content	g 100g FM^{-1}	20	22	88.25	20	18.42	86.8	15

Values were based on farm interviews[1], expert opinion (all co-authors and three grassland experts, see acknowledgements)[2] and the following secondary literature: Bom (1983)[3], Bosch and de Jonge (1989)[4], de Wolf et al. (2019)[6], Feedipedia (2020)[7], Geel and Brinks (2018)[8], Gren (1994)[9], Oerke (2006)[10], PPO (2009)[11], Scheepens (2001)[12], Schröder et al. (2003)[13], Starmans et al. (2015)[14], USDA (2019b)[15], van der Weide et al. (2008)16, and van der Voort (2018)[17].

Justification model input data arable case-study farm

Nitrogen fixation for Lucerne and kidney bean were estimated 122 and 60 kg N ha^{-1} (Berenji et al., 2015). Yellow mustard was selected as cover crop for sugar beet, winter wheat, potato and kidney beans. Yellow mustard is used to prevent for example N leaching but does not lead to extra N fixation. The atmospheric N-fixation of 40 kg N ha^{-1} (BO Akkerbouw, 2004) from yellow mustard equals to its immobilization, therefore, not relevant.

Effective organic matter (EOM) values originated from Handboek voor de Akkerbouw en de Groenteteelt in de Vollegrond (1989).

- For crops in the regenerative scenario, crop residues were allocated to the soil. For sugar beet we allocated 900 kg EOM ha^{-1} to the soil which includes beet leaves and yellow mustard as cover crop. For winter wheat, straw was left on the soil adding 990 kg EOM ha^{-1}. For kidney bean leaves and yellow mustard as cover crop added 480 kg EOM ha^{-1} to the soil.
- Yellow mustard was used as cover crop for sugar beet, kidney bean, potato and winter wheat. Fully developed yellow mustard remains 874 kg EOM ha^{-1} after 1 year. However, the cover crops will develop in different extents in the rotations. The development rate therefore determined the EOM value for the different crops and were 15, 25, 55 and 100% respectively. Yellow mustard was selected for optimal disease suppression (e.g. parasitic nematodes) in the rotation and to not leave the soil bare after harvest of the cash crop.

Diesel use was based on KWIN-agv organic values plus the extra diesel used for using cover crops and irrigation.

Subsidies for the reference scenario were based on farm surveys. For the regenerative scenario we kept subsidies equal for the coming 5 years. Subsidies can be obtained by changing to organic standards or using single practices. Using for example herb-rich grassland can already lead to subsidies of 450-600 euro ha^{-1} (Goyens, 2016; Vandepoel, 2015). Farmers from TiFN's Regenerative Farming project (CoP farmers) which already implementing these practices highlighted in farm surveys that subsidies can go up to 1750 euro ha^{-1}. Based on expert opinion and the uncertainty of subsidies we kept this parameter constant.

Cultivation costs changed for crop production. Values were based on KWIN-agv organic production standards and expert opinion, leaving crop residues on the field and including cover crops. Adjustments were made based on expert opinion.

- Lucerne reduces: less material costs i.e. fertilizer and pesticide use
- Sugar beet increased a lot: material costs reduce due to no use of mined fertilizers and synthetic pesticide use with ~250 euro ha^{-1}, however, labor increases from 12.9 h ha^{-1} to 76 h ha^{-1}. This increase is mainly related to weeding which goes from 1.6 h ha^{-1} to 65 h ha^{-1}.
- Kidney bean: reduced costs were for a large account related due to less material costs from mined fertilizer and pesticide use.
- Chicory: reduced costs were for a large account related due to less material costs from mined fertilizer and pesticide use.
- Potato: reduced costs were for a large account related due to less material costs from mined fertilizer and pesticide use.
- Winter wheat reduced: reduced costs were for a large account related due to less material costs from mined fertilizer and pesticide use.

Labor was determined by farm interviews for the reference scenario and KWIN-V 2018 and AGV 2018. We used KWIN-agv 2018 (p. 191) values and expert opinion to determine labor requirements for the regenerative scenario. Labor changed for crop production. Values were based on KWIN-agv organic production standards, leaving crop residues on the field and including cover crops. Adjustments were made based expert opinion.

- Lucerne: labor stays stable.
- Sugar beet increased a lot: Labor increases from 26 h ha^{-1} to 61 h ha^{-1}. This increase is mainly related to weeding, which goes from 1.6 h ha^{-1} to 65 h ha^{-1}.
- Kidney bean: increased due to more weeding
- Chicory: increased due to more weeding
- Winter wheat: increased a little bit due to 4 h ha^{-1} more hand weeding.

Product prices were kept equal because it is uncertain if organic standards, subsidies or other price premium requirements are met. Data was obtained from a farm survey for the reference scenario. For the regenerative scenario we used expert opinion and KWIN-agv 2018.

Dry matter yields were obtained from a farm survey for the reference scenario. For the regenerative scenario we used expert opinion and KWIN-agv 2018. Crops in the regenerative scenario (sugar beet, winter wheat, potato and chicory) did reduce due to the elimination of pesticides (at least for the first 5 years) and slight reduction in total N fertilization. Crop yields for lucerne and kidney beans reduced a little bit, which could be due to lower N-fertilization rates.

S5.2: Dairy case-study farm

Overview of model inputs obtained from secondary literature. Expert corrections were made based on suggestions by Pedro Janssen, Co Daatselaar, Alfons Beldman and Gertjan Holshof. Below the table we justify the values used as input data.

Reference management includes:
Permanent grassland + pasture manure + slurry + art. fert. + no synthetic pesticide

FD input variable	**Unit**	**Alternated grazing and mowing**		**Mowing only**	**Source**
		Grazed grass	**Grass silage**	**Grass silage**	
Grassland	ha	16.9		23.5	1
Price fresh matter	€ day^{-1}	0.42		0.42	1
Production	kg cow^{-1} day^{-1}	23.9		23.9	1
Nitrogen fixation	kg N ha^{-1} yr^{-1}	0		0	2, 6
Effective org. Matter	kg ha^{-1} yr^{-1}	2000		2000	4
Diesel use	L ha^{-1}	150		178	1
Subsidies	€ ha^{-1}	463		463	1
Cultivation costs	€ ha^{-1}	988		988	1
Regular labor	h ha^{-1} yr^{-1}	18		21	1
Price fresh matter	€ kg^{-1}	0	0.062	0.062	3
Fresh yield	kg FM ha^{-1}	12078	22469	28561	1
Dry matter yield	kg DM ha^{-1}	1969	9010	11453	1
DM content	g 100g FM^{-1}	16,3	40.1	40.1	5
Ash content	g 100g DM^{-1}	10.60	11.13	11.13	5
Nitrogen	g 100g DM^{-1}	2.78	2.48	2.48	2, 5
Phosphorus	g 100g DM^{-1}	0.46	0.41	0.41	2, 5
Potassium	g 100g DM^{-1}	3.43	3.21	3.21	5
Feed saturation value (VW)	-	0,89	1.02	1.02	5
Feed structure value (SW)	-	1,88	3.02	3.02	5
Energy content (VEM)	-	960	888	888	1, 5
Protein content (DVE)	g kg DM^{-1}	92	67	67	5

Regenerative management includes:
Species rich grassland + pasture manure + solid manure + no synthetic pesticide

FD input variable	Unit	Alternated grazing and mowing Grazed grass	 Grass silage	Mowing only	Source
Grassland	ha	16.9		23.5	-
Price fresh matter	€ day^{-1}	0.42		0.42	-
Production	kg cow^{-1} day^{-1}	23.9		23.9	-
Nitrogen fixation	kg N ha^{-1} yr^{-1}	172		172	2, 6
Effective org. Matter	kg ha^{-1} yr^{-1}	1540		1540	4
Diesel use	L ha^{-1}	143		169	3
Subsidies	€ ha^{-1}	463		463	2, 8
Cultivation costs	€ ha^{-1}	988		988	2, 6
Regular labor	h ha^{-1} yr^{-1}	21		25	2, 3, 10
Price fresh matter	€ kg^{-1}	0	0.067	0.067	2, 9, 11
Fresh yield	kg FM ha^{-1}	12078	22469	28561	2, 6
Dry matter yield	kg DM ha^{-1}	1969	9010	11453	6
DM content	g 100g FM^{-1}	16.3	40.10	40.10	6
Ash content	g 100g DM^{-1}	11.88	12.24	12.24	2, 7
Nitrogen	g 100g DM^{-1}	3.06	2.73	2.73	2, 7
Phosphorus	g 100g DM^{-1}	0.41	0.40	0.40	2, 7
Potassium	g 100g DM^{-1}	3.35	3.18	3.18	7
Feed saturation value (VW)	-	0.89	1.02	1.02	2, 5
Feed structure value (SW)	-	1.88	3.02	3.02	2, 5
Energy content (VEM)	-	979	906	906	2, 5
Protein content (DVE)	g kg DM^{-1}	93	68	68	2, 5

Values were based on farm interviews[1], expert opinion (all co-authors and three grassland experts, see acknowledgements)[2] and the following secondary literature: Blanken et al. (2018)[3], Bosch and de Jonge (1989)[4], CVB (2018)[5], de Wit et al. (2004)[6], Feedipedia (2020)[7], Goyens (2016)[8], Hospers (2015)[9], Kadaster & WEcR (2017)[10], and van der Voort (2018)[11].

Justification model input data dairy case-study farm

Milk price is kept the same for the regenerative scenario. Different existing payment schemes exist to value some ecosystem services such as the Dutch planet proof label (Baan, 2019). It, however, is very uncertain if these requirements are met in the regenerative scenario. Together with the case-experts we decided to model alternative farm configurations without a price premium or extra subsidies. We do acknowledge that for example fully transitioning to organic, can add 10 cents to the conventional milk price (Bijttebier et al., 2016).

Milk production is kept the same because studies are, at this point not clear if milk production increases or decreases using regenerative management.

Nitrogen fixation increases from 0 to 172 kg N ha^{-1}. Permanent grassland is adjusted to 0 in the model because N fixation of grassland is prevented from being accessible due to immobilization. The value of 172 kg N ha^{-1} is estimated based on the maximum share of legumes (clover) and the dry matter yield. The maximum share of clover is 30% on peat, on other soil types this may be up to 40-50% (based on expert opinion). Next, we used a rule of thumb which says that for every ton of dry matter of clover ±50 kg N ha^{-1} can be fixated (de Wit et al., 2004) p.13.

N mineralization is normally equal to immobilization and therefore on mineral soils not taken into account. However, on peat soils there is extra N mineralization due to peat oxidation (very dependent on groundwater table). This extra N mineralization is in this study used as a fixed value (189 kg N ha^{-1}) obtained from the farmers Kringloopwijzer documentation. This value of the Kringloopwijzer is within the range of studies estimating this extra N mineralization of peat soil of for example van Kekem et al. (2004) and Kuikman et al. (2005), who estimated N mineralization rates between 160 and 250 kg N ha^{-1}.

Peat oxidation consequences besides extra N mineralization also in extra CO_2 emissions, these extra emissions were obtained from the Kringloopwijzer and were 5125 kg CO_2 ha^{-1}, almost 17% of total on-farm emissions. Very much in line which values found by Kuikman et al. (2005).

Effective organic matter (EOM) is based on values of Handboek voor de Akkerbouw en de Groenteteelt in de Vollegrond (1989) for grassland. For herb-rich grassland we recalculated with 20-30% white clover with an EOM of 850 kg OM/ha. More EOM was also allocated by changing from slurry to solid manure. This is in-line with literature values, showing that cattle slurry provides 48 g EOM kg FM^{-1}, and solid cow manure 114 g EOM kg FM^{-1} (Veeken et al., 2017). This increase is, however, compensated by a higher aerobic degradation process of solid manure compared to the anaerobic degradation process of slurry. Although, the effect on the SOM balance may be limited by changing to solid manure, straw needs to be added which does increase SOM.

From slurry to solid manure, changing from slurry to solid manure has not only consequences for EOM (See EOM), but also effects the N balance, GHG emissions and costs.

- N balance and GHGe are affected by the degradation parameters of the manures in the model. Overall we incorporated lower N_{min} excretion and application losses for solid manure. N_{min} storage (aerobic and anaerobic) losses were higher compared to slurry, as well as the humifaction coefficient.
- Costs: variable costs (costs for application) include extra costs for additional labor and the use for straw as bedding material. Solid manure is less easily handled than liquid slurries. It cannot be pumped and cannot be used with umbilical spreading systems (Cuttle et al., 2007). Investment costs to change the purpose of the barn system from slurry to solid manure were not taken into account, but can be high. If for example farm yard manure is used in combination with straw, capital costs can go up to 570 euro cow^{-1} (Cuttle et al., 2007; Taylor, 2011). These costs include that most dairy cows are housed

in cubicles, which will need to be removed and the building extended, to allow for the greater area required for loose housing.

Diesel use for grassland was based on a farm survey. The lower diesel use for the regenerative scenario was related due to a reduction in N fertilization (no mined fertilizer and less manure) because of the use of leguminous species in the grassland. The reduction in diesel use was 34 l ha^{-1}, estimated using KWIN-agv 2018 values (p. 116 and 191). The use of herbs in grassland on especially peat soils requires reseeding of the herbs which limits the reduction in diesel use. Based on expert opinion we, therefore, chose the estimated reduction 5%.

Subsidies for the reference scenario were based on farm surveys. For the regenerative scenario we kept subsidies equal for the coming 5 years. Subsidies can be obtained by changing to organic standards or using single practices. Using for example herb-rich grassland can already lead to subsidies of 450 -600 euro/ha (Goyens, 2016; Vandepoel, 2015). Farmers from TiFN's Regenerative Farming project (CoP farmers) which already implementing these practices highlighted in farm surveys that subsidies can go up to 1750 euro ha^{-1}. Based on expert opinion and the uncertainty of subsidies we kept this parameter constant.

Cultivation costs were a sum of all costs including for example costs for housing, costs for health care, farmers and hired labor regarding to the production of the grassland. We kept this equal between the reference and regenerative scenario. The reference scenario will require more external inputs like mined fertilizers, however, the regenerative scenario requires reseeding of the herbs which requires the purchase of seeds and more labor. Following expert opinion and farm surveys with the CoP-farmers difference in costs are in practice nihil.

Labor was determined by farm interviews for the reference scenario. We used KWIN-agv 2018 (p. 191) values and expert opinion to determine labor requirements for the regenerative scenario. The increase in labor is justified by the resowing of herbs and harrowing to prepare the grass bed for the seeds. The reduction in fertilization does not lead to reduced labor since the frequency of fertilization remained the same. Reduced labor was also allocated to fields with grazing, due to less fertilization and grassland maintenance.

Fresh grass price was obtained from a farm survey for the reference scenario. For the regenerative scenario we used expert opinion, KWIN-agv 2018 and Biokennis to determine the sales price of herb-rich grassland. The sales price is increasing due to for example a higher nitrogen content which results in higher feed values (VEM). Although the sales price increases, the effect on the model outcome will be limited because most grass will be used on-farm.

Dry matter yield values were obtained from a farm survey for the reference scenario. The yield of silage in alternated grazing and mowing was corrected with 0.95 due to the intensive nature of the system (low grazing). We kept yield values for the regenerative scenario equal because literature does not show significant increases or decreases regarding yield. This was confirmed by expert opinion. Other yield parameters were obtained from CVB (2018) and Feedipedia (2020).

Feed values were obtained from a farm survey for the reference scenario. Based on data of CVB (2018) and Feedipedia (2020), CoP farms and expert opinion we estimated a slight increase in VEM and DVE due to a higher N content of the herbs.

S5.3: Mixed case-study farm

Grassland, expert corrections were made based on suggestions by Pedro Janssen, Co Daatselaar, Wijnand Sukkel, and Gertjan Holshof.

Reference management include:
Permanent grassland, use of pasture manure, slurry and mineral fertilizer, use of pesticide

FD input variable	**Unit**	**Alternated mowing and grazing**		**Mowing only**	**Source**
		Grassland (fresh)	**Grassland (silage)**	**Grassland (silage)**	
Crop area	ha	23.6		10.4	1
Price fresh matter	€ day^{-1}	0.38		0.38	1
Production	kg cow^{-1} day^{-1}	22.7		22.7	1
Nitrogen fixation	kg N ha^{-1} yr^{-1}	0		0	2, 8
Effective org. Matter	kg ha^{-1} yr^{-1}	2000		2000	6
Diesel use	L ha^{-1}	150		178	4
Subsidies	€ ha^{-1}	200		200	1
Cultivation costs	€ ha^{-1}	1200		1200	1
Total labor	h ha^{-1} yr^{-1}	25		30	1
Price fresh matter	€ kg^{-1}	0	0.062	0.062	1, 15, 19
Fresh yield	kg FM ha^{-1}	31193	12695	28074	1
Dry yield	kg DM ha^{-1}	5084	4621	10219	1, 2
DM content	g 100g FM^{-1}	16.3	36,4	36,4	1, 7, 10
Ash content	g 100g DM^{-1}	10.60	11,8	11,8	7, 10
Nitrogen	g 100g DM^{-1}	2.78	2,48	2,48	2, 7, 10
Phosphorus	g 100g DM^{-1}	0.46	0.41	0.41	2, 7, 10
Potassium	g 100g DM^{-1}	3.43	3,21	3,21	7, 10
Feed saturation value (VW)	-	0.89	1.01	1.01	1, 7
Feed structure value (SW)	-	1.88	2.82	2.82	1, 7
Energy content (VEM)	-	960	888	888	1, 7
Protein content (DVE)	g kg DM^{-1}	92	67	67	1, 7

Regenerative management includes:
Herbrich grassland silage and grazing (incr. Share of legumes; crops with a high water use), no/minimal use of pesticide and mined fertilizer, reduce total N fertilization

FD input variable	**Unit**	**Alternated mowing and grazing**		**Mowing only**	**Source**
		Species-rich grassland (fresh)	**Species-rich grassland (silage)**	**Species-rich grassland (silage)**	
Crop area	ha	23.6		10.4	-
Price fresh matter	€ day^{-1}	0.4		0.4	-
Production	kg cow^{-1} day^{-1}	22.7		22.7	-
Nitrogen fixation	kg N ha^{-1} yr^{-1}	190		190	2, 8
Effective org. Matter	kg ha^{-1} yr^{-1}	2000		2000	6, 9
Diesel use	L ha^{-1}	143		169	4
Subsidies	€ ha^{-1}	200		200	2, 12
Cultivation costs	€ ha^{-1}	1200		1200	2, 8, 13, 20
Total labor	h ha^{-1} yr^{-1}	30		35	2, 15, 16
Price fresh matter	€ kg^{-1}	0	0.067	0.067	14, 15, 19
Fresh yield	kg FM ha^{-1}	40488	12450	27532	2, 5, 8, 11, 17, 18
Dry yield	kg DM ha^{-1}	5466	4968	10985	2, 3, 8
DM content	g 100g FM^{-1}	13,5	39,9	39,9	8
Ash content	g 100g DM^{-1}	14.82	16.50	16.50	2, 8
Nitrogen	g 100g DM^{-1}	3.06	2.73	2.73	2, 10
Phosphorus	g 100g DM^{-1}	0.46	0.41	0.41	2, 10
Potassium	g 100g DM^{-1}	3.26	3.05	3.05	10
Feed saturation value (VW)	-	0.90	1.02	1.02	1, 2, 7
Feed structure value (SW)	-	2.00	2.90	2.90	1, 2, 7
Energy content (VEM)	-	989	915	915	1, 2, 7
Protein content (DVE)	g kg DM^{-1}	95	69	69	1, 2, 7

Values were based on farm interviews[1], expert opinion (all co-authors and three grassland experts, see acknowledgements)[2] and the following secondary literature: Abts et al., (2016)[3], Blanken et al. (2018)[4], Bom (1983)[5], Bosch and de Jonge (1989)[6], CVB (2018)[7], de Wit et al. (2004)[8], de Wolf et al. (2019)[9], Feedipedia (2020)[10], Geel and Brinks (2018)[11], Goyens (2016)[12], Gren (1994)[13], Hospers (2015)[14], Kadaster & WEcR (2017)[15], Scheepens (2001)[16], Schröder et al. (2003)[17], Starmans et al. (2015)[18], van der Voort (2018)[19], and van der Weide et al. (2008)[20].

Cropland, expert corrections were made based on suggestions by Co Daatselaar, Wijnand Sukkel and Herman van Schooten.

Reference management includes:

All crops are used as feed, use of pasture manure, slurry, and mineral fertilizer. use of pesticide

FD input variable	**Unit**	**Fodder beet**	**Winter wheat (grain)**	**Winter wheat (straw)**	**Maize**	**Summer Barley (GPS)**	**Lucerne/ peas (GPS)**	**Source**
Crop area	ha	2.52	5.65	-	10.89	1.81	1.69	-
Nitrogen fixation	kg N ha^{-1}	0	0	-	0	0	94	7
Effective org. Matter	kg EOM ha^{-1}	375	990	-	675	1310	1198	2, 5
Diesel use	L ha^{-1}	114	130	-	92	124	72	3, 17
Cultivation costs	€ ha^{-1}	0	0	-	0	0	0	1
Subsidies	€ ha^{-1}	1621	1329	-	1579	1420	422	1
Total labor	h ha^{-1}	30.6	15	-	37	12	5.1	1, 2
Price fresh matter	€ kg^{-1}	0,046	0.17	0.11	0.06	0.3	0.2	17
Fresh yield	kg FM ha^{-1}	101987	14107	7945	44099	16129	43274	1
Dry matter yield	kg DM ha^{-1}	15400	8500	4000	15567	8500	12376	1, 2
Dry matter content	g 100g FM^{-1}	15,1	87	90.2	35.3	52.7	28.6	9
Ash content	g 100g DM^{-1}	8	1.8	10	3.5	50	9.3	9
Nitrogen	g 100g DM^{-1}	1,2	2.02	1.808	1.2	1.12	2.68	9
Phosphorus	g 100g DM^{-1}	1,9	0.36	0.263	0.17	0.31	0.29	9
Potassium	g 100g DM^{-1}	3,45	0.46	1.75	1.2	0.56	2.22	9
Feed saturation value (VW)	-	0,69	0.11	1.66	0.79	0.76	0.93	1, 6
Feed structure value (SW)	-	1,1	0.26	4.3	1.5	2	2.68	1, 6
Energy content (VEM)	-	1079	1183	418	1000	841	786	1, 2, 6
Protein content (DVE)	g kg DM^{-1}	104	126	42	70	48	56	1, 6

Regenerative management includes:

Crop residues back to the field, catch crops after fodder crops (with*), apply solid manure instead of slurry, no use of pesticide, no use of mined fertilizer > organic mineral fertilizer, reduce total N fertilization

FD input variable	**Unit**	**Fodder beet***	**Winter wheat (grain) ***	**Winter wheat (straw part. to soil)**	**Maize**	**Summer Barley (GPS)**	**Lucerne/ peas (GPS)**	**Source**
Crop area	ha	2.52	5.65	-	10.89	1.81	1.69	-
Nitrogen fixation	kg N ha^{-1}	0	0	-	0	0	94	2, 7
Effective org. Matter	kg EOM ha^{-1}	1775	2515	-	675	1310	1198	2, 5, 8, 16
Diesel use	L ha^{-1}	115	105	-	95	76	72	2, 3, 17, 18
Cultivation costs	€ ha^{-1}	0	0	-	0	0	0	2, 12, 17
Subsidies	€ ha^{-1}	1946	1209	-	1801	2293	291	2, 11
Total labor	h ha^{-1}	91	17	-	107	16	5	2, 13, 14, 17
Price fresh matter	€ kg^{-1}	0,046	0.17	0.11	0.06	0.3	0.2	2, 10, 17
Fresh yield	kg FM ha^{-1}	86689	11850	6674	44099	16129	37092	2, 4, 15, 17
Dry matter yield	kg DM ha^{-1}	13090	7140	3360	15567	8500	10608	2, 10, 17
Dry matter content	g 100g FM^{-1}	15,1	87	90.2	35.3	52.7	28.6	9
Ash content	g 100g DM^{-1}	8	1.8	10	3.5	50	9.3	9
Nitrogen	g 100g DM^{-1}	1,2	2.02	1.808	1.2	1.12	2.68	9
Phosphorus	g 100g DM^{-1}	1,9	0.36	0.263	0.17	0.31	0.29	9
Potassium	g 100g DM^{-1}	3,45	0.46	1.75	1.2	0.56	2.22	9
Feed saturation value (VW)	-	0,69	0.11	1.66	0.79	0.76	0.93	1, 2, 6
Feed structure value (SW)	-	1,1	0.26	4.3	1.5	2	2.68	1, 2, 6
Energy content (VEM)	-	1079	1183	418	1000	841	786	1, 2, 6
Protein content (DVE)	g kg DM^{-1}	104	126	42	70	48	56	1, 2, 6

Values were based on farm interviews[1], expert opinion (all co-authors and three grassland experts, see acknowledgements)[2] and the following secondary literature: Blanken et al. (2018)[3], Bom (1983)[4], Bosch and de Jonge (1989)[5], CVB (2018)[6], de Wit et al. (2004)[7], de Wolf et al. (2019)[8], Feedipedia (2020)[9], Geel and Brinks (2018)[10], Goyens (2016)[11], Gren (1994)[12], PPO (2009)[13], Scheepens (2001)[14], Schröder et al. (2003)[15], Starmans et al. (2015)[16], van der Voort (2018)[17], and van der Weide et al. (2008)[18].

Justification model input data mixed case-study farm

Milk price is kept the same, see explanation dairy case-study farm.

Milk production is kept the same, see explanation dairy case-study farm.

Nitrogen fixation

- For grassland increases from 0 to 190 kg N ha^{-1}. Permanent grassland is adjusted to 0 in the model because N fixation of grassland is prevented from being accessible due to immobilization. The value of 190 kg N ha^{-1} is estimated based on the maximum share of legumes (clover) and the dry matter yield. The maximum share of clover is 40% on sand, this could be even higher (based on expert opinion and Louis Bolk data). Next, we used a rule of thumb which says that for every ton of clover dry matter ±50 kg N ha^{-1} can be fixated (de Wit et al., 2004) p.13. This resulted in a value of 220 kg N ha^{-1}, due to uncertainty the value was corrected to a little lower value.
- For Lucerne-peas (GPS) was estimated at 94 kg N ha^{-1} and remained the same, 122 kg N ha^{-1} was estimated based on 70% Lucerne and 30% peas using 122 kg N ha^{-1} (Berenji et al., 2015) for Luzerne and 30 kg N ha^{-1} for peas (FD model LBI 100 van Beek).
- Other crops did not increase N-fixation due to the inclusion of cover crops. Yellow mustard was selected as cover crop which due take up N in the crop from the soil, which prevents leaching compared to a bare soil. The N-fixation of 40 kg N ha^{-1} (BO Akkerbouw, 2004) from the air is equal to immobilization, therefore, not relevant.

Effective organic matter (EOM) values were based on Handboek voor de Akkerbouw en de Groenteteelt in de Vollegrond (1989).

- For herb-rich grassland we recalculated with 20-40% of red clover (EOM of 1165 kg OM ha^{-1}) and white clover (EOM of 1165 kg EOM ha^{-1}). Due to the mixture of deep rooted herbs which increase EOM and other herbs (e.g. white clover) which reduce EOM, we decided to keep the EOM equal to the reference scenario (2000 kg EOM ha^{-1}). If more red clover would be used this could lead into a higher EOM, however, also lower feed values.
- For crops in the regenerative scenario, crop residues were allocated to the soil. For fodder beet we allocated 900 kg EOM ha^{-1} to the soil which includes beat leaves and roots. For winter wheat the model could decide the amount of straw allocated to the soil, feed or bedding material.
- Yellow mustard was used as cover crop for fodder beet and winter wheat adding 131 and 480 kg EOM ha^{-1} respectively. Further explanations see arable case-study farm.

Diesel use for grassland was based on a farm survey. The lower diesel use for the regenerative scenario was related due to a reduction in N fertilization (no mined fertilizers and less manure) because of the use in legumes in the grassland. The reduction in diesel use was 34 l ha^{-1}, estimated by using KWIN-agv 2018 values (p. 116 and 191). The use of herbs in grassland requires reseeding of the herbs which limits the reduction in diesel use. Based on expert opinion we, therefore, chose the estimated reduction 5%. For crops estimates were determined based KWIN-agv organic values + the extra diesel used for using cover crops.

Subsidies are kept the same, see explanation dairy and arable case-study farm.

Cultivation costs for grassland were kept equal for the reference and regenerative scenario. See explanation dairy case-study farm. Cultivation costs changed for fodder production. Values were based on KWIN-agv organic production standards, leaving crop residues on the field and including cover crops. Adjustments were made based on expert opinion.

- Fodder beet increased a lot: material costs reduce due to no use of mined fertilizers and synthetic pesticide use with ~250 euro ha^{-1}, however, labor increases from 12.9 h ha^{-1} to 76 h ha^{-1}. This increase is mainly related to weeding which goes from 1.6 h ha^{-1} to 65 h ha^{-1}).
- Winter wheat reduced: reduced costs were for a large account related due to less material costs from mined fertilizer and pesticide use.
- Maize increased a lot: material costs reduce due to no use of mined fertilizers and synthetic pesticide use with ~180 euro ha^{-1}, however, labor increases from 8.6 h ha^{-1} to 28 h ha^{-1}. This increase is mainly related to weeding which goes from 0 h ha^{-1} to 20 h ha^{-1} and ground preparation 3.9 to 6 h ha^{-1}.
- Summer barley (GPS increases: material costs were reduced. Labor increases due to hand weeding.
- Lucerne-peas (GPS) reduces: less material costs i.e. fertilizer and pesticide use

Labor was determined by farm interviews for the reference scenario and KWIN-V and AGV. We used KWIN-agv 2018 (p.191) values and expert opinion to determine labor requirements for the regenerative scenario. The increase in labor for grassland is justified by the resowing of herbs and harrowing to prepare the grass bed for the seeds. The reduction in fertilization does not lead to reduced labor since the frequency of fertilization remained the same. Reduced labor was also allocated to fields with grazing, due to less fertilization and grassland maintenance. Labor changed for fodder production. Values were based on KWIN-agv organic production standards, leaving crop residues on the field and including cover crops. Adjustments were made based on expert opinion.

- Fodder beet increased a lot: Labor increases from 12.9 h ha^{-1} to 76 h ha^{-1}. This increase is mainly related to weeding, which goes from 1.6 h ha^{-1} to 65 h ha^{-1}.
- Winter wheat: increased a little bit due to 4 h ha^{-1} more hand weeding.

- Maize increased a lot: labor increases from 8.6 h ha^{-1} to 28 h ha^{-1}. This increase is mainly related to weeding which goes from 0 h ha^{-1} to 20 h ha^{-1}) and ground preparation 3.9 to 6 h ha^{-1}.
- Summer barley Labor increases due to hand weeding.
- Lucerne-peas (GPS) labor stays stable.

Product price is kept stable according to the explanation of the dairy and arable case-study farm.

Dry matter yield was obtained from a farm survey for the reference scenario. The yield of silage in alternated grazing and mowing was corrected with 0.9 due to an intensive system (high grazing). For the regenerative scenario we used expert opinion and KWIN-agv 2018. For grassland we kept yield values for the regenerative scenario equal because literature does not show significant increases or decreases regarding yield. This was confirmed by expert opinion. Other yield parameters were obtained from CVB (2018) and Feedipedia (2020). For cropland, yields did change (fodder beet, winter wheat, lucerne-peas) due to diseases (at least for the first 5 years). Crop yields stayed the same for maize and summer barley.

Feed values were obtained from a farm survey for the reference scenario. Based on data of CVB (CVB, 2018) and Feedipedia (2020), CoP farms and expert opinion. We estimated a slight increase in VEM and DVE due to a higher N content of herb-rich grassland. Feed values for crops remained the same.

S6: Overview of objectives, decision variables and constraints in FarmDESIGN

S6.1: Arable case-study farm

Farm-level indicators	Units	Min	Max
Objectives			
Organic matter balance	Kg ha^{-1}		x
Operating profit	€ yr^{-1}		x
Pesticide use	Kg AI ha^{-1}	x	
Imported fertilizers	€ yr^{-1}	x	
Decision variables			
Area sugar beet (reference and regenerative scenario)	ha	0	11
Area kidney bean (reference and regenerative scenario)	ha	0	3
Area winter wheat (reference and regenerative scenario)	ha	0	9
Area potatoes (reference and regenerative scenario)	ha	0	17
Area chicory (reference and regenerative scenario)	ha	0	6
Area lucerne (reference and regenerative scenario)	ha	0	5

Farm-level indicators	**Units**	**Min**	**Max**
Constraints			
Whole farm area	ha	44	46
Labour balance	h yr^{-1}	0	9999
Farm profitability	€ yr^{-1}	20000	200000
N balance	Kg N ha^{-1}	0	999
P balance	Kg P ha^{-1}	0	999
K balance	Kg K ha^{-1}	0	999
Exploration parameters			
Amplitude (F)	-	0,15	
Probability (CR)	-	0,85	
Fixed seed	-	300	
Number of solutions	-	2000	
Number of iterations	-	4000	

S6.2: Dairy case-study farm

Farm-level indicators	**Units**	**Min**	**Max**
Objectives			
Greenhouse gas emissions	Kg CO_2 eq. ha^{-1}	x	
Operating profit	€ yr^{-1}		x
Imported crop products	Kg N ha^{-1}	x	
Imported fertilizers	kg N ha^{-1}	x	
Decision variables			
Dairy cows	-	50	150
Area permanent grassland (grazing/mowing)	ha	0	17
Area permanent grassland (mowing)	ha	0	24
Area herb-rich grassland (grazing/mowing)	ha	0	20
Area herb-rich grassland (mowing)	ha	0	40
Feed_maize silage	kg DM	0	100000
Feed_ wheat straw	kg DM	0	100000
Feed_concentrates	kg DM	0	300000
Feed_grass silage (mowing/grazing)	kg DM	0	160000
Feed_grass silage (mowing only)	kg DM	0	260000
Feed_herb-rich grass silage (mowing/grazing)	kg DM	0	200000
Feed_herb-rich grass silage (mowing only)	kg DM	0	300000
Frac. fed in non-graz. period_concentrates	-	0	1
Frac. fed in non-graz. period_wheat straw	-	0	1
Frac. fed in non-graz. period_maize silage	-	0	1
Frac. fed in non-graz. period_grass silage (gmowing/grazing)	-	0	1
Frac. fed in non-graz. period_grass silage (gmowing only)	-	0	1
Frac. fed in non-graz. period_herb-rich grass silage (mowing/grazing)	-	0	1

Farm-level indicators	Units	Min	Max
Frac. fed in non-graz. period_hreb-rich grass silage (mowing only)	-	0	1
Self-reliance 1_grass silage (mowing/grazing)	-	1	99
Self-reliance 1_grass silage (mowing only)	-	1	99
Self-reliance 2_herb-rich grass silage (mowing/grazing)	-	1	99
Self-reliance 2_herb-rich grass silage (mowing only)	-	1	99
Frac. for fertilization_solid manure	-	0	1
Constraints			
Whole farm area	ha	38	43
Labour balance	h yr^{-1}	0	9999
Farm profitability	€ yr^{-1}	30000	200000
N balance	Kg N ha^{-1}	0	999
P balance	Kg P ha^{-1}	0	999
K balance	Kg K ha^{-1}	0	999
Feed balance deviation/req.			
DM intake ≤100% % of saturation	%	-99999	0
Energy 95-105% of req.	%	-5	5
Protein 100-13-% of req.	%	0	30
Structure >100% of req.	%	0	99999
Exploration parameters			
Amplitude (F)	-	0,15	
Probability (CR)	-	0,85	
Fixed seed	-	300	
Number of solutions	-	2000	
Number of iterations	-	4000	

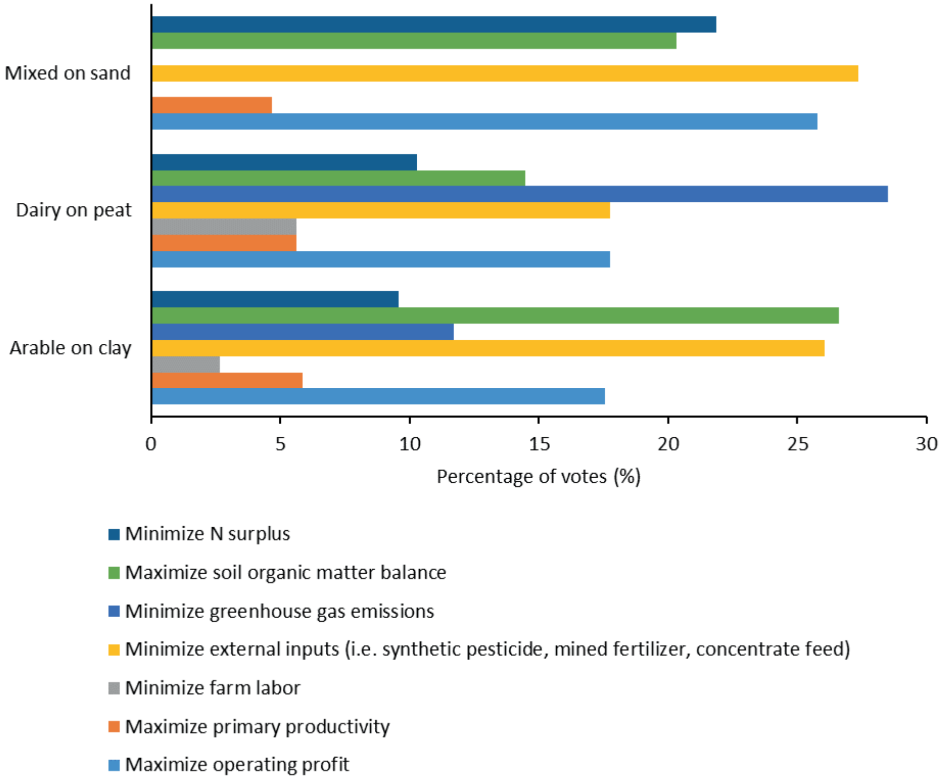
S6.3: Mixed case-study farm

Farm-level indicators	Units	Min	Max
Objectives			
N balance	Kg N ha^{-1}	x	
Operating profit	€ yr^{-1}		x
Import crop products	Kg N ha^{-1}	x	
Imported fertilizers	kg N ha^{-1}	x	
Imported pesticides	kg N ha^{-1}	x	
Decision variables			
Dairy cows	-	50	150
Area permanent grassland (grazing/mowing)	ha	0	24
Area permanent grassland (mowing)	ha	0	11
Area fodder beet	ha	0	3
Area summer barley (GPS)	ha	0	2
Area winter wheat	ha	0	6

Farm-level indicators	**Units**	**Min**	**Max**
Area maizeha		0	11
Area lucerne/peas (GPS)ha		0	2
Area R_herb-rich grassland (grazing/mowing)ha		0	24
Area R_herb-rich grassland (mowing)ha		0	11
Area R_fodder beet + yellow musterdha		0	3
Area R_summer barley (GPS)ha		0	2
Area R_winter wheat + yellow mustardha		0	6
Area R_maize + bladrammenasha		0	11
Area R_lucerne/peas (GPS)ha		0	2
Used as animal feed_imported concentrateskg DM		0	300000
Used as animal feed_imported maizekg DM		0	50000
Used as animal feed_imported winter wheat strawkg DM		0	30000
Used as animal feed_fodder beetkg DM		0	40000
Used as animal feed_summer barley (GPS)kg DM		0	9445
Used as animal feed_winter wheat (grain)kg DM		0	37000
Used as animal feed_winter wheat (straw)kg DM		0	41000
Used as animal feed_maizekg DM		0	160000
Used as animal feed_lucerne/peas (GPS)kg DM		0	20000
Used as animal feed_grassland (silage)kg DM		0	125600
Used as animal feed_ R_fodder beetkg DM		0	40000
Used as animal feed_R_summer barley (GPS)kg DM		0	9445
Used as animal feed_R_winter wheat (grain)kg DM		0	37000
Used as animal feed_R_winter wheat (straw)kg DM		0	41000
Used as animal feed_R_maizekg DM		0	160000
Used as animal feed_R_lucerne/peas (GPS)kg DM		0	20000
Used as animal feed_R_herbrich grassland (silage)kg DM		0	125600
Used as bedding_imported winter wheat strawkg DM		0	300000
Used as bedding_winter wheat straw-		0	1
Used as bedding_R_winter wheat straw-		0	1
Used as green manure_winter wheat straw-		0	1
Used as green manure_R_winter wheat straw-		0	1
Frac. fed in non-graz. period_imported concentrates-		0	1
Frac. fed in non-graz. period_imported maize-		0	1
Frac. fed in non-graz. period_imported winter wheat straw-		0	1
Frac. fed in non-graz. period_fodder beet-		0	1
Frac. fed in non-graz. period_summer barley (GPS)-		0	1
Frac. fed in non-graz. period_winter wheat (grain)-		0	1
Frac. fed in non-graz. period_winter wheat (straw)-		0	1
Frac. fed in non-graz. period_maize-		0	1
Frac. fed in non-graz. period_lucerne/peas (GPS)-		0	1
Frac. fed in non-graz. period_grassland (silage 1)-		0	1
Frac. fed in non-graz. period_grassland (silage 2)-		0	1
Frac. fed in non-graz. period_R_fodder beet-		0	1

Farm-level indicators	**Units**	**Min**	**Max**
Frac. fed in non-graz. period_R_summer barley (GPS)	-	0	1
Frac. fed in non-graz. period_R_winter wheat (grain)	-	0	1
Frac. fed in non-graz. period_R_winter wheat (straw)	-	0	1
Frac. fed in non-graz. period_R_maize	-	0	1
Frac. fed in non-graz. period_R_lucerne/peas (GPS)	-	0	1
Frac. fed in non-graz. period_R_herbrich grassland (silage 1)	-	0	1
Frac. fed in non-graz. period_R_herbrich grassland (silage 2)	-	0	1
Self reliance_grassland (silage 1 and 2)	-	1	999999
Self reliance_R_herbrich grassland (silage 1 and 2)	-	1	999999
Fraction for fertilization_Solid manure	-	0	1
Fraction for fertilization_Fresh manure	-	0	1
Constraints			
Whole farm area	ha	56	62
Bedding balance (deviation)	%	0	10
Labour balance	h yr^{-1}	0	9999
Farm profitability	€ yr^{-1}	30000	200000
N balance	Kg N ha^{-1}	0	999
P balance	Kg P ha^{-1}	0	999
K balance	Kg K ha^{-1}	0	999
Feed balance deviation/req.			
DM intake ≤100% % of saturation	%	-99999	0
Energy 95-105% of req.	%	-5	5
Protein 100-13-% of req.	%	0	30
Structure >100% of req.	%	0	99999
Exploration parameters			
Amplitude (F)	-	0,15	
Probability (CR)	-	0,85	
Fixed seed	-	300	
Number of solutions	-	2000	
Number of iterations	-	4000	

S7: Quick scan – objectives for optimization in FarmDESIGN



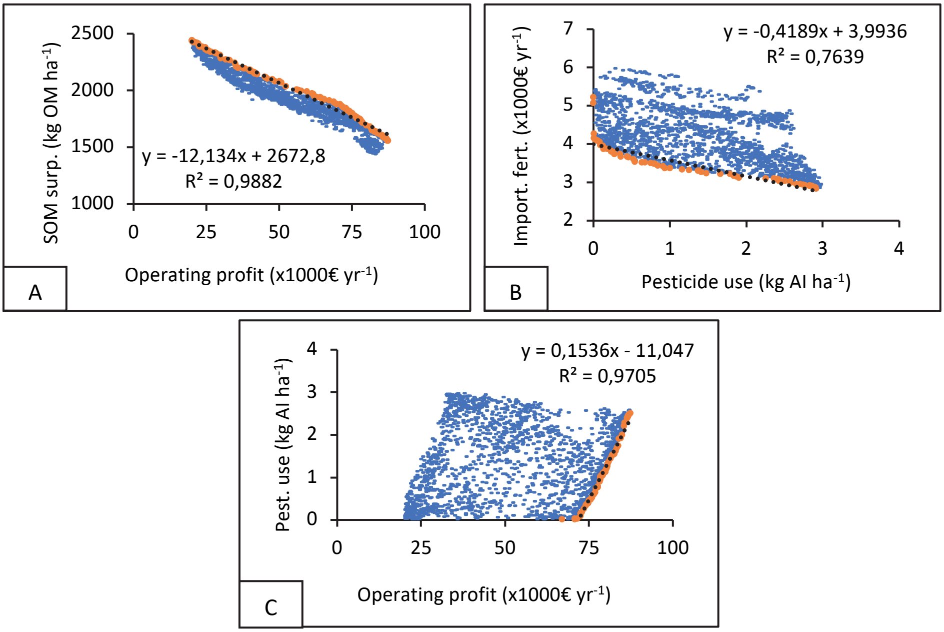
S8: Detecting synergies and trade-offs in solution spaces

In order to identify relationships (i.e. synergies and trade-offs) between optimization objectives within solution spaces we used visual inspection but also regression analysis as a more mathematical approach. Using visual inspection, we looked at the shape of the solution space, as well as its direction. For example, in Figure A the optimization objectives were to both maximize SOM balance and operating profit. Figure A, clearly illustrates a trade-off between SOM balance and operating profit, i.e. an increase in SOM balance leads to a reduction in operating profit. For other solution spaces it was less clear if there was a synergy or trade-off using visual inspection (i.e. Figure B and C). In addition to visual inspection we, therefore, used linear regression as a more mathematical approach (Eq. 1) and added a formula to determine a synergy or trade-off (Eq. 2). The regression analysis was done on pareto-optimal solutions (rank 0 and 1) using 2-by-2 comparison (between 2 objectives) (Goldberg, 1989). Rank 0 and 1 solutions were filtered from the solution space using pareto ranking. The R-squared (R^2) was used as a measure of the strength ($R^2 \geq 0$ and $R^2 < 0.9$ weak; $R^2 \geq 0.9$ strong) of the synergy or trade-off. As such, we can see in Figure A, a strong trade-off between the pareto optimal solutions ($T<0$; $R^2=0.98$), in Figure B a weak synergy ($T>0$; $R^2=0.76$), and in Figure C a strong trade-off ($T<0$; $R^2=0.97$). In the following sections we will show for the various optimization objectives of the three case-study farms if synergies ($T>0$) or trade-offs ($T<0$) occur as well as the strength of the relationship.

Often the relationships in solution spaces will not be linear, and then a more detailed approach would be needed, for instance a segmentation where the “indifferent” parts are separated from the synergy/trade-offs relation. The synergy/trade-off relation might be non-linear, but then the described approach will still give indication for many situations.

$Y = a * x + b$	Determines linear function	Eq. 1
$T = d1 * d2 * a$	Determines synergy or trade-off	Eq. 2
Y, x	Are the coordinates of any point on the line	
a	Slope of the line	
b	Is the y-axis intercept	
T	Indicates a synergy ($T>0$) or trade-off ($T<0$)	
$d1$	Direction of objective 1 (+1 for maximalization; -1 for minimalization)	
$d2$	Direction of objective 2 (+1 for maximalization; -1 for minimalization)	

The following figure shows three solution spaces of the arable case-study farm which were filtered on pareto optimal (rank 1) solutions. The blue dots represent non-pareto optimal solutions, the orange dots represent pareto optimal solutions, the black dotted line shows the linear relationship.



Overview of the synergies, trade-offs, and R^2 of optimization objectives for the case-study farms

Regression analysis was not possible for cells with a “*”, because one of the optimization objectives was constrained to zero.

Arable case-study farm

	Combined scenario		Regenerative scenario	
Objectives	**T**	**R^2**	**T**	**R^2**
Profit vs pesticide use	-0.15	0.97	*	*
Profit vs som balance	-12.13	0.99	-16.15	0.98
Profit vs fert costs	-0.04	0.99	-0.01	0.93
Pesticide use vs som balance	25641.00	0.61	*	*
Pesticide use vs fert costs	-0.42	0.76	*	*
Som balance vs fert costs	0.00	0.97	0.00	0.98

Dairy case-study farm

	Combined scenario		Regenerative scenario	
Objectives	**T**	**R^2**	**T**	**R^2**
Profit vs ghge	-0.12	0.99	-0.14	0.99
Profit vs im. Crop	-2.11	0.99	-2.11	0.99
Profit vs im. Fert	-0.63	0.97	*	*
Ghge vs im. Crop	-21.74	0.95	-65.08	0.96
Ghge vs im. Fert	-12.31	0.98	*	*
Im. Crop vs im. Fert	-0.39	0.98	*	*

Mixed case-study farm

	Combined scenario		Regenerative scenario	
Objectives	**T**	**R^2**	**T**	**R^2**
Profit vs n surpl	-1.85	0.79	-0.71	0.96
Profit vs im. Crop	-3.09	0.98	-3.46	0.91
Profit vs im. Fert	-1.04	0.89	*	*
Profit vs pest use	-0.03	0.81	*	*
N balance vs imp. Crop	-0.15	0.71	-0.21	0.52
N balance vs imp. Fert	-0.38	0.06	*	*
N balance vs pest use	-0.01	0.71	*	*
Im. Crop vs im. Fert	-0.27	0.98	*	*
Im. Crop vs pest use	-0.01	0.98	*	*
Im. Fert vs pest use	0.00	1.00	*	*

S9: Changed input attributes in the SN of the regenerative scenario compared to the reference scenario

S9.1: Arable case-study farm

Reference scenario

Input	Unit	Sugar beet	Chicory	Potato	Kidney been	Winter wheat	Lucerne
Tillage	Yes/no	Yes	Yes	Yes	Yes	Yes	Yes
Number of years with catch crops	yr	0	0	0	0	5	0
Number of years with crop residues left in the field in last	yr	0	0	0	0	0	0
Application of mineral fertilizer	Yes/no	yes	yes	yes	yes	yes	no
Mineral N fertilization*	kg N/ha	75-100	125-150	75-100	75-100	75-100	-
Mineral P fertilization	kg P/ha	<10	<10	<10	<10	<10	-
Application of manure	Yes/no	no	no	yes	no	yes	yes
Manure application techniques	-	-	-	Both	-	Both	Both
Type of manure/compost	-	-	-	Pig slurry	Pig slurry	Pig slurry	Pig slurry
Organic N fertilizer	kg N/ha	-	-	>200	>200	>200	<50
Irrigation	Yes/no	no	no	Yes	no	no	no
Irrigation method	-	-	-	Sprinkler	-	-	-
Irrigation rate	-	-	-	6-12	-	-	-
Irrigation frequency	-	-	-	<10	-	-	-
Chemical pest management	Yes/no	yes	yes	yes	yes	yes	yes
Mechanical pest management	Yes/no	no	no	no	no	no	No

Regenerative scenario

Input	Unit	Sugar beet	Chicory	Potato	Kidney been	Winter wheat	Lucerne
Tillage	Yes/no	No	No	No	No	No	No
Number of years with catch crops	yr	5	5	5	5	5	5
Number of years with crop residues left in the field in last	yr	5	5	5	5	5	5
Application of mineral fertilizer	Yes/no	no	no	no	no	no	no

Input	Unit	Sugar beet	Chicory	Potato	Kidney been	Winter wheat	Lucerne
Mineral N fertilization*	kg N/ha	-	-	-	-	-	-
Mineral P fertilization	kg P/ha	-	-	-	-	-	-
Application of manure	Yes/no	yes	yes	yes	yes	yes	yes
Manure application techniques	-	Both	Both	Both	Both	Both	Both
Type of manure/compost	-	Solid manure	Solid manure	Solid manure	Solid manure	Solid manure	Solid manure
Organic N fertilizer	kg N/ha	75-100	50-75	125-150	125-150	100-125	<50
Irrigation	Yes/no	yes	yes	Yes	yes	yes	No
Irrigation method	-	Sprinkler	Sprinkler	Sprinkler	Sprinkler	Sprinkler	-
Irrigation rate	-	6-12	6-12	6-12	6-12	6-12	-
Irrigation frequency	-	10-20	10-20	10-20	10-20	10-20	-
Chemical pest management	Yes/no	no	no	no	no	no	no
Mechanical pest management	Yes/no	yes	yes	yes	yes	yes	Yes

S9.2: Dairy case-study farm

Input	Unit	Reference scenario		Optimized scenario	
		Alternated grazing-mowing	Mowing only	Alternated grazing-mowing	Mowing only
Number of years with legumes	yr	0	0	5	5
Share of legumes on the field	%	<10	<10	>10	>10
Grassland diversity	N species	1	1	>2	>2
Application of mineral fertilizer	Yes/No	Yes	Yes	No	No
Mineral N fertilization	kg N ha^{-1}	75-100	75-100	0	0
Type of manure	-	Slurry	Slurry	Solid	Solid
Organic N fertilizer	kg N ha^{-1}	>200	>200	75-100	75-100

S9.3: Mixed case-study farm

Reference scenario

Input	**Unit**	**Alternated grazing-mowing**	**Mowing only**	**Summer Barley**	**Maize**	**Fodder beet**	**Winter wheat**	**Lucerne / peas**
Tillage	Yes/no	No	No	Yes	Yes	Yes	No	Yes
N yrs with legumes	yr	0	0	-	-	-	-	-
Share of legumes on the field	-	0	0	-	-	-	-	-
Grassland diversity	-	1	1	-	-	-	-	-
N yrs with catch crops	yr	-	-	0	0	1	3	0
N yrs with crop residues in the field	yr	-	-	0	0	0	0	0
Application of mineral fertilizers	Yes/no	Yes	Yes	No	Yes	Yes	Yes	No
Mineral N fertilization	kg N ha^{-1}	75-100	75-100	-	<50	75-100	75-100	-
Mineral P fertilization	kg P ha^{-1}	<10	<10	-	<10	<10	<10	-
Type of manure	-	Cow slurry	Cow slurry	Cow slurry	Cow slurry	Cow slurry	Cow slurry	Cow slurry
Organic N fertilizer	kg N ha^{-1}	125-150	125-150	<50	125-150	125-150	100-125	125-150
Chemical pest management	Yes/no	yes	yes	yes	yes	yes	yes	yes
Bio/mech pest management	Yes/no	no	no	no	no	no	no	No

Regenerative scenario								
Input	**Unit**	**Alternated grazing-mowing**	**Mowing only**	**Summer Barley**	**Maize**	**Fodder beet**	**Winter wheat**	**Lucerne /peas**
Tillage	Yes/no	No	No	No	No	No	no	No
N yrs with legumes	yr	5	5	-	-	-	-	-
Share of legumes on the field	-	5	5	-	-	-	-	-
Grassland diversity	-	>2	>2	-	-	-	-	-
N yrs with catch crops	yr	-	-	5	5	5	5	5
N yrs with crop residues in the field	yr	-	-	0	0	5	0	5
Application of mineral fertilizers	Yes/no	No	No	No	No	No	No	No
Mineral N fertilization	kg N ha^{-1}	-	-	-	-	-	-	-
Mineral P fertilization	kg P ha^{-1}	-	-	-	-	-	-	-
Type of manure	-	Solid manure	Solid manure	Solid manure	Solid manure	Solid manure	Solid manure	Solid manure
Organic N fertilizer	kg N ha^{-1}	75-100	75-100	<50	100-125	125-150	125-150	<50
Chemical pest management	Yes/no	no	no	no	no	no	no	no
Bio/mech pest management	Yes/no	yes	yes	yes	yes	yes	yes	yes

S10: Sensitivity analysis

The “R” before a crop represents the regenerative management is applied. The color and numbers relate to positive (green; 1) and negative (red; -1) relationships between decision variables and optimization objectives.

Arable case-study farm

Decision_variable	SOM surplus	Pest. use	Imp. fert costs	Profit
HiredRegularLabor	0,01	0,04	-0,07	-0,03
Area sugar beet	-0,33	0,99	-0,49	0,14
Area R_sugar beet	0,50	-0,93	0,29	-0,31
Area lucerne	-0,87	-0,14	0,87	0,97
Area R_lucerne	0,87	0,14	-0,86	-0,96
Area potatoes	-0,13	-0,07	0,33	0,19
Area R_potatoes	-0,25	-0,50	0,78	0,40
Area chicory	-0,08	0,47	-0,54	-0,12
Area R_chicory	0,01	0,07	-0,10	-0,04
Area kidney bean	-0,03	-0,10	0,21	0,08
Area R_kidney bean	-0,54	0,23	0,18	0,48
Area winter wheat	-0,25	-0,17	0,56	0,34
Area R_winter wheat	0,56	0,03	-0,39	-0,47

Dairy case-study farm

Decision variable	Operating profit	GHG em.	Import crop	Import. fert.
Herb silage (alt. mowing and grazing) to animals	0,02	0,12	0,17	-0,24
Herb silage (alt. mowing and grazing) fract. fed in NGP	-0,15	-0,21	-0,24	0,12
Grass silage (alt. mowing and grazing) to animals	0,42	0,07	-0,18	0,99
Grass silage (alt. mowing and grazing) fract. fed in NGP	-0,43	-0,54	-0,49	0,10
Grassland silage (mowing only) to animals	0,48	0,14	-0,08	0,97
Grassland silage (mowing only) fract. fed in NGP	-0,36	-0,35	-0,29	-0,12
Herb silage (mowing only) fract. fed in NGP	-0,32	-0,52	-0,56	0,38
Herb silage (mowing only) to animals	0,38	0,61	0,75	-0,51
Concentrates to animals	-0,17	-0,26	-0,30	0,13
Concentrates fract. fed in NGP	0,56	0,82	0,82	-0,41
Rhoughage (grain_straw) fract. fed in NGP	0,03	0,03	0,03	0,02
Rhoughage (grain_straw) to animals	0,67	0,83	0,93	-0,24
Rhoughage (maize_silage) fract. fed in NGP	-0,11	-0,09	-0,12	-0,06
Rhoughage (maize_silage) to animals	0,33	0,63	0,77	-0,64
Straw for bedding	0,96	0,95	0,87	0,29
Area perm. grassland (alt. mowing and grazing)	0,48	0,14	-0,08	0,97
Area herb grassland (mowing only)	-0,61	-0,37	-0,33	-0,69
Area perm. grassland (mowing only)	0,42	0,06	-0,18	0,99
Area herb grassland (alt. mowing and grazing)	-0,33	0,01	0,29	-0,96
Number of dairy cows	0,99	0,96	0,84	0,36
Hired labor	0,00	-0,04	-0,08	0,10

Mixed case-study farm

Decision variable	N bal.	Operating profit	Import. crop.	Pest. use	Import. fert.
Conentrates (ex) to animals	0,64	0,75	1,00	-0,51	-0,27
Maize silage (ex) to animals	0,01	-0,02	0,32	-0,35	-0,31
Winter wheat straw (ex) to animals	0,13	0,00	0,04	-0,07	-0,04
Winter wheat (straw) to animals	0,03	0,06	0,06	-0,01	0,04
Grass silage 1 to animals	-0,34	0,11	-0,54	0,99	0,86
Grass silage 2 to animals	0,00	0,01	-0,02	0,07	0,03
R_grass_ silage 1 to animals	0,09	-0,18	0,09	-0,39	-0,38
R_grass silage 2 to animals	0,02	-0,01	-0,04	0,00	0,02
R_winter wheat (straw) to animals	-0,09	-0,11	-0,10	0,00	-0,01
Winter wheat (straw) (Ex) to bedding	0,28	0,51	0,46	0,03	0,16
Winter wheat (straw) to bedding	-0,10	-0,12	-0,07	-0,03	-0,08
R_winter wheat (straw) to bedding	-0,02	0,08	0,05	0,06	0,09
Winter wheat (straw) to soil	0,02	-0,04	0,03	-0,10	-0,14
R_winter wheat (straw) to soil	0,04	0,12	0,09	0,01	0,06
Conentrates (ex) fraction fed in NGP	-0,12	-0,10	-0,23	0,17	0,15
Maize (ex) fraction fed in NGP	-0,06	-0,04	-0,11	0,11	0,06
Winter wheat (straw) (Ex) fraction fed in NGP	-0,10	-0,12	-0,09	0,00	-0,06
Fodder beet fraction fed in NGP	-0,02	-0,03	-0,03	0,02	0,01
Summer barley fraction fed in NGP	-0,09	-0,10	-0,14	0,08	0,03
Winter wheat (grain) fraction fed in NGP	-0,22	-0,16	-0,29	0,23	0,18
Winter wheat (straw) fraction fed in NGP	0,04	0,03	0,01	0,01	0,02
Maize fraction fed in NGP	-0,46	-0,41	-0,72	0,55	0,44
Lucerne/peas fraction fed in NGP	-0,25	-0,31	-0,49	0,30	0,22
Grass silage 1 fraction fed in NGP	0,00	-0,13	-0,08	-0,06	-0,06
Grass silage 2 fraction fed in NGP	-0,30	-0,45	-0,59	0,25	0,15
R_summer barley fraction fed in NGP	-0,07	-0,12	-0,07	-0,05	-0,09
R_lucerne/peas fraction fed in NGP	-0,12	-0,09	-0,11	0,05	0,02
R_winter wheat (grain) fraction fed in NGP	-0,26	-0,28	-0,41	0,22	0,14
R_winter wheat (straw) fraction fed in NGP	-0,13	-0,14	-0,25	0,15	0,12
R_maize fraction fed in NGP	0,02	0,07	0,10	-0,07	-0,03
R_fodder beet fraction fed in NGP	0,03	-0,07	-0,02	-0,07	-0,08
R_grass silage 1 fraction fed in NGP	0,11	0,11	0,09	0,00	0,03
R_grass silage 2 fraction fed in NGP	-0,01	-0,09	-0,12	0,06	0,11
Area grassland (alt. grazing and mowing)	0,00	0,06	0,01	0,07	0,09
Area herb grassland (alt. grazing and mowing)	-0,03	-0,10	-0,08	-0,02	-0,06
Area grassland (mowing only)	-0,34	0,11	-0,54	1,00	0,86
Area herb-rich grassland (mowing only)	0,28	-0,20	0,46	-0,99	-0,88
Area fodder beat	0,03	0,02	-0,01	0,01	0,03
Area R_fodder beat	-0,14	-0,17	-0,16	0,02	-0,02
Area lucerne	-0,06	-0,10	-0,04	-0,04	-0,09
Area R_lucerne/peas	0,07	0,04	0,11	-0,15	-0,11

Area maize	0,04	0,15	0,02	0,17	0,22
Area R_maize	-0,02	-0,06	-0,02	-0,04	-0,06
Area R_summer barley	0,01	-0,05	0,03	-0,12	-0,10
Area summer barley	0,08	0,00	0,04	-0,07	-0,03
Area winter wheat	0,24	0,54	0,15	0,39	0,75
Area R_winter wheat	-0,23	-0,53	-0,15	-0,39	-0,75
Number of dairy cows	0,57	0,96	0,86	-0,02	0,21

S11: Additional information case-study farms

S11.1: Arable case-study farm

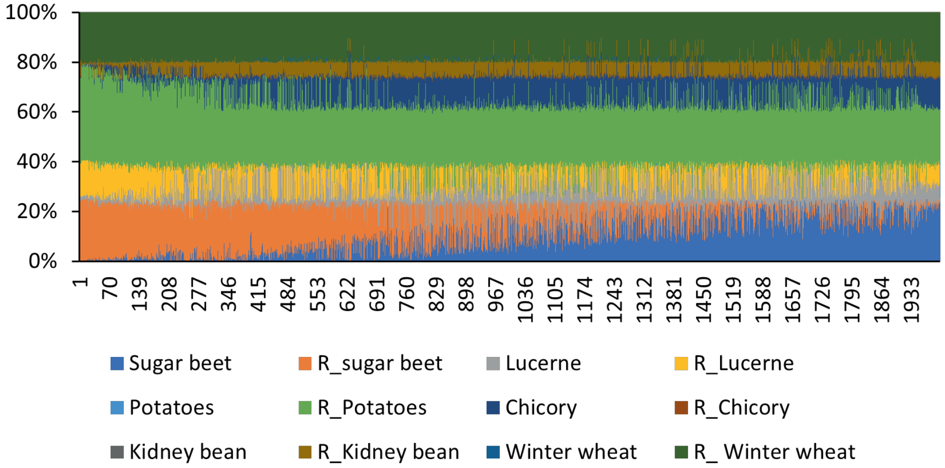
Correlation between optimization objectives of the combined scenario. When R^2 is above 0.9 we consider a synergy or trade-off.

Figure	**Objective 1**	**Objective 2**	**Relationship**	**R^2**
4A	SOM balance	Pesticide use	Linear	0.10
4B	Imported fertilizers	Pesticide use	Linear	0.28
4C	Imported fertilizers	SOM balance	Linear	0.31
4D	Operating profit	Pesticide use	Linear	0,01
4E	Operating profit	SOM balance	Linear	0.92
4F	Operating profit	Imported fertilizers	Linear	0.54

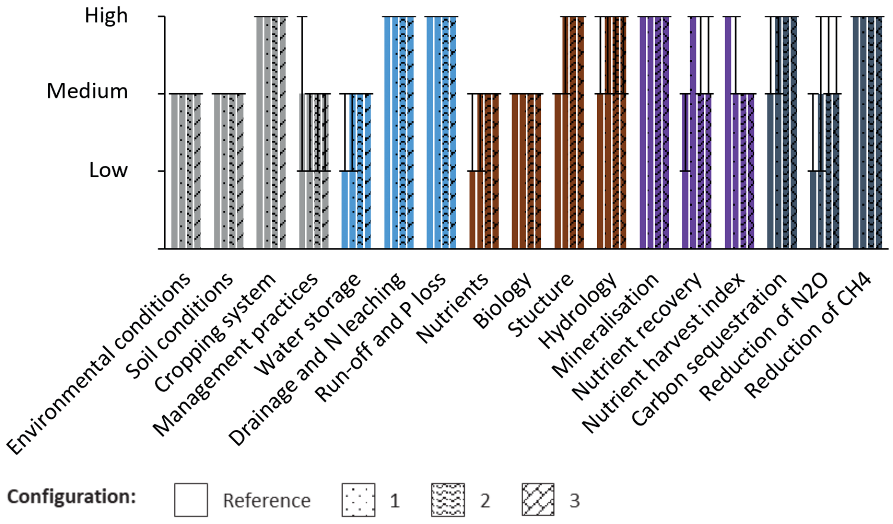
Absolute values of the indicators used for the assessment of regenerative agriculture for the reference and three selected configurations. The absolute values are farm-level averages, since fertilizer and pesticide use varies among the crops used. Fertilization rates for the reference scenario were set according to a farm survey, however, we found that the fertilization rates per crop were divergent compared to typical Dutch fertilization rates. Total on-farm fertilizers remained within national guidelines.

Indicator	**Reference**	**Config. 1**	**Config. 2**	**Config. 3**
Operating profit (€ yr^{-1})	46784	27569	20612	20573
Labor (h yr^{-1})	1096	1421	1489	1621
SOM balance (kg OM ha^{-1})	1136	2272	2409	2053
N balance (kg N ha^{-1})	117	43	47	39
GHG emissions (Mg CO_2-eq. ha^{-1})	4	2	2	2
Pesticide use (kg AI ha^{-1})	6.7	0.3	0.0	0.0
Imported fertilizers (kg N ha^{-1})	244	100	101	95
Relative area of regenerative land-use (%)	0	85	98	100

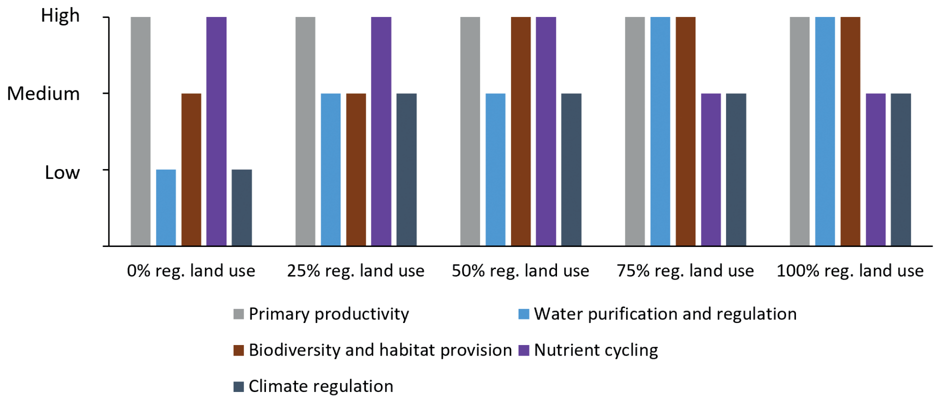
The figure below shows the land use of 2000 alternative farm configurations calculated by FD for combined scenario. The farm configuration showed in this figure are ordered based on farms with a high to low sum of area allocated to the regenerative scenario. The area of land allocated to the reference and regenerative scenario is a sensitive parameter for the final assessment of soil functions.



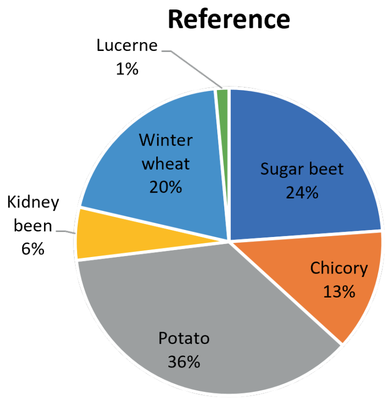
The underlying soil functions of the three case-study farms. The colors grey, blue, brown, purple and dark grey relate to the soil functions primary productivity, water purification and regulation, biodiversity and habitat provision, nutrient cycling and climate regulation respectively.

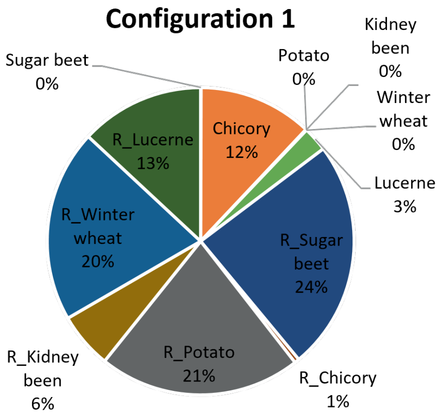


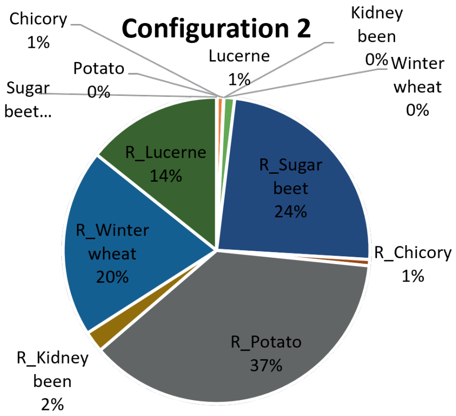
To showcase the effect of land use on the different soil functions the figure below shows how the performance of soil functions will change when selecting farm configurations with various land uses for our dairy case-study farm. In this case we reduced the amount of reference land use with 0%, 25%, 50%, 75% and 100% and allocated this land to regenerative use. The figure below shows soil functions improve un till 75%, after 75% of regenerative land use the score for nutrient cycling reduces to medium. The score for climate regulation can improve if for example less regenerative potato, chicory or sugar beet is grown which in this case are the main drivers for reduced climate regulation.

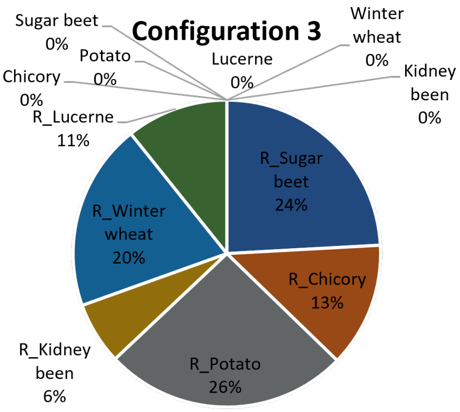


The land use of the different selected farm configurations from the clouds of solutions are shown here below. The “R” indicates the crop managed regeneratively.









S11.2: Dairy case-study farm

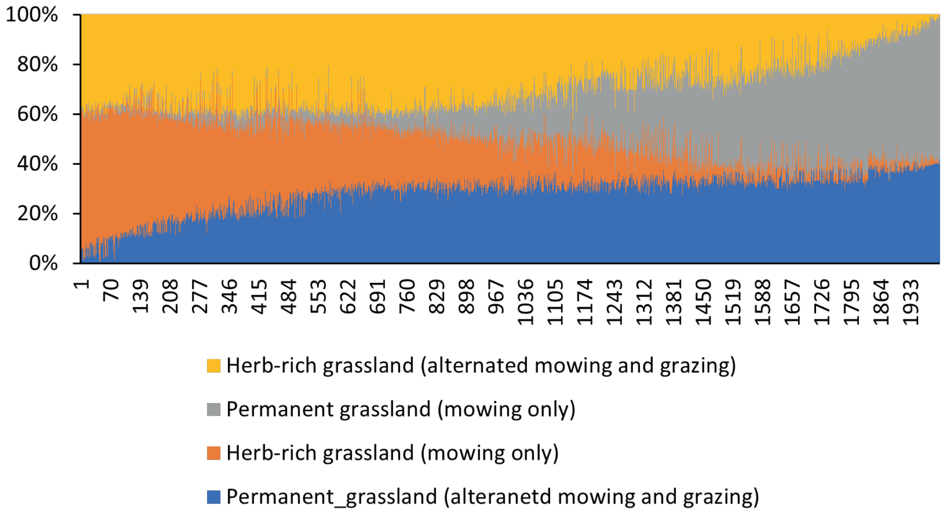
Correlation between optimization objectives of the combined scenario. When R^2 is above 0.9 we consider a synergy or trade-off.

Figure	Objective 1	Objective 2	Relationship	R^2
5A	Imported crop products	GHG emissions	Linear	0.87
5B	Imported fertilizers	GHG emissions	Linear	0.01
5C	Imported fertilizers	Imported crop products	Linear	0.02
5D	Operating profit	GHG emissions	Linear	0,85
5E	Operating profit	Imported crop products	Linear	0.63
5F	Operating profit	Imported fertilizers	Linear	0.21

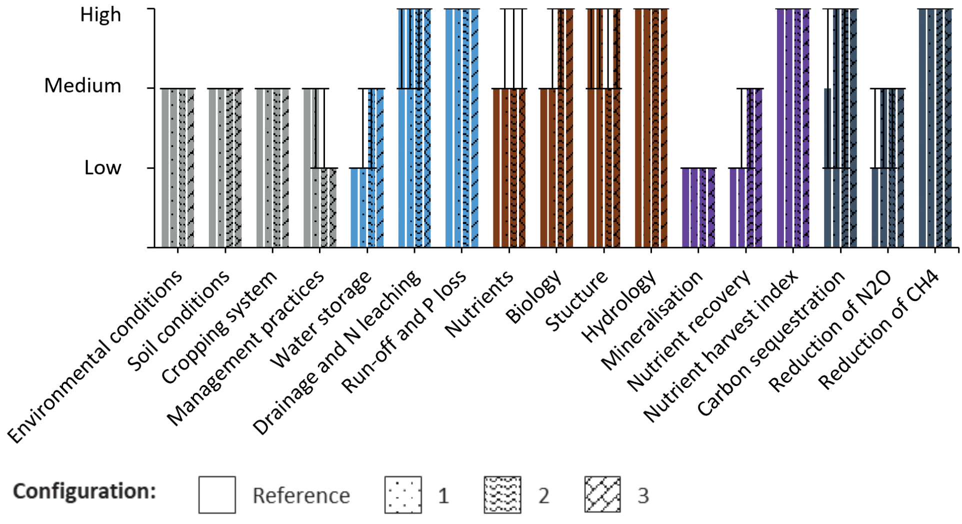
Absolute values of the indicators used for the assessment of regenerative agriculture for the reference and three selected configurations. The absolute values are farm-level averages, since fertilizer and pesticide use varies among the crops used.

Indicator	Reference	Config. 1	Config. 2	Config. 3
Operating profit (€ yr^{-1})	62876	33412	30134	26521
Labor (h yr^{-1})	2989	2863	2928	2873
SOM balance (kg OM ha^{-1})	2741	3512	3494	2788
N balance (kg N ha^{-1})	262	258	274	267
GHG emissions (Mg CO_2-eq. ha^{-1})	30	28	31	26
Imported feed (kg N ha^{-1})	149	223	297	178
Imported fertilizers (kg N ha^{-1})	75	49	26	0
Dairy cow numbers (-)	99	91	93	87
Relative area of regenerative land (%)	0	35	66	100

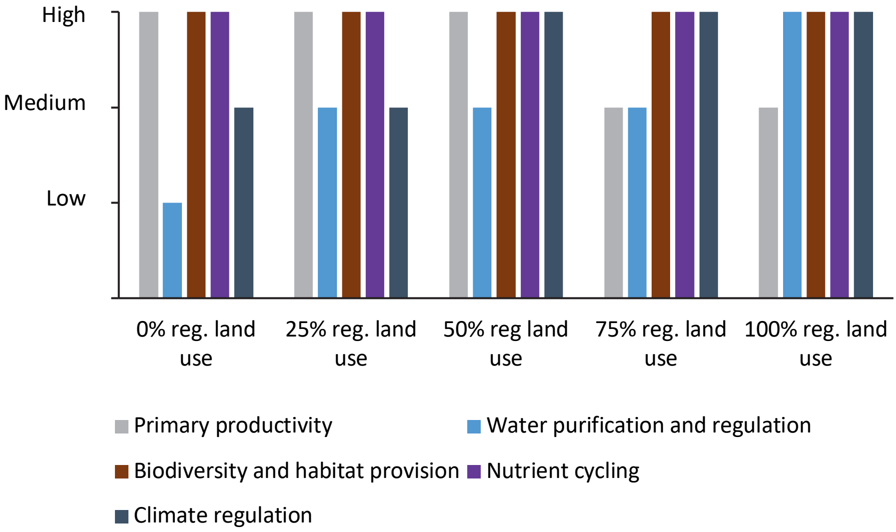
The figure here below shows the land use of 2000 alternative farm configurations calculated by FD for combined scenario. The farm configuration showed in this figure are ordered based on farms with a high to low sum of area allocated to the regenerative scenario. The area of land allocated to the reference and regenerative scenario is a sensitive parameter for the final assessment of soil functions.



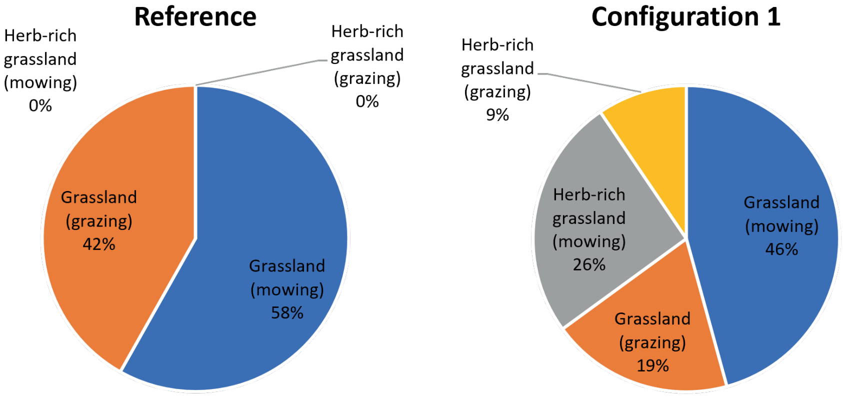
The underlying soil functions of the three case-study farms. The colors grey, blue, brown, purple and dark grey relate to the soil functions primary productivity, water purification and regulation, biodiversity and habitat provision, nutrient cycling and climate regulation respectively.

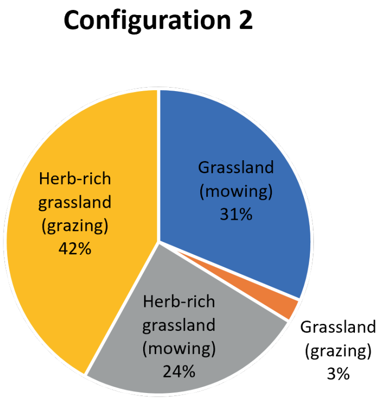


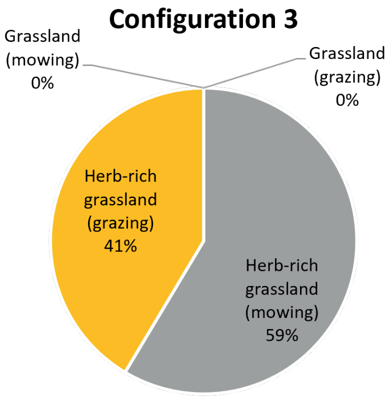
To showcase the effect of land use on the different soil functions the figure below shows how the performance of soil functions will change when selecting farm configurations with various land uses for our dairy case-study farm. For example, it shows that if less than 75% of the area of land was allocated to the regenerative scenario, it would yield in a reduced performance of soil functions i.e. water purification and regulation. Land use with an area of less than 25% allocated to the optimized scenario would also yield in a reduced climate regulation score.



The land use of the different selected farm configurations from the clouds of solutions are shown here below. The “R” indicates the crop managed regeneratively.




Configuration 2


Configuration 3

S11.3: Mixed case-study farm

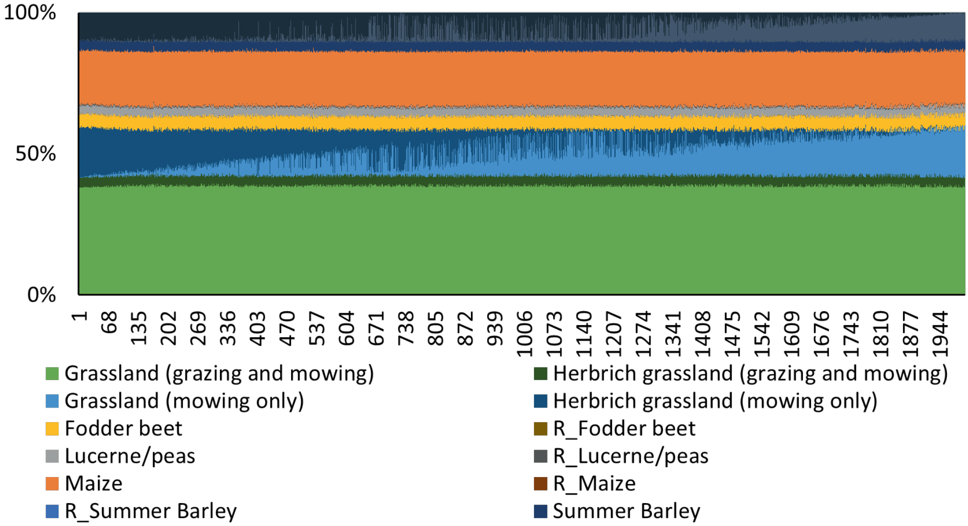
Correlation between optimization objectives of the combined scenario. When R^2 is above 0.9 we consider a synergy or trade-off.

Figure	**Objective 1**	**Objective 2**	**Relationship**	**R^2**
6A	Imported crop products	GHG emissions	Linear	0.87
5B	Imported fertilizers	GHG emissions	Linear	0.01
5C	Imported fertilizers	Imported crop products	Linear	0.02
5D	Operating profit	GHG emissions	Linear	0,85
5E	Operating profit	Imported crop products	Linear	0.63
5F	Operating profit	Imported fertilizers	Linear	0.21

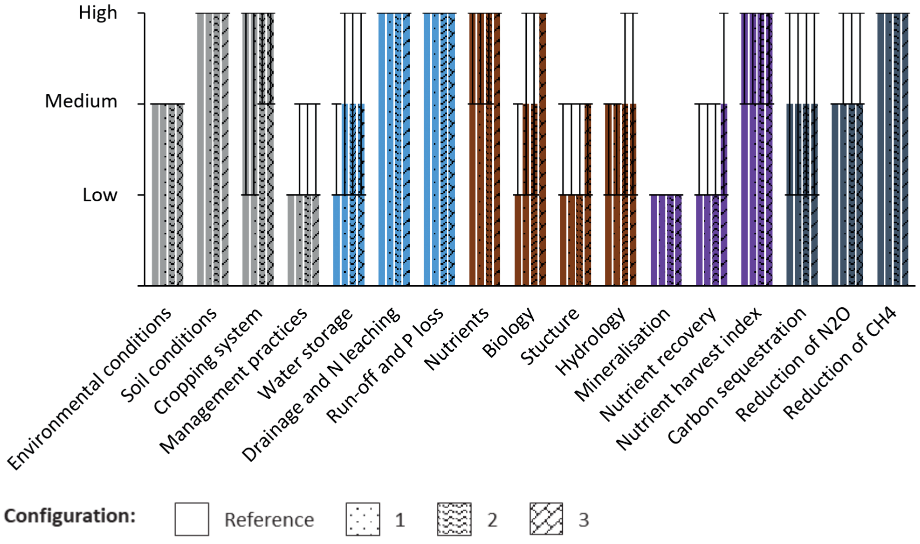
Absolute values of the indicators used for the assessment of regenerative agriculture for the reference and three selected configurations. The absolute values are farm-level averages, since fertilizer and pesticide use varies among the crops used.

Indicator	**Reference**	**Config. 1**	**Config. 2**	**Config. 3**
Operating profit (€ yr^{-1})	66719	32694	30859	47815
Labor (h yr^{-1})	3948	3640	3663	4092
SOM balance (kg OM ha^{-1})	755	1608	1818	1543
N balance (kg N ha^{-1})	59	110	144	66
GHG emissions (Mg CO_2-eq. ha^{-1})	21	19	19	10
Pesticide use (kg AI ha^{-1})	1.4	0.3	0.3	0
Imported feed (kg N ha^{-1})	117	163	168	41
Imported fertilizers (kg N ha^{-1})	84	52	52	0
Dairy cow numbers (-)	116	97	98	70
Relative area of regenerative land (%)	0	31	32	100

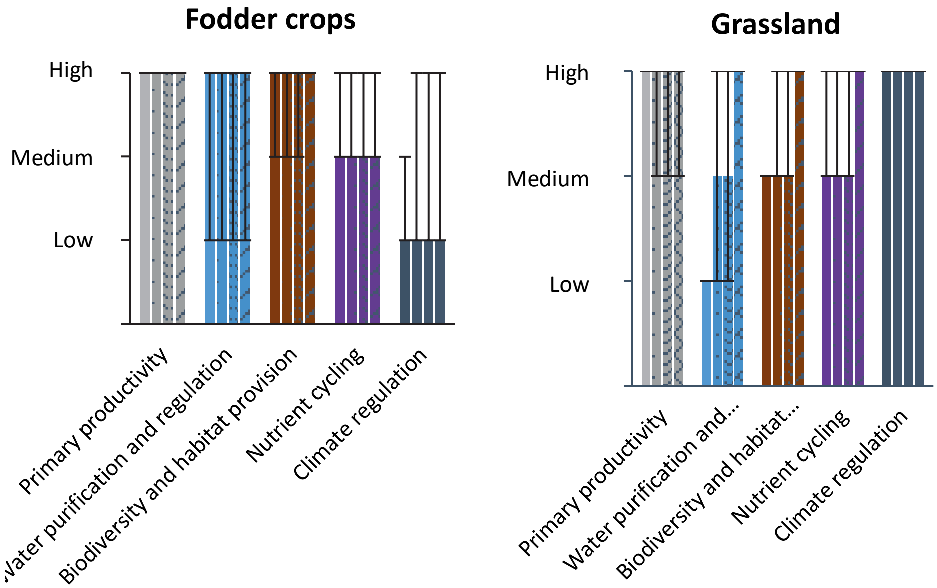
The figure here below shows the land use of 2000 alternative farm configurations calculated by FD for combined scenario. The farm configuration showed in this figure are ordered based on farms with a high to low sum of area allocated to the regenerative scenario. The area of land allocated to the reference and regenerative scenario is a sensitive parameter for the final assessment of soil functions.



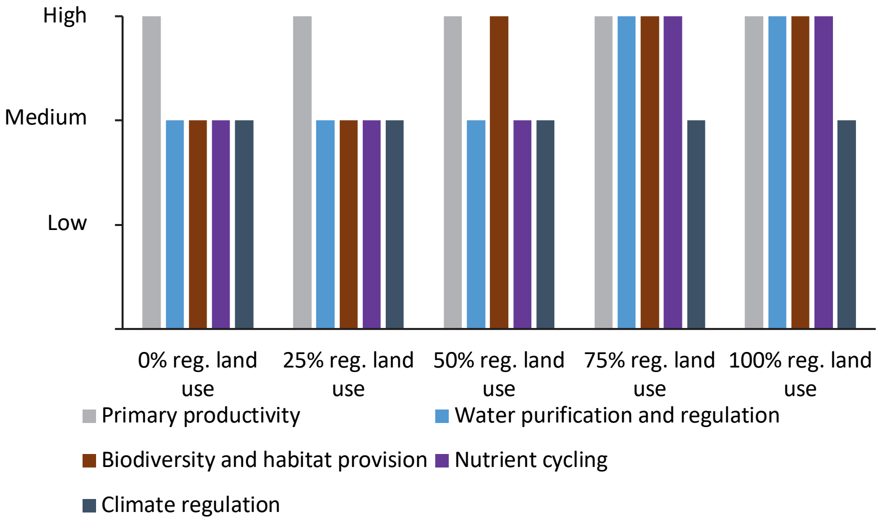
The underlying soil functions of the three case-study farms. The colors grey, blue, brown, purple and dark grey relate to the soil functions primary productivity, water purification and regulation, biodiversity and habitat provision, nutrient cycling and climate regulation respectively.



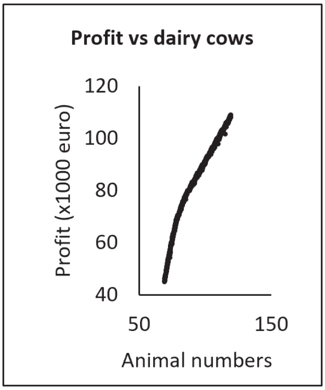
Average scores of soil functions for crop and grassland

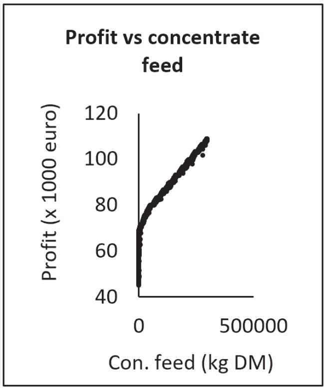


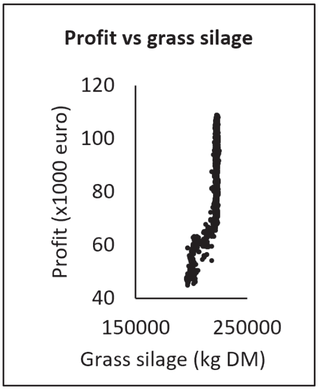
To showcase the effect of land use on the different soil functions the figure below shows how the performance of soil functions will change when selecting farm configurations with various land uses for our dairy case-study farm. For example, it shows that if less than 75% of the area of land was allocated to the regenerative scenario, it would yield in a reduced performance of soil functions i.e. water purification and regulation.



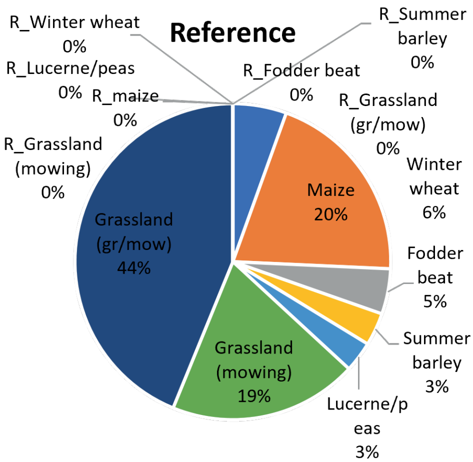
Additional figures showing and explaining the inflection point and relation between

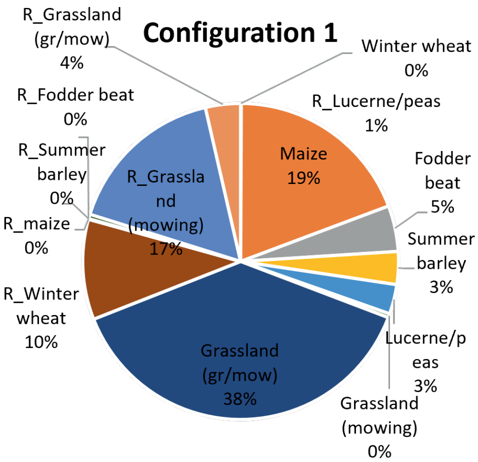


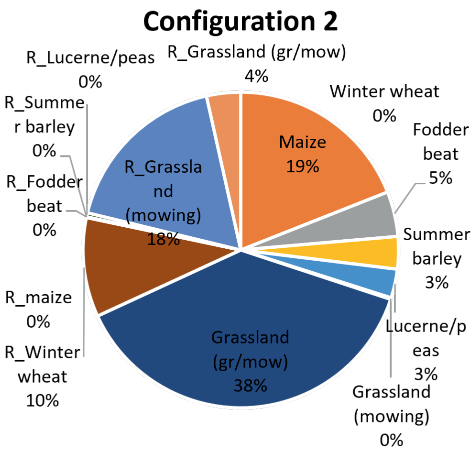


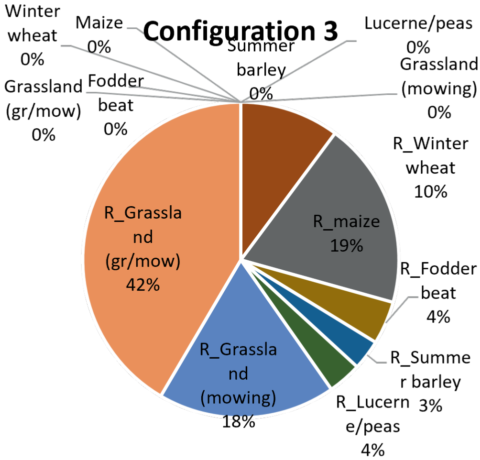


The land use of the different selected farm configurations from the clouds of solutions are shown here below. The "R" indicates the crop managed regeneratively.









Chapter 5

A framework to monitor the 'success' of regenerative agriculture

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Submitted as perspective paper

Abstract

Global food security is threatened by widespread degradation of agricultural land and associated loss of ecosystem services. In response, farming approaches such as regenerative agriculture are heralded by industries and governments as mainstream solutions to keep the global food system within planetary boundaries. The low level of consensus on science-based approaches to the monitoring and verification of the efficacy of such solutions, however, has left many initiatives vulnerable to evidence-based allegations of greenwashing. In this paper, we present a comprehensive perspective on the role of metrics for regenerative agriculture. We subsequently propose a flexible yet coherent framework for the transparent, temporal- and context-sensitive selection of metrics for monitoring the extent to which regenerative initiatives lead to verifiable changes in land management, and as such the degree to which they achieve their goals.

1. Introduction

Global food security is threatened by land degradation: one third of our global land is degraded as a result of erosion, salinization, compaction, acidification, and chemical pollution (United Nations, 2022). In response, emerging approaches to land management, hitherto often considered as niches, are now heralded by industries and governments as mainstream solutions to keep the global food system within planetary boundaries (e.g. Danone, 2021; EIT Food, 2021). Regenerative agriculture is one of such approaches receiving a lot of attention from corporations and decision makers in the food system (Giller et al., 2021). Regenerative agriculture is defined as a way of farming that takes soil conservation as its entry point to contribute to multiple ecosystem services in order to enhance all dimensions (people, planet, and profit) of a sustainable food future (Chapter 2). However, the low level of consensus on science-based approaches to monitoring and verification is restricting the efficacy and transparency of implementation (de Olde et al., 2017a), and has left many initiatives vulnerable to allegations of greenwashing (Creswell, 2022; Diab, 2022). Therefore, there is now an urgent requirement to match the zeal with which regenerative initiatives are pursued and promoted by farmers, industries, and policies, with a robust framework for assessing the effectiveness of regenerative agriculture in delivering its goals (European Commission, 2022a; Wade et al., 2022).

In this knowledge vacuum, a number of monitoring and verification approaches have been developed to assist industries, policy formations, and the primary production sector in setting science-based targets for regenerative agriculture (e.g. Danone, 2021; Donoghue et al., 2022; ROA, 2021). In most cases, these have been developed for specific value-chains, commodities or territorial units; as such they cannot comprehensively capture or include different perspectives on what can be considered ‘good monitoring’, nor the diversity of agronomic, biophysical and socio-cultural contexts between, and even within, individual value chains within the food sector. This has resulted in the emergence of a myriad of individual approaches to monitoring that are competing for validation and scaling.

If we zoom out to learn from approaches to monitoring of agricultural sustainability in general, we find a multitude of frameworks and tools (e.g. Coteur et al., 2019; de Groot et al., 2010; FAO, 2014; van Oudenhoven et al., 2012) to monitor *inter alia* the current status of farming systems, to identify trends, to forewarn the crossing of critical thresholds, to monitor the success of interventions in achieving specific goals, and to incentivize farmers (Siddig et al., 2016; Soulé et al., 2021; Vanham et al., 2019). However, the selection process and use of these metrics has been contested (see e.g. de Olde et al., 2017a; Gasparatos et al., 2008; von Wirén-Lehr, 2001). For example, the selection of metrics is often inconsistent (different initiatives select different metrics to monitor the same goals (de Olde et al., 2017a)) or single-focused (only one metric is selected to capture the performance of a broad topic (e.g. soil carbon to monitor soil health (Liptzin et al., 2022)). We also observe the erroneous application of uniform or generic metrics across contrasting contexts (one-size-fits-all and fixed minimum sets of metrics (Gasso et al., 2015)). Furthermore, metrics that can be used to monitor the adoption rate of interventions (i.e. practice-based metrics) are frequently confused with metrics that capture the efficacy of interventions in the longer term (e.g. result-based metrics) (Braband et al., 2003).

In this paper, we bring together the knowledge of multiple domains in the field of soil monitoring, sustainability science, food systems thinking, and transitioning studies to give a holistic view on using metrics for regenerative agriculture by appraising each metric for the context, location, and temporal timespan for which it is most relevant. Put simply: different metrics are needed to track the efficacy of interventions in different value chains, and at different stages of the intervention, as some of the desired impacts of an intervention (e.g. changes in soil carbon or biodiversity) may take many years to materialize. Monitoring the efficacy of interventions in the intervening period requires different metrics to both incentivize farmers and give quantitative insights into the progress towards the achievement of goals. Instead of proposing a fixed minimum sets of metrics to be applied universally, we put forward a flexible yet coherent framework. This framework provides a transparent, temporal, and context-sensitive selection of metrics and associated measurements for monitoring the extent to which regenerative initiatives lead to verifiable changes in land management practices, results, and outcomes, and as such the degree to which they achieve their goals.

2. Harmonizing terminology

Before we set off on this journey, we must address the terminology used in this paper. The term metric is used among actors (i.e. farmers, industries, and governments) and knowledge domains (e.g. natural monitoring and food systems thinking) in various ways and used interchangeably with terms such as “indicator”. We use the term *metric* according to the Merriam-Webster dictionary (2022a) as a standard of monitoring (e.g. greenhouse gas (GHG) emissions), while *indicators* are defined by the Merriam-Webster dictionary (2022b) as something that is a degree or an amount of something, can be quantified using a certain method, and has a unit (e.g. CO_2 eq. per kg milk). Numerous metrics and measurements have been proposed for the monitoring, the reporting, and the valorization of regenerative agriculture and sustainability in general (de Olde et al., 2017b; Soulé et al., 2021; Vanham et al., 2019). Furthermore, there are many ways in which these metrics can be categorized (e.g. Bockstaller et al., 2015; FAO, 2014) and many different terms referring to the same metric (Figure 1). To harmonize language, Figure 1 illustrates convergent terms that are used for the categorization of metrics considered in this paper (i.e. target-, practice-, result-, and outcome-based metrics). For example, practice-based metrics are referred to by the

OECD (2001) as "*driving force metrics*", while result-based metrics are referred to by Aramyan et al. (2007) as "*performance metrics*"; outcome-based metrics are referred to by the European Union (2018) as "*impact metrics*".

Figure 1. *Overview of the target-, practice-, result-, and outcome-based metrics as well as adapted synonymous terms used in literature. The superscripts correspond with the following references: [1](FAO, 2014), [2](Mansor et al., 2008), [3](Becker, 2010), [4](European Union, 2018), [5](Braband et al., 2003), [6](OECD, 2001), [7](van der Werf and Petit, 2002), [8](Aramyan et al., 2007), and [9](Luján Soto et al., 2020).*

Since regenerative agriculture "takes soil conservation as its entry point to contribute to multiple ecosystem services" (Chaper 2), our quest for a metric framework is aligned with the ambition of the European Commission for monitoring healthy soils for the new Common Agricultural Policy (CAP) (European Commission, 2022a). We distinguish four categories of metrics: target-, practice-, result-, and outcome-based metrics which we exemplify simply with one example each (see bullet points below) and we will elaborate further upon these different metrics in the following sections. The examples below relate to the sole goal of reducing GHG emissions with a focus on carbon in the context of foodscapes. In reality actors can have multiple goals and work in various contexts which can results in both synergies and trade-offs, which can be defined by applying the framework for each goal. To illustrate how metrics can vary we use three scales: at farm-level, within a value chain, and within policy, for the goal of reducing GHG emissions

- *Target-based metrics* indicate the presence of a plan to implement one or more interventions, for example:
    - at farm-level: the presence of a carbon management plan
    - within a value chain: the presence of a corporate net-zero standard target
    - within policy: the publication of a nationally determined contribution to meet commitments to the Paris climate agreement
- *Practice-based metrics* show the degree of implementation of interventions (i.e. practices, activities, new technologies), for example:
    - at farm-level: implementation of a practice e.g. sowing of cover crops
    - within a value chain: number of farms using cover crops
    - within policy: number of farmers that avail of agro-environmental and climate measures under the Common Agricultural Policy
- *Result-based metrics* show the consequences or quality of the interventions, and therefore whether the interventions has the desired effect in the midterm, by quantifying for example:
    - at farm-level: area of ground cover throughout the year
    - within a value chain: average area ground cover in the supplying region
    - within policy: change in area of national ground cover (reduction of bare soil)
- *Outcome-based metrics* show if the intervention has delivered on its original goals, in the end term, for example:
    - at the farm-level: a change in soil organic carbon content
    - within the value chain: a change in the carbon footprint of products
    - within policy: a change in national GHG emissions

3. The role of metrics for regenerative agriculture

3.1 Target-based metrics

Target-based metrics are considered useful, largely because of their ease of monitoring: they do not require high financial or time investments (de Olde et al., 2018). Underlying the use of these metrics is the, often implicit, assumption that the creation of a plan (e.g. to reduce on-farm GHG emissions) will over time lead to the achievement of the goal of the intervention (i.e. to reduce national agricultural GHG emissions). However, the use of target-based metrics has been critiqued, because the plan to implement an intervention is often poorly correlated with the achievement of the goal set, and can only be used as a proxy at best (Braband et al., 2003; FAO, 2014). For example, the Irish Food Board recently reported that its *Origin Green* farm sustainability program had successfully delivered

290,000 on-farm carbon footprint calculations since its inception in 2012, as well as 21,000 associated farmer feedback reports in 2021 alone (Bord Bia, 2021); both can be classified as target-based metrics that track the inception and scaling-out of farm advisory plans. At the same time, the Irish Environmental Protection Agency reported that total GHG emissions from Irish agriculture increased by more than 12% over the same time period (EPA, 2022), illustrating the poor correlation between the target-based metrics and outcome-based metrics, as reported separately by the two state agencies. Although target-based metrics can help to create awareness for actors regarding the importance of specific issues (e.g. climate change) (FAO, 2014), they can be sensitive to evidence-based allegations of greenwashing; we therefore suggest that they are only appropriate where they define a transition process, in which practice, result, and outcome based metrics are also considered.

3.2 Practice-, result-, and outcome-based metrics

Practice-based metrics show the degree to which a plan leads to changed practices. While changes in agricultural practices may still be only loosely correlated to eventual outcomes (Elmiger et al., 2023), practice-based metrics are commonly used in certification schemes (e.g. organic certification), since they allow for the immediate financial incentivization at a time where investment requirements are highest (i.e. at the start of a transition in farm management practices) (Tanaka et al., 2022). Result- and outcome-based metrics deliver more direct insights into the progression towards goals and as such offer better accountability and improved incentivization (Braband et al., 2003; Janus and Holzapfel, 2017). The divergence between result-, and outcome-based metrics lies within the temporal aspect. Result-based metrics show the consequence of changed interventions in the midterm based on activity data and a combination of these result-based metrics inform outcome-based metrics which are strongly aligned to the original goal and quantify the change that has occurred. While widely applied in the health and education sectors, their use in agriculture is currently in a pioneering phase while the suitability of such instruments for the sector is debated (Janus and Holzapfel, 2017). A common pitfall is the application of result- and outcome-based metrics in isolation from practices, this hampers the interpretation and understanding of monitored results and outcomes when the context is not identified (Jones et al., 2021; Wade et al., 2022). For example, when only soil carbon is monitored to track progress towards climate goals, it remains unknown whether this progress can be ascribed to the original intervention or to other factors (e.g. rising energy and fertilizer prices). Therefore, the interpretation of these metrics requires contextualization in terms of practices, pedo-climatic conditions and land use. In Box 1, we illustrate the use of different types of metrics using water quality as an example.

Box 1. Illustration of using practice-, result-, and outcome-based metrics

To illustrate our point, we consider an intervention aimed at improving water quality (*goal*) in agricultural areas (*context*) to inform farmers (*purpose*) (Figure 2). The intervention may be the establishment of a nutrient management plan, in line with the cross-compliance requirement for Good Agri-Environmental Condition (use of Farm Sustainability Tool for Nutrients) of the EU Common Agricultural Policy (European Commission, 2022b). In this case, the successful establishment of a nutrient management plan can be used as a target-based metric, while the implementation of practices (e.g. leguminous or cover crops) at farm level gives a first indication of the degree to which these extension services are being implemented. The *quality and effectiveness* of nutrient management planning is likely to become apparent in the medium term, for example through a reduction in mineral fertilizer application or sales: both are considered result-based metrics. However, these metrics do not only track the success of the nutrient management planning, but are simultaneously sensitive to other active or passive drivers, e.g. a concomitant rise in fertilizer prices. The ultimate outcome-based metric of the intervention, i.e. improved water quality, can only be monitored many years after the intervention, as it takes time for nutrients to migrate and 'be flushed' through the pedosphere and watersheds (Fenton et al., 2011; Schulte et al., 2010). While this outcome-based metric is most closely correlated to the original goal, it will not only reflect the outcome of the original intervention, but also of the many other driving forces (e.g. policies, markets, prices) as they have evolved over the intervening period. This example illustrates how, in isolation, neither practice-based metrics, nor result, or outcome-based metrics, can satisfactorily monitor the success of an intervention over time; this can be overcome by applying a combination of the three categories of metrics.

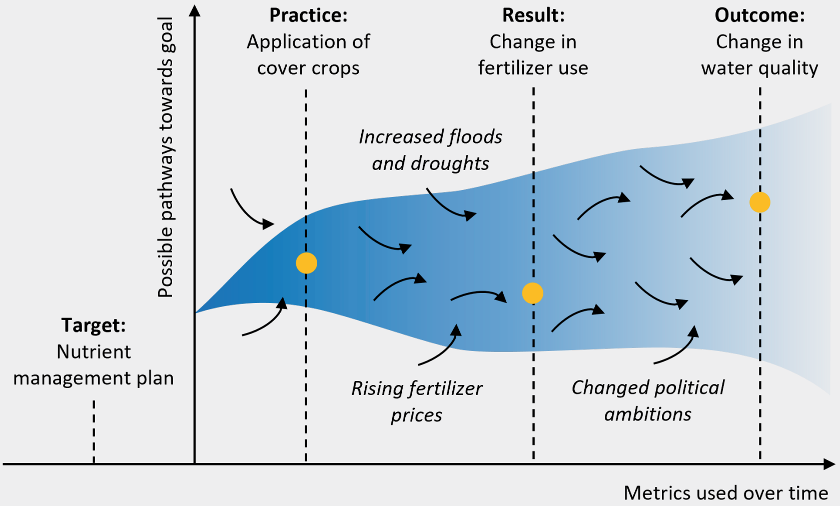

***Figure 2**. Conceptual illustration of the relationship, as well as correlation, between practice-, results-, and outcome-based metrics over time. The yellow dots indicate one of a myriad of possible pathways in response to active and passive drivers (arced black arrows) influencing an intervention aimed at improving water quality.*

4. A flexible yet coherent framework - perspectives for the future

4.1 From a minimum uniform set of metrics to a flexible framework

Given the diversity of metrics available, it is no surprise that, despite numerous attempts (FAO, 2014; Hanegraaf et al., 2019; Hristov and Chirico, 2019), science has thus far failed to agree on one unified minimum set of metrics for the assessment of agricultural sustainability, or specifically regenerative agriculture (Joung et al., 2013; Sikdar, 2003). Whilst the creation of one uniform or generic minimum set of metrics appeals to the objectives of both science, industry, and governments to compare data coherently across a range of applications or value-chains, its uniformity would come at the expense of reduced actor operability and reduced applicability (Gasso et al., 2015). For example, current efforts to standardize metrics and measurements have largely ignored regional and soil-type related biases in quantitative sustainability analyses (Wade et al., 2022). Furthermore, the relevance of each metric depends on the context, purpose, and scale of the monitoring effort, which may range from fundamental research on the impacts of regenerative practices, to supporting land managers in decision-making at a field scale, to monitoring long-term outcomes for policymakers at continental scales (Creamer et al., 2022).

The framework we propose (Figure 3) breaks with the trend of minimal datasets and recommends the context-specific selection of metrics, which is simultaneously underpinned by a comprehensive and unified scientific framework. More specifically, our framework presents a ‘menu of options’ that allows for transparent and evidence-based, yet context-specific selection of metrics for monitoring at different moments in time across spatial scales (i.e. farm to food system-level). The framework guides actors in the selection of relevant metrics and measurements based on three steps: 1) defining the ‘setting’, 2) selecting adequate ‘metrics’, and 3) selecting appropriate ‘measurements’ (Figure 3). While this framework can in principle be used for monitoring the success of all forms of sustainability programs, in this paper we will apply it to the central concept of regenerative agriculture: to monitor the success in restoring soil health to mitigate impacts of climate change, to improve nutrient cycling, to support water quality and availability, and economic prosperity related to sustainable agricultural productivity and human health (Chapter 2). In the following sections we will describe both the framework itself, as well as the process of populating the framework for individual contexts.

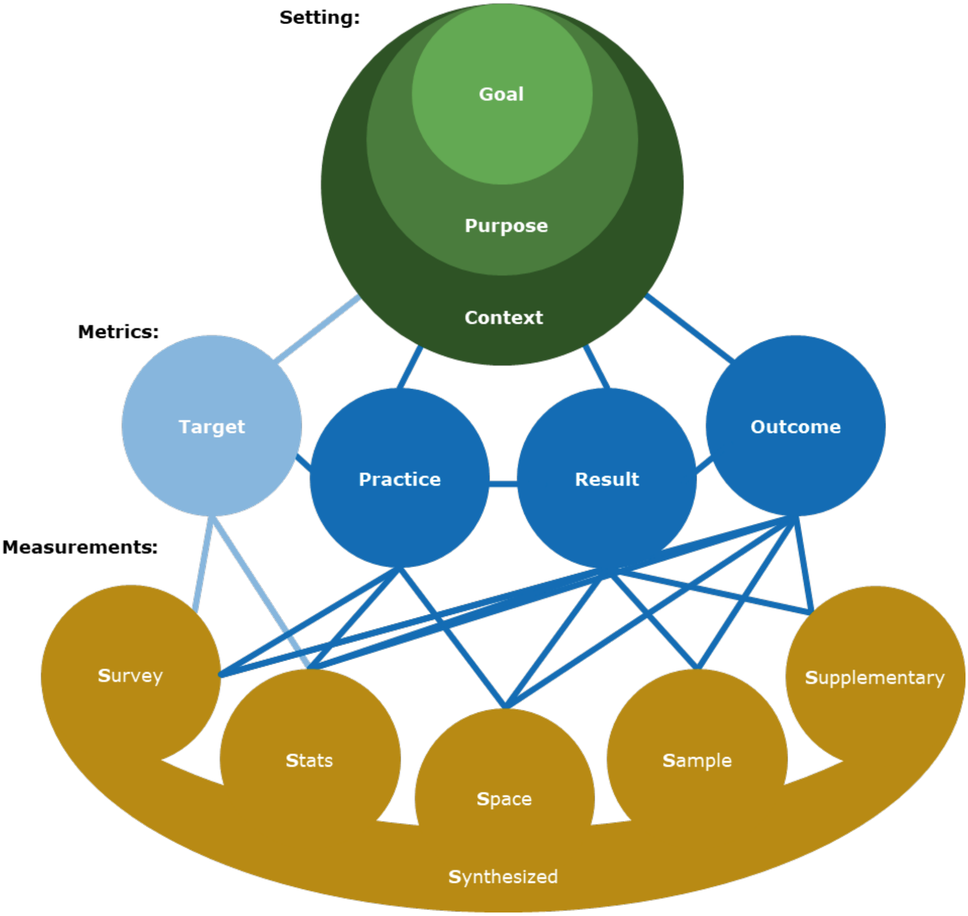

Figure 3. *A flexible yet coherent framework to select metrics and measurements for different settings. Target-based metrics have a divergent color compared to the other metrics to indicate the small or specific role they can play in using metrics to monitor the transition towards regenerative agriculture.*

4.2 The setting of monitoring

The setting defines the spatial scales and system boundaries of the monitoring scheme by assessing:

- The *goals* of monitoring: The actor specifies which goals associated with regenerative agriculture they aim to achieve with their interventions (e.g. reduction in GHG emissions).
- The *purpose* of monitoring: Here actors can distinguish and choose, depending on their role in the agri-food system for example, to inform practical farm management decisions, inform consumers, or to show the territorial impacts for policymakers.

- The *context* of monitoring: Here, the actors define the agricultural system, scale, socio-cultural, economic, and pedo-climatic conditions of the agro-ecosystem of interest, for example, a Dutch arable farm on clay soil, oat milk producers in the southern region of Finland, or Vietnamese agriculture.

These assessments are non-exclusive: monitoring, reporting, and verification programs may include multiple goals (e.g. reduce GHG emissions and improve water quality), purposes (e.g. simultaneously informing farming system and informing consumers), and contexts (arable farmers on clay soil and dairy farmers on peat soil) each of which require different metrics of success.

4.3 Metrics for monitoring

The second step is to select the practice, result, and outcome metrics that enable the monitoring of a transition towards regenerative agriculture. Building on our framework in Figure 3, we recommend the use of a combination of metrics to monitor regenerative agriculture over time, as illustrated in Figure 4. Actors start with a base-line assessment of practice-, result-, and outcome-based metrics selected based on the setting of monitoring. Changes in practices provide immediate information and can be monitored on a yearly basis. Result-based metrics typically describe the direction of transition in two to five years following an intervention. Outcome-based metrics demonstrate the degree of success in achieving the original objectives, and are typically monitored over a longer time-period of five to ten years. Throughout the monitoring timeframe, co-variates such as weather conditions and the timing and type of management interventions may also be assessed and reported, to aid the qualification and interpretation of metrics.

4.4 Measurements for monitoring

The third and final step in establishing the monitoring scheme is the selection of measurements (approaches to data collection) that are associated with each of the metrics (Figure 4) from the long-list of measurements reported in the scientific literature. For example, Soulé et al. (2021) already identified 262 measurements for assessing environmental sustainability, while Zwetsloot et al. (2022) distinguished 289 available measurements of soil biology relating merely to soil multifunctionality.

Here, we can distinguish several categories of measurements:

- Measurements by survey refers to data collection in which farmers are interviewed for obtaining socio-economic and biophysical data, for example labor hours or perceived working conditions.
- Measurements from stats are typically derived from existing databases (e.g. European Farm Accountancy Data Network (FADN) (European Commission, 2022c), and national

governments) on agricultural practices, results, and outcomes, for example on pest management or land use at national scale.

- Measurements from space are typically derived through remote sensing, for example using satellites monitoring land use change (e.g. area of various crop types) and landscape features (e.g. terracing and erosion).
- Measurements by sample refers to any form of on-site collection of empirical data, for example by monitoring species richness and abundance.

Additional measurements may include *synthesized* and *supplementary* measurements. Synthesized measurements include data from for example, modeling approaches, which often uses various categories of measurements as input data. For example, a nitrogen balance is often computed using data from surveys (asking the farmer about management; farm inputs and outputs), stats (standard data about atmospheric nitrogen fixation), and samples (measuring the nitrogen content of feed and manure). Supplementary refers to types of measurements currently not captured by the other categories (e.g. various sensory techniques). Furthermore, the different categories of measurements are not mutually exclusive for example, measurements from surveys or space can also be found in stats.

Once appropriate candidate measurements have been selected for the context-specific monitoring initiative, the final metrics and measurements can flexibly be selected using various approaches, such as the logical sieve presented by Zwetsloot et al. (2022). Using such a logical sieve helps actors to select their criteria for the inclusion and exclusion of metrics and measurements, as well as weightings for their importance. Criteria can include for example, the financial resources required for each type of measurement, as well as time, skills, required infrastructure, reference materials, and reproducibility (de Olde et al., 2017a; Zwetsloot et al., 2022). In Box 2, we show how our framework contributes to monitoring the success of two contrasting farming systems, by using metrics flexibly, however, coherently regarding outcomes and goals.

4.5 Co-selection of metrics and measurements

Actors in the food system are often challenged by the complexity associated with the selection of the most appropriate metrics and measurements because of the myriad of options. It can be challenging to have an overview of which metrics are most suitable for their goals, and which are applicable for their purpose (i.e. who the outcomes of monitoring will be reported to), their time-horizon (i.e. time frame of the project) and their resources (e.g. financial budget and in-house knowledge). Many consult experts; however, even experts disagree on the criteria to define metrics of success (de Olde et al., 2017b). This often results in actors selecting metrics merely on the basis of resources or expediency, that may be inappropriate for their goal and purpose, or that reduce complex concepts such as regenerative agriculture or soil health to a single metric such as soil carbon (Gasparatos et al., 2008).

Box 2. Showcasing flexibility and coherence for monitoring success

To showcase coherence and flexibility in monitoring success, consider the following hypothetical example which is adapted from Schulte et al. (2021) of two farming systems transitioning towards regenerative agriculture. Farming system A focuses on a grass-based ruminant systems in temperate climates (e.g. Europe) and farming system B focuses on rice production systems in South-East Asia. Both farming systems have a reduction in GHG emissions as one of their specified goals. In both cases, a change in greenhouse gas emissions (outcome-based metric) is their main concern, more specifically methane. However, the source of methane is different for these farming systems (different setting): in farming system A, the methane originates from ruminant fermentation, while in farming system B, the methane is created through methanogenesis in the rice paddies. The result-based metrics are therefore, different for these two farming systems. In farming system A, the most relevant result-based metrics are the number of ruminants, type of ruminants (species, breed), supplemented with feed data, all of which can be derived from existing databases and surveys in many countries. In farming system B, the most relevant result metric is the areal extent of rice paddies, which can be derived from remote sensing, supplemented with cultivation and irrigation data. The choice of 'metrics of success' is coherent across these two farming systems, as it is informed by one and the same goal and metric selection process for both farming systems. At the same time the choice of metric is flexible, in that it allows for context-specific metrics and measurements that are meaningful and effective for the specific farming systems.

The selection of adequate metrics requires both expertise about the setting (i.e. purpose and context) of the user, as well as knowledge on the diversity and applicability of metrics and measurements. Therefore, we recommend that metrics and measurements are co-selected jointly by the actors seeking to establish a monitoring campaign, with local experts, extension services or knowledge brokers, where:.

- The actors formulate the goals, purpose, and context of the monitoring effort;
- The local experts, extension services, or knowledge brokers select which practices are relevant, within the specific setting, to achieve the desired outcomes, and which results may be expected in the medium term;
- Scientists may then select a long-list of potential measurements (i.e. survey, stats, space, sample, synthesized) for the metrics of these practices, results, and outcomes;
- By using for example a logical sieve (approach to iteratively filtering metrics and measurements based on exclusion criteria (Zwetsloot et al., 2022)), the actors subsequently create a shortlist of measurements for application.

4.6 Benchmarking

Once monitoring data is being collected, how can we establish whether the numerical data represent a ‘good’ or ‘poor’ progress? Traditionally, monitoring data is benchmarked against reference values. At times, single reference values have been used across a diversity of pedo-climatic conditions; one example is the proposal to use a single benchmark for Soil Organic Matter (SOM) across the EU. Here, failure to recognize that a single reference value may be considered either high or low, depending on the local climatic conditions, led to erroneous inferences on ‘soil health’ in individual EU Member States (Spink et al., 2010).

Furthermore, reference values lack standardization and different metrics may use different types of reference values, namely normative or relative, to monitor success (Acosta-Alba and Van der Werf, 2011). Normative reference values are typically science- or policies-based and represent target values (desirable conditions) or environmental thresholds (limits of environmental pressures, e.g. the planetary boundaries (Rockström et al., 2009)). Relative reference values can be derived by comparing the monitoring data to similar data collected within the same ‘setting’ (e.g. comparing a farming system claiming to be regenerative with a group of farming systems considered mainstream). In some cases, these are not available, especially for data on soil biodiversity (van Leeuwen et al., 2019), which restricts possibilities for standardization (Gasso et al., 2015) and may result in poor comparisons and conclusions (Hortal et al., 2015; Siddig, 2019). In such cases, new ‘local benchmarks’ may be derived through stratified normalization of monitoring data, which is the objective of the EU Horizon Europe research and innovation project BENCHMARKS (Building a European Network for the Characterization and Harmonization of Monitoring Approaches for Research and Knowledge on Soils) (Creamer, 2022).

5. Final remarks

We have arrived at a moment in time where the commonplace expediency in the choices of metrics of success for agriculture can be replaced with a robust scientific framework that brings together and builds on decades of various research worldwide. We show that different types of metrics have their own use and timing, therefore, combining different types of metrics and measurements are key in monitoring the transition towards regenerative agriculture. By centralizing the setting first, our framework is flexible to contrasting contexts and can be used by different stakeholders worldwide (e.g. farmers, industries, governments), to show to which extent regenerative initiatives lead to verifiable changes in land management practices, results, and outcomes, and as such the degree to which they achieve their goals (e.g. improved soil health and farmer incentivization). Using our framework helps to overcomes issues like 'checking the box' approaches, or unnecessary expensive measurements. This coming decade, we find ourselves at a unique crossroads where regenerative agriculture has the attention of farmers, citizens, industry, and policy-makers alike. It is now essential to ensure that the transition process towards mainstreaming regenerative agriculture across farming systems and contrasting contexts, is underpinned by fit-for-purpose scientific knowledge, thus securing a sustainable future for the land that humanity relies on for tomorrow's food and wellbeing.

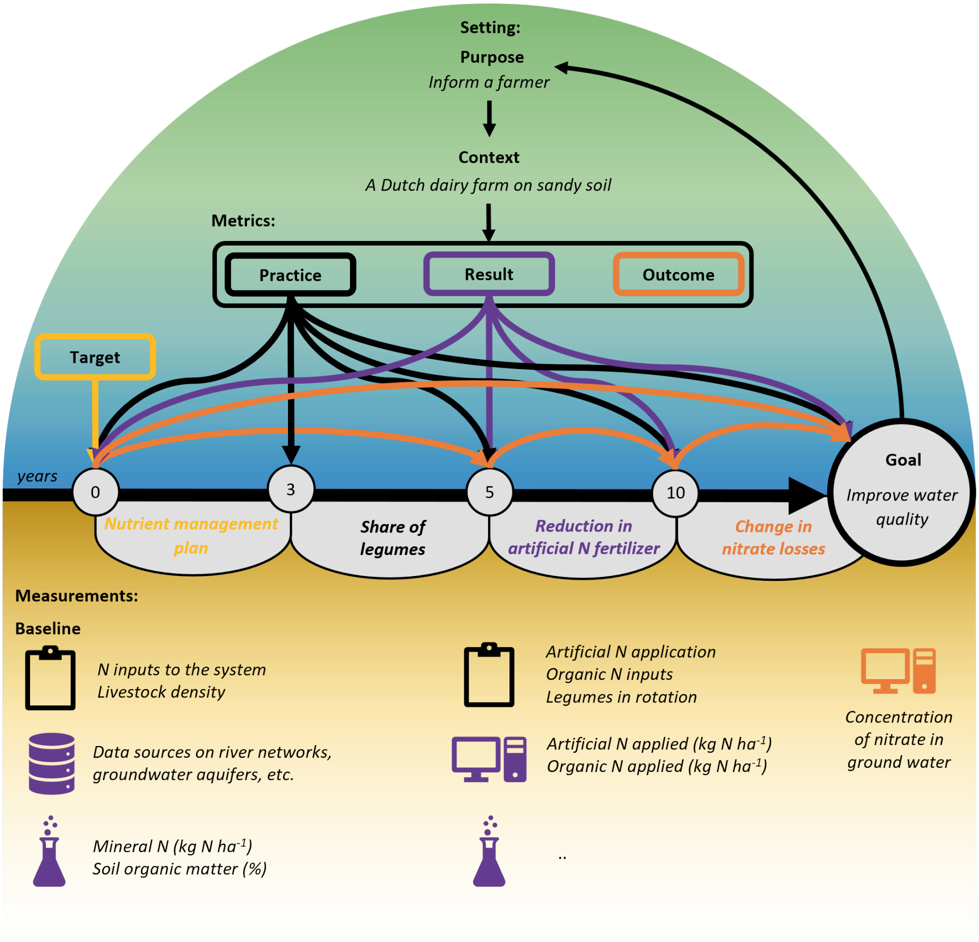

Figure 4. *An illustration of using a combination of metrics and measurements over time to monitor the 'success' of regenerative agriculture using water quality as an example. The process starts with identifying the 'setting' (i.e goal, purpose, context) of monitoring, subsequently it is decided what 'metrics' (i.e. practice, result, outcome) and 'measurements' (survey, stats, space, sample, supplementary, synthesized) are used for an initial baseline assessment and future monitoring.*

Chapter 6

General discussion

Table 1. *Overview of the different chapters with their objectives, approaches, and conclusions.*

Chapter	**Objective**	**Approach**	**Conclusion**
2. Regenerative agriculture – the soil is the base	Determine what is meant with regenerative agriculture.	Global literature review	Regenerative agriculture is an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services, with the objective to enhance the environmental and socio-economic dimensions of sustainable food production.
3. How to make regenerative practices work on the farm: a modelling framework	Make regenerative agriculture meaningful at the farm-level.	Model development	To make regenerative agriculture meaningful at the farm-level I created a modelling framework for an ex-ante design and assessment of regenerative objectives for various farming systems. This modelling framework shows which regenerative objectives are relevant and what practices are applicable for different local-contexts. The framework takes these context-specific objectives and practices center-stage to explore more sustainability futures for farming systems.
4. Tailor-made solutions for regenerative agriculture in the Netherlands	Determine how tailor-made solutions towards regenerative agriculture can be identified as such that they result in meaning-full advice for farmers.	Modelling	This study showed that transitions towards regenerative agriculture requires tailor-made solutions for individual farming systems. By building upon the modelling framework of Chapter 2, I created a wide diversity of tailor-made solutions contributing in varying degrees towards the objectives of regenerative agriculture. Overall I show for three case-study farms that overall environmental performance was improved, however, at the expense of farm profitability.
5. A framework to monitor the efficacy of regenerative agriculture	Discuss the role of metrics for regenerative agriculture and present a flexible yet coherent framework for context-specific selection of metrics and measurements.	Perspective	In order to monitor the transition towards regenerative agriculture I created a monitoring framework to select metrics and measurements flexible for different contexts yet coherent to achieve the goals of regenerative agriculture. I discuss that we need a combination of metrics and measurements together to monitor and valorize farmers successfully for their contribution towards regenerative agriculture.

1. Introduction

The global food system causes severe pressures on the environment (United Nations, 2022). In response, emerging farming approaches like regenerative agriculture are heralded by farmers, industries, and governments as mainstream solutions to keep the global food system within planetary boundaries. As regenerative agriculture is receiving a lot of attention from actors in the food system (Giller et al., 2021), I have set the **main objective of this thesis to better understand practices that contribute towards regenerative agriculture with a focus on dairy and arable farming in the Netherlands.** I show that before deciding on any practices we need to understand what regenerative agriculture means (Chapter 2). I found that regenerative agriculture consists of multiple environmental and socio-economic objectives. These regenerative objectives, however, are not equally relevant for every farming system and local-context. Likewise, regenerative practices are not equally effective or applicable for every farming system and local-context. To make regenerative agriculture meaningful for individual farming systems I developed a modelling framework (Chapter 3) which shows farmers what practices contribute to different regenerative objectives in their specific context (Chapter 4). Decision-making regarding (new) practices, however, also requires understanding of their impact on environmental (e.g. soil health and climate change) and socio-economic aspects (e.g. farm labor and farm profitability). I developed, therefore, another framework to monitor the success of regenerative practices in the long-term (Chapter 5). In this chapter the focus goes beyond farmers and also other food systems actors are included (e.g. industries and policy-makers) to show that the framework is appropriate for various purposes (e.g. informing farmers, certification, incentivization). Building upon our main objective and previous chapters the following sections will further discuss what regenerative practices are, how models are relevant for regenerative practices, and last why monitoring practices is essential for the wider implementation of regenerative agriculture.

2. What are regenerative practices?

We learned from Chapter 2 that regenerative agriculture is an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services. Not surprisingly, regenerative agriculture, therefore, constitutes of practices that focus on regenerating or conserving the health of soils to not only contribute to food production but also to other ecosystems services. Although soil health is an important aspect of regenerative agriculture, the perception of what a healthy soil is and how to manage it properly has changed and been criticized over time (Bünemann et al., 2018). Regenerative practitioners think that a healthy soil is the foundation for a resilient farming system (Regeneration International, 2019; Rodale Institute, 2014), because the soil is the medium that supplies essential nutrients and water, provides habitat for species, and gives support to our plants that need to grow and flourish (FAO and ITPS, 2015). The soil, however, is not only seen as a supplying medium but if well-managed also as a buffer that can increase, for example, water and nutrient retention (Parikh and James, 2012). Regenerative practitioners, therefore, belief that building healthy soils leads to future proof farming systems that are less sensitive for external shocks (e.g. changing climate or raising fertilizer prices) and less dependent on external resources (e.g. less mined or artificial fertilizers, pesticides, or intercontinental feed imports) (Rhodes, 2017; Rodale Institute, 2014).

One of the things we learned from Chapter 3 is that the health of soils in regenerative agriculture relates to soil multi-functionality, which means that regenerative practices aim to contribute to the intricate synergies between mainly five soil functions: primary production, water purification and regulation, biodiversity and habitat provision, nutrient cycling, and climate regulation (Bünemann et al., 2018; Creamer et al., 2022; Vogel et al., 2018). However, using individual or a combination of regenerative practices could also lead to trade-offs in management objectives. For example, eliminating pesticide-use often results in improved soil biodiversity (Oosthoek, 2013), however, concurrently may also result in reduced primary productivity due to increased pests and diseases (Hossard et al., 2015). For this reason we developed a modelling framework that takes soil management practices center-stage and shows how combinations of practices contribute to the objectives of regenerative agriculture; capturing the intricate synergies and trade-offs between management objectives (Chapter 3).

Besides synergies and trade-offs between regenerative practices and management objectives, we learned from Chapter 4 that these regenerative practices are not equally relevant for different farming systems and local contexts (e.g. a dairy farmer on peat soil needs very different practices compared to an arable farmer on clay soil). Therefore, what regenerative practices are, is not uniform and practices should be tailored to a specific farming system in a local context. Moreover, regenerative practices used in Chapter 3 and 4 may take their roots in soil conservation which often focuses on the field-level (e.g. no tillage and cover crops), however, the practices used also constitute of managerial aspects at the farm-level (e.g. optimized crop rotations and reduction of external inputs), national-level (e.g. crop-livestock integration), and global-level (e.g. the elimination of finite resources or harmful pesticides). Here I will explain and discuss some of the practices associated with regenerative agriculture according to Chapter 2 and used in our modelling studies in Chapter 3 and 4 (Figure 1). More specifically, I will focus on two essential practices used in this thesis that help to illustrate the potential and nuances of regenerative practice: minimizing tillage and diversified cropping systems.

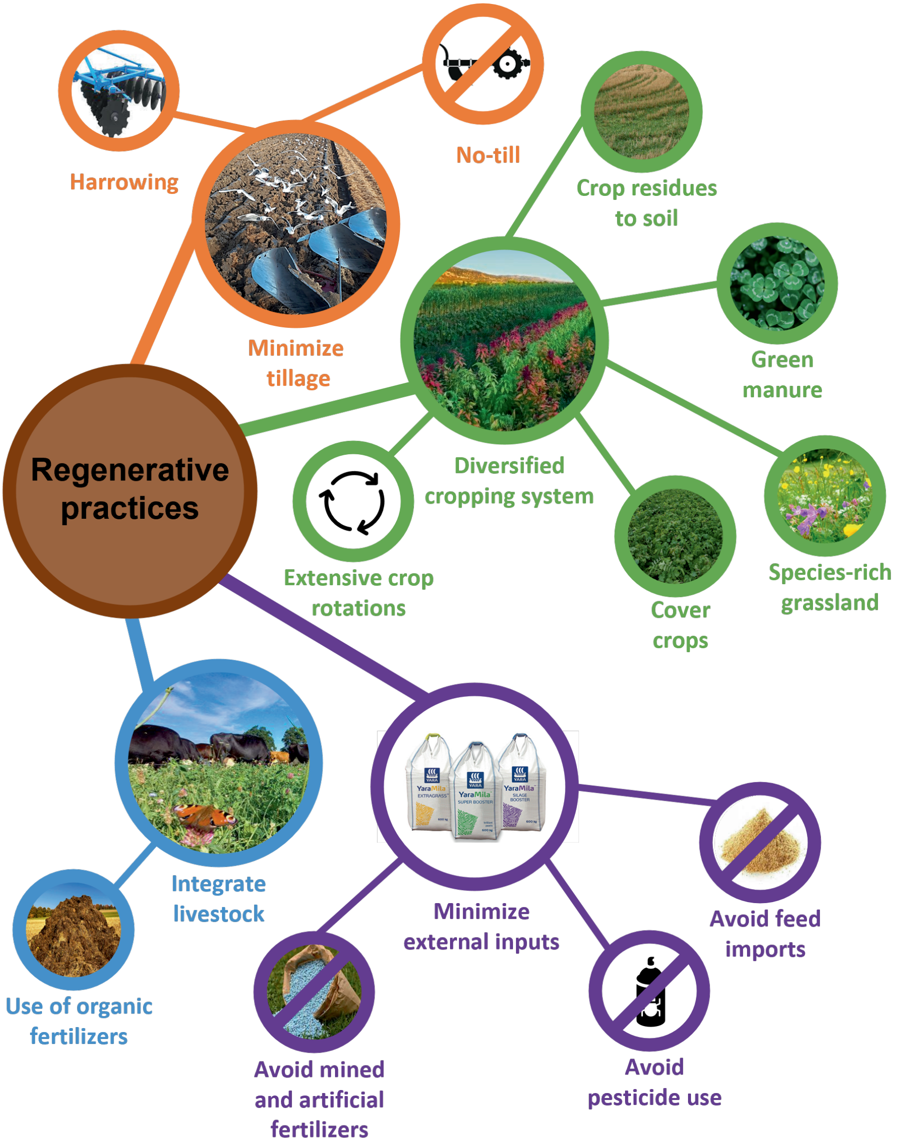

***Figure 1**. Illustration of some of the practices associated with regenerative agriculture.*

2.1 Minimize tillage

An oft used practice in regenerative agriculture is to minimize soil tillage prior to crop establishment (Chapter 2). Tillage usually involves turning over the first 15 – 30 cm of top soil in order to aerate the top layer or facilitating the planting of new crops (de Medeiros Barbosa, 2015). Moreover, tillage buries crop residues, animal manure, compost, and weeds deep into the field, blending it into the soil. In modes of conventional agriculture, tillage generally refers to moldboard ploughing (inversion of the soil) followed by secondary tillage operations such as disking or harrowing (European Commission, 2013). Moldboard ploughing has been found problematic by regenerative practitioners because of mainly two reasons (ReNature, 2022; Spears, 2018): 1) by removing plant matter covering the soil it remains bare, making it vulnerable for wind and water erosion, and 2) by turning over the soil, its structure and life is disturbed.

Regenerative practitioners argue that minimizing tillage or even no-till reduces soil disturbance and, therefore, would improve soil health (Spears, 2018). The absence of heavy tillage machinery, therefore, makes the soil reliant on ecological processes, for example allowing earthworms to aerate the soil and distribute nutrients (Shah et al., 2017). Minimizing tillage includes shallow, non-inversion tillage methods (e.g. harrowing), often with fewer tillage operations per year (van Balen et al., 2023). Over the past decades, various studies have reported positive impacts of minimized tillage on soil health, including better soil structure (Daraghmeh et al., 2009), reduced soil and water erosion (Busari et al., 2015), enhanced soil water holding capacity and water infiltration (Tebrügge and Düring, 1999), reduced greenhouse gas (GHG) emissions (Tian et al., 2013), and increased soil biological activity (D’Hose et al., 2018). The latter shows convergence with the modelling work of Chapter 4, were we found that that minimizing tillage and no-till had a positive effect on the soil function biodiversity and habitat provision.

Although, these studies show potential benefits in their specific contexts we here want to caveat that the effects of reduced tillage are dependent on many variables, particularly crop type, other pre- and intermediate management interventions, and local environmental conditions (soil and climate). For example, one purported benefit of reduced tillage is that it increases soil carbon stocks. However, while in some instances this does occur in for example Europe and the United States (Cooper et al., 2016; Haddaway et al., 2017), others show less promising effects in Sub-Saharan Africa (Giller et al., 2009; Giller et al., 2011). Some evidence even suggests that for the most part reducing tillage largely redistributes carbon within the soil profile rather than substantially increasing it (Powlson et al., 2014).

Moreover, minimizing tillage can also lead to trade-offs, for example, resulting in lower crop productivity, increased topsoil compaction, and suboptimal weed control (Bijttebier et al., 2018; Gruber et al., 2012; Soane et al., 2012). These trade-offs, also come back in our modelling studies (Chapter 4) were I learned that it can be challenging for farmers to move towards minimized tillage. The negative effects of minimized tillage such as increased weeds are often solved by a heavy dependence on herbicides used to suppress weeds and stabilize yields again (Giller et al., 2009). In Chapter 4, however, I did not only minimize tillage but also explored avoiding herbicide use. This led to extra trade-offs, for example, only using minimized tillage reduces sugar beet yields up to five percent (e.g. due to weeds), however, by also avoiding pesticides yields can reduce up to 30 percent with a labor increase of 200 percent (Marlander et al., 2003; PPO, 2009; van der Voort, 2018). The reduced yields are mainly caused by pests and diseases, which commonly occur in the first five years when the system needs to rely on its natural resilience (LaCanne and Lundgren, 2018; Marlander et al., 2003). The increased labor is caused by the need for hand weeding which adds 65 hours per hectare of labor per year (PPO, 2009). To conclude: minimized tillage with its potential to positively impact soil health and other ecosystem services has an important role in regenerative agriculture. Practitioners, however, should carefully consider their local context before introducing minimized tillage due to potential trade-offs and nuances.

2.2 Diversified cropping systems

In order to deal with for example yield losses due to the avoidance of pesticides (illustrated in section 2.1), regenerative practitioners find solutions in crop diversity. The promotion of crop diversity essentially means a transition from monoculture cropping systems to diversified cropping systems: 1) including multiple crop species on a field, and 2) more crop species in a rotation. Monoculture systems enable farmers to treat fields the same, no matter the size, using large-scale machinery that increase management efficiency (Ditzler et al., 2021). Such systems rely heavily on external inputs, since crop production capacities are exploited at the cost of ecological processes which support and regulate natural systems (Foley et al., 2005; Haddad et al., 2015). Moving towards diversified cropping systems can bring, therefore, several advantages (depending on the crop species) such as increased biodiversity, reduced pesticide use, and reduced fertilizer use (Duru et al., 2015; Malézieux, 2012).

Including multiple crop species in the field can be done in various ways such as mixed intercropping, strip cropping, and pixel cropping. When using mixed intercropping multiple crop or herb species are cultivated in the same field without a specific pattern or when using row intercropping multiple species are cultivated in alternating rows (Juventia et al., 2022). In strip cropping multiple crop species are grown adjacent to one another in long and narrow multi-row strips (usually three to nine meters) to allow independent crop management by existing machinery (Juventia et al., 2022). An extra layer of complexity is integrated when moving from strip-, to pixel cropping. Pixel cropping includes the incorporation of various crop species within a ‘pixel’ (one square meter plot) which stimulates the interaction between plant species (Ditzler et al., 2021). Although, these practices may be different in lay-out and come with different modes of operation and complexity their idea is to make use of companion species.

Companion species include crops that have symbiotic relationship with the primary crop and for example, encourage improved resistance to pests and diseases, suppress weeds, and improve growth rigor (Ben-Issa et al., 2017; Tringovska et al., 2015). While companion species could be both annual as perennial, the latter is favored (Chapter 2), because they have more extensive and deeper root systems and don't leave fields fallow in between growing seasons. Therefore, perennials are more resilient to weather extremes (LaCanne and Lundgren, 2018), reduce soil erosion (Pimentel et al., 1997), reduce nutrient runoff (Teague, 2018), improve water conservation (Glover et al., 2010), and carbon sequestration (Elevitch et al., 2018). Systems including perennial intercropping are alley cropping systems, agroforestry systems, and permaculture. The main hurdle of conventional farmers moving to intercropping systems is the increased labor demands (Ditzler et al., 2021; Duru et al., 2015). To this extent intercropping practices were not included in our modelling studies because the models used were not aimed or limited in their capacity to quantify the effect of (new) regenerative practices (e.g. strip or pixel cropping) and to a large extent the required data was not available. In Chapter 4 I did, however, create scenarios for dairy farming systems including species-rich grassland. Using multiple forb species showed to improve the soil function of biodiversity and habitat provision. Moreover, by using clover species (i.e. white and red clover) it also enabled the fixation of atmospheric nitrogen (50 kg N ha^{-1}) (de Wit et al., 2004), therefore, reducing total N fertilization.

Including more crop species in a rotation has the potential to bring several advantages for both ecosystem delivery as primary productivity. While, in 1950s to 1960s, it was felt that artificial fertilizers could completely replace crop rotations without loss of yield, there is now a consensus that this is not the case and that crop rotations can improve yields (Bullock, 1992). For example, maize, in a two-year crop rotation with soybean, yields five to 20% more than continuous maize production (Bullock, 1992; Crookston et al., 1991). However, besides improving yields more extensive rotations could also increase nutrient cycling, assist in managing weeds, reduce soil erosion, and decrease plant diseases and insect pests (Shah et al., 2021). For example, it became regulation to cultivate sugar beet in a minimum rotation of 3 years in Sweden to reduce cyst numbers in the soil (Olsson, 2004; Stevanato et al., 2019), in regenerative management even a five to seven-year rotation is recommended in addition to cover crops for improved cyst suppression and soil health (Larney et al., 2016; Regenerative Organic Alliance, 2021). Therefore, in Chapter 4 I created a scenario in which sugar beet was grown in a five-year rotation. Cover crops were used in this rotation to serve multiple purposes such as preventing nutrient leaching, reducing external inputs, sequestering carbon, suppressing pests, and increasing biodiversity (see also Kim et al., 2020). In the case of sugar beet, cover crops especially played an important role in cyst suppression and reduction of total N fertilization. For example, to suppress cyst nematodes yellow mustard was used (Hoek, 2017) and leguminous plants (e.g. Lucerne) were used that fixate nitrogen from the atmosphere to reduce N fertilization (Fageria et al., 2005).

2.3 'Good Agriculture Practice' in regenerative agriculture

The use of the discussed practices is not new neither unique to regenerative agriculture. These practices also find their roots in other approaches to sustainable farming such as organic agriculture. Some even argue that these regenerative practices can generally be considered as 'Good Agriculture Practice' (Giller et al., 2021) and remain integral to conventional farming (Sumberg and Giller, 2022). If the practices of regenerative agriculture are not new, the obvious question arises: 'what makes regenerative agriculture so unique?' In recent years various authors (e.g. Giller et al., 2021a; Newton et al., 2020) studied this question like I did in this thesis and concluded that this comprises not the practices perse, but rather the practices in combination with the aspirations (all dimensions of sustainable food production), priorities (e.g. soil health), and history (e.g. originates from practitioners) of regenerative agriculture compared to other farming approaches.

By concluding that regenerative practices also take root in other approaches to sustainable farming, it means that valuable lessons can be learned from, for example, organic agriculture which shares similar practices as regenerative agriculture. These lessons include data on the effect of convergent practices on crop parameters. The KWIN-agv (Kwantitatieve Informatie – Akkerbouw en Vollegrondsgroenteteelt) of van der Voort (2018), for example, is a Dutch book that presents extensive lists of crop parameters (e.g. yield, profit, labor requirements) under organic management. Other lessons learned show the effects of applying certain practices (e.g. no synthetic pesticides and artificial fertilizers) on objectives convergent to regenerative agriculture (e.g. climate change). For example, Aguilera et al. (2015) did a lifecycle analysis comparing conventional and organic arable systems in Spain and showed that organic management reduced GHG emissions in rainfed cereals. More specifically, they showed that reducing pesticides use (1 to 0 g CO_2e kg^{-1}) only had limited effects on reducing GHG emissions, that fossil fuel use increases under organic management (137 to 152 g CO_2e kg^{-1}) and that the main driver for reducing GHG emissions was a reduction in fertilizer N production and use (181 to 24 g CO_2e kg^{-1}). Such numbers of books and other studies can be used as input data or comparison materials for other research. Put simply: there is merit in building on the learnings from other approaches to sustainable farming from the last hundred years. These learnings should be used in regenerative agriculture to avoid and leapfrog similar pitfalls that may arise.

3. The relevance of modeling in regenerative agriculture

We now know that regenerative practices are not equally relevant or applicable for every farming system and local context (e.g. pedo-climatic conditions). It, therefore, is from upmost importance that we show farmers which regenerative objectives and practices are most relevant in their local-context (Giller et al., 2021). Showing farmers which practices to use can be done in different ways, for example by creating 'learning networks' (e.g. Matous and Todo, 2015; Moschitz et al., 2015) where farmers with the same ambitions come together to leapfrog pitfalls and share successes (e.g. www.regenerativefarming.nl; www.lighthousefarmnetwork.com). Another approach is empirical research, in which experimental farms are used to monitor the efficacy of specific practices (Austen et al., 2022; LaCanne and Lundgren, 2018), so that others can translate this knowledge and use it in their own unique setting. In addition, modeling can be used (this thesis) as a relative quick approach to predict and estimate the success of practices (e.g. Pannell, 1996; Reidsma et al., 2018). Although, models require vast amounts of data, expertise, and their results comes with uncertainty, they are nowadays widely accepted by scientists and used in sustainability assessment (Kephe et al., 2021).

Farmers use models for example for developing cropping plans, tracking field activities, and forecast and monitor profits (e.g. Agrivi (2022) and Granular (2022)). Researchers use it to develop more sustainable future farming systems (Chapter 3 and 4) or food systems (Ericksen, 2008; Karlsson et al., 2021; van Selm et al., 2022). Furthermore, industries use it for scoring and labelling their products (The Carbon Trust, 2022) and governments use it to assess their progress towards goals (Britz, 2005). Table 2, gives an overview of different reviews quantifying and discussing sustainability models for different purposes (e.g. livestock systems, cropping systems, soil health, value chain). We, however, found that most of these models have only limited applicability to assess regenerative farming systems due to the an enormous disconnect between farm- and soil health models.

Table 2. *Review papers analyzing existing models.*

Author	Focus	Number of models
Van der Linden et al. (2020)	European livestock models	215
Molendijk et al. (2018)	Tools for sustainable soil management	32
Fleskens et al. (2017)	Soil quality apps	13
De Olde et al. (2016)	Sustainability assessment at farm-level	48
Paola et al. (2016)	Crop growth and yield models	70
Chen et al. (2013)	Sustainability assessment for industry	50
Lehtinen et al. (2011)	LCA tools for industries	25
Gentil et al. (2010)	LCA models for waste	50
Janssen and van Ittersum (2007)	Bio-economic farm models	42

3.1 A disconnect between farm models and soil health models

While soil health is the basis of regenerative agriculture (Chapter 2) many farm models often do not take soil health into account or make only tenuous references to it and consider a homogeneous soil type for the whole farm (Chapter 3). Figure 2 shows a review of van der Linden et al. (van der Linden et al., 2020) that addresses different sustainability themes indicated in European livestock models. This review shows that only 12 (6%) of the 215 models address soil health. Further looking into these 12 models, the main indicators for soil health were a nitrogen and carbon balance, and only one model enabled field scale assessment. It may be that the models discussed in van der Linden et al. (2020) are not intended to address soil health or data was missing. Nevertheless, it shows that soil health is not jet used as a common indicator to measure the sustainability of the food system.

Contrastingly, models that are specifically focusing on the assessment of soil multi-functionality (e.g. Soil Navigator and Open Soil Index) operate at a field-level and acknowledge the diversity of soil properties within farms (Debeljak et al., 2019; Ros and Fujita, 2019). These soil assessment models, however, commonly lack an assessment of the environmental and socio-economic impacts of management practices at farm-level. Jones et al. (2017) highlighted the lack of integrated models that can assist with assessing environmental performance across multiple scales. Therefore, in Chapter 3 I established a framework that combined two models: Soil Navigator, a decision support tool to assess and optimize multi-functionality at field-scale, and FarmDESIGN, a bioeconomic model that assesses environmental (e.g. GHG emissions) and socio-economic indicators (e.g. farm profitability, labor) at farm-level. This framework does not only allow the assessment on all objectives of regenerative agriculture, it also contributes to the exploration of a multitude of more sustainable farm futures. Although, combining soil health and farm orientated models increases the capability to assess regenerative agriculture, it also increases the degree of complexity.

3.2 The contemporary challenge of increasing complexity

The optimalisation of farming systems towards regenerative agriculture is complex and comes with a high knowledge requirement, as it requires detailed insights into soil multifunctionality at a field-level and knowledge about broader systems objectives at a farm-level. The contemporary key challenge of using ex-ante modelling approaches to predict future impacts of regenerative agriculture is, therefore, coping with ‘restrained complexity’ (Baaken, 2022; Zhang et al., 2021). The restrained complexity is already highlighted in section 3.1 showing the disconnect between farm and soil health models. In this section we take the two models used in this thesis (Soil Navigator and FarmDESIGN) as an example to illustrate these challenges, however, the challenges account for a wide range of other models as well.

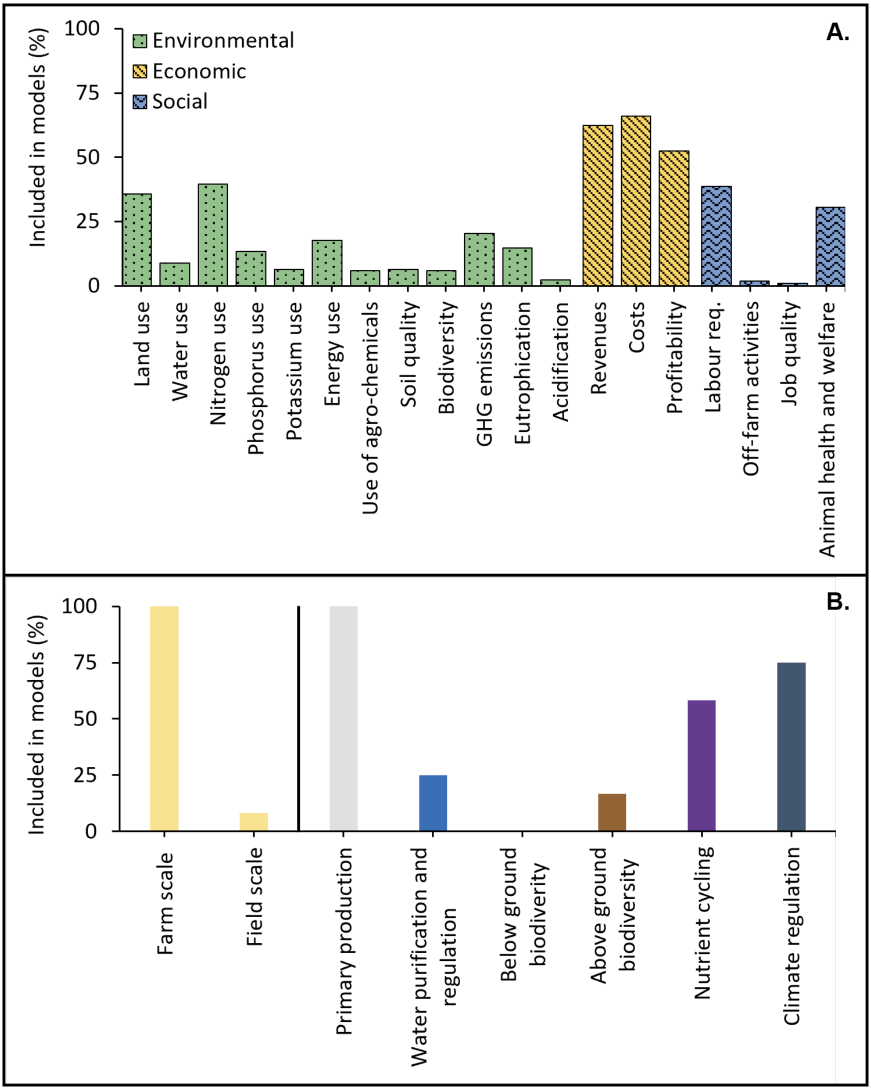

Figure 2. *Environmental, economic, and societal sustainability themes addressed in 215 European livestock models (A) adopted from van der Linden (2020) and the soil functions that were addressed in the livestock models that addressed soil quality (B).*

When using models that are designed as decision support tools they help for example with deciding what practices are most relevant in local contexts. However, this also means that the practices suggested are limited to the inventory of the model. For example, Soil Navigator includes an inventory of around 90 practices (e.g. apply solid manure) and directions of change (e.g. reduce N application) to improve soil functions. However, there are many more practices available for soil management. A review of Rietra et al. (2022) already showed 154 meta-analysis dedicated to mapping soil management practices. Practices that are currently not incorporated in Soil Navigator, however, are key in regenerative agriculture, are the inclusion of various crops (e.g. cabbage, broccoli, soya), using multiple fertilizers on a field or farm (e.g. solid manure, slurry of different animal species, and different compost types), using fixed traffic lanes, using light-weight machinery, and differentiating between the impacts of pesticides (some are more harmful than others); some more radical practices that are not incorporated are strip cropping, agroforestry, and silvo-pasturing. It may be challenging to model such practices due to the intricate synergies and trade-offs occurring between the model components (Power, 2010; Zwetsloot et al., 2020), which must then be captured and parameterized. Limited inventories of practices for models and especially decision support tools may result in hampering the wider implementation of such practices.

Although some models such as Soil Navigator are restrained to certain practices, other models like FarmDESIGN show great flexibility. Models like FarmDESIGN allow to use for example multiple fertilizer types, pesticides, and all possible crop-livestock combinations and species (Groot et al., 2012). However, this flexibility is guaranteed by the high requirement of input parameters at the farm-level. While in Soil Navigator users select a crop with preprocessed data at the field-level (Chapter 2), FarmDESIGN asks for at least 70 input parameters for one crop in order to calculate all available indicators. This high requirement of parametrization comes at the expense of user operability, however, does allow to change the data to the users own needs. For example, crop yields, labor requirements, and emissions are not the same for farmers across regions and are highly dependent on management, market orientation, climate, and soil type. This means that users can adjust the input parameters to their local context if data is available.

Besides the limitations of the individual discussed models, I want to highlight that using these individual models together (Chapter 3 and 4) contributes to addressing the complexity of the soil (e.g. nutrient cycling and water regulation), while at the same time addressing wider sustainability aspects (e.g. farm labor and GHG emissions) in farm redesigns. By definition, regenerative agriculture uses soil conservation practices as the entry point for environmental and socio-economic sustainability, and it is these practices that take center-stage in the recommendations of Soil Navigator. At the same time, multi-objective optimization of FarmDESIGN showed that even for individual farming systems there are multiple viable reconfigurations using a wide range of regenerative practices (e.g. using solid manure; reducing tillage, synthetic pesticides, and inorganic fertilizers). In Chapter 3 and 4, I modelled with a five year crop rotation. Although, this modelled time horizon is not unusual for modelling studies (Adelhart Toorop et al., 2020; Timler et al., 2020), many of the desired effects of regenerative agriculture only become visible over a longer time horizon (Robertson et al., 2014; Teague and Kreuter, 2020). For example, increasing the soil organic matter content on mineral soils can take more than five years (Powlson et al., 1998). Only after this period the positive effects on water and nutrient retention, and yields can be noticed (Menšík et al., 2018). Therefore, I suggest that modelling studies extend their time horizon, to capture the benefits associated with regenerative management (i.e. environmental and economic). Currently, this is challenging as data on the long-term effects of regenerative practices for different pedo-climatic conditions are largely lacking (Johnston and Poulton, 2018).

3.3 The crux of modelling: data availability

Data availability can be considered the crux of modelling, since modelers often need data yet to be collected or data which requires transformation. In section 2.2 I already highlighted the need for data on (new) regenerative practices such as strip and pixel cropping to enable further exploration of applying these practices with, for example, models. Empirical research considering long-term trials could provide the data needed to run models for specific objectives, however, there is a limited number of long-term trials that consider these (new) regenerative practices. There are some long-term regenerative farming system trials (>30 years) from for example the Rodale Institute (Moyer, 2013; Rodale Institute, 2011). These experimental trials, however, often take place in other local contexts (in this case even other continents U.S. vs EU) which limits their useability for European and African contexts. More recently, due to the increased popularity of regenerative agriculture, there are many more long-term experimental trials started or starting (e.g. the 1000 Farms Initiative of Lundgren (2022) and the 100 Million Farmer multistakeholder platform of the World Economic Forum (2022)) the results, however, are yet awaiting to be harvest.

Besides experimental trials there is already a lot of data available from open access databases (e.g. FADN and EuroSTAT), however, these databases mainly present averages of current-mainstream-conventional farming systems. Only limited data is available about regenerative farming systems (Jordon et al., 2022; Zhang et al., 2021). Data from open access databases can be used for some individual organic practices (e.g. reduced tillage) which are to an extent convergent with regenerative practices. However, the majority of data about individual practices is often not directly useable because farm-level modelling often considers combinations of practices that affect each other (Chapter 6, section 2). Moreover, databases (e.g. FADN and EuroSTAT) do often not provide data of individual farming systems but regional averages which may not match the users context. Data can also be presented in the different units or only derivatives are available that do not match the model requirements (Fountas et al., 2006). In all these cases data transformation is needed before the data can be used to feed into the models (Munson, 2012). In Chapter 3, we show an approach for data transformation in which besides calculations also local experts were used to check the legitimacy of the calculated estimates. Some studies mention that much of the needed data requires improved data sharing in which, for example, the collaboration and infrastructure with farmers, researchers, and food chain companies is addressed (Moore et al., 2022).

3.4 Scaling-up regenerative agriculture

Although, this thesis focused on field and farm-level modelling of regenerative agriculture, there is still an enormous gap in showing the potential of regenerative agriculture at scale: regional, country, continental, and global (Duncan et al., 2020; Jordan et al., 2022; Zhang et al., 2021). Scaling-up regenerative agriculture enables to answer question such as: how would global agriculture look like when fully transitioned to a regenerative food system (e.g. less or more extensive livestock systems), how much food can be produced (e.g. per country), and what would be the environmental benefits (e.g. on track towards the Sustainable Development Goals)? Such questions are important to be answered in order to guide policy debates and develop national and international strategies for the wider implementation of regenerative agriculture. I would like to present this section, therefore, as an afterthought for future research.

This thesis showed that regenerative agriculture is a farming approach which allows for a multitude of solutions dependent on the pedo-climatic conditions and motivations of farming (Chapter 2 and 4). However, we should avoid that the motivations of farmers are overruling the boundaries of our planet, local ecosystems, and the welfare of animals and human beings (Muscat et al., 2020; van Zanten et al., 2018). The optimum design of regenerative agriculture at scale, therefore, will vary between local contexts, resulting in a mosaic of optimized solutions constrained by local environmental boundaries starting with the soil (Figure 3). Regional models could help us with creating these ‘mosaics of solutions’ as well as deciding on the shape and size of such mosaics by making regenerative designs of landscapes suitable for different narratives of agriculture (e.g. circular dairy farming, regenerative crop production, agroforestry, nature areas). Such regional models already exist, Dengerink and Brouwer (2020), for example allready reviewed 10 food system models used by the Wageningen University and Research. Dengerink and Brouwer (2020) show that food systems models are often designed for specific objectives to explore the relation between food system activities and their environmental drivers and outcomes (Ericksen, 2008; Ingram, 2011) or nutrition and health outcomes (Global Panel, 2016; Willett et al., 2019). Here I will further discuss how food system models can contribute to determining the size and shape of mosaics of solutions for regenerative agriculture.

3.4.1 The size of mosaics of solutions

The size of mosaics refer here to the size of agriculture, particullar regions, or farming systems. In which the size of agriculture, among other things, determines the amount of food produced. Food system models are able to show actors how much food can be produced to achieve global food security with the associated environmental impacts (Ericksen, 2008; Ingram, 2011). For example, calculate how to close the global yield gap, responding to the quest of ‘feeding 10 billion people in 2050’ (Springmann et al., 2018). In this case the amount of food produced and, therefore, the size of agriculture is dependent on for example dietary guidelines. Such modellling exercitions show that instead of producing more food, we may need a better distribution of food (Nooghabi et al., 2018). Meaning that in some parts of the world (e.g. Europe and US) we need to consume and produce less (since we are coping with nutrient surplusses – overconsumption), while in other parts of the world (e.g. Africa) we need to consume and produce more (to cope with malnutrition). Food system models coping with the size and location of food production and consumption are currently the main topic of many political debates since there are multiple pathways to achieve global food security (e.g. land sparing or land sharing (Grau et al., 2013)). Regenerative practicioners tend to encourage a more localized pathway of food production, however, there are studies that show that this can be challanging in some parts of the world (van Ittersum et al., 2016).

Other studies, using food system models, focus on altering dietary guidelines and quantify what would happen if humanity would move towards plant-based diets and avoid feed-food competition (e.g. Springmann et al., 2018; van Kernebeek et al., 2016; van Zanten, 2016). Using such models, van Selm et al. (2022) show that in Europe GHG emissions can be reduced up to 31% and arable land use can be reduced with 42%. Moreover, Karlsson et al. (2021) show using similar principles that European livestock production can be reduced by 51% for pig meat, 68% for poultry meat, 5% for ruminant milk, and 10% for ruminant meat. These examples show that there is ample opportunity to explore the consequences of alternative approaches of food productionusing food systems models. By further developping these food system models we could centre-stage healthy soils as a prerequisite for food production (in the context of regenerative agriculture) to see how this alters environmental impacts and global food supply.

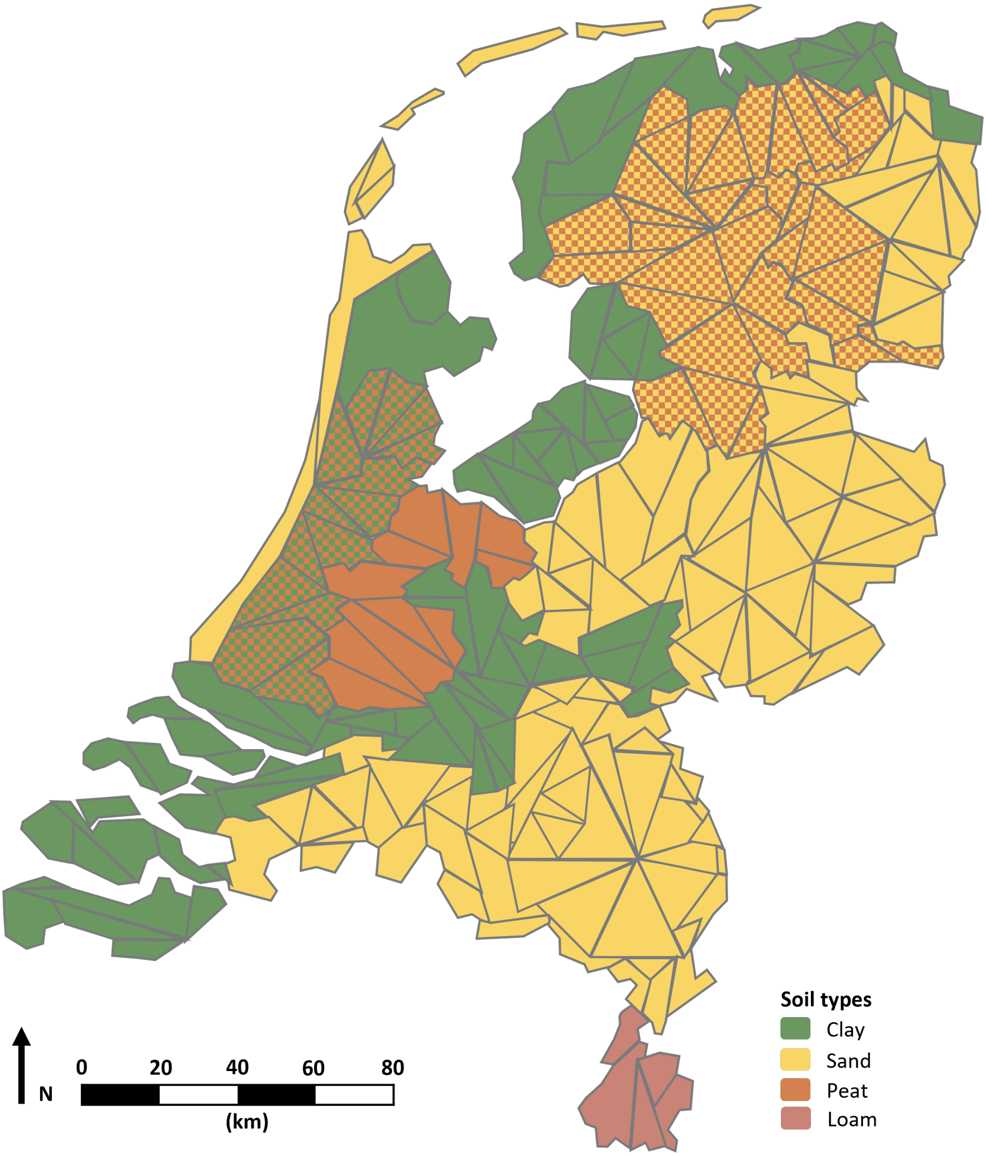

Figure 3. *The Netherlands divided in mosaics suitable for different narratives of sustainable farming.*

3.4.2 The shape of mosaics of solutions

The shape of mosaics refers here to different types of land use and best managament practices in the context of regenerative agriculture for different farming systems, regions, and continents. From Chapter 3 and 4 it became clear that we need tailor-made solutions for regenerative agriculture since different farming systems in different local contexts face different challanges and need different solutions. Food system models give opportunity to upscale lessons learned from field and farm-scale designs to regional and national scale designs (Gaitán-Cremaschi et al., 2019). Using food system models we can, based on the themes of regenerative agriculture, determine what type or combination of farming systems can be best used in various regions. These shapes of mosaics go beyond dairy and arable farming alone (this thesis) and should also adress other land uses such as pig and poultry production, bulbs and flower farming, and the preservation of nature and forrest areas (Dengerink and Brouwer, 2020). Such food system models that focus on the shape of mosaics can give very different perspectives compared to field and farm-level models (Dengerink and Brouwer, 2020).

In Chapter 3 and 4, for example, I model at the farm-level and discuss the opportunities towards regenerative dairy farming on peat soil. Although, the recommendations included specific suggestions such as the inclusion of clover in grassland to reduce artificial N fertilization, it was not considered to entirely change land use. Moreover, currently, 400 million hectarers of land worldwide are peat areas which contain 30% of all global soil carbon (Parish et al., 2008). These peat areas, in their natural state, have only marginal agricultural capability because of their high groundwater table and low carrying capacity. Therefore, farmers have drained these soils to increase the carrying capacity for heavy livestock grazing such as dairy cattle (Parish et al., 2008; van Boxmeer et al., 2021). Although, using peat soil for marginal grassland avoids feed-food competition (van Zanten, 2016), drained peat soils are a burden for climate regulation because of the enourmes amounts of carbon that gets lost due to peat oxidation, which can be higher than enteric emissions of the cows grazing in these areas themselves (van Boxmeer et al., 2021). I hypothesize that food system models (or even landscape models) could give different perspectives compared to field-, and farm-level models for the use of peat soils in regenerative agriculture. More specificly, in a regenerative context is may be that livestock production on peat soils is avoided due to its detrimental trade-offs with climate regulation, and instead peat soils are solely used as wetlands for nature conservation (Günther et al., 2020; Kreyling et al., 2021). To conclude, food system models are to date not used in the context of regenerative agriculture, however, show great potential in showing pathways for the wider implementation of regenerative agriculture. These pathways can guide policy makers and industries in making the right decisions, thus securing a sustainable future for the land that humanity relies on for tomorrow’s food and wellbeing.

4. Monitoring regenerative agriculture

From our modelling work in Chapter 4, we learned that reduced profitability could be a consequence of moving towards regenerative management using current business models. I argue that if business models change by also incentivizing other regenerative outcomes (e.g. improved biodiversity or reduced GHG emissions) besides primary productivity alone, regenerative farmers could have a sound profitability. However, building incentivization mechanisms around results and outcomes requires caution, since it can disadvantage farmers in their transition period (Chapter 5). Farmers in their transition period may face high investments costs by changing to regenerative management and reduced yields due to their avoidance of pesticide use, while the desired impacts of interventions on outcomes (e.g. changes in biodiversity) may take many years to materialize. In this case the application of regenerative practices could be used as an additional metric to results and outcomes for the immediate financial incentivization at a time where investment requirements are highest (Tanaka et al., 2022). Therefore, in Chapter 5, I argue that actors (e.g. farmers, industries, and policy-makers) need a combination of metrics (i.e. both practice, result, and outcome-based metrics) for improved incentivization and to bring regenerative agriculture to a success.

Ideas for monitoring and incentivization already exist (e.g. price premiums (Chee, 2004) and subsidies (Lotz et al., 2018)), however, it is currently unclear what role industries and governments could play in supporting such business models to support the valorization of regenerative objectives (Gosnell et al., 2019; Sivertsson and Tell, 2015). Monitoring and incentivization programs rely on metrics. The selection process and use of metrics ,however, has been contested (de Olde et al., 2017a; Gasparatos et al., 2008; von Wirén-Lehr, 2001). For example, the selection of metrics is often inconsistent (different initiatives select different metrics to monitor the same goals (de Olde et al., 2017b)) or single-focused (only one metric is selected to capture the performance of a broad topic (e.g. soil carbon to monitor soil health (Liptzin et al., 2022)). We also observe the erroneous application of uniform or generic metrics across contrasting contexts (one-size-fits-all and fixed minimum sets of metrics (Gasso et al., 2015)). Furthermore, metrics that can be used to monitor the adoption rate of interventions (i.e. practice-based metrics) are frequently confused with metrics that capture the efficacy of interventions in the longer term (e.g. result-based metrics) (Braband et al., 2003). In this knowledge vacuum, it is often found difficult for actors to decide what metrics to use and in what context. This is also addressed by the European Commission (2022a) which is working on a Soil Health Law proposal as part of the EU soil strategy for 2030, in which they highlight the quest for a monitoring framework that can be used for monitoring multiple goals (e.g. soil biodiversity and climate regulation) and for different purposes (e.g. tracking progress towards goals and incentivization).

In Chapter 5, we bring together and connect the knowledge of multiple domains in the field of soil monitoring, food systems thinking, and transitioning studies to give a holistic view on the role of metrics for regenerative agriculture. Subsequently, I have put forward a framework flexible to be used in different contexts (e.g. arable farming on clay soil and dairy farming on peat soil) and for different purposes (e.g. tracking progress towards goals and incentivization) to monitor the extent to which regenerative initiatives lead to verifiable changes in land management practices, results, and outcomes, and as such the degree to which they achieve their goals. Although, our quest for a monitoring framework is aligned with the ambitions of the European Commission, a monitoring framework alone will not be enough to make regenerative agriculture a success. If we zoom out to learn from approaches to monitoring of agricultural sustainability in general, we find a multitude of studies presenting frameworks for divergent and convergent purposes (e.g. Coteur et al., 2019; de Groot et al., 2010; FAO, 2014; SBTN, 2022; van Oudenhoven et al., 2012). These studies highlight that such frameworks come with a high degree of complexity and a translation is needed from framework to tool to enhance user operability.

Transforming our monitoring framework to a tool would not only benefit user operability but also consistency. Currently the selection of metrics and measurements in our framework is based on the knowledge of local experts. The knowledge of local experts can be highly divergent and may even fall short to determine the right metrics and measurements of success (de Olde et al., 2017b). First, determining the pertinence of different metrics and measurements is complicated as they are dependent on the local context and the purpose of measuring (Creamer et al., 2022). Second, there are various technical criteria to consider when selecting metrics and measurements (Zwetsloot et al., 2022). These can relate among others to 1) more practical matters such as ease of data sampling, overall costs, or possibility to store samples (Doran and Parkin, 2015; O'Sullivan et al., 2017), 2) sensitivity of a measurement to spatio-temporal variation in management (Andrews et al., 2004), and 3) interpretation of data generated by the method (Bünemann et al., 2018). Such challenges can be addressed by translating the framework into a decision support tool that, for example, weights certain selection criteria over others depending on the context of monitoring. Such tools for other purposes already exist, for example, Zwetsloot et al. (2022) developed a flexible tool for selecting measurements for soil multi-functionality called BIOSIS and Ritz et al. (2009) developed a 'logical sieve' for selecting biological indicators. Here I set the challenge for future research to translate our theoretical framework into a tool that can be used for actors for the monitoring of regenerative agriculture.

In research, however, many tools are developed for assessing sustainability in general and their actual contribution to change is questioned due to their limited adoption rate (Alrøe and Noe, 2016; de Olde et al., 2018; Triste et al., 2014). This is partially caused because researchers often get funded to design new frameworks but not their implementation (de Olde et al., 2018). Theoretical frameworks and tools are often at best tested on a small set of case-studies, however, miss gradual standardization for their wider implementation (Bockstaller et al., 2015). While potential is there to do research in for example public-private partnerships, which has the potential to link knowledge into action (Österblom et al., 2020; Warsen et al., 2018), the role of the private sector to invest in the scientific evidence of regenerative agriculture remains limited compared to their investments in marketing campaigns advertising it (Fawcett-Atkinso, 2021). The wide range of NGO's (e.g. The Nature Conservancy, the World Wildlife Fund, Greenpeace, Friends of the Earth), multinational companies (e.g. Danone, General Mills, Kellogg's, the World Council for Sustainable Business Development) and charitable foundations (e.g. IKEA Foundation) currently direct the transition of regenerative agriculture with pleasing aspirations and their own developed certification schemes. However, an independent structure that factchecks the legitimacy of these organizations and connected farming systems is not present (Hatanaka and Busch, 2008; Ingenbleek and Meulenberg, 2006), leaving regenerative agriculture in the sensitive position to be greenwashed (Giles, 2019). Some even argue, that the current lack in science-based and independent certification mechanisms is the exact reason for industries to commit to regenerative agriculture instead of already established an regulated approaches like organic agriculture (Cadloff, 2021). I argue, therefore, that initiatives should use science-based frameworks with independent certification structures and support their implementation (as tools) and standardization, translating the scientific knowledge within these frameworks into action. This benefits the legitimacy of the initiatives and benefits the adoption rate of science-based tools which prevents dispersion of efforts. Initiatives can for example use the tools in their sustainability assessment of farming system or work in public-private partnerships to safeguard a respectable amount of financial resources for building knowledge and taking it into action (Akhtar-Schuster et al., 2011). Equally supporting the building of knowledge and taking it into action not only ceases dispersion of efforts, it also catalyzes the transition towards regenerative agriculture.

5. Conclusions

Current global environmental, economic, and social challenges urge agriculture to change to more sustainable approaches of production. Regenerative agriculture established itself at the forefront of these approaches as a solution to keep our global food system within planetary boundaries. This thesis explored the meaning of regenerative agriculture and how practices can contribute towards its implementation. The following conclusions can be drawn from the research presented in this thesis:

This thesis was the first to review definitions about regenerative agriculture. Our review showed that there was a high level of convergence between definitions presenting environmental objectives (in particular regarding the soil) and divergence among socio-economic objectives (e.g. animal welfare). As a dot on the horizon for future initiatives to start with, I proposed to define regenerative agriculture as an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production. Moreover, I found that the practices oft-associated to regenerative agriculture are not new neither unique to regenerative agriculture and also find their root in other approaches to sustainable farming. I concluded, therefore, that regenerative practices do not make regenerative agriculture unique perse, rather the practices in combination with the aspirations (all dimensions of sustainable food production), priorities (e.g. soil health), and history (e.g. originates from practitioners) of regenerative agriculture.

For the primary production sector the multiple objectives of regenerative agriculture were found not equally relevant or applicable due to variation in farm archetypes and pedo-climatic conditions. To make regenerative agriculture meaningful at the farm-level I aimed to find a modelling framework which could assess and redesign farming systems towards a mode of regenerative agriculture. However, I discovered a huge disconnect between soil health and bioeconomic models. I created, therefore, a modelling framework which combines a soil health model with a bioeconomic model for an ex-ante design and assessment that shows which regenerative objectives are relevant and what practices are applicable for different farming systems in local-contexts. The framework takes context-specific objectives and practices center-stage to explore future farming systems towards regenerative agriculture.

Using the modelling framework I showed that transitioning towards regenerative agriculture requires tailor-made solutions for individual farming systems. The modelling framework is able to explore a wide diversity of tailor-made solutions contributing in varying degrees towards the objectives of regenerative agriculture. Overall I showed for three case-study farms that overall environmental performance was improved, however, at the expense of farm profitability. I argue, therefore, that primary productivity alone is a suboptimal indicator to evaluate the performance of regenerative farming systems which besides productivity also contributes to other ecosystem services. If business models change to ensure regenerative farmers can maintain a sound profitability, it will stimulate as wider transition towards regenerative agriculture. Still future research is needed to explore the impact and opportunities for regenerative agriculture at scale.

Besides modelling, we also need to monitor the efficacy of transitioning towards regenerative agriculture. I created, therefore, a monitoring framework to select metrics and measurement flexible for different contexts yet coherent to achieve overarching goals. I discuss that we need a combination of metrics and measurements over time to monitor the success towards regenerative agriculture and incentivize farmers for their contributions. To stimulate the uptake of such a framework, the next steps for future research are, to develop a tool based upon the framework and make sure it will be used by food system actors (e.g. independent certification agencies).

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Summary

The global food system causes severe pressures on the environment. In response, farming approaches that thus far were considered as a niche, are now heralded by industries and governments as mainstream solutions to keep the global food system within planetary boundaries. Regenerative agriculture is one of these farming approaches receiving a lot of attention from actors in the food system. The absence of a clear scientific definition and the low level of consensus on science-based approaches to the monitoring and verification of regenerative agriculture, however, has left many initiatives vulnerable to evidence-based allegations of greenwashing. This thesis, therefore, aims to understand what is meant with regenerative agriculture, to explore how farmers can contribute to regenerative dairy and arable farming, and to determine how success of farming systems towards regenerative agriculture can be monitored.

Chapter 2 describes what is meant with ‘regenerative agriculture’ based on a global literature review. For this review 279 articles were collected associated with regenerative agriculture, in which 28 articles presented a definition for regenerative agriculture. The level of convergence and divergence between these definitions were analyzed, which resulted in the core themes of regenerative agriculture. From this review regenerative agriculture is proposed to be defined as: an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production.

The definition proposed in Chapter 2 can be achieved by multiple regenerative objectives (e.g. improve soil health and alleviate climate change) and practices (e.g. minimize tillage and minimize external inputs), which were found not equally relevant or applicable for every farming system and local context. For example, a dairy farmer on peat soil faces very different challenges and enhances very different practices compared to an arable farmer on a clay soil. Subsequently to a more general definition, **chapter 3**, aimed to make regenerative agriculture meaningful at the farm-level. This was done by developing a modelling framework that combines a soil model (Soil Navigator) with a bio-economic farm model (FarmDESIGN) to show farmers what practices contribute to different regenerative objectives in their specific context. This modelling framework takes soil management practices center-stage to explore a multitude of alternative farm futures. From this study I learned that optimizing farming systems towards regenerative agriculture is complex and comes with a high knowledge requirement, as it requires detailed insights into soil multifunctionality at a field-level and knowledge about broader systems objectives at a farm-level. While this study successfully demonstrated an initial combination of using Soil Navigator and FarmDESIGN for the ex-ante design and assessment of a farming system,

further research was needed to apply the modelling framework to a wider diversity of farming systems.

In **Chapter 4**, therefore, the modelling framework was applied to three contrasting farming systems in the Netherlands (i.e. a dairy farm on peat soil, an arable farm on clay soil, and a mixed farm on sand soil) to determine if tailor-made solutions can be created for conventional farming systems towards regenerative agriculture. In total, 4,000 tailor-made solutions were evaluated for their environmental (e.g. greenhouse gas emissions) and socio-economic performance (i.e. farm labor and profitability) per case-study farm in their local context. For all farming systems, environmental performance was improved in the solutions dominated by the use of regenerative management practices. For example, greenhouse gas emissions were reduced by 50% for the arable case-study farm (from 4 to 2 Mg CO_2 eq. ha^{-1}; from 172 to 94 Mg CO_2 eq.), 6% for the dairy case-study farm (from 30 to 28 Mg CO_2 eq. ha^{-1}; from 1230 to 1050 Mg CO_2 eq.), and 23% for the mixed case-study farm (from 21 to 16 Mg CO_2 eq. ha^{-1}; from 1178 to 916 Mg CO_2 eq.), while maintaining soil functionality at high capacity for four out of the five soil functions. This overall improvement in environmental performance due to the application of regenerative management practices, however, also resulted in reduced farm profitability for all case-study farms by on average 50%. Reduced farm profitability as a consequence of shifting towards regenerative management could halt the transition towards regenerative agriculture and we, therefore, argue that business models should change to valorize other regenerative objectives besides primary productivity alone.

Decision-making regarding practices, however, also requires understanding of the environmental and socio-economic impact of potential (new) regenerative practices (e.g. strip cropping) and initiatives (a group of regenerative farmers). This can be done by monitoring. In **Chapter 5**, a comprehensive perspective on the role of metrics for monitoring regenerative initiatives at different scales is given. Subsequently, a monitoring framework is developed for the transparent, temporal- and context-sensitive selection of metrics for monitoring the extent to which regenerative initiatives lead to verifiable changes in land management, and as such the degree to which they achieve regenerative goals.

Finally, **Chapter 6** brings the insights of the preceding chapters together by discussing what regenerative practices are, how models are relevant for regenerative agriculture, and why monitoring is essential for the wider implementation of regenerative agriculture. In this chapter I further discuss some of the regenerative practices (e.g. minimal tillage and diversified cropping systems) and argue that these are not new neither unique to regenerative agriculture and find their roots also in, for example, organic and circular agriculture. I conclude, therefore, that regenerative practices do not make regenerative agriculture unique perse, rather the practices in combination with the aspirations (all dimensions of sustainable food production), priorities (e.g. soil health), and history (e.g.

originates from practitioners) of regenerative agriculture. Moreover, I caveat that the success stories of regenerative practices (e.g. minimizing tillage) may require some nuance since the positive effects on, for example, soil health is dependent on many variables (e.g. particularly crop type, other pre- and intermediate management interventions, and local environmental conditions). I discuss that a way to embrace complexity but simplify decision making on what practices to use is modelling. Currently I see, however, a huge disconnect between farm and soil health models which prevents adequate assessment of practices on all objectives of regenerative agriculture. A last aspect I elaborate further upon is the role of food system actors in monitoring the success for farming systems that move towards regenerative agriculture. Here, I illustrate that we need a combination of metrics to show the success of regenerative agriculture, while also incentivizing regenerative initiatives.

Overall, it is concluded that regenerative management can contribute positively to the transition towards sustainable food systems, however, an enabling environment for practitioners has yet to be established. This coming decade, we find ourselves at a unique crossroads where regenerative agriculture has the attention of farmers, citizens, industry and policy makers alike. As actors, let us now rise to the challenge to the mainstreaming of regenerative agriculture across farming systems and contrasting contexts, thus securing a sustainable future for the land that humanity relies on for tomorrow’s food and wellbeing.

Samenvatting

Ons wereldwijde systeem om voedsel te produceren levert een zware druk op het milieu, dit is bijvoorbeeld te zien aan ons klimaat dat verandert en het verlies van vele diersoorten in onze omgeving. Als reactie hierop, worden vormen van landbouw, die eerder gezien werden als niches, nu geprezen door de industrie en overheden als gangbare oplossingen voor een duurzame landbouw. Regeneratieve landbouw is op dit moment een van de meest populaire vormen van duurzame landbouw. Een wetenschappelijke definitie voor regeneratie landbouw ontbreekt tot op heden en er is ook weinig overeenstemming over methodes om te monitoren en verifiëren of regeneratieve initiatieven ook echt regeneratief zijn. Dit heeft ervoor gezorgd dat veel initiatieven die claimen regeneratief te zijn nu beschuldigd worden van ‘green washing’. Met ‘green washing’ wordt bedoeld dat initiatieven zich maatschappelijk verantwoordelijker voordoen dan dat ze daadwerkelijk zijn. Dit proefschrift onderzoekt daarom wat er wordt bedoeld met de term ‘regeneratieve landbouw’, hoe boeren kunnen bijdragen aan regeneratieve landbouw, hoe duurzaam regeneratieve praktijken daadwerkelijk zijn voor het milieu en hoe we het succes van regeneratieve initiatieven meetbaar kunnen maken.

In **Hoofdstuk 2** wordt er gestart met een mondiale literatuurstudie om uit te zoeken wat ‘regeneratieve landbouw’ betekent. In totaal werden er 279 wetenschappelijke artikelen verzameld, waarvan 28 artikelen een definitie presenteerde voor regeneratieve landbouw. Binnen deze 28 definities is de mate van overlap en verschil onderzocht. Dit onderzoek resulteerde in de kernthema’s van regeneratieve landbouw. Op basis van dit onderzoek werd er gesteld dat we regeneratieve landbouw kunnen definiëren als een vorm van landbouw waarbij bodembescherming het startpunt is. Dit betekent dat men probeert praktijken die een negatieve invloed hebben op bodemkwaliteit te beperken en praktijken te stimuleren die een bijdrage leveren aan een gezonde bodem. Bijvoorbeeld in de suikerbietenproductie gebruikt men pesticiden om schadelijke aaltjes te bestrijden. Deze pesticiden zijn echter ook schadelijk voor andere aaltjes en organismen. In plaats van pesticiden kan men ook slimme gewasrotaties stimuleren. In deze slimme gewasrotaties zou men eerst gewassen kunnen telen die onaantrekkelijk zijn voor schadelijke aaltjes om pas daarna suikerbieten te telen. Vanuit het oogpunt bodembescherming wordt vervolgens bijgedragen aan meerdere milieu en sociaaleconomische doelen zoals het verbeteren van het klimaat, het investeren in bovengrondse biodiversiteit, het genereren van genoeg financiële opbrengsten en het verbeteren van het welzijn van mens en dier.

Echter, niet alle kernthema’s van regeneratieve landbouw zijn even relevant voor elk landbouwsysteem in hun eigen omgeving. Bijvoorbeeld, een melkveehouder op veenbodem heeft hele andere uitdagingen en oplossingen nodig om regeneratief te worden dan een akkerbouwer op kleibodem. Daarom wordt in **Hoofdstuk 3** de betekenis van regeneratieve landbouw specifiek gemaakt op bedrijfsniveau. Dit is gedaan door een theoretisch raamwerk te ontwikkelen waarbij een bodemmodel is gekoppeld aan een boerderijmodel. Deze rekenmodellen zijn samen in staat om de doelstellingen van regeneratieve landbouw te kwantificeren en te laten zien welke regeneratieve praktijken het meest relevant zijn voor landbouwsystemen in hun eigen omgeving.

In **Hoofdstuk 4** is het raamwerk uit Hoofdstuk 3 toegepast op drie typische landbouwbedrijven in Nederland: een akkerbouwbedrijf op kleibodem, een melkveebedrijf op veenbodem en een gemengd bedrijf (combinatie van melkvee en voedergewassen) op zandbodem. Deze studie laat zien hoe we met het raamwerk oplossingen kunnen creëren voor gangbare bedrijven naar een vorm van regeneratieve landbouw. In totaal werden er 4000 op maat gemaakte oplossingen gecreëerd per bedrijf, specifiek voor hun eigen omgeving. Dit geeft een boer veel ruimte om te kiezen welke set aan oplossingen bij hem of haar past. De regeneratieve doelstellingen betreft milieu verbeterde voor alle bedrijven die hoofdzakelijk regeneratieve praktijken gebruikten. Broeikasgasemissies werden bijvoorbeeld verminderd met 50% voor het akkerbouw case-bedrijf (van 4 naar 2 Mg CO_2 eq. ha^{-1}; van 172 naar 94 Mg CO_2 eq.), 6% voor het melkvee case-bedrijf (van 30 naar 28 Mg CO_2 eq. ha^{-1}; van 1230 naar 1050 Mg CO_2 eq.) en 23% voor het gemengde case-bedrijf (van 21 naar 16 Mg CO_2 eq. ha^{-1}; van 1178 naar 916 Mg CO_2 eq.), met behoud van een gezonde bodem. Deze algehele verbetering van regeneratieve doelstellingen betreft milieu als gevolg van regeneratieve praktijken resulteerde echter ook in een lagere financiële opbrengst van gemiddeld 50% voor alle bedrijven. Een lagere financiële bedrijfsopbrengst als consequentie van het toepassen van regeneratieve praktijken kan de transitie naar regeneratieve landbouw tegenhouden. In dit proefschrift wordt daarom gesteld dat verdienmodellen moeten worden veranderd om ook waarde te geven aan regeneratieve doelen naast alleen productiviteit. Als een bedrijf bijvoorbeeld zorgt voor een lagere uitstoot van broeikasemissies of voor meer biodiversiteit zou dit financieel beloond moeten worden.

Het overwegen van landbouwpraktijken vraagt ook om kennis betreft milieu en sociaaleconomische prestaties van (nieuwe) regeneratieve praktijken (zoals stroken teelt). Dit kunnen we doen door verschillende soorten indicatoren te monitoren en verschillende soorten meetmethodes te gebruiken. Sommige initiatieven kiezen ervoor om de duurzaamheid van bedrijven te bepalen door regeneratieve praktijken te tellen, andere initiatieven gebruiken modelmatige benaderingen door de effecten van praktijken te berekenen (de Kringloopwijzer), en weer andere kiezen ervoor om de effecten van praktijken te meten in bijvoorbeeld de bodem. In **Hoofdstuk 5** wordt er een uitgebreid perspectief gegeven over de rol van indicatoren voor het monitoren van regeneratieve initiatieven op verschillende schaalniveaus, bijvoorbeeld op boerderij, regionaal en wereldniveau. Vervolgens, wordt er een raamwerk gepresenteerd voor de flexibele selectie van indicatoren voor verschillende initiatieven die inzicht geven in het behalen van regeneratieve doelen. In andere woorden, dit raamwerk kan gebruikt worden om de bijdrage van bepaalde aanpassingen in landbeheer meetbaar te maken ten behoeve van regeneratieve doelen.

Ten slotte brengt **Hoofdstuk 6** de inzichten uit de voorgaande hoofdstukken samen door te bespreken wat regeneratieve praktijken zijn, hoe modellen relevant zijn voor regeneratieve landbouw en waarom monitoren essentieel is in de transitie naar regeneratieve landbouw. In dit hoofdstuk wordt er dieper ingegaan op een aantal regeneratieve praktijken (zoals niet kerende grondbewerking en mengteelten) en wordt er gesteld dat deze praktijken niet nieuw of uniek zijn voor regeneratieve landbouw. Deze praktijken vinden hun oorsprong ook in bijvoorbeeld biologische en kringlooplandbouw. Er wordt daarom geconcludeerd dat de geassocieerde praktijken regeneratieve landbouw niet uniek maken. Eerder de praktijken in combinatie met de doelen (alle dimensies van duurzame voedselproductie), prioriteiten (zoals bodemgezondheid), en geschiedenis (komt oorspronkelijk vanuit boeren) van regeneratieve landbouw. Verder wordt er gewaarschuwd dat de succesverhalen over regeneratieve landbouw zoals niet kerende grondbewerking enige nuance vergen. De reden hiervoor is dat de positieve effecten van niet kerende grondbewerking op bijvoorbeeld bodemgezondheid sterk afhankelijk zijn van veel variabelen zoals gewastype, andere managementactiviteiten en de omgeving waarin de activiteit wordt toegepast. Het context specifiek maken van regeneratieve praktijken en doelstellingen in verschillende landschappen is complex en hangt af van veel factoren. Daarom is er in dit proefschrift een modelleermethode bedacht om de complexiteit te omarmen en tegelijkertijd de besluitvorming te vereenvoudigen. Momenteel zien we een enorme disconnectie tussen bedrijfsmodellen en bodemgezondheidsmodellen. Dit verhindert een adequate beoordeling op alle doelstellingen van regeneratieve landbouw. Een laatste aspect dat verder wordt uitgewerkt is de rol van voedselsysteemactoren in het monitoren van succes voor bedrijven in de transitie naar regeneratieve landbouw. Hier wordt geïllustreerd dat we een combinatie aan indicatoren nodig hebben om zowel het succes van regeneratieve landbouw te monitoren en tegelijkertijd regeneratieve initiatieven consequenter te waarderen.

Over het algemeen kan er worden geconcludeerd dat regeneratieve landbouw een positieve bijdrage levert aan de transitie naar duurzame voedselsystemen. Er moet echter nog wel een milieu gecreëerd worden waarin regeneratieve praktijken kunnen worden toegepast. Het komende decennium bevinden we ons op een uniek kruispunt waar regeneratieve landbouw de aandacht heeft van zowel boeren, burgers, industrie en beleidsmakers. Laten we nu de uitdaging aangaan om regeneratieve landbouw gangbaar te maken en zo een duurzame toekomst veilig te stellen voor het land waarop de mensheid vertrouwt voor het voedsel en welzijn van morgen.

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About the author

Loekie Schreefel was born on the 10th of June 1992 in Amsterdam, the Netherlands. His interest in regenerative agriculture started in 2014 when he was researching novel foods sources when obtaining his BSc-degree in Mechanical Engineering from the University of Applied Sciences of Amsterdam, the Netherlands. During his bachelor he did a major in Entrepreneurship and wrote a BSc-thesis about the design of circular large-scale production systems to produce housefly larvae (*Musca domestica*) for feed. This motivated him to further study circular and sustainable bioproduction systems.

In 2017, he obtained a MSc in Biosystems Engineering from the Wageningen University, the Netherlands. His first MSc-thesis focused on the assessment of the thermal environment of mealworm (*Alphitobius diaperinus*) kept in a large-scale production system. This study was conducted at the Farm Technology group and the Laboratory of Entomology of the Wageningen University in collaboration with Proti-Farm (a large scale producer of edible insects). A second thesis focused on greenhouse gas emissions produced by growing mealworms (*Tenebrio molitor*) assessed by flow-through respirometry. This study was conducted within the inVALUABLE project lead by the Danish Technological Institute and in collaboration with the Farm Technology group and Laboratory of Entomology of the Wageningen University.

In 2018, he joined the Farming Systems Ecology group and Animal Production Systems group of the Wageningen University to start his PhD as part of the Regenerative Farming Project lead by TiFN (Top Institute for Food and Nutrition). Here he worked on the identification of the biophysical characteristics of regenerative agriculture and worked towards its implementation in the Netherlands. The findings of his work were presented at international conferences, invited lectures, webinars, symposia, and published in peer-reviewed scientific journals. During his time in the Regenerative Farming Project, Loekie was part of the core-team to produce project deliverables as well as communicating his research to key-stakeholders such as industry partners, NGO’s, other researchers, and farmers.

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PE&RC Training and Education Statement

With the training and education activities 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 oof a minimum total of 32 ECTS (=22 weeks of activities).

Overview of activities:	**ECTS**
Review of literature	**4.5**
• Regenerative agriculture – the soil is the base (2020).	
Writing of project proposal	**4.5**
• Towards regenerative agriculture: the case of dairy and arable farming in the Netherlands (2019).	
Post-graduate courses	**7.0**
• Systematic Approaches to reviewing literature; WUR (2019).	
• Modelling and optimization with GAMS; WIAS (2020).	
• Environmental Impact Assessment of Livestock Systems; WUR (2019).	
Deficiency, refresh, brush-up courses	**2.0**
• Analysis and design of organic farming systems; FSE (2019).	
Competence strengthening / skills courses	**2.4**
• Scientific writing; Wageningen in'to languages (2019).	
• Supervising BSc & MSc thesis students; Education Support Centre WUR (2020).	
Scientific integrity courses	**0.6**
• Scientific integrity; Wageningen Graduate Schools (2020).	
PE&RC Weekend, day, and other events	**1.2**
• PE&RC Day - The Social Network of Nature (2018).	
• PE&RC First years weekend (2019).	
Discussion group, local seminar or other scientific meeting	**9.2**
• A2R: kick-off workshop Regenerative Farming Project; the Netherlands (2018).	
• Regenerative farming expert meetings; the Netherlands (2018-2022).	
• Teagasc seminar; online; Ireland (2021).	
• Soil functions workshop; the Netherlands (2021)	
• Food4Sustainability seminar; online; Portugal (2022).	
• Cool Farm Alliance Annual Meeting; online; UK (2022).	

International symposia, workshops and conferences **10.6**

- Wageningen Soil Conference; the Netherlands (2019).
- TiFN Retreat conference; the Netherlands (2019).
- WIAS Science conference; the Netherlands (2020).
- EAAP conference; online; Portugal (virtual) (2020).
- Euracademy conference; online; Greece (virtual) (2021).
- Circular@WUR conference; the Netherlands (2022).
- LCA FOODS conference; Peru (2022).

Societally relevant exposure **1.0**

- Decade of Action interview, pioneers in regenerative agriculture (2022).
- Knowledge clip about regenerative agriculture (2022).

Lecturing / Supervision of practical's / tutorials **0.3**

- Biosystems Design (2018).
- Exploring the Future of Food and Farming (2021).

Supervision of BSc / MSc students **24**

- The environmental impact of regenerative agriculture: the case of non-inversion tillage at arable farms on clay soil in the Netherlands
- A modelling study of the potential for regenerative agriculture on mixed farms on sandy soil in the Netherlands
- Collaboration for innovation, road towards regenerative agriculture
- Regenerative agriculture: case of the Netherlands
- Internship report on regenerative agriculture in the Netherlands
- Regenerative farming in the Netherlands
- Restoring soils: effects of regenerative agriculture on soil quality of dairy an arable farms in the Netherlands
- Exploring systemic barriers hindering the transition to circular agriculture in the Netherlands

Colophon

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