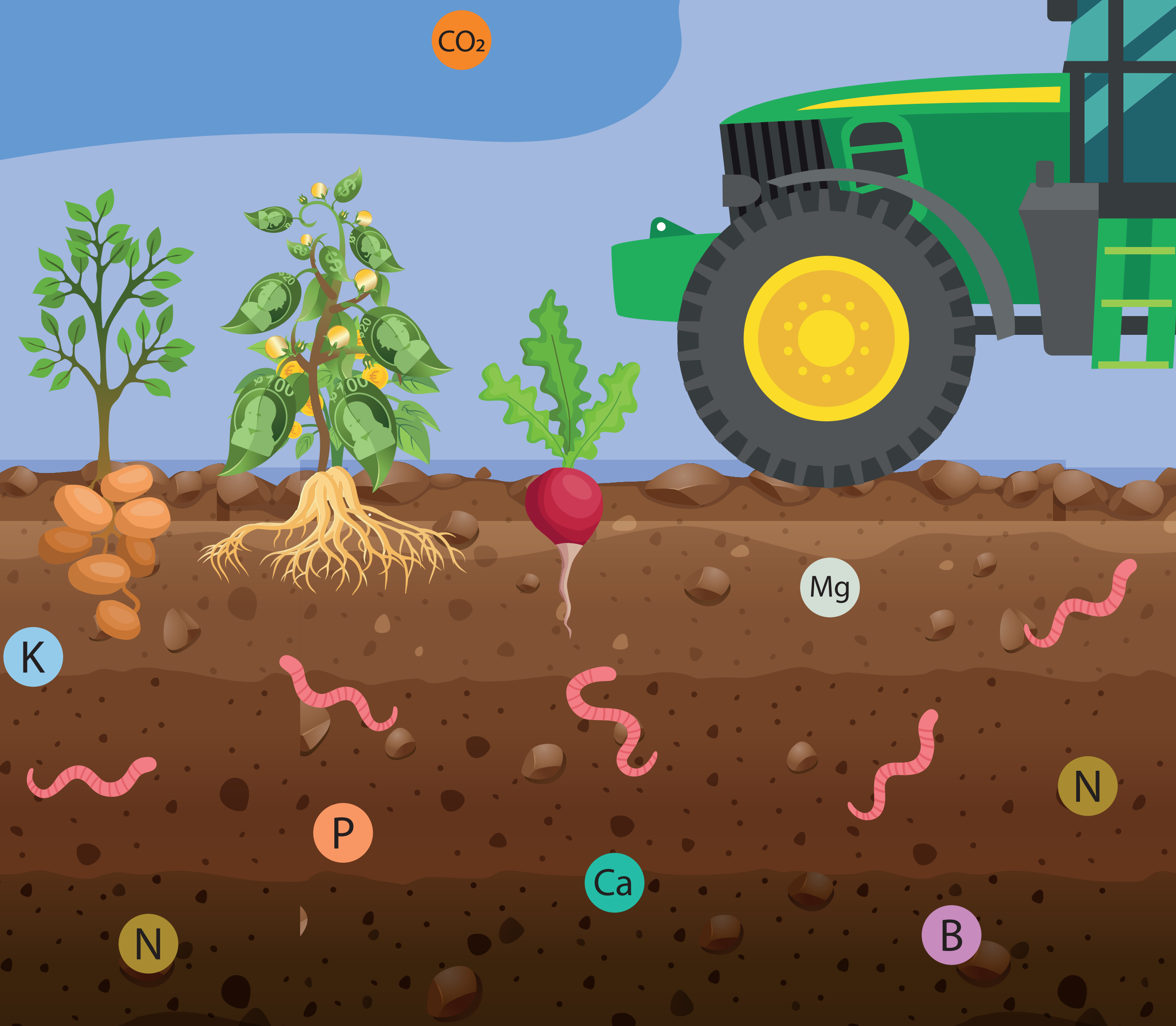
THE ECONOMIC VALUE OF SUSTAINABLE SOIL MANAGEMENT

Maarten Kik



Propositions

1. Soil quality can be improved while simultaneously increasing farm income.
   (this thesis)

2. Subsoil compaction is the largest threat to soil quality in the Netherlands.
   (this thesis)

3. The insufficient recognition of societal impact within the current scientific systems hampers science to effectively address societal concerns.

4. Everyone involved in farm-related research has to know how to operate a tractor.

5. The European Green Deal endangers food security.

6. Working from home inhibits creativity and collegiality.

Propositions belonging to the thesis, entitled

The economic value of sustainable soil management

Maarten Kik

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The economic value of sustainable soil management

Maarten Kik

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The economic value of sustainable soil management

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Thesis

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Prof. Dr A.P.J. Mol,

in the presence of the

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General Introduction

1.1 The importance of soil quality

Nowadays, soils are recognized as more than mere growing media for crops (Rinot et al., 2019). They play a crucial role in food, fuel, and fibre production, water cycling and purification, carbon sequestration, biodiversity conservation, and nutrient cycling (Schulte et al., 2014). Consequently, soil quality is a pivotal factor influencing crop productivity, farm resilience and the environmental quality of arable farming systems (Stevens, 2018). The terms "soil quality" and "soil health" are often used interchangeably. Bünemann et al. (2018), in a comprehensive review, concluded that the distinction between these concepts has evolved from a matter of principle to a matter of preference, considering them essentially equivalent. In this thesis I adopt the concept of "soil quality" which is defined as "The ability of a specific soil type to function within natural or managed ecosystems, supporting the productivity of plants and animals, maintaining or enhancing water and air quality, and providing a suitable environment for human health and habitation" (Karlen et al., 1997).

At a global scale, soil quality is currently facing notable challenges. The growing global population and the need to ensure food production worldwide have put considerable pressure on agriculture (Rinot et al., 2019). However, the availability of agricultural land is decreasing due to factors like urbanization and industrial development (Alexandratos & Bruinsma, 2012). If these developments are not managed sustainably, they can lead to soil degradation, which refers to the decline in the soil's ability to provide ecosystem services such as provisioning of food and water regulation (Koch et al., 2013; Schwilch et al., 2016). It is estimated that one-third of the world's agricultural soils are currently facing degradation (FAO & ITPS, 2015). Soil degradation has detrimental effects on food security, water retention, and biodiversity, as these aspects rely on the functions provided by healthy soils (Koch et al., 2013). Some examples of soil degradation include subsoil compaction caused by heavy machinery traffic in fields (Hamza & Anderson, 2005), loss of soil organic matter in the topsoil (Squire et al., 2015) and soil erosion, which results in on-site issues like nutrient loss and reduced productivity, as well as off-site problems such as eutrophication and sediment deposition (Li & Fang, 2016).

Future developments will put even further emphasis on soil quality. To avoid key soil threats such as erosion, floods, loss of soil organic matter, compaction and sealing, the European Commission proposed a soil health law that aims to achieve healthy soils by 2050 (Eu Soil Health Law, 2023). The effect of soil degradation can, in the short run, partly be compensated with inputs like fertilizers and pesticides, although this has a trade-off with regard to e.g. nutrient leaching and pesticide emission (Squire et al., 2015). However, application of these inputs is increasingly being restricted and questioned, as evident from the EU Farm-to-Fork strategy which includes targets for reducing pesticide use by 50% and fertilizer use by 20% by 2030 (Boix-Fayos & de Vente, 2023; Montanarella & Panagos, 2021). Moreover, climate change is expected to increase the frequency and impact of extreme weather events, underscoring the needs for soils being capable to adapt to weather variations (Wall & Smit, 2005). A well-functioning soil might improve the resilience of farming systems (Cong et al., 2014; Ge et al., 2016).

Soil quality holds significant importance not only for farmers, who operate and often own the land, but also for other actors involved in agricultural value chains. The decline in soil quality and subsequent reduction in crop yields can have wide-ranging impacts on these actors. As farming constitutes a key activity within agricultural value chains, any decline in soil quality affects the entire value chain. Furthermore, arable farms are integral components of regional ecosystems, and a decline in soil quality directly impacts actors reliant on the environmental quality of these ecosystems. An example of such interdependence is the contamination of groundwater by excessive nitrate leaching, which poses challenges for drinking water companies. All of the above highlights the pivotal role of soil quality in agricultural ecosystems and the societal context around these systems.

1.2 Sustainable soil management as an economic problem

Based on the importance of soil quality and the ongoing process of soil degradation there is a strong call for the implementation of sustainable soil management, which can be defined as "meeting the present needs of crop productivity and ecosystem services without compromising soil needs for future generations" (adapted from Smith & Powlson, 2007).

However, implementation of sustainable soil management is not self-evident because of the following factors:

1. *Unknown long-term impact of production management*: A lack of methods to quantify the long-term effects of production management, i.e. the complete set of physical and non-physical inputs made by the farmer, on soil quality can lead to short-sighted management decisions (Brady et al., 2015). This mechanism is twofold: first, for many soil quality parameters it is not yet possible to ex-ante quantify their evolution as a response to farmers' production management. For example, it is not yet possible to do an accurate ex-ante calculation of the impact of field traffic on bulk density of the soil (Rücknagel et al., 2015). Second, the impact of soil quality on future crop yield is still ambiguous. Brady et al. (2015) found that short-term benefits of sustainable soil management are small whereas "the potentially large long-term benefits are difficult to quantify".
2. *Soil quality interrelations*: Soil quality is a complex concept that consists of many interrelated functions (Bouma, 2014). Within these functions, trade-offs exist where optimizing one soil function goes at the expense of another soil function. For example, cultivation of a cover crop has a positive impact on soil structure and is a source of organic matter, but the cover crop might also serve as a host-crop for plant-parasitic nematodes (Adetunji et al., 2020; Puissant et al., 2021). These interrelations are also one of the main reasons why an ex-ante assessment of soil quality as described in factor 1 is so difficult.
3. *Soil quality versus short-term profit*: Pressure on short-term profit poses challenges for implementation of sustainable soil management since economic benefits typically manifest in the long-term. Hijbeek et al. (2018) mention for example that practices to improve soil organic matter can be hampered when short-term profits outweigh long-term benefits. Note that this trade-off is different from limiting factor 1. Development of the soil organic content as a response to production management can be modelled and calculated and there is widespread consensus on the importance of a sufficient level of organic matter input (Mandryk et al., 2014). However, because of pressure on the short-term profit, farmers can still prefer short-term profit over (uncertain) long-term benefits of improving soil quality.
4. *Agricultural productivity versus ecosystem services*: Optimization of soil quality towards one function, e.g. agricultural productivity, might go at the expense of the ability of the soil to deliver ecosystem services (O'Sullivan et al., 2018; Schulte et al., 2014; Stevens, 2018). A fundamental underlying problem is that benefits of soil quality manifest for multiple actors and these actors have different interests. Bouma & McBratney (2013) therefore consider this type of problems as "wicked" problems that have no single, logical solution. Only a series of options where economic, environmental and social requirements of involved actors are carefully weighted can contribute to solutions. An example of this trade-off is crop nitrogen (N) supply: For farmers, the prime interest is to ensure optimal N availability for the crop to realize sufficient production levels. However, optimal crop N availability might come at the costs of higher emissions to the environment, thereby impacting for example drinking water companies.
5. *Tailor-made production management*: Proper implementation of sustainable soil management strongly depends on the initial situation regarding soil quality and current production management. These properties are typically heterogenous among farms; production management therefore has to be tailored at farm-level. This hampers a swift and quick implementation. For instance, for carbon sequestration the impact strongly depends on current carbon saturation of the soil (Lessmann et al., 2022; Moinet et al., 2023). Thus, whereas at one farm or even field an increase in soil organic matter content and subsequent management decisions for that purpose are required, this can be totally different on another farm or field.

Figure 1.1 visualizes the impact of the factors limiting for implementation of sustainable soil management in the economic context of a farm.

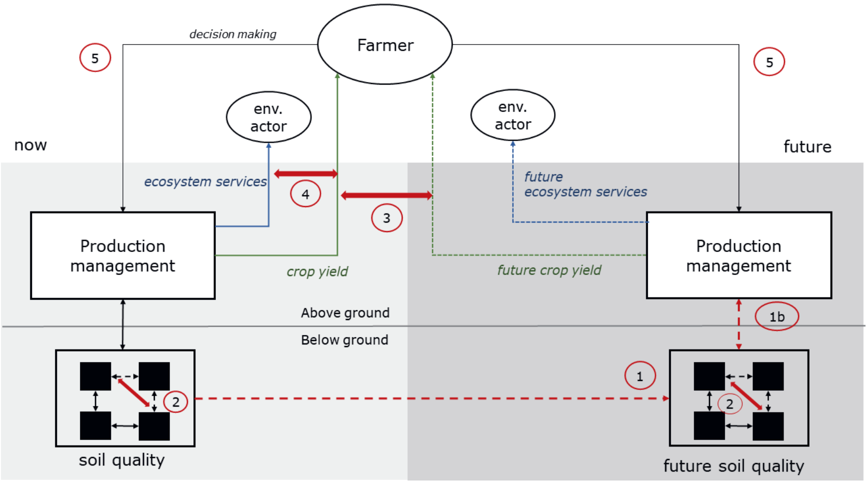

Figure 1.1 – Key factors hampering implementation of sustainable soil management in arable farming systems. 1: Unknown long-term impact of production management on future soil quality (1) and future crop yield (1b). 2: Soil quality interrelations & trade-offs. 3: Trade-off short-term profit versus long-term soil quality. 4: Trade-off yield versus current & future ecosystem services. 5: Implementation of right production management decisions. Env. actor = environmental actor.

From Figure 1.1 it follows that current unsustainable production management decisions can lead to a decline in future soil quality. In turn, this might result in a lower future crop yield and other ecosystems services, thereby threatening long-term farm survival and negatively impacting agricultural value chains and environmental actors. At the farm-level, achieving a sufficient yearly income and long-term continuity of the farm are prime goals for farmers (Kay et al., 2012). Regarding these goals, the implementation of sustainable soil management can be considered an economic problem.

1.3 Scientific gaps for the economic value of sustainable soil management

Considering sustainable soil management as a socio-economic problem, the challenge is to implement the right production management decisions at the farm-level that ensure (1) profit for a sufficient yearly farm income and (2) long-term preservation of soil quality in which the economic, social and environmental interest of not only the farmer but also other actors are carefully weighted. Therefore, we need insight into the Economic Value of Sustainable Soil Management ($EVSM$), which is vital for decision makers at all levels, e.g. farmers, value chain actors and policy makers. In order to obtain quantitative insight into $EVSM$, a scientific breakthrough is required in fields of (1) soil quality, (2) the role of farmers and other actors, and (3) bio-economic modeling.

Soil quality

Soil quality is a complex concept that consists of many interrelated indicators. Since the $EVSM$ is determined by the quality of the soil as a whole and not by single indicators, an integrated approach towards soil quality is required. Such an integrated approach requires chemical, physical and biological indicators, and interrelations between indicators and target values (Bouma, 2014; Rinot et al., 2019). Preferably, data for these indicators has to be available at large-scale and against low-cost to ensure scalability (Rinot et al., 2019; Ros et al., 2022). Important contributions to the integrated assessment of soil quality have been made through soil quality indices e.g. the Cornell Soil Health Assessment (Idowu et al., 2008), and the Open Soil Index (Ros et al., 2022). Although these soil indices are a valuable contribution, a limitation is that they are intended to assess the status quo of the soil. However, in order to assess future $EVSM$, insight in the evolution of soil quality indicators as a response to farmers' management is required (Stevens, 2018).

Role of farmers and other actors

Farmers are the operators and often owners of the land, but farmers do not make their decisions independently. They operate in a context of other actors with sometimes contrasting expectations on sustainable soil management. Despite that previous research calls for the involvement of actors beyond farmers (Bouma, 2014; Bouma & Montanarella, 2016; Bünemann et al., 2018; O'Sullivan et al., 2018), surprisingly little attention has been paid to a structured inventory of actors in sustainable soil management from an economic, social and environmental perspective. Such an inventory can contribute to better understanding the contrasting expectations on sustainable soil management from different actors.

Bio-economic modeling

The optimization of farmers' production management has been part of numerous bio-economic farm models, which are amongst the most widely spread methods to re-design farming systems (Janssen & van Ittersum, 2007). Most of these models use a linear programming framework where profit is one of the most common objectives whereas constraints typically include availability of resources such as labor, irrigation water and land (Castro et al., 2018; Castro & Lechthaler, 2022). The added value of such models has been proven as they allow to evaluate trade-offs and synergies between different production management strategies and thus support the design of alternative systems (Dury et al., 2012; Schreefel et al., 2022). Although many of these models (e.g. Dogliotti et al., 2005; Groot et al., 2012a; Louhichi et al., 2010) include some soil quality parameters, such as nutrients flows and soil organic matter, they typically only make tenuous references to the integral concept of soil quality (Schreefel et al., 2022). On the other hand, integrated soil quality assessment tools, such as in Debeljak et al. (2019) and Ros et al. (2022), often lack an integration of the socio-economic impact of production management decisions at farm-level. Schreefel et al. (2022) make a valuable contribution to bridge this gap by coupling the soil assessment tool Soil Navigator of Debeljak et al. (2019) to the bio-economic farm model FarmDesign by Groot et al. (2012). In this study, Schreefel et al. (2022) optimize multiple functions of soils using qualitative suggestions of the Soil Navigator as inputs in FarmDesign. Despite the added value of this approach, the understanding of the socio-economic aspects of sustainable soil management in the farm context still needs further advancements to quantitively assess $EVSM$.

Therefore, I aim for a quantitative integration of the relation between integral soil quality and production management embedded in a farm's socio-economic context. This results in four prerequisites for bio-economic modeling. First, soil quality in the bio-economic model has to be included as integral concept (Bouma, 2014). Second, building further on studies that already include important production management decisions such as cropping plan and crop rotation (Alfandari et al., 2015; Capitanescu et al., 2017; Pahmeyer et al., 2021), inclusion of further production management decisions such as cover crops, manure application, fertilizer application and crop residue management is a prerequisite for soil quality and hence $EVSM$ (Kanellopoulos et al., 2014). Third, the *ex-ante* integral assessment of soil quality as a response to a comprehensive set of production management decisions requires accurate modeling of these decisions over time. For example in a simple crop rotation of "potatoes – wheat – sugar beets – corn", planting a cover crop of winter radish after wheat might have a different impact than planting the cover crop after corn. Therefore, we build further on the approach of developed by Dogliotti et al. (2003) to create feasible crop rotations over time, which than serve as the basis for allocation of other production management decisions. Fourth, the impact of production management decisions is strongly dependent on the farm context (e.g. soil type, climate, cropping plan), which is highlighted by Hannula et al. (2021) and Young et al. (2021). Therefore, a bio-economic model needs to provide outcomes representing the context of application. Bio-economic modeling fulfilling these prerequisites will help to overcome the limitations for implementation of sustainable soil management, thereby contributing to preservation of long-term soil quality and farm income.

1.4 Research objective

The overall objective of this thesis is to assess the economic value of sustainable soil management in arable farming systems. To achieve the overall objective, the following sub-objectives are defined, i.e. to:

1. Define the Economic Value of Sustainable Soil Management ($EVSM$) and establish a conceptual framework for sustainable soil management in an arable farming context.
2. Provide an analysis of the actors involved in sustainable soil management in the Netherlands.
3. Develop and illustrate a bio-economic modeling approach to optimize $EVSM$ at farm level.
4. Explore $EVSM$ on existing Dutch arable farms in future scenarios.

The Netherlands was chosen as a case study country. In the Netherlands, high product demands coincide with fierce competition for land by e.g. urbanization resulting in land scarcity and high land prices (CBS, 2016). In turn, these high land prices force farmers towards intensive land use with relatively high economic returns. However, this intensive land use endangers soil quality through increasing risks of soil-borne diseases, soil compaction and low levels of soil organic matter (Akker & Hoogland, 2011; Dogliotti et al., 2003; Mandryk et al., 2014). The choice for the Netherlands as a case study country implies that the focus of this thesis is on intensive agriculture in high-input high-output systems in Western countries. In the Netherlands, agricultural ecosystems, natural ecosystems and rural livelihoods are in close interaction with each other which leads to high societal and environmental demands on farming systems (Schulte et al., 2019). Arable farmers and dairy farmers are the main land users in the Netherlands, but I chose to focus on arable farming to assess $EVSM$ in the interaction between soil quality, crops and production management. Livestock is certainly relevant in this system as illustrated by Groot et al., (2012) and Schreefel et al., (2022) but outside the scope of this thesis.

1.5 Methodological framework and thesis outline

This thesis consists of six chapters: A general introduction (this chapter), four research chapters that elaborate on the objectives defined above (chapter 2-5) and a general discussion and conclusion (chapter 6). Figure 1.2 presents a methodological framework of this thesis.

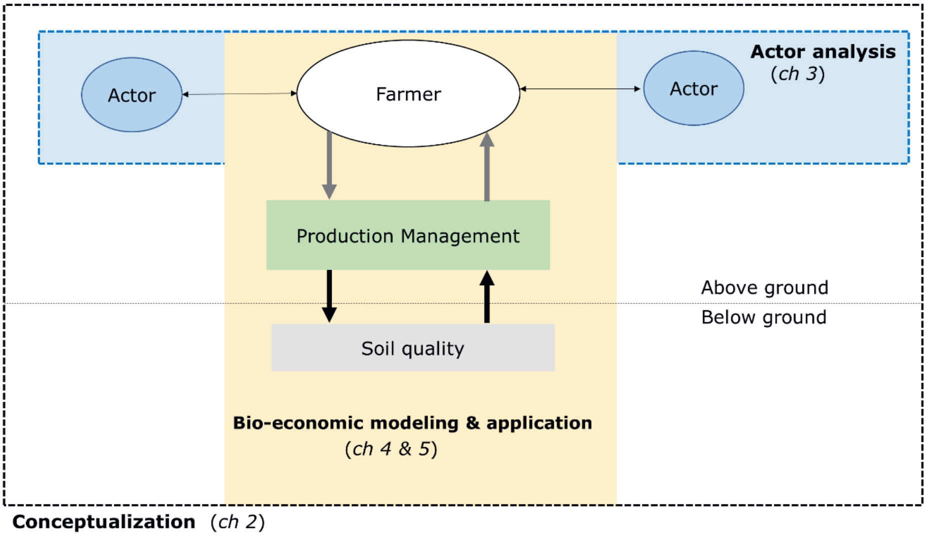

Figure 1.2 – Methodological framework highlighting the main research themes and chapters of this thesis.

Chapter 2 defines $EVSM$ and embeds farmers and their production management in a context of other actors. Subsequently, this chapter establishes a conceptual framework for sustainable soil management in an arable farming context that integrates disciplinary knowledge on soil quality management and crop production management. *Chapter 3* is a elaboration of the context of actors in which arable farmers operate. This chapter presents an inventory of actors involved in sustainable soil management in the Netherlands. Subsequently, this chapter explores the priorities and power-interest of actors regarding sustainable soil management. *Chapter 4* is the quantitative implementation of the conceptual framework presented in Chapter 2. This chapter explains the bio-economic modeling approach FARManalytics which can be used to optimize $EVSM$ at farm-level. The model approach is illustrated for standard farm types in the Netherlands. *Chapter 5* contains a further application of the FARManalytics modeling approach. This chapter explores $EVSM$ for nine existing Dutch arable farms in different future scenarios.

Table 1.1 - Summary of chapters in this thesis.

Chapter	Objective	Approach
2. Conceptual framework	Define Economic Value of Sustainable Soil Management ($EVSM$) and provide framework for sustainable soil management	Conceptualization
3. Actor analysis	Provide analysis of actors involved in sustainable soil management	Actor inventory, survey & Analytical Hierarchy Process
4. Bio-economic model FARManalytics	Develop and illustrate FARManalytics bio-economic modeling approach	Bio-economic modeling: development & illustration
5. $EVSM$ on arable farms in future scenarios	Optimize *EVSM* on Dutch arable farms in future scenarios with FARManalytics	Bio-economic modeling: application & scenarios

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2

The economic value of sustainable soil management in arable farming systems – A conceptual framework

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2.1 Abstract

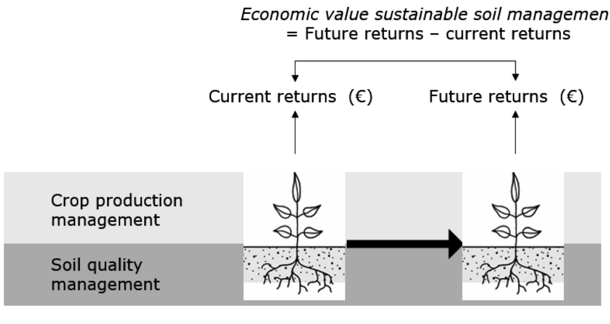
Soil quality is an important determinant of agricultural productivity, farm resilience and environmental quality. Despite its importance, the incorporation of sustainable soil management in economic models is lacking. This study approaches farmers as decision makers on soil management. Sustainable soil management may be an investment that goes at the expense of short-term returns but increases future soil quality. Hence, the key problem is economic: establishing long-term sustainable soil management at a minimized loss of income. In this study, we define the Economic Value of Land (EVL) as the cumulative returns of a piece of land over a period in time. Maximum long-term EVL is obtained if a soil's potential is maximally utilized in a sustainable way. From this follows that the Economic Value of Sustainable soil Management $(EVSM)$ is defined as the difference between a sustainable and unsustainable EVL. To acquire a fundamental understanding of $EVSM$, agronomic and technical factors must be integrated with economics. Production management, the complete set of physical and non-physical inputs is the primary determinant of future soil quality and hence EVL. Maximizing EVL first requires a fundamental understanding of soil quality management: What are the properties of soil quality and how are these influenced by crop production? Subsequently, production management has to be organized in such a way EVL is maximized. This study provides an overview of soil quality management and crop production management linked to economics. The framework provides a qualitative blueprint for bio-economic modeling and a basis for policies to enhance sustainable soil management.

Keywords: Soil quality, economic value of land, sustainable soil management, crop production, ecosystem services

Highlights:

- Economic conceptualisation of sustainable soil management
- Definition of Economic Value of Land (EVL) as the basis for financial returns
- EVL based on agricultural productivity and soil-based ecosystem services
- Land use activities and inputs determine current returns and future soil quality
- Management of soil quality and crop production towards maximizing long-term EVL

Visual abstract



2.2 Introduction

Soil quality is a primary determinant of crop productivity, farm resilience and the environmental quality of arable farming systems (Stevens, 2018; Karlen et al. 1997). Soil quality can be defined as: "The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al. 1997). The latter is increasingly under pressure, as a rising global population results in both an increasing demand for agricultural products (Alexandratos and Bruinsma, 2012) and decreasing availability of land because of competition for space. Managing these requirements in an unsustainable way could lead to soil degradation, e.g. erosion, loss of soil organic matter and soil compaction (Koch et al. 2013). Currently, one-third of the worldwide available agricultural soils faces degradation (FAO and ITPS, 2015).

Soil quality will become more and more important in the near future. Currently, soil degradation can be partly camouflaged with the use of inputs like fertilizers and pesticides, although at the trade-off of e.g. nutrient leaching and pesticide emission (Squire et al. 2015). As the maximum application levels of these inputs is increasingly restricted, soil degradation will become apparent. Due to climate change, the frequency and impact of extreme weather conditions is likely to increase. Therefore the capacity of soils to adapt to weather variation will become more urgent (Wall and Smit, 2005). A well-functioning soil might improve the resilience of farming systems (Ge et al. 2016; Cong et al. 2014).

Soil quality is not only of key importance to farmers who operate and often own the land, but also beyond the farm level. It is a crucial parameter when it comes to sustainable food production within agricultural value chains, or for water regulation or emission mitigation within regional ecosystems (Greiner et al. 2017; McBratney et al. 2014; Koch et al. 2013).

There is a strong call for the implementation of sustainable soil management: meeting the present needs of crop productivity and ecosystem services without compromising soil needs for future generations (adapted from Smith and Powlson, 2007). A large number of studies establish links between soil quality, agricultural production and the provisioning of ecosystem services by soils, e.g. Bünemann et al. (2018), Greiner et al. (2017), Schwilch et al. (2016) and Dominati et al. (2010). However, the relation between farm management and soil quality has received surprisingly little attention. Within farm management, achieving a sufficient yearly income and long-term continuity of the farm are the prime goals for farmers (Kay et al. 2012). Considering these goals, the implementation of sustainable soil management can be regarded as an investment. These investments may reduce short-term income of the farmer but are expected to have a positive effect on the long-term farm income, farm resilience and provision of ecosystem services. Currently, insight in the long-term effect of sustainable soil management is lacking, which hampers implementation (Brady et al. 2015). Moreover, current profit margins are on average small, leading to limited possibilities to invest in long-term prospects. Hence, we can state that implementing sustainable soil management is a socio-economic problem.

Various studies already addressed the economic aspects of soil quality. Dominati et al. (2014) and Robinson et al. (2013) proposed a framework for economic valuation of ecosystem services. However, the authors do not address how farm management influences the delivery of these ecosystem services. Stevens (2018) presented a conceptual approach towards the economics of soil health. The Stevens' optimal control model is an extension of the work of Burt (1981) and McConnel (1983) that focussed on the economically optimal level of soil quality for individual farmers. Although Stevens (2018) made a valuable contribution, the study does not provide insight in the economic consequences in case unsustainable management of soil quality is applied. Insight in the economic consequences of soil degradation is crucial to show the benefits of sustainable management. Second, Stevens (2018) assumes well-behaved, unambiguous, and quantifiable relationships between soil quality, farm management practices and crop yield. By ignoring the technical, spatial, and temporal aspects of agricultural production as for example highlighted in Dury et al. (2012), agricultural production systems are oversimplified. Stevens (2018) himself advocates future emphasis on these issues. Third, the social benefits of soil health including the relationship of such benefits with agricultural production and its economic consequences, require more attention. Studying such relationships is of pivotal importance because societal benefits and agricultural production often have conflicting expectations on soil quality.

The current study explicitly builds on Stevens (2018). We use the Economic Value of Sustainable Soil Management ($EVSM$) as a quantitative basis for the farmers' returns on investment in soil quality. Using the concept of $EVSM$, we explain the long-term economic consequences of soil quality degradation. Insight in $EVSM$ is crucial for farmers as it allows them to make financially rational decisions. For other actors around the farmer, insight in $EVSM$ can be used to create the proper financial incentives for implementation of sustainable soil management. As the management of the farmer is crucial, $EVSM$ cannot be seen in isolation of technical and agronomic knowledge on soil quality and arable production. Building further on Stevens (2018), we address the fact that agricultural systems are much more complex in practice. Building further on our concept of $EVSM$, we further elaborate the technical, spatial and temporal aspects of crop production highlighted in Dury et al. (2012). Additionally, we explain the relationships between societal benefits and agricultural production in sustainable soil management.

The aim of this chapter is to (1) define the Economic Value of Sustainable Soil Management ($EVSM$), (2) establish a framework for sustainable soil management in an arable system context and (3) integrate disciplinary knowledge of soil quality management and crop management.

The remainder of this chapter is structured as follows. Section 2.3 provides the economic conceptualization of sustainable soil management. Section 2.3 includes a framework for sustainable soil management in the context of arable farming. Section 2.4 and Section 2.5 provide technical and agronomic knowledge on soil quality and crop production respectively to implement sustainable soil management in arable farming. Both sections address knowledge gaps for implementation of sustainable soil management. The chapter ends with a Discussion, including an illustration of the framework and implications for further use.

2.3 Economic conceptualization of sustainable soil management

This section presents an economic conceptualization of sustainable soil management. Within this economic conceptualization, production management refers to the set of decisions that can be made by the farmer in an arable production system. Production management includes all physical inputs (e.g. fertilizer and plant protection products) and non-physical inputs (e.g. management choices, labor and capital). For an extensive overview of these inputs we refer to Ustaoglu et al. (2016).

Production management can be categorized in one of the following three strategies:

(1) Unsustainable production management: Production management consists of unsustainable practices causing a decline in soil quality, particularly in the mid-long run
(2) Sub-optimal production management: the soil's potential is not fully utilized. Production management can be intensified without affecting soil quality.
(3) Sustainable production management: the soil's potential is fully utilized in a sustainable way. Soil quality and subsequently farm income does not decline over time.

For a farmer as financially rational decision maker aiming at maximization of long-term income and farm continuity the key question is how to choose production management in such a way that long-term farm income is maximized in a sustainable way. This section defines the economic range for sustainable production management. The upper bound of this range is when production management becomes too intensive and subsequently soil quality starts to decline. The lower bound is the production management resulting in the minimum required farm income. In order to further define and illustrate the range for sustainable soil management we make the following assumptions:

- Farmers are the decision makers on production management. However, they operate in a context with other actors that can influence their decisions
- Farmers are the owners of the land, they want to continue their farm business in the long term, either via inheritance or takeover of the complete farm.
- Production management can consist of many options that will be elaborated in Section 2.4. For illustration purposes we assume that the whole set of production management options can be integrated into a vector production management intensity, ranging from an extensive production management to very intensive production management [1]. Defining production management as a vector allows us to illustrate the range of sustainable management. When production management is sub-optimal, more intensive production management results in a higher yield. Beyond the point where production management is sustainable, a higher production management intensity causes a decline in soil quality.
- In this illustration we consider a hypothetical farm on a given location for a long period of time. Over time, the production management of the farmer is constant, i.e. in a steady state.
- Soil quality can be divided in inherent soil quality and manageable soil quality (Dominati et al. 2010). Inherent soil quality can hardly be influenced by management, e.g. soil texture (Schwilch et al. 2016), while manageable soil quality (e.g. soil structure and soil organic matter content) responds dynamically to the applied management,. Therefore, SQ refers to the manageable part of soil quality.

Under these assumptions, production management (PM) is the primary determinant of soil quality. Hence, soil quality (SQ) can be defined as a function of the following elements:

$$SQ = f(PM, W) \tag{1}$$

Where:

- PM: Production management
- W: Weather conditions: average weather conditions during growing seasons

The two key outputs of an arable farming system are the physical crop yield Y and ecosystem services E. Ecosystem services are defined as "the benefits people obtain from ecosystems" (MEA, 2005). Contradictory to production, these ecosystem services often have the characteristics of a public good (Pascual et al. 2015). Their benefits manifest outside the farm level for the public at large. Y and E represent the total crop yield and delivery of soil-based ecosystem services from the whole arable farming system in a long-term steady state. Y and E can be defined as a function of the following elements:

$$Y = g(SQ, E, PM, W) \tag{2}$$

$$E = h(SQ, Y, PM, W) \tag{3}$$

For an overview of soil-based ecosystem services we refer to Dominati et al. (2014) and Adhikari and Hartemink (2016). For better understanding, we simplify by abstracting away from uncertainty to gain more tractability in our approach. We consider W as exogenous factor beyond control of the farmer. Assuming that in a steady state situation W is constant over time, we exclude W from Equations (1) to (3). Subsequently replacing SQ by Equation (1) in Equation (2) and (3) shows that in the long-term the output level of Y and E is dependent on PM.

$$Y = g(f(PM), E, PM) \tag{4}$$

$$E = h(f(PM), Y, PM) \tag{5}$$

Equations (4) and (5) show that the choice for PM has a direct impact on Y and E via $g(PM)$ and $h(PM)$ as well as an indirect effect via $SQ = f(PM)$. These equations show that in a long-term steady state situation PM via SQ is the primary determinant of the output level of Y and E.

[1] Due to the many different options of production management one might ask whether it is justifiable to aggregate them into one vector. However, the underlying elements such as level of fertilization or cropping plan intensity are scalable. We therefore argue that for illustration purposes this approach is justifiable.

Depicting the above graphically, Figure 2.1A shows a hypothetical response curve of the output level of Y for a chosen PM intensity by the farmer. The yield curve increases for higher PM intensity until point α. Beyond α, a higher PM intensity does not result in a higher yield. Such a situation may imply a decline in SQ, which is not yet expressed in crop yield. The decline in SQ may be camouflaged by using more inputs. Beyond point β, PM is too intensive and unsustainable: the soil's potential to generate yield is over-exploited. Subsequently, soil quality declines and yield starts to decrease. From a technical point of view, two areas can be distinguished in Figure 2.1A: Area 1 represents unsustainable soil management, Area 2 represents sub-optimal management.

Figure 2.1B introduces the hypothetical response curves for ecosystem services. As follows from Equation 4 and 5, Y and E both depend on each other and PM. E can have two types of relations with Y:

- *Competing*: E has a response curve that is opposite to the response curve of Y. Providing E_c at an optimal level requires a different level of PM than the optimum level of PM for yield. Whereas Y in Figure 2.1B is maximal at point α, E_c is maximal at (or before) point γ.
- *Mutual*: E and Y have a similar response curve (E_m). The output of Y and E_m do not go at the expense of each other.

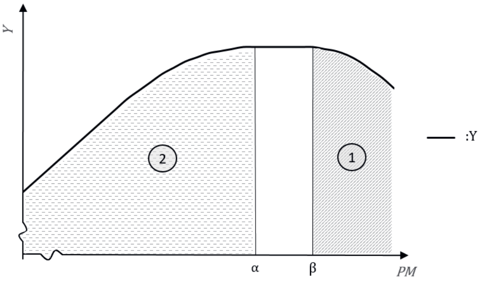


Figure 2.1A – Yield (Y) response to an increasing production management (PM) intensity in an arable production system. Area 1 represents the area with unsustainable PM. Area 2 represents the area with sub-optimal PM.

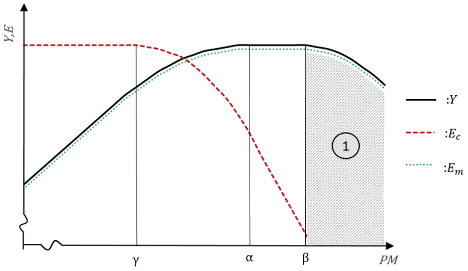


Figure 2.1B – Response of Y and ecosystem services E to an increasing PM intensity. E can be competing with Y (E_c) or mutual (E_m).

Similarly to Figure 2.1A we can define an area of unsustainable management in Figure 2.1B. However, the area for sub-optimal management cannot be clearly defined as also delivery of E plays a role. The area of sub-optimal management is defined by the minimum required level of E_c and the minimum yield required for a sufficient income. Whereas from a technical point of view we cannot yet derive an optimum level of PM, we can derive an economic optimum if we introduce prices of outputs Y and E and costs of PM. Subsequently, the total net return generated in the arable production system can be defined as the Economic Value of Land (EVL):

$$EVL = P_Y Y + P_e E - P_{PM} PM \tag{6}$$

In which:

- EVL is the total net return of a certain piece of land to the user of the land over a defined period of time.
- P_Y: Output price of Y
- P_E: Financial reward for delivery of ecosystems services e.g. a cross-compliance subsidy or payment by another actor (Powlson et al. 2011; Prager et al. 2011)
- P_{PM}: Costs of production management

Inserting Equation 4 and Equation 5 into Equation 6 shows that one can derive a steady state optimal PM and thus SQ by maximizing EVL through the choice of PM.

$$EVL = P_Y\, g(f(PM), E, PM) + P_E\, h(f(PM), Y, PM) - P_{PM} PM \tag{7}$$

Figure 2.2A builds upon Figure 2.1A by showing the EVL response for PM. In this figure, EVL is based on the revenue from Y and costs of PM and no financial reward for E.

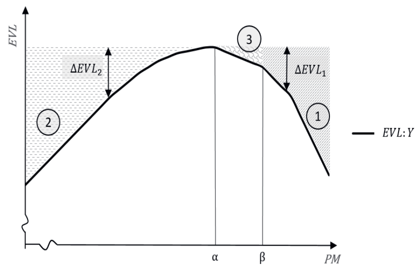


Figure 2.2A - Total returns from agricultural land (EVL) in relation to Production Management (PM) intensity. ΔEVL_1 in the area of unsustainable management 1 represents the economic loss of soil quality degradation due to too intensive production. ΔEVL_2 in the area of sub-optimal management represents the economic loss of sub-optimal PM.

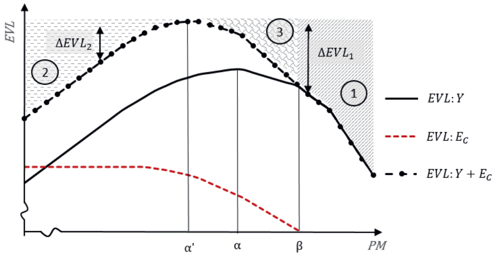


Figure 2.2B - Total return expressed as EVL for yield Y and ecosystem services E_c. Due to the return on ecosystem services $EVL{:}E_c$, the optimum level of PM moves from α to α'.

Until point α, the EVL curve in Figure 2.2A has a similar pattern as the Y curve in Figure 2.1A. Maximum yield and therefore maximum EVL is achieved[2] at point α. In area 2, there is an economic loss from sub-optimal PM. Between α and β, EVL decreases gradually. Although there is no decrease in Y yet (Figure 2.1A), the higher intensity of PM is expected to result in higher costs and therefore a decreased EVL. Area 3 can therefore also be considered as an economic loss of sub-optimal PM. Beyond point β, EVL declines due to a decrease in yield caused by unsustainable management. Hence, area 1 represents the economic loss of unsustainable management. In a situation where crop yield is the only income of the farmer, sustainable soil management is achieved at point α, resulting in $EVL{:}sustainable$. At any other point, we can define the Economic Value of Sustainable Soil Management ($EVSM$) as the difference between $EVL{:}sustainable$ and any other value of EVL. Figure 2.1A illustrates this with ΔEVL_2 in the sub-optimal area 2 and with ΔEVL_1 in the unsustainable area 1.

In addition to the returns for Y, we introduce a return for E_c in Figure 2.2B. The total EVL is the sum of both returns. Because of the substantial return on E_c, the maximum EVL is achieved at point α'. Before α', PM is sub-optimal as more returns on Y can be achieved without compromising the return on E_c. ΔEVL_2 represents the loss of $EVSM$ due to sub-optimal PM. Between point α' and β, PM is also sub-optimal. Although soil quality does not decrease yet, EVL could have been higher by choosing PM intensity α'.

Figure 2.2B shows that farmers can be stimulated by (financial) incentives to adopt a PM intensity which is beneficial for the delivery of ecosystem services. Figure 2.2B shows a rather extreme situation where as a result of a high return on E_c, the maximum EVL can be substantially increased. Given that currently yield is by far the largest source of income, a financially rational return for E_c would be at least a compensation for the EVL lost due to a reduction of Y. Note that in Figure 2.2A the magnitude as well as the shape of the curves play a pivotal role. The lower the returns on E_c the more the farmer will choose his PM to maximize Y.

[2]: Compared to Figure 2.1A, the position of α can shift to the left if costs of production management increase and subsequently marginal returns decrease.

EVL response curves for mutual ecosystems services in Figure 2.2B are omitted because they do not have an impact on the optimum level of PM. For both a situation with and without a return on delivery of ecosystem services we show the lower and upper bounds for sustainable soil management from an economic perspective. From this economic conceptualization we can draw the insights:

- Both from a technical and economic point of view it is not in the long-term interest of the farmer or other actors to go beyond a sustainable level of production management and thereby degrade soil quality.
- The lower bound of the range for sustainable soil management is defined by the reward for ecosystem services.

The economic conceptualization above highlights the crucial role of production management with regard to sustainable soil management and defines this in an economic context. For a farmer aiming at maximizing long-term EVL, the following key economic questions must be addressed to gain insight in $EVSM$:

(1) If EVL is at maximum sustainable level, how to maintain soil quality via the choice of production management so EVL stays maximal?
(2) If EVL is not maximal, how to choose production management so that EVL is maximized?
(3) If soil quality declines, how to change production management so EVL will return to its maximal level?

To acquire a fundamental understanding of $EVSM$, the agronomic factors that determine the answers to these questions should be linked with economics. The following section provides a framework for sustainable soil management on farm-level for an arable farming system. The framework connects the EVL with management of soil quality and crop production in an arable system.

2.4 Framework for sustainable soil management in arable farming

Although a farmer is the prime decision maker regarding soil management, he or she does not make decisions independently. The framework in Figure 2.3 illustrates that farmers manage EVL within a context with other actors.

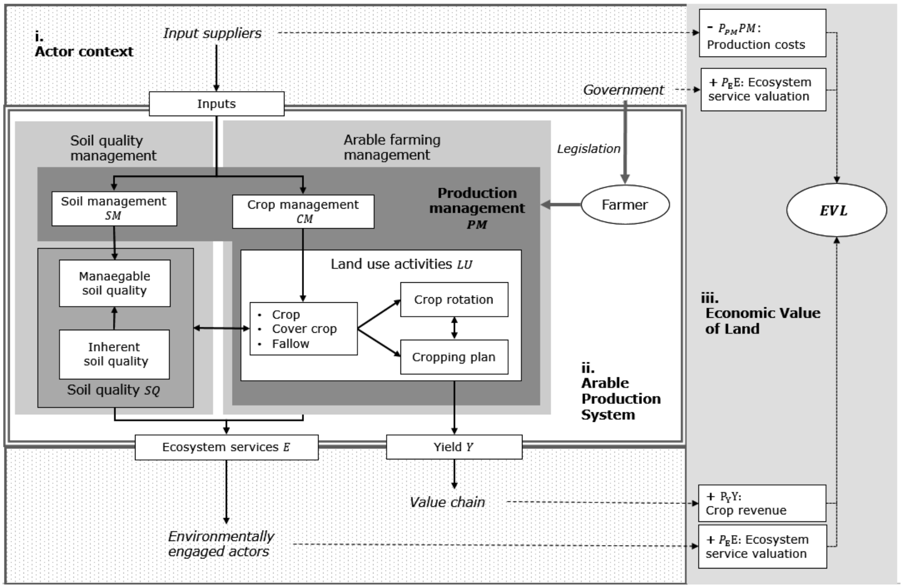


Figure 2.3 - Framework integrating the Economic Value of Land (EVL) in an arable farming system.

The key elements of the framework are (i) the context of actors around the farmer, (ii) the Arable Production System (APS) and (iii) the Economic Value of Land (EVL). Figure 2.3 shows that the EVL is determined by the following aggregated factors: (1) the production management (PM) and (2) soil quality. PM can be subdivided in soil management (SM), crop management (CM) and land use activities (LU). Disaggregation of LU_t shows that these in turn consist of the cultivation of a crop, cover crop or fallow period on a certain field at a moment in time t in a given sequence of activities (adapted from Dogliotti et al. 2004 and Van Ittersum and Rabbinge, 1997). Within LU_t, two key concepts are the crop rotation and cropping plan. Crop rotation is defined as the sequence of land use activities on a field (adapted from Castellazzi et al. 2008). The cropping plan is the acreage of crops and their spatial distribution within a particular year (Dury et al. 2012). It determines the total yield of product on the farm in a particular year within the context of soil characteristics and quality, weather conditions, varietal characteristics, input levels and occurrence of weeds, diseases and plagues.

Crop management (CM) is the set of agronomic inputs related to one particular land use activity, e.g., a fertilizer or pesticide application in a crop within a particular growing season. Soil management (SM) represents a set with soil management inputs such as drainage, terracing or field levelling. Soil management aims at altering the soil properties for the benefits of the whole set of land use activities over multiple growing seasons.

The framework addresses which elements of sustainable soil management can be controlled by the farmers. Following this framework, in-depth insight in two areas is needed: (1) Soil quality management: What are the properties of soil quality and how are these properties influenced by production management and (2) Arable farming management: How to organize production management in such a way that EVL is maximized?

2.5 Soil quality management

In Section 2.4, soil quality management was presented in an aggregated way related to EVL. However, in order to sustainably maximize EVL, a fundamental understanding of soil quality is required, providing basic insight in soil quality parameters, their interrelations and the way they are influenced by production management.

Soil quality is a complex concept containing many interrelations that cannot be simplified to a set of independent indicators. Bouma (2014) states the following aspects have to be taken into account when assessing the impact of land use on soil quality.

(1) Trade-offs between various characteristics of soil quality, i.e. optimizing the value of one soil characteristic may go at the expense of another. For example, addition of organic material with a high C/N ratio has a positive effect on the soil organic matter content but decreases mineral nitrogen content.
(2) Optimizing the value of soil quality characteristics towards production may go at the expense of the soils' capacity to deliver ecosystem services, as explained in Section 2.3.

Figure 2.4 illustrates soil quality management by explaining the relation between the production management and the main chemical, physical and biological components of soil quality.

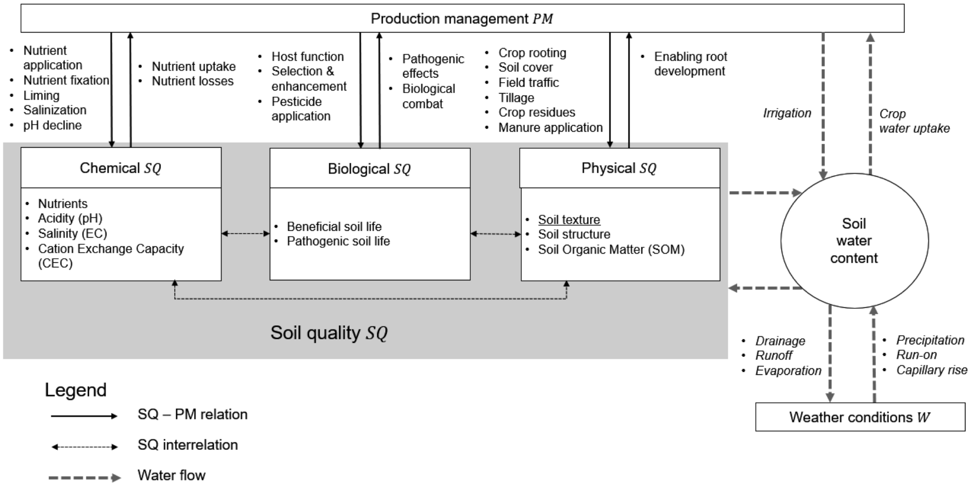


Figure 2.4 - Illustration of the various factors determining soil quality management. Underlined Soil Quality (SQ) properties are inherent and thus hardly influenced by production management.

The soil properties in Figure 2.4 can be assessed and measured (Dominati et al. 2010). The main chemical properties are the nutrient stocks, acidity, salinity and Cation Exchange Capacity (CEC). Losses occur if nutrient availability does not match with the crop demand (Janssen and de Willigen, 2006). Inputs of nutrients can either occur via application of fertilizer, manure or fixation by legumes (Schröder et al. 2004). Soil pH can decrease naturally due to precipitation or alternatively by application of acid fertilizers. Soil acidification can be prevented by using the right type of fertilizer or counteracted by applying lime (Haynes and Naidu, 1998). Soil salinization can occur via irrigation water that is too high in salt or through capillary rise from salty groundwater. The Cation Exchange Capacity is the ability of the soil to hold cations. As most nutrients are cations, the CEC is a primary determinant of the nutrient retention capacity. The CEC is influenced by the clay content, the organic matter content and the pH of the soil (Dominati et al. 2010).

Soil texture is an inherent soil property representing the proportion of sand, clay and loam particles. Soil structure is the spatial arrangement and aggregate formation of these soil particles. A good soil structure enables water and oxygen infiltration and stimulates crop rooting and nutrient uptake. Intensive rooting crops have a positive effect on soil structure (Bronick and Lal, 2005), while heavy field traffic and lack of soil cover can negatively affect soil structure (Dogliotti et al. 2003; Hamza & Anderson, 2005). Soil Organic Matter (SOM) consists of the residues of plants, animal manure and soil organisms. SOM maintains a key function within the soil: SOM has a positive effect on soil structure, water retention and nutrient availability (Franzluebbers, 2002).

Soil life can have either a beneficial or a pathogenic effect. One of the most important beneficial roles is the decomposition of plant residues and mineralisation of nutrients (Altieri and Nicholls, 2003). Another function is to act as natural enemies to combat diseases (Birkhofer et al. 2008). Soil-borne diseases are caused by fungi, bacteria, viruses and nematodes that have a pathogenic effect on plants. The choice for a particular crop, the crop variety, the rotation and the production management all affect soil life and pathogen development.

Chemical, biological and physical soil quality are interrelated. One of the most important interactions between chemical and biological properties is mineralisation and immobilisation of nutrients by the soil life. The chemical composition of the soil, i.e. the pH, acidity and nutrient stock determine the composition and activity of the soil life. An important aspect in the interaction between chemical and physical soil properties is the effect of ion types on the structure of soils. Na^+ resulting from soil salinization destroys soil structure, whereas adding Ca^{2+} by application of lime has a beneficial effect on soil structure. Soil physical properties determine the activity of soil life. Soil structure is a primary determinant for the exchange of oxygen, water and nutrients and hence for soil life as such. On the other hand, soil biota have an important role in the formation of soil structure, e.g. formation of channels by earthworms (Boyle et al. 1997).

The soil water content is defined as the water content in the layer of the soil that is accessible for crop roots. The soil water content affects the physical, biological and chemical properties. Soil water content determines for example the solubility of nutrients, structure formation and activity of soil life. Soil physical properties are the direct determinant for soil water content.

To find the maximum sustainable EVL the following knowledge gaps for soil quality can be defined, on which further research is needed for a sound quantification of $EVSM$:

(1) Soil quality cannot yet be explained as a complete set of properties that are quantitative and measurable. Attempts have been made via so-called soil quality indices that try to capture soil quality as a unidimensional index (Stevens, 2018).
(2) The interrelations and magnitude of interrelations between different soil quality parameters are unknown. One of Stevens' (2018) criticisms on soil quality indices is their tendency to oversimplify the complex interactions between the various parameters of soil quality.
(3) Measuring soil quality can be expensive. So although a certain soil quality parameter can be measured and quantified, it does not make sense from an economic point of view (Stevens, 2018).
(4) Impact of production management on soil quality is not fully understood and quantifiable. For example the effect of field traffic on soil structure is hard to quantify (Hamza & Anderson, 2005).
(5) The response curves for yield and ecosystem services to soil quality parameters are to a large extent unknown, due to (i) the large time coefficient of soils: soils only respond slowly to changes in management and environment (Van Ittersum and Rabbinge, 1997), (ii) changes in production management over time and (iii) high dependency on the context, e.g. climate and location.

From the above, it becomes clear that even detailed aspects of soil quality (e.g. SOM content) have economic relevance. Via crop residue management, application of manure and cover crops, SOM content can be influenced, which in turn has a short-term and long-term impact on soil quality. This will impact future EVL, as explained in Section 2.3. This not only applies for SOM, but for all aspects of soil quality.

2.6 Arable farming management

Figure 2.3 described the factors that determine the arable farming management in an aggregated form related to EVL. However, the latter includes several simplifications and assumptions that require further elaboration. Section 2.3 introduced crop rotation and cropping plans as the concepts that determine the spatial and temporal allocation of land use activities and production management. Temporal and spatial allocation of LU and CM are heterogenous. For example, because of changing crop demands and variation in growing seasons, sequences of land use activities vary over time. Different soil types on the farm and availability of resources such as irrigation water cause variation in space. Figure 2.5 provides an illustration of the spatial and temporal allocation of LU and CM in an arable farming system.

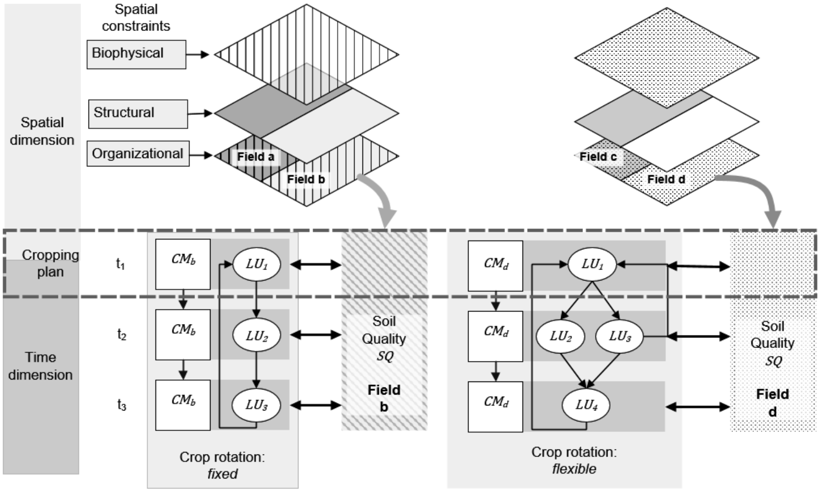


Figure 2.5 - Illustration of factors determining arable farming management. In the spatial dimension, spatial constraints determine allocation of land use activities (LU) *and crop management* (CM) *to a certain field. The time dimension represents the sequence of* LU *and* CM *over the year. Figure adapted from* Dury, (2011).

A first type of spatial constraints on land use are biophysical constraints. They represent properties of the fields that are hard to change, e.g., the soil type of a field. Structural constraints concern the resource availability e.g., access to water for irrigation. These constraints can be adapted in a long-term planning horizon (Dury, 2011). Organizational constraints can be changed within one growing season. The complete set of constraints determines the land use activities and the related production management on a field. For example, some crops will only be cultivated on a certain soil type where irrigation is available. Although the same crops can be cultivated on fields with different spatial constraints, crop management can be different. For example, potatoes on sandy soil need different nutrients or irrigation compared to potatoes on clay soils.

In Figure 2.5, the cropping plan integrates the spatial and the temporal dimension (Dury et al. 2012). The cropping plan is the combination of crops and their respective acreage on the fields b and d. The crop rotation determines the temporal dimension of crop production (Castellazzi et al. 2008). Figure 2.5 illustrates a crop rotation over three years. The crop rotation on field b is a fixed crop rotation: the rotation has a predefined duration and crop sequence. The crop rotation on field d is a flexible crop rotation, the duration and crop sequence are variable. Figure 2.5 shows that the crop management at a given moment in time is influenced by the previous crop management activities and also influences future crop management activities. Although the crop sequence on two plots with equal properties is the same, crop management does not have to be the same. For example, if on these two plots wheat is grown, selling the straw for one of the plots implies other consequences on future crop management than keeping the straw on the field and incorporating it into the soil.

The spatial and temporal planning aspects of crop production systems have been approached via cropping plan selection models (Dury et al. 2012). Although a vast body of models exists to support farmers in their short-term optimization of farm income, these models do not sufficiently address the long-term effects on soil quality. For a sound quantification of $EVSM$, the following knowledge gaps regarding modeling of arable farming systems can be defined:

(1) Take the time dimension of crop rotation into account. Many existing models optimize the cropping plan for only one year and ignore temporal effects between crops (Dogliotti et al. 2003; Klein Haneveld and Stegeman, 2005).
(2) Address spatial variability to a sufficient scale. Many existing models tend to over-simplify spatial variation in planning of land use activities (Dury et al. 2012).
(3) Approach cropping plan decisions as a dynamic concept. Many existing models assume static cropping plan decisions, made only once per year or rotation. Dury et al. (2012) argue that cropping plan decisions are a dynamic process that are subject to a considerable degree of uncertainty, resulting in a flexible crop rotation as depicted in Figure 2.5. This implies that long-term maximization of EVL calls for a dynamic model.
(4) Include soil quality and arable production as a dynamic concept. Many existing models use a target-oriented approach, i.e., the required production management is derived from a target yield level that does not respond dynamically to the environment (Van Ittersum & Rabbinge, 1997). A production function as used in crop growth models simulates crop yields based on soil quality production management and weather conditions (Jones et al. 2003; Stöckle et al. 2003). Implementing such an approach would require detailed information on soil quality and crop-soil relations.

In summary, spatial and temporal allocation of land use activities and crop management have economic relevance. A certain production management implemented by a farmer on a piece of land determines the short-term EVL on that piece of land. In the long-term, the sequence of land use determines the development of SQ and subsequently EVL. Optimization of soil quality therefore cannot be seen in isolation of important concepts like cropping plans and crop rotation.

2.7 Discussion

This chapter introduced the concept of the Economic Value of Land (EVL) and derived from this the Economic Value of Sustainable Soil Management ($EVSM$), and presented its interdisciplinary and conceptual-theoretical foundations. These included the relationships between economic concepts and fundamentals of soil quality and arable farming.

2.7.1 Key findings

In this study, we defined the $EVSM$ as the difference in financial returns between sustainable and unsustainable soil management, where financial returns are calculated based on the Economic Value of Land (EVL): the total returns of a piece of land over a given time period. A positive difference indicates that it is in the long-term interest of the farmer to improve soil quality. Besides yield and the costs to generate that yield, this study also addresses the demands of society for ecosystem services as part of the EVL. However, the optimum soil quality for crop yield is not always the same as the optimum for these ecosystem services. To create an incentive for farmers, a financial compensation of at least the value of lost production has to be considered in order to maintain the EVL.

The choice for land use activities (i.e. crops) and the related set of inputs in a particular year are made by the farmer and determine the EVL in that year. Over time, land use activities and inputs are the primary determinants of future soil quality. Therefore, the key economic question is how to reach or maintain a sustainable level of EVL by managing the land use activities and related inputs. This study shows that answering this question requires a fundamental understanding of soil quality parameters and the relation of these parameters with land use activities and their related inputs. The follow-up question is how to organize the land use activities and inputs in space and over time to reach maximum EVL in a sustainable way.

2.7.2 Reflection on the framework

In order to increase the credibility of the framework, we assess the potential gains as well as shortcomings and remaining challenges of the framework based on three criteria. The first criterion is the *comprehensiveness* of the framework to reach the research objective (Van Oudenhoven et al. 2012). The second criterion is the *correctness* i.e. the extent to which the framework is a valid and correct representation of reality (Manson, 2003). The last criterion entails the *practical applicability*, i.e. the extent to which the presented framework can be applied in a broad range of land use systems (Van Oudenhoven et al. 2012).

For the comprehensiveness of this study, we used a broad definition of sustainable soil management that not only focuses on production but also on soil-based ecosystem services. Such an approach is a prerequisite for sustainable development as an exclusive focus on agricultural production may go at the expense of the delivery of these ecosystem services (Bouma, 2014). In this study, we assumed farmers to be the landowner, but we excluded the market value of land as part of the EVL. If a farmer wants to continue farming, sale of the land is not an option, hence the market value can be excluded[3]. However, if the farmer wants to stop farming, selling the land for agricultural or non-agricultural purposes becomes an option. Market value can also have a disturbing effect if it becomes disproportionally large compared to the returns from production. To enhance further comprehensiveness of the framework, inclusion of the market value might be a valuable approach.

In many situations farmers are not the owners of the land. Nevertheless, the framework remains applicable. In case of a long-term lease contract, the goals of farmers and land owners align, as both of them aim for maximization of long-term EVL. This is underpinned by the study of Deaton et al. (2018).On the contrary, short-term lease contracts impose a serious risk for soil degradation because of over-exploitation in the short-term and lack of long-term investments in soil quality. If the benefits of an investment in soil quality manifest outside the period of land use, there is no incentive for the farmer to invest in soil quality. Close monitoring of soil quality by e.g. a soil quality index and creating financial incentives for sustainable soil management, e.g. a reduced rent, are possible solutions for land owners. More suggestions to implement sustainable soil management in a situation of split ownership and usage of land can be found in Deaton et al. (2018). This study presented an interdisciplinary approach, which is a prerequisite for a comprehensive framework. According to Bouma (2010), only an integrated approach, combining physical, chemical, biological and space–time techniques, can fully demonstrate soil science’s potential to solve sustainability issues.

Concerning the correctness of the framework, an assumption within this study is farmers’ incentives are purely financial. However, farmers can have other incentives than financial ones, e.g. lifestyle and personal considerations (Austin et al. 1998). Although income maximization might not be the prime goal, a sufficient level of income is a basic requirement for farm survival. Hence, we can state that economic aspects of sustainable soil management remain important even if income maximization is not the primary incentive. This framework states that soil-based ecosystem services which go at the expense of farmers’ private benefits require a compensation. However, several authors have questioned the role of financial compensation and have argued for voluntary commitment instead (Juerges and Hansjürgens, 2018; Pascual et al. 2015; Verspecht et al. 2011). Our framework shows that delivery of ecosystem services does not always go hand in hand with farmers EVL. In such cases, it is up to the farmer to decide whether he or she is satisfied with a reduced EVL or that compensation by other actors is needed. The first case indicated a voluntary commitment to ecosystem services, the latter the need for financial involvement of the actors that benefit from the ecosystem services. As a sufficient EVL is a prerequisite for farm survival, we argue that a financial reward for ecosystems can be an integrated part of sustainable development. In Section 2.3, we assume the price of outputs and the costs of inputs as exogenous variables. However, these variables can to a certain extent be controlled by the decision maker. Crop prices, for example, can partly be controlled via sale contracts. This implies that beyond the choice for land use activities and the related inputs, farmers can maximize EVL based on additional elements.

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[3]: Sale of the land and continue farming is an option when a sell-and-lease-back construction applies.

The practical implementation of $EVSM$ calls for a few important reflections. This framework demonstrates the essential role of $EVSM$ to support soil quality. Moreover it presents an outline on how to calculate the $EVSM$: the difference in returns from a maximum sustainable long-term EVL and the current level of EVL. Whereas the latter can be easily quantified, the maximum sustainable long-term EVL is not yet quantifiable. Despite this shortcoming, the current set-up allows to judge options for sustainable soil management based on their expected contribution to future EVL. A logical next step is to define the maximum sustainable long-term EVL based on the knowledge gaps concerning soil quality management and arable farming management. Fixing these knowledge gaps would further enhance the use of $EVSM$. A valuable approach would be to link the concept of $EVSM$ to the concepts of production ecology as described by Van Ittersum and Rabbinge (1997). Our study shows that the concept of EVL and $EVSM$ is applicable for various scenarios. A simple scenario involves a farmer maximizing EVL for his own long-term benefits. In such a scenario, soil sampling, monitoring schemes for soil quality and decision support systems are useful means of support for the farmer. A more complex scenario involves both farmers and environmentally engaged actors who benefit from soil-based ecosystem services. Such a scenario requires monitoring of these ecosystems services, as well as establishing a financial reward.

2.7.3 Conclusions

This chapter introduces sustainable soil management as a socio-economic problem: establishing long-term sustainable soil management at a minimized loss of income. We introduced the Economic Value of Sustainable Soil Management ($EVSM$) as a foundation for economic based decision making on soil quality. The land use activities, i.e. crops, cover crops or fallow periods and related physical and non-physical input are the primary determinants of soil quality and hence $EVSM$. The complex nature of soil quality and many interactions with farm management highlight the need for decision-support via bio-economic farm models (Robinson et al. 2013). This study provides a qualitative blueprint for such a model. A farmer is the prime decision maker in a context with other actors who can have competing requirements on soil quality. This framework illustrates how these competing requirements interact with the farmer’s incentives. Results from this study can therefore be used as a basis for the development of policy and business models towards sustainable soil management.

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3

Actor analysis for sustainable soil management – A case study from the Netherlands

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3.1 Abstract

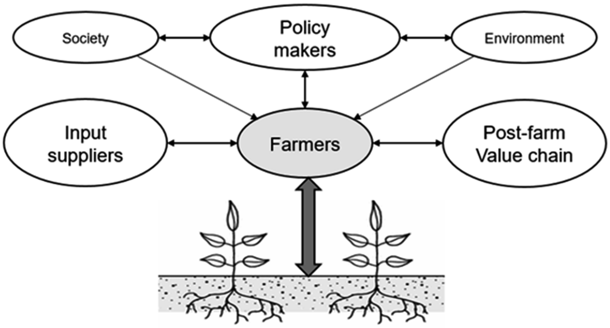
Soil quality is an important determinant of the productivity, environmental quality and resilience of agricultural ecosystems. In addition to the farmer, there are other actors who may have different interests in soil quality, hampering the implementation of sustainable soil management. To date, these actors have received surprisingly little attention. This study presents an inventory of actors involved in sustainable soil management, including farmers, but also value chain participants (e.g. input suppliers and processors), environmentally engaged actors and policy makers. We applied Analytical Hierarchy Process (AHP) to elicit actors' priorities for soil sustainability criteria. AHP is a method of multi-criteria analysis that uses pairwise comparisons to assess the relative importance of criteria. Additionally, we differentiated actors based on their involvement and perceived ability to influence decision-making. Based on the results of a survey, actors were placed in a power-interest grid. In this grid, the self-perceived power and interest of actors was differentiated from their power and interest as perceived by other actors. The main findings were that a complex and heterogenous network of actors exists around the farmer. Within this network, farmers and related value chain participants showed a priority for economic soil sustainability criteria. Environmentally engaged actors were confirmed to have a clear priority for environmental criteria. The power-interest grids underscored the prime role of farmers and the relatively high power of value chain participants. The self-assessment of power-interest compared to assessment by others revealed noticeable differences, especially for NGOs and environmentally engaged actors. This study provides an overview of which actors to involve in decision-making on sustainable soil management, which is illustrated for the EU mission "Soil Health and Food".

Keywords: Soil quality, sustainable soil management, actor analysis, Analytical Hierarchy Process (AHP), power-interest mapping

Highlights:

- We made an inventory of 30 actors in sustainable soil management in the Netherlands
- Farmers show priority for economic criteria of sustainable soil management
- Value chain actors have high power and interest in sustainable soil management
- Power-interest self-assessment of actors compared to assessment by other actors
- We provide insights for quantitative research and policy making

Visual abstract



3.2 Introduction

A rising global population results in an increased demand for agricultural products (Alexandratos and Bruinsma, 2012). At the same time, competition for space due to e.g. urbanization and development of industrial areas has led to a decreased availability of agricultural land (Amundson et al. 2015). Soil quality is a key factor in agricultural production, as it determines the crop productivity, farm resilience and environmental quality of agricultural ecosystems (Stevens, 2018; Karlen et al. 1997). Unsustainable soil management can lead to soil degradation (Koch et al. 2013), including erosion, loss of soil organic matter and soil compaction. One-third of the worldwide available agricultural land is already moderately to highly degraded (FAO and ITPS, 2015). Moreover, the soil's capacity to deal with extreme weather conditions like droughts is getting increasingly important (Wall and Smit, 2005), and therefore, preserving or improving soil quality is an increasingly pressing issue.

Soil quality is of pivotal importance to farmers since they operate and often own the land. Farmers must make a sufficient economic return on the farm, whilst also meeting environmental and societal demands. However, beyond farmers, soil quality affects other actors as well. An actor is defined as an individual, group or organisation who takes action in the view of a problem situation (Koppenjan & Klijn, 2004). The literature provides a vast but disparate overview on definitions of stakeholders and actors. Although the terms "actor" and "stakeholder" are often used interchangeably, we prefer to use "actor". In our vision, "actor" is a more suitable term for those institutions that do not have a clear stake but still play an important role in the problem or situation, e.g. governments.

Farms are at the beginning of a value chain, hence a decline in soil quality (e.g. via crop yield) has an impact on the following actors in this value chain. Agricultural ecosystems are part of regional ecosystems. A decline in soil quality influences actors that depend on these ecosystems. An example is drinking water companies that face pollution of groundwater with nitrate due to an insufficient nutrient retention capacity. Because actors have different interests in soil quality, they might have different priorities on how to sustainably manage soil. Bouma & McBratney (2013) define soil quality as a "wicked" environmental problem: many actors are involved, each with different opinions and interests. Wicked problems are hard to solve, as they require a set of options in which the expectations of all actors involved need to be balanced.

Previous research underscores the need to involve actors beyond famers in sustainable soil management (Bünemann et al. 2018; Bouma & Montanarella, 2016; Bouma, 2014). For instance, Butler et al. (2013) provide an overview of actors involved in land use and water quality management in the Great Barrier Reef in Australia. O'Sullivan et al. (2018) present a framework to bridge the gap between science, stakeholders and policy. However, surprisingly little attention has been paid to a structured inventory of actors involved in soil quality from an economic, environmental and social perspective. Although the above-mentioned studies identify a broad range of actors, they do not explicitly address their priorities in sustainable soil management. Not all actors have the same priorities and therefore involved actors do not always merit equal levels of consideration (Freeman, 2010; Cohen, 1996). Examples of studies identifying actors' priorities are Petrini et al. (2016) and Duke and Aull-Hyde (2002). Identifying an actors' priority does not inform us on the importance we should attribute to that actors' priority as not all actors have equal power to influence decisions and equal active involvement in the problem (Cohen, 1996). For example, a non-governmental organization (NGO) can have a clear priority on nature conservation and have a high degree of interest. However, the NGO lacks direct power to influence decisions. Therefore, the actors' degree of interest and power to influence decisions also have to be taken into account (Raakjær Nielsen & Mathiesen, 2006; Honert, 2001). To the best of our knowledge, an integrated actor analysis consisting of a comprehensive actor inventory, assessment of actors' priorities and the degree of power and interest of involved actors has not been applied to sustainable soil management.

The aim of this study is to provide a comprehensive analysis of the actors involved in sustainable soil management in the Netherlands. To achieve this aim, we defined the following research questions:

(1) Who are the actors in sustainable soil management in the Netherlands, what are their roles and their underlying relationships?

(2) What are the priorities of these actors regarding sustainable soil management?

(3) What is the power of actors to influence decisions and their degree of interest in sustainable soil management?

(4) How can this study contribute to implementation of sustainable soil management?

We answer research question 1 with an actor inventory based on literature and expert reflections. We use a survey spread among all defined actor groups to elicit actors' priorities for soil sustainability criteria. The survey is also used to determine the degree of power and interest of the actors involved. Actors' power and interest are assessed based on (a) their self-assessment and (b) assessment by others. The fourth research question is answered using an illustration on how the results of our study can be used for the recent EU mission "Soil Health and Food" (European Commission, 2020).

We use the Netherlands as a case study. High product demands and fierce competition for space by e.g. urbanization and recreation generate land scarcity (CBS, 2016). Agricultural ecosystems, natural ecosystems and rural livelihoods are in close interaction with each other, which leads to high societal and environmental demands on famers (Schulte et al. 2019). We focus on the actors involved in soil quality on arable and dairy farms in the Netherlands as they are the main land users (CBS, 2019).

3.3 Methods

3.3.1 Actor inventory

In this study, we conceptualize actors using network theory (Koppenjan and Klijn, 2004). A key characteristic of this theory is the presence of powerful central actors, on which the other actors in the network depend for communication (Rowley, 1997). Arable and dairy farmers are the central actors in sustainable soil management because they manage the land, often own it, and have a prime interest in preserving soil quality as the basis for their current and future income.

We used a stepwise approach adapted from Chapter 2 in Haan & Heer (2012) and Section 7.3 in Koppenjan & Klijn (2004) to create an initial inventory of actors. First, we made a primary selection of actors based on literature and existing projects on soil quality. As a second step, we described the role of each actor. In the third step we made groups of actors based on their role, e.g. suppliers of seeds, fertilizer and pesticides were all grouped as "input suppliers". The fourth step was to validate the selection of actors, the role of these actors and their grouping in an iterative process with eight experts chosen from our network. The experts had diverse backgrounds in the field of economics, soil science, agronomy, engineering and environment. In the final step we selected the actors based on the expert validations. We included all actors mentioned by more than one expert.

We used relationships derived from the actors' role and group to structure the actor inventory. We focussed on the direct relationships of the central actor with other actors. Farmers as central actors can have three different types of relation with other actors (adapted from Rowley, 1997). (1) A finance-based and formal relationship based on transfer of products, services or external effects of production, (2) a formal relationship based on a hierarchical position, e.g. through legislation or product requirements and (3) an informal influence e.g. via societal pressure or lobbying. In addition, we distinguish primary and secondary actors. Primary actors have financial transactions with the central actor and can have formal requirements. Such actors typically are investors, customers and suppliers, as well as public actors whose regulations must be obeyed (Jawahar and McLaughlin, 2001). Secondary actors lack these formal relationships but still have enough influence to merit consideration. If their expectations are violated, they will be able to influence primary actors (Garvare and Johansson, 2010). Typical examples of secondary actors are NGOs and knowledge institutions (Garvare and Johansson, 2010).

3.3.2 Actors' priorities

We used Analytical Hierarchy Process (AHP) developed by Saaty (1980) to elicit actors' priorities. AHP is a method of multi-criteria analysis that uses pairwise comparisons between criteria to assess the relative importance of each criterion (Saaty, 1980). AHP is a proven and frequently applied method for multi-criteria analysis and the study of actors involvement in natural resource management problems (Cegan et al. 2017; Petrini et al. 2016; Segura et al. 2014; Kukrety et al. 2013; Duke & Aull-Hyde 2002). Moreover, AHP is a non-statistical method which makes it especially useful for this study, as our focus is on a broad inclusion of actors rather than on representativeness.

AHP requires the set-up of a hierarchical goal tree (Gallego et al. 2019). Figure 3.1 presents the AHP goal tree for this study. The first level refers to the overall goal, sustainable soil management in the Netherlands. The second level represents the criteria that should be considered to achieve the overall goal. These criteria are the three pillars of sustainability: environmental, social and economic factors (Ren et al. 2016). This division is common in the application of AHP in natural resources management challenges (Petrini et al. 2016, Kukrety et al. 2013).

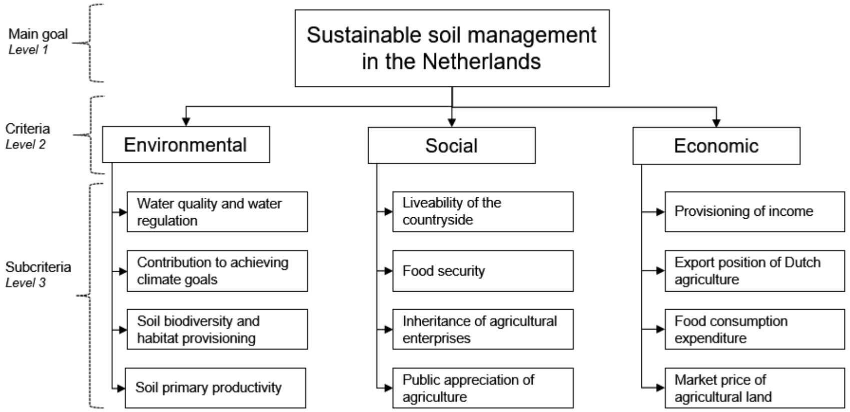


Figure 3.1 – Hierarchical goal tree of criteria for sustainable soil management in the Netherlands.

Choosing appropriate criteria that fit the context and reflect the concerns of the actors involved is one of the main challenges in multi-criteria decision making studies (Petrini et al. 2016; Garfì & Ferrer-Martí, 2011). Therefore, we defined subcriteria in an iterative procedure based on Gamper & Turcanu (2007) and Koppenjan & Klijn (2004). First, we made a pre-selection of subcriteria based on literature and the role of the actors involved (Petrini et al. 2016; Schulte et al. 2014; Kukrety et al. 2013; Duke & Aull-Hyde 2002). Secondly, the criteria were validated and revised by the eight experts that also validated the actor inventory. In the last step we defined four subcriteria for each of the criteria based on the consensus among the experts. Table 3.1 provides a detailed definition of the subcriteria.

Table 3.2 – Definition of subcriteria for sustainable soil management in the Netherlands.

Subcriterion	Description
Water quality and water regulation	The function of the soil in maintaining a good quality of surface water and ground water and the role of the soil in protection against flooding and drought
Contribution to achieving climate goals	Restriction of greenhouse gas emission (CO_2, N_2O, CH_4) and the ability of the soil to sequester CO_2
Soil biodiversity and habitat provisioning	Diversity and presence of soil life and the role of the soil in the provisioning of a habitat for soil life
Soil primary productivity	The capacity of the soil to produce biomass for the use of food, fuel and fiber
Liveability of the countryside	Attractiveness of the landscape and surroundings in rural areas, for the purposes of living, work and recreation
Food security	Sufficient, safe, nutritious and affordable food
Inheritance of agricultural enterprises	Inheritance of agricultural enterprises to the next generation
Public appreciation of agriculture	Appreciation of society for the agricultural sector
Provisioning of income	The ability to gain sufficient income via wage, profit, rent or interest in the business an actor is working in
Export position Dutch agriculture	Value and position of the Dutch agriculture on international scale
Food consumption expenditure	Total expenditures by households on food
Market price of agricultural land	Market price of land for agricultural production

In the survey, respondents first made pairwise comparisons of all environmental subcriteria, which entails six comparisons. In a similar way, respondents made pairwise comparisons for the social and economic subcriteria. Finally, the respondents had to make pairwise comparisons of the criteria environmental, social and economic. In all pairwise comparisons the respondent ranked the importance using the AHP rating scheme provided in Table 3.2. In total, respondents made 21 pairwise comparisons: 3 for the criteria and 18 for the subcriteria.

Table 3.3 – AHP rating scheme as provided to the respondents in this study, based on Petrini et al. (2016)

Rating	Importance of criterion A over criterion B
1	Equally important
3	Slightly more important
5	Moderately more important
7	Strongly more important
9	Highest degree of importance

After the responses were collected, we calculated the actor priorities. Therefore we aggregated the pairwise comparisons of the individual respondents using the geometric mean (Aczél & Saaty, 1983). The result is the pairwise comparison (PC) matrix. From the PC matrix, priorities were calculated based on the geometric mean method (Dong et al. 2010; Saaty, 1990). The overall priority weights were calculated for the subcriteria by multiplying the weight of each subcriterion with the weight of the corresponding criterion. The overall priority weights of all subcriteria sum up to 1 and represent the priority of an actor group towards each subcriterion.

AHP assumes that respondents are consistent in their assessment. However, complete consistency in the pairwise comparisons is rare (Saaty 1980). The consistency ratio (CR) in the aggregated PC matrices of every actor group was calculated according to the maximum eigenvalue method of Saaty (1980). Saaty (1980) considers values of CR <0.1 as acceptable. We chose a CR threshold of 0.3 because the aim of this study was to have a first impression of different priorities among actors, which allows a higher degree of inconsistency. For the sake of inclusiveness, the responses of actor groups that violated the CR threshold were also included in the results. These groups were indicated with an asterisk in Table 3.4, the actors' priority table.

3.3.3 Actors' power-interest

We used power-interest grids, two-dimensional grids with the relative interest and power of actors (Bryson, 2004). We used the following definitions of power and interest in the survey:

Power: A relationship in which actor A can get another actor B to do something they otherwise would not have done (Mitchell et al. 1997). This can occur through various mechanisms such as legislation, financial incentives and social pressure.
Interest: The degree to which actors are concerned about the problem and their subsequent active or passive involvement.

In the survey respondents were asked to assess power and interest on a scale with integer values ranging from 0 to 10. First, respondents were asked to assess their own power and interest in sustainable soil management on arable and dairy farms. Secondly, respondents were asked to assess the power and interest for all other actors of the actor inventory. This procedure yielded two datasets: one dataset with the position of every actor according to their own assessment and one dataset with the position based on the assessment made by other actors.

We made power-interest grids that presented the position of the actors based on their own assessment and the assessment by others. We placed every actor in the grid based on the median of the responses for that actor. For all actor groups with more than eight respondents, a Mann-Whitney test was carried out to check whether the self-assessment of power and interest differed significantly from the power and interest as assessed by others.

3.3.4 Survey design

We developed an online survey using Qualtrics[1]. Prior to its distribution, we tested the quality of the survey through cognitive interviews with five potential respondents in different actor groups. A cognitive interview is performed to test whether potential respondents have the right interpretation of the questions asked in the survey. The survey consisted of two parts. Part A was used to elicit actors' priorities as described in Section 3.3. Part B was used for actors' power-interest. Respondents were asked to fill in both parts.

The inventory consists of a large spectrum of actors. Some include thousands of individuals (i.e. farmers), whereas others include only a few (e.g. only handful leading retailers in the Netherlands). Hence, the actor inventory is very heterogeneous, which impeded representative sampling. Nevertheless, inclusion of at least one individual of all actor groups would allow a first inventory of possible differences between groups. Therefore, emphasis was placed on a broad inclusion rather than on representativeness (Lamarque et al. 2011). For the actors including arable farmers, dairy farmers, urban residents and rural residents we aimed at a minimum of ten respondents. For all other actors, our aim was to have at least one respondent. In case we were able to retrieve more responses, a larger number was included as this adds to the representability. We used a combination of judgmental and snowball sampling to send the survey to representatives of the different actor groups. The survey was spread within our network and sent to professional organisations of the different actor groups. The survey was sent out between September 2019 and December 2019.

3.4 Results

3.4.1 Actor inventory

The actor inventory (Figure 3.2 & Table 3.3) is structured around the value chain, with the farmer as the central actor. "Land & capital providers" provide land or a loan to farmers. The long-term relationship and special status of land enable "Land & capital providers" to have formal requirements on the land use by farmers, indicated by the dashed line in Figure 3.2. "Service providers" and "Input suppliers" provide physical or non-physical inputs to the farmer. The farmer decides which inputs to use and hence has formal influence. After harvest, most agricultural products enter a post-farm value chain, which commonly consists of subsequent stages before end products are consumed. "Post-farm value chain actors" can have formal influence on the farmer, e.g. by setting production standards.

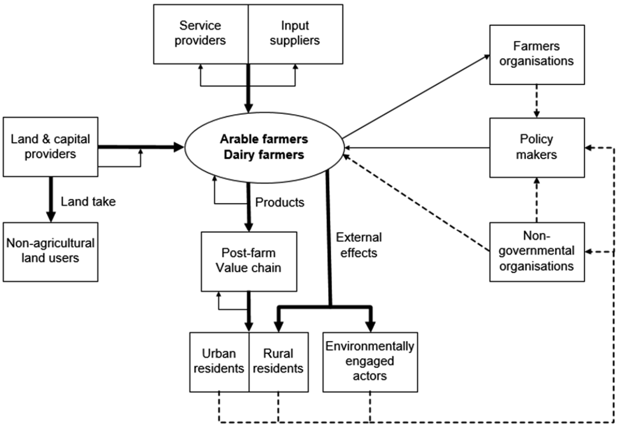


Figure 3.2 – Inventory of actor groups involved in sustainable soil management in agricultural ecosystems in the Netherlands. Bold lines represent a finance-based formal transfer of goods, services or external effects. Normal size solid lines represent formal influence between actors. These arrows branch off from thicker arrows if they represent a formal influence in return for a flow of goods, services or capital. Dashed lines represent informal influence between actors.

"Environmentally engaged actors" are influenced by external effects of production, e.g. a drinking water company is influenced by nutrient leaching. These actors often lack formal relationships with farmers. In order to meet their demands on the occurrence of externalities, they seek influence via policy makers or representative groups e.g. "Non-governmental organisations" (Hoffman, 2001; Carroll & Buchholtz, 1996). "Urban residents" and "Rural residents" are both consumers of agricultural products. "Rural residents" are directly influenced by external effects of production. As they have limited power on their own, these actors seek to influence via e.g. "NGOs" and "Policy makers". "Policy makers" issue and maintain regulations. These translate into formal requirements for farmers and other actors. As one individual farmer has limited influence on policy making, farmers join into "Farmers' organisations" to increase power. Farmers have formal relationships with "Farmers' organisations" via memberships.

Table 3.3 – Description of actors, actor roles and actor classification types involved in sustainable soil management in the Netherlands. Reference numbers list the following citations: Reyers et al. (2009)[1], Butler et al. (2013)[2], Bünemann et al. (2018)[3], Calker et al. (2005)[4], O' Sullivan et al. (2018)[5], Barrios et al. (2006)[6], Bouma & Montanarella, (2016)[7], (Schulte et al. 2015)[8].

Actor (group)	Acronym	Actor role	Actor type	Reference
Arable farmers	AF	Use agricultural land with the primary goal of crop production	Central actor	2,3,5,6,7
Dairy farmers	DF	Use agricultural land with the primary goal of feed production for dairy cows	Central actor	2,3,5,6
Land & capital providers				
Financial institutions	FI	Provide loans to farmers to finance purchase and possession of land	Primary	3
Land owners	LO	Own agricultural land, but are not the actual users, lease land to farmers	Primary	1,8
Input suppliers				
Crop breeders	CB	Breed and distribute plant reproductive material to arable and dairy farmers	Primary	
Crop input suppliers	CIS	Supply crop inputs, e.g. crop protection agents, fertilizers and compost to farmers	Primary	
Technology suppliers	TS	Produce and distribute mechanisation and installations to farmers and contractors	Primary	
Feed suppliers	FS	Supply and or produce concentrates and by-products (e.g. beet pulp) to dairy farmers	Secondary	
Intensive livestock farmers	IF	Own limited or no own land and have to dispose manure, mainly to arable farmer	Secondary	
Service providers				2
Advisors	AD	Advice farmers and other actors on soil management	Secondary	3,5,6
Soil sensing providers	SSP	Offer monitoring of soil properties as a service to farmers and other actors	Secondary	
Contractors	CT	Carry out field operations commissioned by farmers, e.g. sugar beet harvest	Secondary	
Crop insurance providers	CI	Offer farmers insurance against uncertain events, e.g. extreme weather	Secondary	3
Real estate & land agents	RE	Moderate in the trade and use of agricultural land	Secondary	
Post-farm value chain				
Agricultural purchasers	AP	Purchase and process agricultural products from farmers to ready-to-use products	Primary	2,3,4,5,8
Distributors & retail	DR	Distribution of ready-to-use products within distribution network or to consumer	Primary	8
Certification bodies	CEB	Certification of product stream according to a common standard	Secondary	
Policy makers				7
Regional government	RG	Develop land management policy on regional level (e.g. at municipality or province level)	Primary	1,8
National government	NG	Develop land management policy on national level, implemented via various ministries	Primary	1,5,8
European Union	EU	Develop policy on land management via Common Agricultural Policy (CAP) and other directives	Primary	5,8
Representative groups				
Famers organisations	FO	Represent farmers' interest, mainly in the field of policy making	Primary	3,4
Agricultural communities	AC	Regional cluster of farmers around certain theme, e.g. nature conservation	Primary	
Non-governmental organisations	NGO	Represent societal interest around a certain theme on behalf of a group of citizens	Secondary	2,5,6,7
Society				
Urban residents	UR	Citizens that do not live in the direct neighbourhood of agricultural productions systems	Secondary	2
Rural residents	RR	Citizens that live in rural areas and are directly influenced by agricultural production	Secondary	2,3
Environmentally engaged actors				
Water users	WU	Source water in the environment of agro-ecosystems for non-agricultural purposes	Secondary	
Water boards	WB	Regional governmental body concerned with management of water streams and water quality	Secondary	3
Nature managers	NM	Manage natural areas in close neighbourhood of agricultural ecosystems	Secondary	3
Other				
Non-agricultural land-users	NAL	Withdraw land from farmers to use it for other purposes (e.g. urbanization)	Secondary	
Knowledge institutions	KI	Conduct research and or provide education concerning soil management	Secondary	1,3,5,6,7

3.4.2 Actors’ priorities

Based on the survey, we were able to retrieve 139 valid responses for the actors’ priorities. The central actors (arable and dairy farmers) showed a clear priority for ‘farm income’ and other economic subcriteria in Figure 3.2.

Except for “Feed suppliers (FS)”, “Soil sampling providers (SSP)” and “Real estate & land agents (RE)” all input suppliers and service providers had ‘income’ as their highest priority, although their priority for income was lower compared to farmers. Although “Feed suppliers (FS)” had the highest priority for the social criterion “farm inheritance”, they also assessed high priorities to economic subcriteria. “Soil sampling providers (SSP)” and “Real estate & land agents (RE)” assessed high priorities to environmental subcriteria. In the post-farm value chain, “Agricultural purchasers (AP)” had a strong priority for economic criteria, especially for the subcriterion ‘income’. “Distributors and retail (DR)” showed a deviating priority: they were the only actor to show the highest priority for the criterion ‘social’.

Although ‘economics’ was by far the most preferred criterion in the value chain, “Water users (WU)”, “Water boards (WB)”,” Nature managers (NM)”, “NGOs” and “Regional governments (RG)” preferred the ‘environmental’ criterion. Within the environmental criterion, “Water users (WU)” and “Water boards (WB)” had the highest priority for the subcriterion “water quality”, which can be explained by their actor role. “Nature managers (NM)”, “NGOs” and “Regional governments (RG)” had the highest priority for environmental subcriterion “soil biodiversity”. Despite its dominant position on the international agenda, the environmental criterion “GHG goals” is only ranked as second highest priority by the actors “Financial institutions (FI)”, “NGOs” and “Water boards (WB)”.

Table 3.4 – Actors' priorities for consolidated subcriteria of sustainable soil management in the Netherlands. GHG goals refers to Greenhouse Gas Goals. Priorities are elicited using Analytical Hierarchy Process (AHP)[2].

Actor group	*Farmers*		*LC providers*		*Input suppliers*					*Service providers*				*Value chain*		*Gov.*	*Represent.*		*Society*		*Environmental*			*Other*
	AF	DF	FI	LO*	CB	CIS	TS	FS*	IF	AD	SSP	CT	RE	AP	DR*	RG*	FO	NGO*	UR*	RR	WU	WB	NM*	KI
Environmental																								
Water quality	0.04	0.05	0.06	0.02		0.07	0.03	0.02		0.04	0.07	0.06	0.12	0.05	0.06	0.09	0.08	0.12	**0.12**	0.10	**0.54**	___		**0.14**
GHG goals	0.01	___	**0.16**	0.02	0.05	0.01		0.03	0.01	___		0.02		0.03	0.02	0.16	0.04	**0.17**	0.08	0.04		**0.13**	0.05	0.06
Soil biodiversity	0.05	0.05	**0.21**	0.05	0.07	0.03	0.03	0.02		0.04	**0.21**	0.07	0.09	0.05	0.04	**0.17**		**0.32**	0.11	0.08	**0.11**	0.09	**0.30**	0.12
Primary productivity	0.10	0.10	0.13	0.09	**0.16**	0.11	0.11	0.07	0.11	0.10	**0.40**		**0.21**		0.08	0.07	0.11	0.10	0.10	**0.10**	0.03		0.10	0.12
Social																								
Liveability countryside	0.03	0.03	0.02		0.02		0.03		0.02	0.04	0.01		0.03	0.02		0.04	0.06	0.02	0.03		0.03	0.03	0.08	0.04
	0.03	0.03	0.09	0.11	0.04	0.06	0.06	0.08	0.03	0.07	0.03	0.05	**0.12**	0.04	**0.30**	0.06	0.06	0.06	0.05	0.07	0.03	0.03	0.04	0.07
Inheritance	0.04	0.05	0.08	**0.08**	0.03	0.13	0.05	**0.20**	0.05	0.06	0.05	0.07	0.08	0.04	0.05	0.06	0.04		0.06	0.09	0.03	0.03	0.02	0.08
Public appreciation	0.06	0.06	0.07	0.08	0.04	0.02	0.08	0.11	0.06	0.05	0.02	0.09	0.08	0.04	**0.26**	0.05	0.04	0.03	0.05	0.08	0.03	0.02	0.01	
Economic																								
Income	**0.36**	___	0.06	0.12	**0.22**	___	___		**0.31**	___	0.02	**0.25**	0.11	**0.29**	0.06	**0.16**	**0.23**	0.05	**0.16**	___	0.03	0.04	0.04	**0.17**
Export	**0.10**	**0.11**	0.04	**0.16**	0.13	0.05	0.09	0.08	0.09	0.12	0.02	0.08	0.06	0.12	0.01	___		0.01		0.07	0.03	0.02		0.04
Food expenditure	0.08	0.09	0.06	0.07	0.08	**0.16**	**0.13**	0.09	0.09	**0.13**	0.03	0.09	0.04	0.09	0.03	0.05	0.08	0.01	0.11	0.08	0.03	0.03	0.04	0.05
Market price	0.09	0.11	0.03	**0.15**	0.11	0.08	0.09	0.09	**0.13**	0.08	0.03	0.06	0.02		0.01	0.07	0.08	0.01	0.07	0.08	0.03	0.03	0.06	0.05
Nr of respondents	18	21	2	3	4	1	5	2	7	5	2	7	1	6	1	4	3	4	12	10	1	5	2	13

[2]: An asterisk in the acronym of the actor group means that the response at the aggregate level was inconsistent using a consistency ratio of 0.3 (Aczél and Saaty, 1983). Cells with bold underlined values represent the highest priority of every actor. Cells with bold values present the second highest priority. Cells with an underlined value show the lowest priority of an actor group

AF:	Arable farmers	TS:	Technology suppliers	RE:	Real estate & land agents	UR:	Urban residents
DF:	Dairy farmers	FS:	Feed suppliers	AP:	Agricultural purchasers	RR:	Rural residents
FI:	Financial institutions	IF:	Intensive livestock farmers	DR:	Distributors & retail	WU:	Water users
LO:	Land owners	AD:	Advisors	RG:	Regional government	WB:	Water boards
CB:	Crop breeders	SSP:	Soil sampling providers	FO:	Farmers organizations	NM:	Nature managers
CIS:	Crop input suppliers	CT:	Contractors	NGO:	Non-governmental organizations	KI:	Knowledge institutions

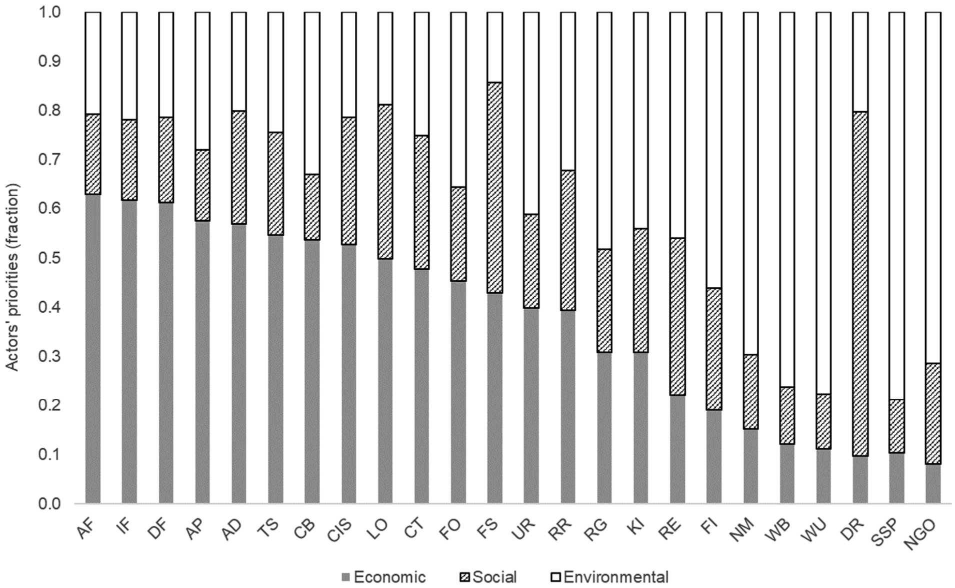


Figure 3.3 – Actors' priorities for criteria of sustainable soil management in the Netherlands. Priorities were elicited using Analytical Hierarchy Process (AHP). Actors are sorted in descending order of their priorities for the economic criterion.

A chi-square test, using an alpha of 0.5 resulted in the rejection of the null hypothesis assuming equal priority for criteria among actors.

Table 3.4 and Figure 3.3 show that 'economics' is the dominant criterion in sustainable soil management. In particular, the subcriterion related to income was important as 14 out of 24 actors have income as their highest priority. The other economic subcriteria were perceived as far less important, especially by actors who had the highest priority for environmental criteria. The criterion 'social' was not directly associated with sustainable soil management. The social subcriteria were ranked only four times with the highest or second highest priority by the actors "Distributors & retail", "Real estate & land agents", "Feed suppliers" and "Land owners". Figure 3.3 clearly illustrates that besides 'economics', 'environment' was the other dominant criterion. An important range of actors including "Financial institutions (FI)" had the highest priority for 'environment'.

3.4.3 Actors' power-interest

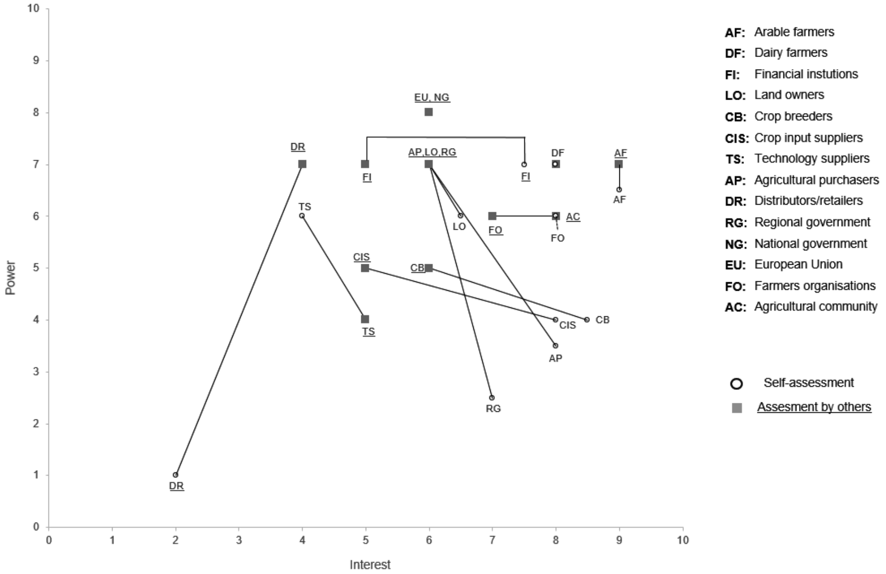


Figure 3.4 – Power and interest grid of central and primary actors in sustainable soil management in the Netherlands. The dots represent the power and interest of the actors according to their own assessment. The grey boxes present the power and interest according to other actors. Black lines connect the assessment made by others to the self-assessment of actors. When the grey box of an actor is not connected, no self-assessment was available.

Based on the survey we were able to retrieve 131 valid responses for the actors' power-interest. Central actors, i.e. arable and dairy farmers, had high power and high interest. Figure 3.4 also illustrates that for farmers there was a small difference between their own assessment and the assessment by others. "European union (EU)", "National government (NG)", "Financial institutions (FI)", "Land owners (LO)" and "Farmers' organisations (FO)" all had high power and considerable interest according to their own assessment. According to the assessment made by others, "Agricultural purchasers (AP)", "Regional government (RG)" and "Distributors & retail (DR)" were powerful actors, while according to their own assessment their power was considerably lower. "Crop breeders (CB)", "Crop input suppliers (CIS)" and "Technology suppliers (TS)" had moderate power according to their own assessment and the assessment by others. Their role as input providers makes them rather following actors instead of leading actors. The power-interest grid underpinned "Land owners (LO)" and "Financial institutions (FI)" have a lot of power to impose requirements on farmers. For all actors except "Distributors and retail (DR)" and "Technology suppliers (TS)", self-assessments of interest were higher than the assessments made by others. A possible explanation might be the selection of the survey sample. As sustainable soil management is a specific subject, respondents with an above average interest are more likely to respond. Hence, the interest in sustainable soil management for the actor they represent might turned out higher than estimated by other actors.

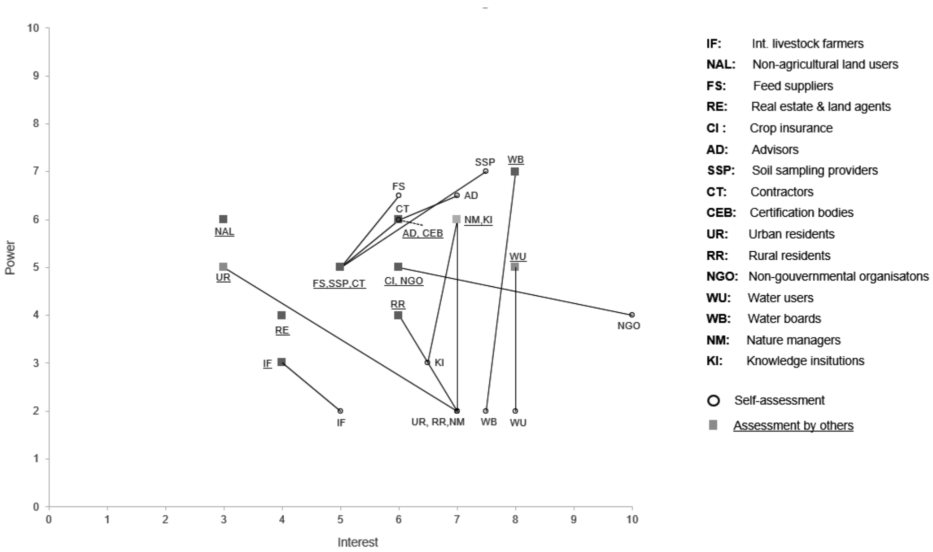


Figure 3.5 – Power and interest grid of secondary actors in sustainable soil management in the Netherlands. The black-white dot represents the power and interest of the actors according to their own assessment. The grey box is the power and interest according to other actors. Black lines connect the assessment made by others to the self-assessment of actors. If the grey box of an actor is not connected no self-assessment was available.

According to their own assessment, "Nature managers (NM)", "Knowledge institutions (KI)", "Water boards (WB)" and "Water users (WU)" were secondary actors with a considerable interest but low power (Figure 3.5). Based on the assessment of other actors, they indeed had an interest but also relatively high power. An explanation might be the sensitive nature of power: people often are somewhat resistant to admit they have the power to influence decisions. "Urban residents (UR)" and "NGOs" had a much higher interest based on their own assessment than on the assessment made by others. This observation can also be explained by the composition of the sample and nature of the subject: "Urban residents" and "NGO" with an above average interest are more likely to respond, which results in a higher interest than assessed by other actors. "Feed suppliers (FS)", "Soil sampling providers (SSP)" and "Contractors (CT)" had moderate power and interest according to the assessment made by others, which could be explained by their passive role as a supplier.

Table 3.5 indicates differences between self-assessments of power and interest and those made by other actors using results from a Mann-Whitney test. For "Urban residents (UR)" the interest differed significantly between the self-assessment and the assessment by others. For "Rural Residents (RR)" the same applies for power.

Table 3.5 – P values from the Mann-Whitney test on difference between own assessment of power and interest and the assessment of power and interest made by other actors.

	Arable farmers	Dairy farmers	Urban residents	Rural residents	Knowledge institutions
Interest	0.731	0.455	0.001	0.084	0.303
Power	0.167	0.443	0.069	0.004	0.059

Table 3.6 provides the underlying data for the power-interest grids. For both datasets, this table presents the minimum, median (q_2) and maximum value. The dataset with assessment of power and interest by other actors had a higher number of respondents, therefore Table 3.6 also presents the values of first quartile (q_1) and third quartile (q_3).

The assessment by of power and interest by others shows a variation between 0 and 10 for almost all actors included. Based on the value of q_1 and q_3 in the assessment by others, the spreading around the median is relatively low for the central actors arable and dairy farmers. A high spreading in the assessment of power and interest by other can be found for "Urban residents (UR)" and "Rural residents (RR)". Spreading in the power-interest assessment by others for "Water users (WU)", "Water boards (WB)" and "Nature managers (NM)" is relatively low.

Table 3.6 – Administrative table with minimum (min), first quartile (q_1), median (q_2), third quartile (q_3) and maximum value for power-interest for actors in sustainable soil management. The dataset consists of the self-assessment of power-interest and the assessment made by other actors. For both datasets, the number of respondents (n) is presented.

	Self-assessment							Assesment by others											
	Interest			Power				Interest						Power					
Actor	min	q_2	max	min	q_2	max	n	min	q_1	q_2	q_3	max	n	min	q_1	q_2	q_3	max	n
AF	4	9	10	2	7	10	15	5	8	9	10	10	111	2	6	7	8	10	111
DF	5	8	10	4	7	10	17	1	6.3	8	9	10	106	1	5	7	8	10	106
FI	7	7.5	8	6	7	8	2	0	3	5	6	9	110	0	5	7	8	10	113
LO	5	6.5	8	6	6	6	2	0	4	6	8	10	112	0	5	7	8	10	112
CB	8	8.5	9	3	4	5	4	0	3	6	7	9	101	0	4	5	7	10	99
CIS	8	8	8	4	4	4	1	0	3	5	6.5	9	98	0	3	5	7	10	107
TS	3	4	9	2	6	7	5	0	2	5	7	10	96	0	3	4	6	10	98
FS	5	6	7	5	6.5	8	2	0	2	5	6	8	103	0	3	5	7	10	104
IF	0	5	8	0	2	2	7	0	2	4	6	10	109	0	2	3	5	10	105
AD	5	7	8	2	6.5	7	6	0	3	6	7	10	102	0	4	6	8	10	105
SSP	6	7	8	7	7.5	8	2	0	3	5	7	10	102	0	3	5	6.5	9	106
CT	5	6	10	5	6	8	7	0	3	5	7	10	102	0	3	5	7	10	102
CI								0	3.5	6	7	10	105	0	3	5	6	10	105
RE								0	2	4	5	9	97	0	2	4	6	10	98
AP	8	8	9	3	3.5	5	6	0	4	6	7	9	101	0	5	7	8	10	101
DR	2	2	2	1	1	1	1	0	2	4	7	10	106	1	6	7	9	10	113
CEB								0	3	6	8	10	109	0	4	6	8	10	109
RG	6	7	8	2	2.5	3	4	0	4	6	7.5	10	108	0	5	7	8	10	109
NG								0	5	6	8	10	110	1	6	8	9	10	113
EU								0	4	6	7	10	109	1	5	8	9	10	113
FO	8	8	9	5	6	6	3	1	5	7	8	10	118	1	4	6	7.8	10	118
AC								0	6	8	8	10	114	0	4	6	7	10	114
NGO	9	10	10	2	4	6	4	0	4	6	8	10	105	0	4	5	7	10	106
UR	2	6.5	9	0	2.5	10	12	0	1	3	5.8	9	94	0	2	5	7	10	99
RR	2	7	10	0	2	5	8	0	4	6	7	10	101	0	2	4	6	10	101
WU	7	7	7	0	0	0	1	0	6.5	8	9	10	107	0	4	5	7	10	107
WB	2	8	9	2	2	5	5	0	6	8	8	10	107	0	5	7	8	10	106
NM	7	7	7	2	2	2	1	0	6	7	8	10	114	0	4	6	8	10	116
NAL								0	1	3	5	10	104	0	4	6	8	10	110
KI	2	6.5	9	1	3	8	12	0	5	7	8	10	100	0	3	6	7	10	102

3.5 Discussion and conclusions

In this study we defined the following research questions: (1) Who are the actors in sustainable soil management in the Netherlands, what are their roles and their underlying relations? (2) What are the priorities of these actors regarding sustainable soil management? (3) What are their power to influence decisions and degree of interest in sustainable soil management and (4) How can this study contribute to implementation of sustainable soil management?

3.5.1 Outcomes of the study

The actor inventory showed that beyond farmers a diverse group of actors is involved in sustainable soil management. We identified suppliers of physical and non-physical inputs, post-farm value chain participants, actors influenced by external effects of production and policy makers. Most existing literature categorized actors in sustainable soil management at a more general level. For instance, Bampa et al. (2019) categorized actors in (a) farmers/local land users, (b) regional stakeholders and (c) European stakeholders. Bouma et al. (2012) categorized actors in (a) knowledge institutions, (b) enterprises and business, (c) NGO and society and (d) governments. This study describes actors and their role in sustainable soil management in much greater detail compared to previous studies. Therefore, results provide a clear overview of which actor must be involved in decision making on sustainable soil management.

Actors' priorities for soil sustainability criteria were assessed using Analytical Hierarchy Process (AHP) (Saaty, 1980). Farmers and participants in the value chain around the farmer show a strong priority for economic criteria, especially income. In a study assessing priority for soil functions, O'Sullivan et al. (2018) found that farmers and industry had high priority for primary productivity and nutrient cycling. This aligns with the results of this study, as these functions have a direct relation with income. Nutrient cycling is essential for primary production, which may explain why farmers have a higher priority for this soil function compared to other functions. Wang and Aenis, (2019) used a checklist in which actors could prioritize ecosystem services. In a case study in Southwest China, farmers had a high priority for fresh water and food. Environmentally engaged actors showed a clear priority for environment. Social criteria were less associated with sustainable soil management as only a few actors showed a priority for these criteria. In addition to the actor inventory, actors' priorities add important information on how the different actors are expected to behave in a transition towards sustainable soil management. Common priorities among actors can serve as basis for coalition forming.

Actors' power and interest towards sustainable soil management was assessed using power-interest grids. Teklemariam et al. (2015) recognize power-interest grids as a valuable tool in actor analysis for land deals. In previous literature on sustainable soil management, power and interest were mainly addressed in a more qualitative way (Rust et al. 2020; Brown et al. 2015; Mumtas and Wichien, 2013). Farmers were confirmed to be the prime actors as they had high power and high interest regarding sustainable soil management. In line with Rust et al. (2020), "Land owners" and value chain actors were found to be powerful actors. We made a valuable addition towards the traditional power-interest analysis as described in Bryson (2004) by splitting actors' self-assessment and the assessment by other actors. This yielded interesting results, i.e. "Agricultural purchasers", "Distributors and retailers" and "Environmentally engaged actors" had limited self-perception of power, whereas others perceived them as powerful actors. Such a situation might be an indicator for a locked-in situation where nobody takes action. Actors that have low power according to their own assessment may be waiting for others to act. Similarly, when others assess the previous actor with a considerable degree of power, they may wait until this actor undertakes action. Thus, different parties will be waiting for each other to make the first move. Using this method is a valuable approach to detect locked-in situations in other wicked natural resources management problems as well.

3.5.2 Limitations of the study

A major point of attention in the development of an actor inventory is the set-up of an unbiased and complete set of actors (Reed et al. 2009; Wang and Aenis, 2019). We applied a stepwise approach, including expert validation, to develop an unbiased and complete inventory of actor types. Nevertheless, some limitations exist. The actor inventory did not address the presence of compound actors. Compound actors are actors represented by different departments that do not necessarily have the same involvement in the problem area, e.g. the actor "national government" consists of different ministries (Koppenjan and Klijn, 2004). Another limitation is that the inventory assumed that a particular actor always can be represented by one actor type, while according to their activities they might fit in multiple actor types.

We used the frequently applied Analytical Hierarchy Process (AHP) to elicit actors' priorities. One of the major drawbacks of AHP is possible subjectivity in the criteria (Petrini et al. 2016). We established criteria in a stepwise approach including expert validation to reduce subjectivity. AHP requires homogenous and independent criteria (Saaty, 1990). Criteria within this study were not completely independent, e.g. the subcriterion primary productivity depends on water quality and regulation, which is another criterion. Dependency in criteria and the ambiguous question procedure of AHP could have been a cause of the inconsistency in actors' priorities (Kukrety et al. 2013). Alternatives, e.g. the Best-Worst Method, may be considered in future research to reduce the inconsistency in responses while simultaneously lowering the cognitive load of the survey (Rezaei, 2015).

The focus of our survey was on inclusiveness of the different actors rather than on representativeness within one actor group. Unfortunately, this resulted in a small sample of primary actors like financial institutions, land owners and distributors and retailers. For the national government and the European Union, we were not able to get a response at all. For a thorough understanding of priorities and positions, a survey appears to be insufficient. Based on the results of the study we could not explain some striking observations such as the high priority of financial institutions for environmental criteria and the low perceived degree of power and interest of distributors and retail. A common approach used in literature is to accompany the survey with qualitative interviews (Raakjær Nielsen and Mathiesen, 2006). In future studies, more attention should be given to the variety of priorities and positions within an actor group. Although the methodology of the actor analysis is sound, one should use some degree of caution in using actors' priorities and actors' power-interest of this study in decision-making. The sample size is too small to generate generalizable results, even in the Dutch context.

3.5.3 Agricultural Innovation Systems approach for sustainable soil management

In order to realize future food systems there is a key role for Agricultural Innovation Systems (AIS) (Klerkx and Begemann, 2020). An AIS is concerned with the networks of actors from science, business, civil society and government that coproduce the suite of technological, social, and institutional innovations that co-shape these future food systems (Klerkx and Begemann, 2020). Sustainable soil management can be seen as a prerequisite for such future food systems. Pigford et al. (2018) argue that AIS need to become mission-oriented: these missions need to tackle grand societal and planetary challenges. A recent example of such a mission-oriented agricultural innovation system is the EU mission on soil health (European Commission, 2020). Our study can contribute such innovation processes by identifying the networks of actors and gain insight in the position of actors.

We want to illustrate our contribution to the mission-oriented agricultural innovation system of soil health via the example of the soils' potential to mitigate climate change via carbon sequestration. Once a mission has been defined, according to Klerkx and Begemann (2020), the following question is who are involved and how to address the different involvement of actors. The inventory of actors can be used to identify which actors are involved in an innovation. In this example, the first and crucial actors involved are farmers. Climate goals are mainly issued via policy makers. NGOs can put climate goals on the agenda of policy makers via societal pressure. Farmers changing practices might impact the products they deliver, as well as the inputs they purchase. Subsequently, input suppliers and post-farm value chain participants will be affected. Once the potential actors involved have been identified, common priorities among actors and complementary power-interest bases can serve as a basis for coalition forming. A fertile ground would be to form a coalition of actors with common priorities, high power and high interest. In this example, farmers, input suppliers and value chain participants have a high priority for income. Contradictory to farmers and value chain participants, governments and NGOs have a high priority for environmental criteria. Whereas governments have high power but a relative low degree of interest, NGOs have low perceived power but a high degree of interest. For actors like NGOs, it is especially interesting to collaborate with actors with high power but limited interest, as they might be able to put their interest on the agenda of a powerful actor. To foster collaboration between actor coalitions with contradictory priorities, there might be a crucial role for actors with priorities on both sides. In the example, such a role might be fulfilled by regional governments and financial institutions. Regional governments have a priority for both environmental criteria and economic criteria. Although financial institutions do not show a clear priority for economic criteria, they have direct formal relationships with farmers and high power to influence decisions.

3.5.4 Conclusions

Despite its limitations, this is the first study combining a comprehensive inventory of actors, actors' priorities for soil sustainability criteria and actors' power and interest to influence decisions. As such, this study contributes to the literature, as to the best of our knowledge such an approach has not yet been performed in the field of sustainable soil management. Farmers were confirmed to be the prime actor. Therefore, the main question that arises from this study is: How and by whom can farmers be motivated to act not only in their own interest but also in the interest of other actors towards sustainable soil management? Therefore, the key element of innovations is to create incentive structures around the farmer. Future quantitative research should investigate how these incentives translate to management on farm level. The insights of this study can provide information on the scale and approach of such quantitative studies. They also allow policy makers to align policies with actor priorities and ongoing private multi-actor collaborations for sustainable soil management.

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4

FARManalytics – a bio-economic model to optimize the economic value of sustainable soil management on arable farms

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4.1 Abstract

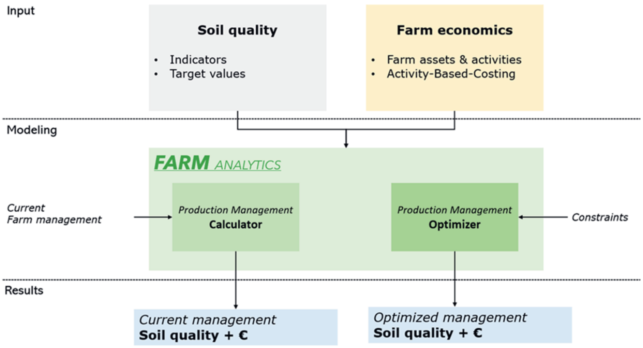
Soil quality is an important determinant of agricultural productivity and environmental quality. Despite its importance, few economic models incorporate sustainable soil management. The objective of this study is to develop and illustrate FARManalytics: a bio-economic model to gain quantitative insight in the economic value of sustainable soil management. First, we defined a comprehensive set of chemical, physical and biological soil quality indicators and quantitative rules on how these indicators respond to farmers' production management over time. Second, we introduce an economic calculation framework that enables accurate calculation of the contribution of different production management decisions towards farm income using Activity-Based-Costing. The set of soil quality indicators and economic calculations serve as the basis for the bio-economic model FARManalytics, which consists of two modules: (1) the PM *calculator*, a module that calculates the impact of current production management on soil quality and farm economics and (2) the PM *optimizer*, a module that uses Mixed-Integer-Linear-Programming to maximize farm income within predefined soil quality indicator constraints. The decision variables are the cropping plan, crop rotation, cover crops, manure & fertilizer application and crop residue management. We illustrate the added value of the model by applying it to an extensive and intensive farm type, both on clay and sandy soil. These farm types are derived from the Farm Accountancy Data Network (FADN) in the Netherlands. FARManalytics demonstrates that it is possible to increase farm income with up to €940 ha^{-1} year^{-1} on clay soil and up to €683 ha^{-1} year^{-1} on sandy soil, while meeting all soil quality targets except subsoil compaction vulnerability. The latter was among the most limiting soil quality indicators for the farm types in this study, together with soil organic matter input, wind erosion vulnerability and plant-parasitic nematodes. FARManalytics integrates the impact of production management decisions on soil quality and economics at farm level. Combined with representative farm types, the bio-economic modeling approach of FARManalytics can provide useful information for policy support. FARManalytics can also be tailored to provide decision support for individual farms, based on data that is commonly available on arable farms at low cost.

Keywords: Soil quality, sustainable soil management, Activity-Based-Costing, bio-economic modeling, optimization, arable farming

Highlights

- Sustainable soil management is important for agricultural productivity but often lacking in economic models.
- The objective is to gain insight in the economic value of sustainable soil management via bio-economic modeling.
- Farm income can be raised up to €940 ha^{-1} year^{-1} while meeting all soil quality target values except subsoil compaction.
- The FARManalytics model integrates soil quality, farm economics and farmers' production management.
- FARManalytics can be used to inform policy decisions and can be tailored at individual farm level using existing data.

Visual abstract



4.2 Introduction

Soil quality plays a key role in agricultural productivity and environmental quality (Stevens, 2018). An increasing demand for agricultural products and a decreasing area of agricultural land (Alexandratos & Bruinsma, 2012) lead to increased pressure on our agricultural system, resulting in erosion, soil compaction, loss of soil organic matter, nutrient leaching and pesticide emission (Koch et al. 2013; Squire et al. 2015). Sustainable soil management should help overcome these threats by meeting present productivity needs without compromising soil needs for future generations (adapted from Smith & Powlson, 2007).

Sustainable soil management can be regarded as an economic problem (Stevens, 2018; Kik et al. 2021a): an investment that aims at long-term soil quality and hence farm income, but might reduce short-term profit. Currently, insight in this trade-off between short-term and long-term economic impact is missing, hampering the implementation of sustainable soil management. Kik et al. (2021a) define the Economic Value of Land (EVL) as the cumulative returns of a piece of land over a period of time. Maximum sustainable EVL is obtained if a soils' potential is fully utilized in a sustainable way, i.e. soil quality and farm income do not decline over time (Kik et al. 2021a) . Following from this, the Economic Value of Sustainable Soil Management ($EVSM$) is defined as the difference between the maximum sustainable EVL and the current EVL of the farmer. Farmers' production management (PM), i.e., the complete set of physical (e.g. fertilizer and plant protection products) and non-physical inputs (e.g., labor and capital) is the primary determinant of soil quality and hence of EVL. Building further on Dury et al. (2012) and Stevens, (2018) , Kik et al. (2021a) developed a conceptual framework for modeling $EVSM$.

Optimizing farmers' production management has been included in numerous bio-economic farm models, which are amongst the most widely spread methods to re-design farming systems (Janssen & van Ittersum, 2007). Most of these models use a linear programming framework where profit is one of the most common objectives and constraints typically include availability of resources such as labor, irrigation water and land (Castro et al., 2018; Castro & Lechthaler, 2022). The added value of such models is proven as they allow to evaluate trade-offs and synergies between different production management strategies and thus support the design of alternative systems (Dury et al., 2012; Schreefel et al., 2022). Although many of these models (e.g. Dogliotti et al., 2005; Groot et al., 2012; Hediger, (2003), Louhichi et al., 2010); Schuler & Sattler, (2010) include some soil quality parameters such as nutrients flows and soil organic matter they typically only make tenuous references to integral concept of soil quality (Schreefel et al., 2022). On the other hand, integrated soil quality assessment tools such as Debeljak et al., (2019) and Ros et al., (2022) often lack an integration of the socio-economic impact of production management decisions at farm-level. Schreefel et al., (2022) make a valuable contribution to bridge this gap by coupling the soil assessment tool Soil Navigator of (Debeljak et al., 2019) to the bio-economic farm model FarmDesign by Groot et al., (2012). In this study, Schreefel et al., (2022) optimize multiple functions of soil using qualitative suggestions of the Soil Navigator for input in FarmDesign. Despite the added value of this approach to understand the socio-economic aspects of sustainable soil management in the farm context, still further advancements have to made to quantitively assess $EVSM$. Therefore, we aim for a quantitative integration of the relation between integral soil quality and production management embedded in a farm's economic context. In such an approach, soil quality has to be included as an integral concept (Bouma, 2014) because ultimately the combination of all soil functions determines long-term soil quality and hence EVL. To build further on studies that already include important production management decisions such as cropping plan and crop rotation (Alfandari et al., 2015; Capitanescu et al., 2017; Pahmeyer et al., 2021), additional production management decisions such as cover crops, manure application, fertilizer application and crop residue management have a crucial impact on soil quality and EVL. (Kanellopoulos et al., 2014). The *ex-ante* integral assessment of soil quality as a response to a comprehensive set of production management decisions requires inclusion of a sound set of agronomic decision rules that accurately model the impact of these decisions over time. We build further on the approach of Dogliotti et al. (2003) to create feasible crop rotations over time, which than serve as the basis for allocation of other production management decisions. The proper implementation of production management decisions is strongly dependent on the farm context (e.g. soil type, climate, cropping plan), which is highlighted by Hannula et al. (2021) and Young et al. (2021). Therefore, we aim for a bio-economic modeling approach that can be tailored at the farm-level using i.e. soil samples and current resource availability so the model is able to suggest concrete alternative production management decisions to reach soil quality targets embedded in the economic context of the farm.

The aim of this study is to develop and illustrate the FARManalytics bio-economic modeling approach. We define four sub-objectives to reach this aim:

(1) Establish a comprehensive set of chemical, physical and biological soil quality indicators, including target values, interrelations between indicators and indicator responses towards production management to be used as constraints in the bio-economic model.
(2) Develop a quantitative economic framework to calculate the contribution of production management elements towards farm income.
(3) Develop a bio-economic model that (a) calculates the impact of current production management on soil quality and farm economics and (b) optimizes farmers' production management to reach maximum $EVSM$
(4) Illustrate our model by applying it to four representative farm types.

We use the Netherlands, where there is a high demand for agricultural products and intensive land use due to fierce competition for land use, as a case study to illustrate the model. The focus of our study is the farm-level as the farmer is the primary actor in sustainable soil management and decision maker on production management (Kik et al., 2021b). Although our focus is at the farm-level, we only consider the farm activities directly related to crop production, but including inputs such as labor and capital (Fresco & Westphal, 1988). We focus on crop yield as the primary output and do not include the options to generate additional farm income through the provisioning of additional ecosystem services.

4.3 Methods

4.3.1 Soil quality

A first step towards developing soil quality constraints was to establish a set of soil quality indicators. We first selected soil quality measurements and associated indicators encompassing the various aspects of soil functioning (Rinot et al., 2019). We defined four criteria to select indicators:

1. The set of indicators has to reflect the variation in soil functions contributing to $EVSM$ at farm level (Bünemann et al., 2018; Ros et al., 2022).
2. For scalability, data has to be available at large scale and acceptable costs (Rinot et al., 2019). Additionally, the indicator has to account for specific conditions and must be expandable with new indicators or objectives.
3. The evolution of soil quality indicators over time as response to farmers' production management has to be quantifiable (Stevens, 2018).
4. Targets in the form of threshold values have to be available (Rinot et al., 2019). They can be based on experimental evidence, literature or expert judgement.

Based on these criteria and in consultation with the developers of two existing Dutch soil quality indicator sets (the Open Soil Index (OSI) and Soil quality indicators Agricultural soils Netherlands (SAN)(De Haan et al., 2021; Ros et al., 2022)), we arrived at the definitive list of soil quality indicators (De Haan & Ros, 2021 personal communication, November 8, 2021). See Appendix A4-1.

We made major adjustments and additions to three indicators. First, we included a more detailed calculation of nitrogen (N) flows compared to either OSI or SAN. N-flows play a key role in crop production and can largely be influenced by production management decisions (Silva et al., 2021). We developed calculation rules for the tactical modeling of N-flows based on the NDICEA model (Van der Burgt et al. 2006), an empirical N-budget model using first order mineralisation kinetics for soil organic matter that has been validated for Dutch circumstances. Second, we extended the current OSI indicator for subsoil compaction vulnerability based on site specific corrections derived from Rücknagel et al. (2015) and the Terranimo model (Lassen et al., 2013). In its current form, the OSI indicator for subsoil compaction is based on predefined calculations with the SOCOMO model (Van Den Akker, 2004). Its use to assess the impact of changes in production management soil management dynamically is limited.

Terranimo is a dynamic model configured for Dutch circumstances that allowed us to quantify the impact of production management decisions on subsoil compaction vulnerability. Rücknagel et al. (2015) provide guidelines for integrating subsoil compaction vulnerability at cropping plan level. Third, we added an indicator for the development of plant-parasitic nematodes (PPN) and soil-borne pathogens (SBP) based on the Dutch nematode and pathogen schemes (Molendijk, 2022; Termorshuizen et al., 2020). Whereas OSI and SAN only include the current status of nematodes and pathogens, these two schemes allowed us to make a semi-quantitative assessment on their evolution over time as a response to PM.

Table 4.1 presents the complete set of indicators, clustered as chemical, physical and biological indicators, including threshold values or ranges derived from field experimental evidence (t) or expert judgement (r). For each indicator, we also list modeling constraints. Whereas the indicators are used to assess soil quality at a specific location at a certain point in time, the constraints are used to set minimum or maximum requirements on the farmers' production management. For example, with respect to soil organic matter (SOM, nr. 13 in Table 4.1) the indicator is defined as the percentage of SOM in the topsoil with a target value of minimum 2%. The modeling constraint refers to a minimum input level of SOM in kg ha^{-1} year^{-1}. The constraint value depends on the target value of the indicator i.e., if the percentage of SOM is below the target value, then the required effective SOM input is higher.

Table 4.1 - Soil quality indicators and soil quality constraints included in FARManalytics. Indicator minimum thresholds (t_min) or maximum thresholds (t_max) are either based on field experimental evidence (t) or expert judgement (r). Nutrient acronyms: N = Nitrogen, P = Phosphorus, K = Potassium, S = Sulfur, Mg = Magnesium. The values for 11, 14 and 15 rely in part on original development, aside from the mentioned source.

Soil quality indicators										**Soil quality constraints**		
category	*nr.*	*indicator*	*acronym*	*source method*	*unit*	*t_min*	*t_max*	*type*	*source constraint*		*min.*	*max.*
chemical	1	N balance	Nbal	NDICEA[1]				t	CBAV[2]/Silva[8]	N adv/N sur	Crop N adv.[a]	N surplus (80)
	2	P Availability Index	PAI	CBAV[2]	(index)	20/25[a]	45	t	CBAV[2]	P adv/P norm	P adv[a]	P norm
	3	K Availability Index	KAI	CBAV[2]	(index)	11[b]	20[b]	t	CBAV[2]	K adv/K bal	K adv[a]	100
	4	S balance	Sbal	CBAV[2]				t	CBAV[2]	S adv/S nur	Supt[a]	S surplus (200)
	5	Mg Availability Index	MAI	OSI[3]	mg kg^{-1}	45		t	CBAV[2]	Mg adv	Mg adv[b]	
	6	Acidity	pH	CBAV[2]		5[b]	7[b]	t	CBAV[2]	NV balance	pH advice[b]	
	7	Cation Exchange Capacity	CEC	OSI/G. Ros[4]	mmol+ kg^{-1}	100		r	OSI/G. Ros[4]	SOM/pH	CEC SOM /pH[c]	
Physical	8	Crumbling Ability	CRA	OSI[3]	(index)	6		t	OSI[3]	CRA_pm_index	7[e]	
	9	Wind Erosion Vulnerability	WEV	OSI[3]	(index)	6		t	OSI[3]	WEV_pm_index	6	
	10	Slaking Vulnerability	SV	OSI[3]	(index)	6		t	OSI[3]	SV_pm_index	7[e]	
	11	Subsoil Compaction Index	SCI	OD/Terranimo[5]				t	Akker & Bakema[5]	SCI		0.2
	12	Plant Available Water	PAW	OSI[3]	(mm water)	50		r	OSI[3]	SOM	PAW SOM[d]	
	13	Soil Organic Matter	SOM	NDICEA[1]	(%/kg ha-^{1})	2		r	OSI[3]	SOM input	min SOM[e]	
Biological	14	Plant Parasitic Nematodes	NEM	OD /PPN scheme[6]				r	ODM /PPN scheme[6]	NEM PCI		200
	15	Soil-Borne Pathogens	SBP	OD/SBP scheme[7]				r	ODM /SBP scheme[7]	SBP PCI		200

References: [1]: van der Burgt et al. (2006), [2]: CBAV, (2022) *[3]: Ros et al. (2022), [4]*: Ros (personal communication, March 15, 2022) *[5]:Bakema & van den Akker (2021), [6]:* Molendijk (2022)*, [7]:* Termorshuizen et al. (2020)*, [8]:* Silva et al. (2021)

Additional information targets: [a]: cropping plan dependent, [b]: cropping plan & soil type dependent, [c]: CEC depends on pH and SOM content. Constraints are set on pH and SOM, [d]: PAW can be controlled via SOM. Constraint is set on SOM, [e]: CRA and SV can be controlled via PM decisions and SOM content. Constraints are set both on SOM content and production management decisions directly. [f]: dependent on SOM required for CEC, CRA, SV, PAW and SOM itself.

After selecting soil quality indicators, we established their relevant interrelations and the relations with production management (Kik et al. 2021a). Figure 4.2 visualizes the basic principles underlying these interrelations. An extensive (and where possible quantitative) overview of all soil quality indicator interrelations can be found in Appendix A4-2.

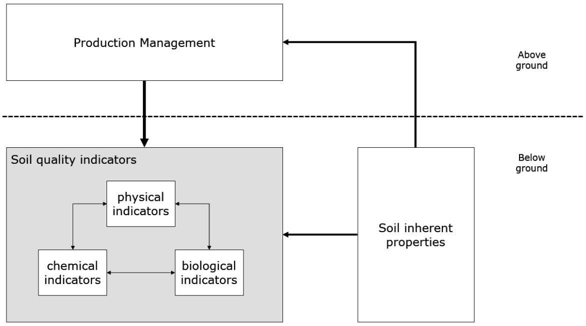


Figure 4.2 - Principles of the interaction between production management, soil quality indicators, soil inherent properties and the interrelations between chemical, physical and biological soil quality indicators.

Because of trade-offs and synergies between various soil quality indicators, for example between K availability and Cation Exchange Capacity, it is essential to include their interrelations in modeling (Rinot et al., 2019; Stevens, 2018; Bouma, 2014). Moreover, many soil quality indicators depend on soil inherent properties. For example, the relation between SOM decomposition and soil texture. Farmers' production management is the primary determinant of soil quality. Kik et al. (2021a) provide a basic overview on how production management decisions at a strategic, tactical and operational level influence soil quality. Strategic choices relate to long-term production management decisions, e.g., which cropping plan and crop rotation design (Dury et al. 2012). Tactical choices are the choices made within the growing season, e.g., cover crop choice or the manure application regime (Dury et al. 2012). Choices at the operational level are highly dynamic and typically are made on a day-to-day basis, e.g., whether and how much to irrigate during a period of drought. The focus of this study is on the strategic – tactical production management decisions. Table 4.2 presents the production management decisions included in our bio-economic modeling approach, and Table 4.3 presents how each of them relate to the soil quality indicators.

Table 4.2 – Definition and illustration of farmer' production management decisions included in bio-economic modeling approach FARManalytics.

PM element	Definition	Example
Cropping plan[1]	Acreage of crops and their spatial distribution within a particular year	• 50 ha winter wheat (WW) • 25 ha sugar beet (SB) • 25 ha ware potatoes (WP)
Crop rotation[2]	The sequence of crops grown on a field	• WW-SB-WW-WP • WW-WW-SB-WP
Cover crop[3]	A close-growing crop that provides soil protection, seeding protection and soil improvement between periods of main crop production	• Yellow mustard planted after winter wheat (1-Aug) and terminated before potato planting (1-Apr).
Manure	Organic matter originating from livestock husbandry or composting	• 30 ton ha^{-1} pig slurry applied 1-Mar • 20 ton ha^{-1} compost applied 1-Oct
Fertilizer	Application of plant nutrients through natural or synthetically produced fertilizer	• 200 kg Calcium Ammonium Nitrate (27% N) application on 1-May
Crop residue management	Decision to sell crop residues to generate revenue or keep them on the field to enhance soil quality	• Sell wheat straw • Keep wheat straw

[1]: Dury et al. (2012), [2]: Castellazzi et al. (2008) [3]: Ramesh et al. (2019)

Table 4.3 – Relations between soil quality indicators and production management. Production management decisions indicated in bold are considered in this study. An "x" represents a quantitative relationship included in the model. A "-" represents a known relationship not yet included in the model.

		Soil quality indicators														
		Chemical							*Physical*						*Biological*	
	Production management decisions	N	P	K	S	Mg	pH	CEC	CRA	WEV	SV	SCI	PAW	SOM	PPN	SBP
Strategic dimension	*Farm set-up*															
	Production system	x	x	x	x	x										
	Mechanization & installation configuration											x				
	Tillage system	-							-	-	-	-	-	-		
	Land use activities															
	Cropping plan	x	x	x	x	x	x		-	-	-	x		x	x	x
	Crop rotation	-			-				-	-	-				x	x
	Cover crops	f1	-	-	-				-	-	-	-		x	x	x
	Fallow periods	-	-	-	-				-	-	-				x	x
	Soil management															
	Organic manure	x	x	x	-	-	x			-		x		x		
	Lime (CaO) & Gypsum (CaSO^4)				x	x	x		-			x				
	Field improvements (e.g. drainage/indundation)								-		-	-	-		-	-
	Crop management															
	Crop cultivar selection	-													x	x
	Crop residue management	x	x	x	-					-	-	x		x		
Tactical dimension	**Fertilzer application regime**	x	x	x	x	x	x					-				

N = Nitrogen, P = Phosphorous, K = Potassium, S = Sulfur, Mg = Magnesium, CEC = Cation Exchange Capacity, CRA = Crumbling Ability, WEV = Wind Erosion Vulnerability, SV = Slaking Vulnerability, SCI = Soil Compaction Index, PAW = Plant Available Water, SOM = Soil Organic Matter, PPN = Plant Parasitic Nematodes, SBP = Soil-Borne Pathogens.

Digital appendix A4-3 entails extensive factsheets that explain all calculations, required data and references for every soil quality indicator and their response to production management decisions.

4.3.2 Farm economics

Precise calculations of the contribution of different production management decision to EVL are a prerequisite for bio-economic modeling. The calculation framework focuses on the calculation of EVL at farm level but only considering crop production activities, using a business-economics approach including opportunity costs (Kay et al. 2012). Since FARManalytics aims to support strategical-tactical decisions, variable as well as fixed costs of production management have to be addressed. Variable costs can often be easily attributed to a specific activity on the farm (e.g., fertilizer applied on potatoes is a direct cost item for potatoes), but it is much more complex to attribute fixed costs to a specific activity (e.g. costs of a tractor used in multiple crops). Inaccurate attribution of costs and revenues to production management decisions can lead to over- or underestimations. This so-called "cross subsidisation bias" can result in poor management decisions (Gupta & Galloway, 2003; Mattetti et al. 2022). To ensure accurate model input, we used Activity-Based-Costing (ABC) to attribute fixed costs towards the respective production management decisions. In ABC, allocation of fixed costs is done based on activities, which are the PM elements in this research(Drury, 2008). ABC requires data on the costs of assets used, a cost driver to translate costs in activity-specific costs and the utilization rate of the assets in production management decisions (Mattetti et al. 2022). To illustrate the principle of ABC we assume a tractor costing €$10{,}000\,year^{-1}$. The utilization rate of the tractor is $400\,h\,year^{-1}$ in wheat and $600\,h\,year^{-1}$ in potatoes. If we apply ABC with tractor usage in hours as cost driver, the costs are proportionally applied to wheat (€$4{,}000$) and potatoes (€$6{,}000$).

Kik et al. (2021a) defined the Economic Value of Land (EVL) as "The total net return of a certain piece of land to the user of the land over a defined period of time". We define a farm as an entity owning or using a certain area of land. The general formula to calculate EVL for a farm is:

$$EVL_{farm} = EVL_c + EVL_{cc} + EVL_m + EVL_{cr} + EVL_f \tag{1}$$

In which:

- EVL_c ($€\, ha^{-1}$) : EVL from crop production
- EVL_{cc} ($€\, ha^{-1}$) : EVL from cover crop cultivation
- EVL_m ($€\, ha^{-1}$) : EVL from manure application
- EVL_{cr} ($€\, ha^{-1}$) : EVL from crop residue management
- EVL_f ($€\, ha^{-1}$) : EVL from fertilizer application

Figure 4.3 visualizes the procedure to calculate EVL.

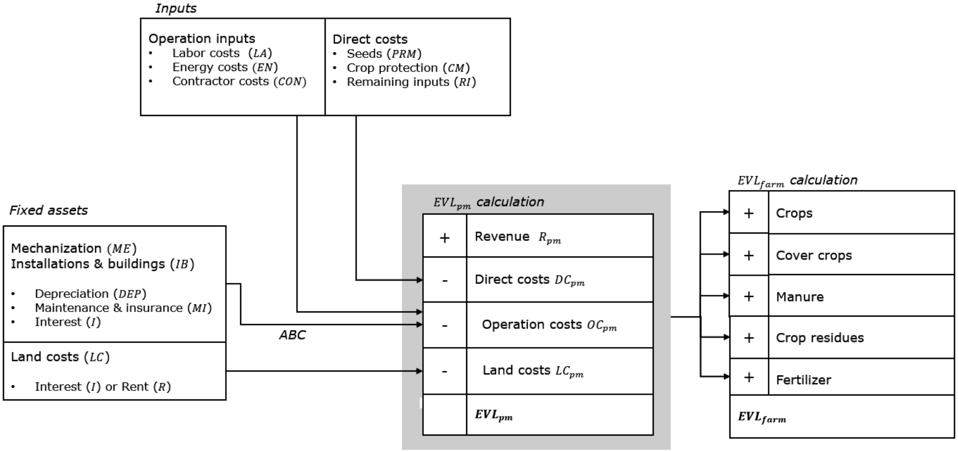


Figure 4.3 – Outline of the calculation of Economic Value of Land (EVL) as an economic indicator for various farm production management decisions. Costs of mechanization and installation & buildings are attributed using Activity-Based-Costing (ABC).

Because the procedure is the same for all production management decisions, we substituted the indices c, cc, m, cr, f with pm in the following calculations. For any of the production management decisions EVL is the revenue (R_{pm}: $€\, ha^{-1}$) minus the direct costs of production (DC: $€\, ha^{-1}$), operation costs (OC: $€\, ha^{-1}$) and land costs (LC: $€\, ha^{-1}$).

$$EVL_{pm} = R_{pm} - DC_{pm} - OC_{pm} - LC_{pm} \tag{2}$$

Note that not all items of the EVL calculation are applicable for every production management decision. For example, fertilizer application itself does not generate revenue. Yields are determined using a target-oriented approach, which implies that yields are static and do not respond to changes in the environment, such as soil quality (Van Ittersum & Rabbinge, 1997). Revenue is calculated as the physical output (Y_{pm} : $kg\ ha^{-1}$) times the price of the output (P_{pm}):

$$R_{pm} = Y_{pm} * P_{pm} \tag{3}$$

Direct costs consist of the costs of inputs used for a production management decision. This entails amongst others plant reproductive material (PRM: $€\, ha^{-1}$), costs of crop protection (CP: $€\, ha^{-1}$) and remaining input costs (RI: $€^{-1}$) :

$$DC_{pm} = PRM_{pm} + CP_{pm} + RI_{pm} \tag{4}$$

Operation costs are total costs of either field operations or storage and processing operations. Since storage and processing are essential activities responsible for a substantial part of the costs of some production management decisions, they are included in the calculations. Examples are grading and storage of seed potatoes and cold storage of carrots in boxes. As indicated in Figure 4.2, operation costs include costs of mechanization (ME_{pm}: $€\, ha^{-1}$) and costs of installations and buildings (IB_{pm} : $€\, ha^{-1}$), labor costs (LA_{pm} : $€\, ha^{-1}$), energy costs (EN_{pm}: $€\, ha^{-1}$) and contractor costs (CON_{pm} : $€\, ha^{-1}$):

$$OC_{pm} = ME_{pm} + IB_{pm} + LA_{pm} + EN_{pm} + CON_{pm} \tag{5}$$

We applied ABC to calculate ME_{pm} and IB_{pm} in ($€\,ha^{-1}$). The first step was to calculate FA_y ($€\,year^{-1}$): yearly costs of fixed assets. These costs include depreciation (DEP), maintenance and insurance (MI) and interest (I) which all can be expressed in a percentage of the replacement value ($\%\,RV^{-1}$):

$$FA_y = (DEP + MI + I) * RV \tag{6a}$$

The second step was to calculate the costs per hour by dividing total yearly costs by the use of assets ($UA : h\,y^{-1}$) in all production management decisions at farm level:

$$FA_h = \frac{FA_y}{UA} \tag{6b}$$

The last step is to calculate OC_{pm} by multiplying the total usage in a production management decision by the costs per hour:

$$OC_{pm} = UA_{pm} * FA_h \tag{6c}$$

4.3.3 Bio-economic model FARManalytics

The bio-economic modeling approach 'FARManalytics' consists of three components: (1) Soil quality (SQ) and EVL datasets which serve as inputs, (2) the PM calculator, a module to calculate the impact of current production management and (3) the PM optimizer (Figure 4.3).

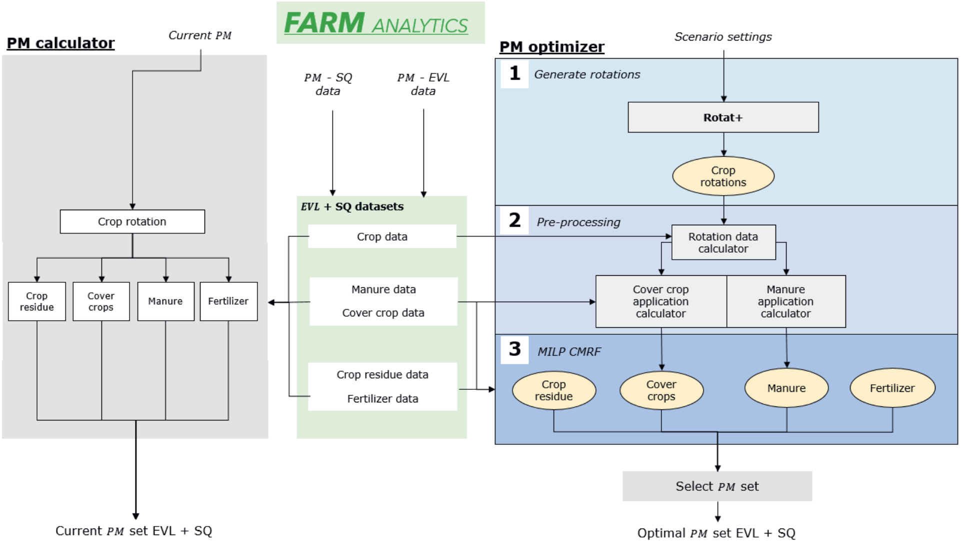


Figure 4.3 – Schematic overview of the FARManalytics bio-economic modeling approach to calculate and optimize the impact of a farmer's production management (PM) on soil quality and economics (EVL).

The $SQ - EVL$ datasets are based on the soil quality indicators presented in Section 4.3.2 and the economic calculations in Section 4.3.2 As follows from Figure 4.3, these datasets are created for the production management elements crops, cover crops, manure, crop residues and fertilizer (definitions and examples in Table 4.2). The $SQ - EVL$ datasets are used for both the calculation of the impact of current production management and as input for optimization in the PM optimizer. The module PM calculator calculates the impact of the current production management on soil quality and EVL by linking the $SQ - EVL$ datasets to the current management. In the PM calculator, all choices for production management decisions must be made by the user.

The PM optimizer module consists of three subsequent submodules: (1) Generate crop rotations, (2) Pre-allocation of cover crops, manure, crop residue and fertilizer (CMRF), and (3) A Mixed-Integer-Linear-Programming (MILP) model to optimize CMRF choices.

In the first submodule, crop rotations are generated using ROTAT+ (Dogliotti et al., 2003). Based on agronomic rules e.g., maximum crop frequency and minimum period of repeat between the same crops, ROTAT+ generates all feasible crop rotations. As the number of feasible crop rotations generated by ROTAT+ can impede the computational feasibility of running submodule two and three, we implemented a heuristic: within the ROTAT+ output we select the rotations with the highest crop EVL at rotational level. This set of rotations goes through submodule two and three. If an optimal solution is found, calculations stop. If no optimal solution is found, we select the set of rotations with the second highest crop EVL and run submodule two and three of PM optimizer. This procedure is repeated until a feasible solution is found or until all feasible rotations are processed.

Within a generated crop rotation, the second submodule calculates the basic rotation data, such as the length of the rotation, crop plant dates and crop harvest dates. These data are then used in the subsequent pre-processing algorithms "cover crop application calculator" and "manure application calculator". The aim of these algorithms is to limit the options for cover crops and manure applications only to the feasible options. Given the crop rotation, both algorithms determine when cover crops and manure can be applied in an agronomically feasible way. For example, if there are less than eight weeks between the harvest date of a crop and the plant date of the subsequent crop, growing a cover crop is considered infeasible. User-defined choices determine whether it is feasible to apply a certain type of manure before or in a crop. For example, it is not feasible to apply slurry on clay soil before seed onions because it would negatively impact their storage quality. The output of both pre-processing algorithms for the MILP model are matrices indicating which cover crops or manure types can be considered at a certain phase in the crop rotation.

Submodule three in PM optimizer maximizes EVL at farm level according to Equation 1. In general form, the optimization problem can be written as:

$$\begin{aligned} &maximize\ c'x \\ &subject\ to \quad Ax = b \\ &\qquad\qquad\quad\ x \geq 0 \end{aligned}$$

In which $c'x$ is the objective function: maximize EVL from the decision variables (production management decisions) at farm-level over time of one rotation.

The decision variables in the model are the following:

- Cover crops *(binary):* Plant cover crop cc in year t.
- Manure application *(continuous):* Quantity of manure type m in year t.
- Crop residues (*binary*): Sell or keep crop residues cr of crop c in year *t*.
- Fertilizer (*continuous*): Quantity of fertilizer type *f* in year *t*.

$Ax = b$ represents the constraints, which consist of three types:

- *Agronomic* constraints ensure the agronomic feasibility of the chosen solution. Agronomic constraints refer for instance to a lower bound of manure per application and an upper bound of at most one cover crop per season.
- *Legal* constraints limit the usage of N from animal manure, total N and total P according to the Dutch nutrient legislation.
- *Soil quality* constraints (Table 4.1): constraints on production management to ensure soil quality targets are achieved, with the underlying assumption that if soil quality constraints are met soil quality is preserved. Because of their dynamic nature, the N, S and pH constraints are applied yearly, whereas other soil quality constraints are applied over the length (in years) of the rotation.

Submodule two and three of PM optimizer must be performed for all crop rotations generated in submodule one. The last step is to select the crop rotation with optimized CMRF choices that has the highest EVL while meeting the soil quality constraints.

4.4 Model illustration

4.4.1 Farm types and scenarios

To illustrate the model, we defined four standard farm types based on the Dutch Farm Accountancy Data Network (FADN), managed by Wageningen Economic Research and KWIN AGV 2022 (Van der Voort, 2022). KWIN AGV is a Dutch handbook containing quantitative standards for arable farming. Yields, prices, costs of inputs and costs of assets where all determined based on KWIN AGV 2022. For the land costs, we took the long-term land rent price from KWIN AGV 2022. We evaluated the impact of production management on soil quality and EVL for two arable farm types (intensive, extensive) on two different but representative soil types (clay, sand) (Table 4.4). For each soil type an extensive and intensive current production management regime has been defined. The extensive production management focuses more on preserving soil quality with an extensive crop rotation, the use of cover crops where possible and input of cattle slurry and solid manure. The intensive production management focuses on short-term profit with an intensive crop rotation, a limited number of cover crops and preferential use of pig and cattle slurry as manure.

Table 4.4 – Current production management decisions on four different Dutch farm types to illustrate the FARManalytics bio-economic modeling approach. See footnote for explanation of acronyms.

	Farm types			
PM decisions	**Clay extensive**	**Clay intensive**	**Sand extensive**	**Sand intensive**
Crop rotation	WP-WW-SB-WW-WP-WW-SB-WW	WP-WW-SO-SB-WP-WW-CA-SB	WP-SC-WB-SB-WP-SC-WB-SB	WP-WB-SB-CA-WP-SC-SB-SO
Cover crops	(WW) -> Winter radish	(WW) -> Yellow Mustard	(WB) -> White radish (SB year 4) -> Winter rye	(WB) -> White radish (SC) -> Winter rye (SB year 3) -> Winter rye (SO) -> Yellow mustard
Crop residue management	Keep wheat straw	Sell wheat straw	Keep barley straw	Sell barley straw
Manure & lime	WW crop : 40 ton ha^{-1} CS WW autumn : 20 ton ha^{-1} CSM	WP spring :25 ton ha^{-1} PS WW crop :27.5 ton ha^{-1} PS WW autumn :20 ton ha^{-1} CS	WP spring :30 ton ha^{-1} CS SC spring :30 ton ha^{-1} CS SC autumn :20 ton ha^{-1} GFTC WB autumn :12.5 ton ha^{-1} CSM SB spring :30 ton ha^{-1} CS	WP spring :35 ton ha^{-1} CS SB spring :35 ton ha^{-1} CS CA spring :30 ton ha^{-1} CS SC spring :35 ton ha^{-1} CS SO spring :30 ton ha^{-1} CS
Fertilizer (kg N/P/K/S/Mg ha^{-1})				
WP : ware potatoes	167N/135K/68S/20Mg	140N/135K/68S/16Mg	108N/14P/111K	122N/18P/111K
SB : sugar beets	108N/16Mg	108N/16Mg	59N	59N
SO : seed onions		133N/147K/68S/14Mg		93N/25P/108K
CA : carrots		59N/107K/68S/4Mg		76N/25P/78K
WW : winter wheat	108N/16Mg	95N/14Mg		
WB : winter barley			143N/90K/47S	143N/90K/47S
SC : silage corn			49N/36K	49N/18P/36K

Crops: WP = ware potatoes, SB = sugar beets, CA = carrots, SO = seed onions, WW = winter wheat, WB =winter barley, SC = silage corn

Manure: PS = pig slurry, CS = cattle slurry, CSM = cattle solid manure, GFTC = GFT compost

Fertilizer: N = Nitrogen, P = P_2O_5, K = K_2O, S = SO_3, Mg = MgO

We designed the following scenarios, which were applied on every farm type:

- Baseline (*b*): Continuation of current production management during one complete rotation
- Profit (*p*): Optimization of production management choices in the tactical dimension without soil quality constraints, except for crop nitrogen requirements and legal nutrient norms. Optimization in the tactical dimension only refers to potential changes in the cover crops, manure, crop residues and fertilizer.
- Soil quality tactical (*st*): The profit scenario including all soil quality constraints as defined in Table 4.1. However, this scenario does not consider changes in crop rotation.
- Soil quality strategic (*ss*): Optimization of production management in the strategic dimension including soil quality constraints and potential changes in crop rotation and cropping plan. For

both the extensive and intensive farm types, changes in crop rotation can be made based on the crops that are currently on the intensive farm types because this farm type has the highest diversity of crops. In the extensive *ss* scenarios, a minimum share of 50% of crops in the rotation has to be cereals (incl. corn) whereas this is minimum 25% in the intensive scenarios.

We distinguish a soil quality tactical scenario and a soil quality strategic scenario because of the substantial difference in time by which the proposed changes in production management can be implemented. The changes in the soil quality tactical scenarios can usually be implemented on short notice without the need to drastically alter the farm set-up. For example, planting other cover crop species usually only implies ordering other cover crop seeds from the supplier. In contrast, changing the cropping plan might require a farmer to invest in new capital assets such as machinery or installations.

An additional soil cover constraint is applied in all scenarios except the profit scenarios. This constraint ensures that the soil is covered by either a crop or a cover crop for a specified percentage of the time of the rotation. For clay soil this is 75%, and for sandy soil 70%. Additional constraints were set on cover crops regarding the frost vulnerability and regrowth scores. Both scores are in the range of zero to five. A score of zero implies a that a cover crop regrows after termination or is not vulnerable to frost. In contrast, a score of five means that a cover crop does not regrow and is highly susceptible to frost. Since regrowth and frost resistance are often undesirable, only cover crops with a score of four or five were withheld.

In the scenario analysis, we did not apply the P-advice constraint as the P-norm was lower for all farm types. Since the P-norm then becomes the limiting factor, it was not possible to implement the P-advice constraint. Furthermore, we also did not apply the SCI constraint because with the current crops cultivated on the farms the threshold value could never be met.

4.4.2 Results

The results section is structured as follows: First we show the results of the crop EVL calculation for the farm type 'clay intensive'. Subsequently, we show the results of the scenario calculations and discuss the results in the order baseline – profit – soil quality tactical – soil quality strategic. Finally, we show a trade-off curve for the key soil quality indicator Soil Organic Matter vs. EVL.

Crop EVL

Table 4.5 shows the results of the crop EVL calculation on the farm type 'clay intensive'. The EVL for winter wheat is negative, i.e. −€233 ha^{-1}, which is not surprising as in the Netherlands winter wheat is mainly cultivated as a break crop. Break crops are cultivated to benefit soil quality in the first place, not as a cash crop(Robson et al. 2002). The net EVL for ware potatoes is just slightly positive, i.e. €20 ha^{-1}, despite the relatively high revenue of €8,080 ha^{-1}, as the costs of crop inputs (€2,240 ha^{-1}), field operations (€2,226) and storage operations (€2,494) have a negative impact on the financial returns. With an EVL of €2,683 ha^{-1}, onions are the most profitable crop: crop revenue is approximately €2,000 ha^{-1} higher than for potatoes, while the total costs are comparable. Despite a revenue of only €3,900 ha^{-1}, sugar beets are the second most profitable crop with an EVL of €933 ha^{-1}. This can be explained by the low field operation costs and the absence of storage and processing costs. Although the revenue for carrots is almost three times the revenue of sugar beets, the EVL is only 50% of that of sugar beets. A costly harvest leads to high field operations costs for carrots (> €2,000 ha^{-1}), on top of high storage & processing costs due to the use of expensive box storage and mechanical cooling. The results of the crop EVL calculation show that the comprehensive economic calculations yield interesting differences in the financial returns between crops that would not have become clear based on a simple gross margin approach. For example, the gross margin of ware potatoes (€8,080 − €2,240 = €5,840) is substantially higher than the gross margin of sugar beets (€3,900 − €636 = €3,264) while the ultimate EVL of sugar beets is €903 higher.

Table 4.5 – Economic Value of Land (EVL) as economic indicator for crops cultivated on a 100 ha arable farm on clay soil in the Netherlands.

Crop	**Unit**	**Ware potatoes**	**Winter wheat**	**Seed onions**	**Suger beets**	**Carrots**
Revenue	*€ ha^{-1}*	8,080	2,080	9,883	3,900	11,799
Direct costs						
Crop inputs	€ ha^{-1}	2,240	437	1,760	636	1,470
Total direct costs	*€ ha^{-1}*	2,240	437	1,760	636	1,470
Operation costs crop cultivation	€ ha^{-1}					
Labour	€ ha^{-1}	494	100	338	156	713
Energy	€ ha^{-1}	212	80	189	118	212
Mechanization	€ ha^{-1}	1,520	257	1,074	352	1,045
Contractor work	€ ha^{-1}	0	339	577	605	1,745
Total operation costs crop cultivation	*€ ha^{-1}*	2,226	776	2,177	1,231	3,714
Operation costs storage & processing						
Inputs storage	€ ha^{-1}	515		116		0
Labor	€ ha^{-1}	50		50		125
Energy	€ ha^{-1}	132		282		1,074
Mechanization	€ ha^{-1}	314		314		641
Installations & buildings	€ ha^{-1}	1,483		1,401		3,224
Total operation costs storage & processing	*€ ha^{-1}*	2,494	0	2,162	0	5,063
Land costs	*€ ha^{-1}*	1,100	1,100	1,100	1,100	1,100
EVL crop	**€ ha-1**	**20**	**-233**	**2,683**	**933**	**451**

Table 4.6 shows the main results for EVL and the soil quality constraints for the baseline scenarios and the soil quality strategic scenario for all four farm types.

Baseline scenario
In all baseline scenarios the legal norm for P-application is lower than the P-advice (Table 4.6). In all baseline scenarios the Subsoil Compaction Index (SCI) exceeds the threshold value but extensive farms (*CE* and *SE*) have a better SCI score compared to intensive farms (*CI* and *SI*). This can be explained by the higher share of cereals that have a lower SCI impact. Besides P-advice and SCI, *CE_b* fulfils all soil quality thresholds. Additional concerns in *CI_b* are the high N-surplus and the low input of K. In *SI_b* and *SE_b*, the input of Sulfur (S), Magnesium (Mg) and Neutralizing Value (NV) is insufficient as S and Mg fertilization and liming (input of NV) are not in the current production management. Due to the very low Cation Exchange Capacity (CEC) of the sandy soil, an input of 4,564 kg SOM ha^{-1} is required to rise the CEC. Farms on sandy soils do not fulfil this threshold, although the input of SOM is substantially higher in *SE_b* compared to *SI_b*. Cultivating crops vulnerable for *Meloidogyne Chitwoodi* and *Pratylenchus Penetrans* causes the target value for these nematodes to be exceeded in *SI_b*. In both *CE_b* and *SE_b*, total EVL is negative (Table 4.6).

Profit scenario
Table 4.7 lists the production management choices for all scenarios. Table 4.8 breaks down the EVL in its underlying components for all scenarios on all farm types. In the profit (*p*) scenario there are no soil quality constraints apart from the crop nitrogen requirements. Excluding cover crops results in an EVL increase between €80 ha^{-1} and €178 ha^{-1} (Table 4.6 and 4.8). The results also show the economic importance of pig slurry: its inclusion results in an EVL increase of €10 to €93 and it helps to reduce fertilizer use (e.g., €188 ha^{-1} higher EVL due to reduced fertilizer use in *CI_p* compared to *CI_b*). Crop residues are always sold to generate additional EVL compared to the baseline, yielding €150 ha^{-1} on clay soil and €62 ha^{-1} on sandy soil. In all profit scenarios, total EVL increases substantially compared to all baseline scenarios, However, this is at the expense of soil quality. For example in scenario *SI_p*, the input of SOM is only 1187 kg ha^{-1} whereas the threshold is 4564 kg ha^{-1}.

Table 4.6 – Economic Value of Land (EVL) and related soil quality indicators outcomes for scenarios. With regard to soil quality indicators we show minimum (t_min, in grey) and maximum thresholds (t_max, yellow) and calculation results. If the thresholds are not met, results are underlined and indicated in red. See footnote for explanation of acronyms.

Indicators											
theme	*indicator*	*type*	*unit*	*CE_b*	*CE_ss*	*CI_b*	*CI_ss*	*SE_b*	*SE_ss*	*SI_b*	*SI_ss*
EVL	crop	result	(€ ha^{-1})	1222	1683	1672	1803	697	1087	1113	1252
	cover crop	result	(€ ha^{-1})	-178	-70	-80	-138	-89	-102	-163	-102
	manure	result	(€ ha^{-1})	-10	32	58	35	-6	-43	29	-44
	crop residue	result	(€ ha^{-1})	0	180	75	90	0	100	31	75
	fertilizer	result	(€ ha^{-1})	-256	-107	-264	-81	-201	-84	-218	-97
	land	result	(€ ha^{-1})	-1100	-1100	-1100	-1100	-600	-600	-600	-600
	total	result	(€ ha^{-1})	-322	618	361	609	-199	358	192	484
N legal	N manure legal	t max	(kg ha^{-1})	170	170	170	170	170	170	170	170
	N manure applied	result	(kg ha^{-1})	134	133	112	146	107	109	118	109
	N total legal	t max	(kg ha^{-1})	248	221	209	218	152	141	161	153
	N total applied	result	(kg ha^{-1})	199	144	177	133	157	112	161	118
N	N advice	t min	(kg ha^{-1})	216	203	194	195	178	156	174	167
	N available	result	(kg ha^{-1})	258	205	248	205	216	163	233	178
	N surplus	t max	(kg ha^{-1})	80	80	80	80	80	80	80	80
	N surplus	result	(kg ha^{-1})	69	30	92	35	49	11	78	31
P	P advice	t min	(kg ha^{-1})	83	88	80	80	77	80	71	73
	P norm	t max	(kg ha^{-1})	60	60	60	60	60	60	60	60
	P applied	result	(kg ha^{-1})	58	60	59	60	61	60	57	60
K	K advice	t min	(kg ha^{-1})	151	144	206	187	216	188	232	210
	K applied	result	(kg ha^{-1})	203	146	166	187	255	201	225	210
	K surplus	t max	(kg ha^{-1})	100	100	100	100	100	100	100	100
	K surplus	result	(kg ha^{-1})	52	2	-40	0	39	13	-7	0
S	S uptake	t min	(kg ha^{-1})	32	35	36	35	36	38	38	35
	S applied	result	(kg ha^{-1})	44	40	52	42	25	39	24	36
	S surplus	t max	(kg ha^{-1})	200	200	200	200	200	200	200	200
	S surplus	result	(kg ha^{-1})	12	5	17	7	-12	0	-13	1
Mg	Mg advice	t min	(kg ha^{-1})	0	0	0	0	74	74	74	74
	Mg applied	result	(kg ha^{-1})	83	38	39	45	56	79	35	76
pH	NV advice	t min	(NV ha^{-1})	0	0	0	0	164	150	162	146
	NV applied	result	(NV ha^{-1})	0	0	0	0	0	219	0	219
CRA	CRA required	t min	(index ha^{-1})	6	6	6	6	6	6	6	6
	CRA score	result	(index ha^{-1})	8	8	8	8	8	8	8	8
WEV	WEV required	t min	(index ha^{-1})	6	6	6	6	6	6	6	6
	WEV score	result	(index ha^{-1})	8.6	8.6	8.6	8.6	6.2	6.7	6.4	6.6
SV	SV required	t min	(index ha^{-1})	7	7	7	7	7	7	7	7
	SV score	result	(index ha^{-1})	9.1	9.1	9.1	9.1	7.8	7.8	7.8	7.8
SCI	SCI required	t max	(index ha^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	SCI score	result	(index ha^{-1})	0.27	0.2	0.39	0.36	0.33	0.26	0.43	0.37
SOM	SOM lim. factor		(-)	SOM	SOM	SOM	SOM	CEC	CEC	CEC	CEC
	SOM required	t min	(kg ha^{-1})	1915	1915	1915	1915	4564	4564	4564	4564
	SOM input	result	(kg ha^{-1})	4765	2854	1881	2937	4074	4564	2662	4564
NEM	max NEM PCI	t max	(€ PRL ha^{-1})	0	0	0	0	0	0	0	0
	Meloidogyne Chitwoodi	result	(€ PRL ha^{-1})	0	0	0	0	58	146	296	196
	Pratylenchus Penetrans	result	(€ PRL ha^{-1})	0	0	0	0	20	153	233	176
SBP	max SBP PCI	t max	(€ PRL ha^{-1})	0	0	0	0	0	0	0	0
	Rhizoctonia Solani	result	(€ PRL ha^{-1})	0	101	101	126	7	46	157	76
	Scliortinia	result	(€ PRL ha^{-1})	0	0	0	27	0	0	137	14
	Verticilium Dahlae	result	(€ PRL ha^{-1})	0	0	3	0	0	0	4	0

Farm type & scenario acronyms: C = clay, S = Sand, I = intensive, E = extensive, _b = baseline, _ss = soil quality strategic

Soil quality indicators: N = Nitrogen, P = Phosphorous, K = Potassium, S = Sulfur, Mg = Magnesium, CEC = Cation Exchange Capacity, CRA = Crumbling Ability, WEV = Wind Erosion Vulnerability, SV = Slaking Vulnerability, SCI = Soil Compaction Index, PAW = Plant Available Water, SOM = Soil Organic Matter, PPN = Plant Parasitic Nematodes, SBP = Soil-Borne Pathogens.

Soil quality tactical scenario

In the soil quality tactical scenario (*st*) the model maximizes EVL while fulfilling soil quality thresholds by changing cover crop choice, manure & fertilizer application and crop residue management. Cover crops are planted to achieve the soil cover requirement. On sandy soil, winter radish and *avena strigosa* are the preferred cover crops: winter radish is a non-host for the nematode *meloidogyne chitwoodi* and *avena strigosa* is a non-host for the nematode *pratylenchus penetrans*. By choosing these cover crops, the model is able to fulfill the soil cover constraint without violating the nematode constraint. Cattle slurry is preferred over pig slurry as it allows a higher input of K and SOM. This results in a decrease in EVL generated with manure compared to the profit scenarios, e.g. €29 ha^{-1} in *CE_st* compared to €68 ha^{-1} in *CE_p*. On sandy soil, applying additional compost helps to meet the SOM target value. Because input of compost is a cost, EVL generated with manure application decreases with respectively €45 ha^{-1} for *SE_st* and €101 ha^{-1} for *SI_st* compared to the baseline. Model results show a substantial decrease in fertilizer usage. The application of N fertilizer is reduced with approximately 50% in all *st* scenarios. P and K fertilizer are barely used anymore. Subsequently, EVL increases in the range of €78 ha^{-1} in *SE_st* up to €181 ha^{-1} in *CI_st* compared to baseline. S and Mg fertilizer are applied on sandy soil to reach the target values. Betacal, available as a rest stream from sugar beet processing, is applied to increase and maintain pH at low costs. Even with soil quality constraints, crop residues are sold in all scenarios to generate additional EVL.

Soil quality strategic scenario

The soil quality strategic scenario also allows for changes in the cropping plan and crop rotation. In *CE_ss* a 5-year rotation with sugar beets, seed onions and winter wheat is preferred. Within the 50% space for intensive crops, sugar beets and seed onions have the highest EVL. In *CI_ss* 75% of the rotation can include intensive crops. Compared to the baseline, this scenario changes by increasing the frequency of seed onions and lowering the frequency of ware potatoes and sugar beets. A similar pattern can be observed in *SE_ss* and *SI_ss*. In *SE_ss*, silage corn is still cultivated despite its low revenue because there is no better alternative: 50% of the rotation must be filled with extensive crops and two consecutive cultivations of winter barley are not allowed. The ability to choose other cropping plans and crop rotations substantially increases the EVL while soil quality thresholds (except SCI) can be achieved; e.g., the increase in total EVL of CE_ss compared to CE_b is €940 ha^{-1}.

Table 4.7 – Production Management choices made by bio-economic modeling approach FARManalytics for scenarios on arable farm types in the Netherlands.

			Covercrops										Crop residues *(s: sell/ k: keep)*										Manure (*avg. ton ha*$^{-1}$ *y*$^{-1}$)			Lime	Fertilizer (*avg. kg ha*$^{-1}$ *y*$^{-1}$)				
Nr	Scenario	Crop rotation (-)	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	type 1	type 2	type 3	*(avg. ton ha-1 y-1)*	N	P	K	S	Mg
1	CE_b	WP-WW-SB-WW-WP-WW-SB-WW		WR$_a$		WR$_a$		WR$_a$		WR$_a$				k		k		k		k			CS: 20	CSM: 10			130	0	34	7	18
2	CE_p	WP-WW-SB-WW-WP-WW-SB-WW												s		s		s		s			CS: 7.5	PS: 12.5			77	0	0	0	0
3	CE_sqt	WP-WW-SB-WW-WP-WW-SB-WW		OVP$_s$		OVP$_s$								s		s		s		s			CS: 31.7	PS: 3.2			64	0	0	3	3
4	CE_sqs	SO-WW-SB-WW-WW		OVP$_s$										s		s	s						CS: 19.2	PS: 8			65	0	0	2	2
5	CI_b	WP-WW-SO-SB-WP-WW-CA-SB		YM$_a$				YM$_a$						s				s					CS: 10	PS: 13.1			110	0	69	14	14
6	CI_p	WP-WW-SO-SB-WP-WW-CA-SB												s				s					CS: 7.5	PS: 12.5			48	0	0	0	0
7	CI_sqt	WP-WW-SO-SB-WP-WW-CA-SB		OVP$_s$	AV$_s$			OVP$_s$		AV$_s$				s				s					CS: 40				48	0	0	4	4
8	CI_sqs	WP-WW-SO-SB-WP-CA-WW-SO-SB-WW		OVP$_s$	AV$_s$				OVP$_s$			AV$_s$		s				s			s		CS: 29.6	PS: 4.0			45	0	6	3	3
9	SE_b	WP-SC-WB-SB-WP-SC-WB-SB			WR$_a$				WR$_a$						k				k				CS: 22.5	CSM: 3.1	GFTC: 5		90	3	59	4	0
10	SE_p	WP-SC-WB-SB-WP-SC-WB-SB													s				s				PS: 15.4				44	0	0	0	0
11	SE_sqt	WP-SC-WB-SB-WP-SC-WB-SB	AV$_s$		OVP$_s$				AV$_s$						s				s				CS: 28.5	GRC: 11.0		BET: 1.3	48	0	32	16	15
12	SE_sqs	SB-SC-WB-SO-WB-SB-WB-SC-SO-WB			AV$_s$		AV$_s$			AV$_s$					s		s		s			s	CS: 27.2	GFTC: 1.6	GRC: 9	BET: 1.3	39	0	0	18	15
13	SI_b	WP-WB-SB-CA-WP-SC-SB-SO		WR$_a$				RY$_s$	RY$_s$	YM$_s$				s									CS: 29.4				90	13	67	2	0
14	SI_p	WP-WB-SB-CA-WP-SC-SB-SO												s									PS: 15.4				35	0	0	0	0
15	SI_sqt	WP-WB-SB-CA-WP-SC-SB-SO		WR$_s$			AV$_s$	AV$_s$	AV$_s$					s									CS: 25	GRC: 13.3		BET: 3.7	48	0	40	16	15
16	SI_sqs	WP-WB-SO-SB-WP-CA-WB-SO-WB-SB		AV$_s$					AV$_s$		AV$_s$			s					s		s		CS: 14.3	GRC: 8.7	GFTC: 1.5	BET: 1.3	45	0	10	14	13

Farm types: CE: Clay Extensive, CI: Clay Intensive, SE: Sand extensive, SI: Sand intensive

Scenarios: b: baseline, p: profit, st: soil quality tactical, ss: soil quality strategic

Crop acronyms: WP: Ware potatoes, SB: Sugar beets, CA: Carrots, SO: Seed onions, WW: Winter wheat, WB: Winter barley, SC: Silage corn

Cover crop acronyms: WR: Winter radish, OVP: Mixture of oats, vetch and phacelia, YM: Yellow mustard, AV: Avena Strigosa, RY: Winter rye.
$_a$ = autumn termination, $_s$ = spring termination.

Manure: PS: Pig slurry, CS: Cattle slurry, CSM: Cattle solid manure, GFTC: GFT compost, GRC: Green compost

BET = Betacal flow (Liquid lime-rich res stream available from sugar beet processing).

Table 4.8 – Economic Value of Land as economic indicator broken down in its different components for scenarios on arable farm types in the Netherlands.

		Scenarios															
pm element	*unit*	*CE_b*	*CE_p*	*CE_st*	*CE_ss*	*CI_b*	*CI_p*	*CI_st*	*CI_ss*	*SE_b*	*SE_p*	*SE_st*	*SE_ss*	*SI_b*	*SI_p*	*SI_st*	*SI_ss*
crop	(€ ha^{-1})	1222	1222	1222	1683	1672	1672	1672	1803	697	697	697	1087	1113	1113	1113	1252
cover crop	(€ ha^{-1})	-178	0	-88	-70	-80	0	-172	-138	-89	0	-129	-102	-163	-42	-172	-102
manure	(€ ha^{-1})	-10	68	29	32	58	68	28	35	-6	77	-51	-43	29	77	-72	-44
crop residue	(€ ha^{-1})	0	150	150	180	75	75	75	90	0	62	62	100	31	31	31	75
fertilizer	(€ ha^{-1})	-256	-123	-108	-107	-264	-76	-83	-81	-201	-71	-123	-84	-218	-55	-130	-97
land	(€ ha^{-1})	-1100	-1100	-1100	-1100	-1100	-1100	-1100	-1100	-600	-600	-600	-600	-600	-600	-600	-600
total	**(€ ha^{-1})**	-322		105	618	361	639	420	609	-199		-144		192	524	170	484

Farm types: CE = clay extensive, CI = clay intensive, SE = sand extensive, SI = sand intensive.
Scenarios: b = baseline, p = profit, st = soil quality tactical, ss = soil quality strategic.

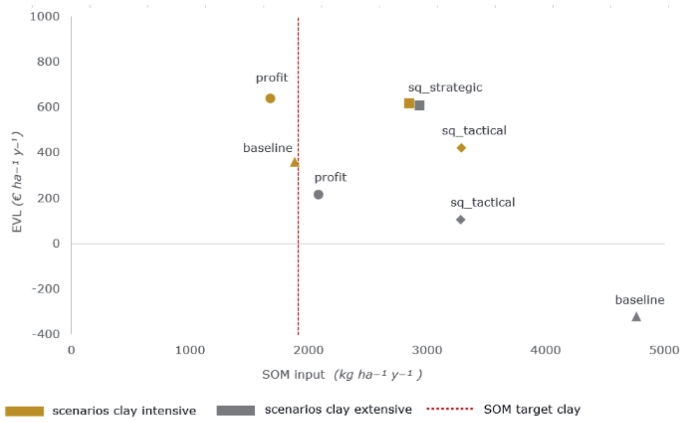


Figure 4.4A - Trade-off plot for Soil Organic Matter (SOM) input vs. Economic value of Land (EVL) based on outcomes of bio-economic modeling approach FARManalytics for standard farms on clay soil.

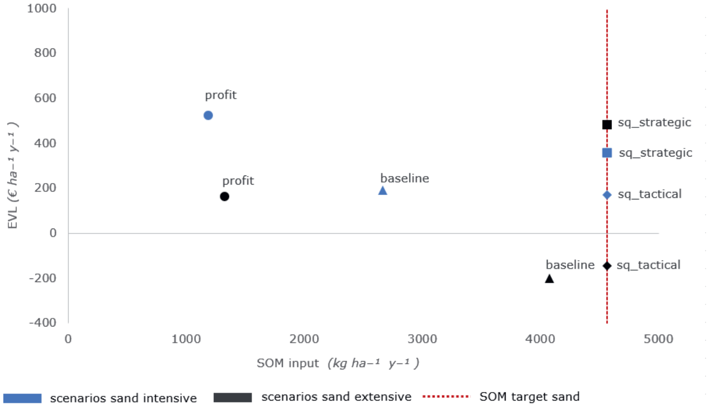


Figure 4.4B - Trade-off plot for Soil Organic Matter (SOM) input vs. Economic value of Land (EVL) based on outcomes of bio-economic modeling approach FARManalytics for standard farms on sandy soil.

Trade-off analysis

From the above it becomes clear that SOM is one of the most limiting soil quality indicators, especially on sandy soils. To illustrate the models' capability for more in-depth analyses, Figure 4.4A and Figure 4.4B present a trade-off plot for SOM input against the EVL for all scenarios. The baseline scenarios for clay extensive and sand extensive perform well on SOM input but poor on EVL. This is exactly the other way around for the profit scenarios on clay intensive and sand intensive: these scenarios result in high EVL but low SOM input. SOM input is a limiting factor on sandy soil, but not on clay soil as all the optimized scenarios on clay soil are exactly on the target value. The trade-off plots show that when the model is able to change more PM decisions (i.e., crop rotation in soil quality strategic scenarios), the trade-off between SOM and EVL can be overcome. For all farm types, the SOM threshold can be met while increasing EVL compared to the baseline scenarios.

All model input data, model settings and results are available via online Appendix A4-4.

4.5 Discussion & conclusions

The objective of this study was to develop and illustrate FARManalytics, a bio-economic modeling approach to maximize economic returns expressed as Economic Value of Land (EVL) while preserving soil quality. FARManalytics is illustrated for scenarios on four standard farm types in the Netherlands.

4.5.1 Model outcomes and model behaviour

For FARManalytics to provide added value, it should provide credible outcomes with regard to soil quality indicators and farm economics in different scenarios.

Baseline scenario
The model is able to calculate the impact of current farmers' production management on soil quality and economic value of land (EVL) on different soil types and scenarios. For example, the farm types "clay intensive" and "sand intensive" have a higher EVL but a lower score on the soil quality indicators soil organic matter (SOM) input and subsoil compaction vulnerability compared to the farm types "clay extensive" and "sand extensive". The model calculates correctly that crop and soil requirement differ per soil type i.e., higher levels of SOM, lime and nutrients on sand compared to clay.

Profit scenario
When farmers optimize their management for short-term profit few soil quality constraints are applied, only legal nutrient norms and a requirement for sufficient nitrogen (N) input are taken into account. As expected, cover crops are not implemented as they have a negative direct impact on EVL and in the absence of soil quality constraints there is no incentive to do so. Pig slurry is the preferred manure type, as it is available at a price premium for the arable farmer. This is confirmed by substantial decreases in fertilizer use because except for N, for which there are no minimal nutrient input requirements. Crop residues are always sold to generate additional revenue.

Soil quality tactical scenario
In the tactical scenario, soil quality constraints are applied and the model is allowed to change the cover crops, manure, fertilizer and crop residue management within the existing rotation. The model can meet the soil quality targets without implementing relatively costly (ca. €250 ha^{-1}) cover crops. This contradicts current common practice in Dutch arable farming where cover crops such as winter wheat are grown after all early harvested crops. Farmers' might perceive additional benefits from cover crops than those currently included in our soil quality indicator set. The agronomic benefits of cover crops are also broadly acknowledged in literature including soil organic matter build-up, minimal nutrient losses and improved soil structure (Hao et al. 2023; Adetunji et al. 2020). The types of cover crops themselves are credible: on clay soil oats, vetch and phacelia are preferred as they are vulnerable to frost, do not regrow and provide up to 75 kg N ha^{-1} for the following crop. On sandy soil, winter radish and *avena strigosa* are preferred as they do not host problematic plant-parasitic nematodes. Regarding manure, cattle slurry and compost are preferred over inorganic fertilizers and pig slurry. Cattle slurry is freely available and a valuable source of nutrients and SOM. Additional compost is applied on sandy soil, as it can provide more organic matter per unit phosphorous (P), where the P application is legally limited by manure regulations. Taking all soil quality constraints into account, the model is still able to substantially reduce fertilizer use. These results differ greatly from the current practice in the baseline scenario. Regarding N, one explanation is that the model considers, contrary to current practice, all possible sources of N (i.e. deposition, soil mineralization and mineralization from manure). However, N losses such as volatilization, leaching and denitrification during the growing season are not taken into account which may lead to an overestimation of the amount of available nitrogen. Given the organic matter and nutrient inputs via manure and compost, in combination with the relatively high contents in the soil, P and potassium (K) fertilizer are not needed. Even with all soil quality constraints in place, crop residues of winter wheat and winter barley can be sold in all scenarios. Selling these crop residues results in additional EVL (€250 - €300 ha^{-1}) while the associated removal of nutrients and SOM can be compensated by other management choices (i.e. applying manure or growing cover crops). Nevertheless, this result is remarkable: on Dutch farms it is common practice to keep the crop residues on the field for their perceived benefits on soil quality.

Soil quality strategic scenario
Changing the cropping plan or crop rotation had a substantial impact on the EVL on farm level, particularly when onions were included. This finding illustrates the added value of our economic calculation framework for crop EVL in line with the conclusions drawn by Mattetti et al. (2022) who state

that “the existence of robust and reliable cost is of outmost importance for making informed decisions”. Our findings correspond to those of others, e.g. Alfandari et al. (2015) and Capitanescu et al. (2017), who show that the cropping plan is of major importance for both agronomical and economic performance. Despite the pivotal role of the cropping plan, inclusions of other PM decisions such as cover crops, manure, fertilizer and crop residues are crucial to meet soil quality thresholds (Dogliotti et al. 2005). For example, soil organic matter can be optimized by applying manure or compost and growing cover crops. The soil quality threshold can never be met solely based on changes in the cropping plan.

Synthesis
Nutrient management, soil compaction and soil organic matter input pose major challenges for soil quality in the Netherlands (Mandryk et al., 2014; Ros et al., 2022; Silva et al., 2021). Numerous studies recommend PM decisions based on models, field experiments or statistical analysis. For example:

- Silva et al. (2021) studied the impact of different nutrient sources (fertilizer, manure) on N uptake efficiency and N surplus.
- Hanse et al. (2011) studied the impact of subsoil compaction on sugar beet yield and found that lower soil stress caused by lower axle load and less field operations reduce the occurrence and impact of soil compaction.
- Hijbeek et al. (2018) studied farmer intentions to adopt production management decisions such as input of animal manure or compost, cereal crops in crop rotation and cover cropping to increase SOM content.

All these studies focus on management recommendations for a specific indicator on field level. However, the decision-making process at the farm level must take all soil quality aspects into account in a specific socio-economic context (Schreefel et al., 2022). FARManalytics allows to make decisions with a holistic view on soil quality and the inclusion of socio-economic aspects can help to select production management decisions that ensure the long-term preservation of soil quality while maintaining a financially robust strategy. This is illustrated in the sand soil quality scenarios, where an ambitious SOM threshold has to be met: the solution provided by FARManalytics is to use a combination of compost and slurry and still sell crop residues. The input of compost and slurry ensures sufficient input of SOM and nutrients, while selling crop residues increases the EVL.

4.5.2 Model evaluation

FARManalytics is a bio-economic modeling approach that integrates the impact of production management choices on soil quality and economics at farm level. However, the current set-up of FARManalytics has some limitations.

Soil quality indicator selection
Compared to some other studies, on soil quality indicators, our study contains a limited number of physical and especially biological indicators (Dominati et al., 2010; Greiner et al., 2017; Jónsson & Davídsdóttir 2016). Bünemann et al. (2018) review studies with a more extensive set of physical indicators (e.g., penetration resistance, hydraulic conductivity and aggregate stability) and biological indicators (e.g., soil respiration, earthworms, and microbial diversity). The main reasons why we did not include these indicators are: (1) their evolution over time as a result from production management could not be calculated, (2) indicator data is not available or (3) threshold values are not available. Bünemann et al. (2018) and Ros et al. (2022) also described this limitation.

Soil quality indicator set-up
The current indicator set is based on Dutch national circumstances, calculations and samples. We believe this approach is justifiable, as agronomy is always controlled by local site conditions and no commonly accepted international set of soil quality indicators is available. The indicator set can, however, be extended to other site conditions: indicators and constraints can be supplemented or replaced by more representative ones for other countries to do comparable analyses. For some quality indicators (e.g., Cation Exchange Capacity and plant parasitic nematodes), thresholds are based on expert judgement. Broader application and validation would be encouraged to generate field experimental evidence. Detailed limitations and recommendations for every soil indicator are provided in the soil quality factsheets in Appendix A4-3.

Target-oriented approach

FARManalytics uses a target-oriented approach in which the required value of soil quality indicators and PM is derived from a target yield level that does not respond dynamically to the environment (Van Ittersum & Rabbinge, 1997). However, one of the key questions that remains is: how does crop yield and future EVL respond to changes in soil quality? Answering this question requires detailed production functions where yield is a function of soil quality. Although such functions exist for individual components, such as nitrogen and are included in crop models e.g. Jones et al., (2003), to the best of our knowledge such functions are currently not able to capture soil quality and its interrelations as a whole. We recommend that such functions are based on long-term field experiments. Examples where such functions can be based on can be found in Bongiorno et al. (2019), Schrama et al. (2018) and Korthals et al. (2014).

Production management decisions

Although the current set-up covers the most crucial production management decisions, the model can be extended to include additional decisions. First, we suggest including crop cultivar selection, as different cultivars of the same crop can have substantially different impacts on soil quality. Second, more detailed decisions regarding machinery used in field operations could be included as a means to control the limiting indicator subsoil compaction vulnerability.

Risks & uncertainty

FARManalytics is a static and deterministic model with the objective to maximize EVL. However, in reality dynamics (e.g., weather circumstances) and uncertainty (e.g., fluctuating input- and output prices) are of pivotal importance (Ridier et al., 2016; Lien & Hardaker, 2001). Farmers might be willing to implement PM with lower returns, but also at lower risks and uncertainty (Dury et al., 2012). A first step to gain more insight in the risks and uncertainty involved in production might be to do a sensitivity analysis on model inputs and run different worst- and best-case scenarios (Kleijnen, 1994). A more thorough solution is to explore the options for stochastic or robust optimization (Najafabadi et al., 2019; Yue et al., 2022).

4.5.3 Implications for use of model

Our study proves that integrating soil quality and economics at farm level contributes to solving the socio-economic challenge of sustainable soil management. FARManalytics can be used as a decision support system in the following contexts:

- *Policy impact analysis:* FARManalytics provides insight in the impact of current management on farm economics and long-term soil quality based on a reasonable number of input variables that are commonly available. When combined with representative farm types such as the farm types in this study, this can yield valuable information on where issues with soil quality will arise. FARManalytics can provide alternative PM decisions that increase farm level EVL while preserving soil quality. These results can provide insight in the effectives of different production management decisions on soil quality and farm EVL, and can therefore inform policy on sustainable soil management.
- *Farm-level decision support*: FARManalytics can be tailored to individual farms for a thorough economics analysis, informing decisions to increase short-term income. One example, from the scenarios in this study is to cultivate more seed onions instead of ware potatoes. When tailored to individual farms, FARManalytics can also provide insight in the expected development of soil quality and EVL. Common strategies to achieve maximum sustainable EVL for the scenarios in this study are (1) optimizing the cropping plan, (2) reducing fertilizer use and (3) selling crop residues. Optimal alternative strategies are strongly dependent on the initial soil status and economic situation of the farm, but FARManalytics can be tailored to fit the specific circumstances of farms. For credible results at farm-level it is of outmost importance that the input data is complete and matches local and farm conditions.

The following potential future developments could further improve FARManalytics:

- Inclusion of more physical and biological indicators. Availability of sound soil quality indicators and subsequent agronomic advice hampers further extension of the model.
- Integration stand-alone tools: FARManalytics provides integral insight in crops, cover crops and manure and fertilizer application at a level of detail comparable to other stand-alone tools. Integrating more tools into FARManalytics will make FARManalytics more userfriendly for bio-economic modeling of individual farms.
- Link to farm management systems: Many of the inputs for FARManalytics are already registered in farm management systems. Direct integration would make FARManalytics modeling more straightforward.

4.5.4 Conclusions

- This study presents and illustrates FARManalytics, a bio-economic model that provides quantitative insight in the economic aspects of sustainable soil management at farm level.
- Subsoil compaction vulnerability, soil organic matter input and plant-parasitic nematodes are identified as the main soil quality issues.
- Farm income can increase with up to €940 ha^{-1} $year^{-1}$ on clay soil and with €683 ha^{-1} $year^{-1}$ on sandy soil by appropriate management.
- The main shortcoming of the model are the limited number of physical and biological soil quality indicators included and the static and deterministic modeling approach.
- FARManalytics for standard farm types can inform policy impact analysis. If required data are available, FARManalytics can be tailored to individual farms.

4.6 References

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Appendices

A4-1 Soil quality indicator selection

Table A4-1 : For every indicator it is listed whether they failed (f) or passed (p) the selection criteria for soil quality indicators defined in Section 2.1. Those in green are included, those in yellow are included in adjusted form. Indicators in red are excluded.

	indicator theme	OSI	unit	criteria check	BLN	unit	criteria check
1	Nitrogen (N)	N supplying capacity soil	(kg ha-1 year-1)	f:1, p: 2,3	Potentially mineralisble nitrogen (PMN)	g kg-1	f: 1,2,3
					N total	mg kg-1	f:1, p: 2,3
2	Phosphoruous (P)	P availability index	(index)	p: 1,2,3	P soil stock (P-Al)	g P205 100g-1	p: 1,2,3
					P plant available (P CaCl2)	mg P kg-1	p: 1,2,3
3	Potassium (K)	K availablity index	(index)	p:1,2,3	K soil stock (K - CEC)	mmol+ kg-1	p: 1,2,3
					K plant available (K-CaCl2)	mg K kg-1	p: 1,2,3
4	Sulphur (S)	S supplying capacity soil	(kg ha-1 year-1)	f:1, p: 2,3			
5	Magnesia (Mg)	Mg availability index	(index)	p:1,2			
6	Zinc (Zn)	Zn availability	(mg kg-1)	f:1			
7	Cupper (Cu)	Cu availability	(mg kg-1)	f:1			
8	Acidity (pH)	pH	(-)	p: 1,2,3	pH	(-)	p: 1,2,3
9	Cation Exchange Capacity (C	CEC	mmol+ kg-1	p: 1,2,3			
10	Topsoil structure	Aggregate stabiliy (CEC occupation)	(% CEC-1)	p: 1,f: 2,3	Aggregate stability (wet sieved water stable a	(-)	p: 1, f:2,3
		Crumbling ability	(index)	p: 1,2,3			
		Slaking vulnerability	(index)	p: 1,2,3			
		wind erosion vulnerability	(index)	p: 1,2 f:3			
11	Subsoil structure	Subsoil compaction risk	(index)	p:1, f: 2,3	Penetration resistance (penetrometer)	(mPa)	p: 1, f:2,3
					Dry bulk density (guts)	(kg m3-1)	p:1, f:2,3
12	Soil water regulation	Soil Water Content (PTF)	(m3 m-3)	p: 1,2,3	SWC (Pedotransfer/sandbox)	(m3 m-3)	p: 1,2,3
		Drought/wetness yield loss	(% yield loss)	p: 2, f: 1,3			
13	Soil Organic Matter (SOM)				SOM content	%	p: 1,2,3
					Soil Organic Carbon	%	f: 1, p: 2,3
					Decomposable fraction organic matter	mg kg-3	f: 1,2,3
14	Pathogenic soil life	Nematode development (draft)		p:1,2 f:3	Plant parasetic nematodes	# 100 ml-1	p:1 f: 2,3
15	Beneficial soil life	Microbial activity (PMN)	g kg-1	f: 1,2,3	Nematodes populaton & diversity	taxa 100 ml-1	p:1, f:2,3
		Plague and disease resistance	% SOM	SOM included	Bacterial biomass		p:1, f:2,3
					Fungal biomass		p:1, f:2,3
					Earthworm population & diversity	taxa m-2	p:1, f:2,3

A4-2 Soil quality interrelations

Table A4-2: Interrelations between soil quality indicators. For explanation of acronyms see Table 4.1. Relations that are included in the FARManalytics model are indicated in bold.

			Independent indicators																
Dependent indicators			*Chemical*												*Biological*			*Inherent*	
category	*acronym*	*nr.*	N	P	K	S	Mg	pH	CEC	CRA	WEV	SV	SCI	PAW	SOM	PPN	SBF	TXT*	$CaCO_3$
			a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q
Chemical	N	1	■					**1f**							**1m**			**1p**	
	P	2		■															
	K	3			■			**3f**	**3g**						**3m**			**3p**	
	S	4				■									4m			**4p**	
	Mg	5					■		**5g**										
	pH	6						■							**6m**			6p	**6q**
	CEC	7						**7f**	■						**7m**			**7p**	
Physical	CA	8						**8f**		■			8k	8i	**8m**			**8p**	8q
	WEV	9									■				**9m**			**9p**	
	SV	10								10h		■	10k		**10m**			**10p**	
	SCI	11											■	11i	**11m**			**11p**	
	PAW	12											12k	■	**12m**			**12p**	
	SOM	13						13f							■			13p	
Biological	PPN	14						14f								■		14p	
	SBF	15											15k	15i			■	15p	

Description of soil quality indicator relationships are available in the digital appendix of this chapter.

Digital appendix

Digital appendices of this chapter (A4-3 and A4-4) are available via:

https://wageningenur4-my.sharepoint.com/:f:/g/personal/maarten_kik_wur_nl/Ei3GIvvwOxdLnJ4Vk4GkSokBf8r4qZcfkRr7uYNhae4iNg?e=MnVFc2

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5

Economic optimization of sustainable soil management – A Dutch case study

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5.1 Abstract

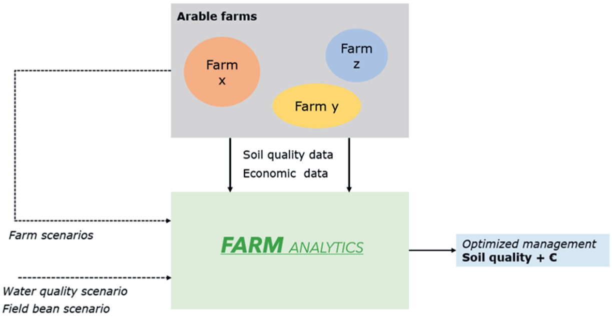
Soil quality is a major determinant of agricultural productivity and environmental quality. The sustainable management of soil can be considered an economic problem. Currently, insights into the economic value of sustainable soil management are hampered by the lack of an integrated approach to soil quality, production management, and farm economics. The objective of this study is to optimize the economic value of sustainable soil management on arable farms and to assess the impact of various management strategies. We use the bio-economic model FARManalytics. FARManalytics integrates a set of chemical, physical, and biological soil quality indicators into an economic optimization model framework. It is used to determine how production management can yield the highest farm income while preserving soil quality. We evaluated the impact of various management strategies for nine arable farms in the Netherlands that were heterogeneous in soil type, size, and cropping plans. First, we studied the performance of these farms regarding soil quality and farm economics. Second, we optimized production management to achieve maximum income while meeting soil quality targets using farm-specific scenarios, which addressed specific challenges for soil quality and the environment. Third, we explored the impact of recent policy measures to preserve water quality and to increase the contribution of local protein production to soil quality and farm economics. Nutrient status, subsoil compaction vulnerability, and soil organic matter content were identified as soil quality bottlenecks. By selecting the appropriate soil measures, the farm income could be increased up to € 704 ha^{-1} in most cases while meeting soil quality targets, with the exception of subsoil compaction. Water quality policy regulations severely limit farm management options, which reduces potential farm income. Adding field beans (*Vicia faba*) into the crop rotation could potentially replace some cereals and positively contribute to farm income and sustainable soil management. However, protein rich crops like field beans are not yet able to compete with cash crops like potatoes or onions. This study shows that sustainable soil management can increase farm income while improving soil quality. Moreover, we show that FARManalytics can be applied at farm level to solve local and regional challenges regarding agronomic and environmental targets. Further application of FARManalytics can support decision-making at farm level, for policymakers and other value chain actors.

Keywords: Soil quality, sustainable soil management, farm economics, scenario analysis, Mixed-Integer Linear Programming

Highlights

- Bio-economic modelling of soil quality and farm economics on arable farms in the Netherlands.
- In the current situation, 75% of soil quality indicators stay above critical levels.
- Bottleneck indicators are subsoil compaction and soil organic matter input.
- Farm income can be increased up to € 704 ha^{-1} while meeting soil quality targets.
- Using field beans as an alternative crop may positively affect farm income and soil quality.

Visual abstract



5.2 Introduction

Soil quality is a major determinant of crop productivity, farm resilience and environmental quality of agricultural ecosystems (Karlen et al., 1997; Kumar & Karthika, 2020; Stevens, 2018). Current unsustainable farming practices threaten soil quality worldwide (Koch et al., 2013). Subsoil compaction caused by heavy field traffic, loss of soil organic matter, acidification, decline of biodiversity, nutrient losses, and erosion are examples of such threats (Kumar & Karthika, 2020; McBratney et al., 2014; Ros et al., 2022; Yang et al., 2020). Deteriorated chemical, physical, and biological soil functions will likely have an adverse impact on crop production in the long term. Changes in the climate, like increased occurrence of droughts and floods, and a growing world population may further add to these threats at global and regional levels, making it more challenging to achieve food security (Amundson et al., 2015; McBratney et al., 2014; Wall & Smit, 2005).

Sustainable soil management has to overcome these threats by meeting present productivity needs without compromising soil quality for future generations (adapted from Smith & Powlson, 2007). Various studies have shown that good soil management practices can boost soil quality and mitigate the adverse impact of agriculture on the environment. Examples include practices to increase soil organic matter, to minimize synthetic inputs, to reduce soil disturbance, to keep soil covered, and to diversify crops and crop rotations (Adetunji et al., 2020; Castellazzi et al., 2008; Silva et al., 2021). Combining these measures creates synergies of various ecosystem services the soil provides; the optimal combination depends on the current soil quality status and on the agroecosystem properties controlling these services (Young et al., 2021)

Given the long history of efforts to embed improved soil management measures into mainstream agriculture, there are abundant studies that deal with barriers that limit the adoption of SSM in agriculture. Currently, the implementation of SSM is not evident due to the following five key limiting factors.

(1) Insufficient insights into the relationship between soil quality and farmers' production management, namely the complete set of physical and non-physical input made by the farmer (Brady et al., 2015; Kik et al., 2021a). For example, soil compaction from field traffic is difficult to measure (Rücknagel et al., 2015) and its impact on crop yield and quality is not always clear.
(2) Interactions among soil quality indicators (Bouma, 2014; Stevens, 2018) and agroecological conditions, such as weather and groundwater availability. There are trade-offs to be made where optimizing one soil quality indicator might come at the expense of another. For example, cover crops have a beneficial impact on soil structure, soil organic matter, and reduce nitrate leaching, but they might serve as a host crop for plant-parasitic nematodes (Adetunji et al., 2020; Puissant et al., 2021), reducing crop yield and enhancing soil nutrient surpluses.
(3) Trade-offs between long-term soil quality (>10 years) and annual farm income (Bos et al., 2017; Kik et al., 2021a; Stevens, 2022). Pressure on short-term profit resulting from current narrow crop margins makes it difficult to invest in long-term soil quality, in particular when farmers do not own the fields they cultivate (Stevens, 2022). Potential gains from increased soil quality are uncertain and typically manifest in the long term. For example, a higher organic matter input from compost, crop residue incorporation, or catch crops will increase the soil organic matter (SOM) content, but it is costly in the short term (Kik et al., 2023).
(4) Trade-offs between agricultural productivity and environmental quality. (O'Sullivan et al., 2018; Schulte et al., 2014; Stevens, 2018). Optimizing soil quality for agricultural productivity might come at the expense of environmental quality. For example, an economically optimal crop nitrogen (N) fertilization level might come at the cost of high N-emissions to the environment trespassing critical thresholds for groundwater quality, surface water quality, or nitrous oxide emissions (Silva et al., 2021).
(5) Proper implementation of sustainable soil management strongly depends on the initial soil quality and current farm management. Therefore, sustainable soil management must be tailored at the farm level to effectively tackle current bottlenecks and achieve the target values for soil quality indicators to sustain crop production in the long term (Young et al., 2021). If these target

values are not defined and the impact of these measures is highly site-dependent (Hannula et al., 2021), general implementation is undesirable. For example, the impact for carbon sequestration strongly depends on the current carbon saturation level of the soil (Lessmann et al., 2022; Moinet et al., 2023).

Implementation of sustainable soil management is included in numerous bio-economic models, which are among the most popular farming system redesign methods (Janssen & van Ittersum, 2007). Integrative bio-economic models evaluate trade-offs between farms and synergies between different farm management strategies, but most of these models only make tenuous references to soil quality (Schreefel et al., 2022). Examples of such studies can be found in Bos et al. (2017), Dogliotti et al. (2005), and Mandryk et al. (2014). According to Schreefel et al. (2022), models that focus on the assessment of soil quality and its multifunctionality largely lack integration of the environmental impact and socio-economic impact at farm level. Schreefel et al. (2022) therefore make a valuable contribution by integrating the Soil Navigator soil assessment model (Debeljak et al., 2019) into the FARMdesign bio-economic farm model (Groot et al., 2012). Schreefel et al. (2022) focus primarily on optimizing the multifunctionality of soil using nutrients flows and soil organic matter as soil quality indicators. The Soil Navigator uses qualitative decision rules to assess the effects of management on soil functions, and although this is a sound approach to address the multifunctionality of soil functions, quantification of the Economic Value of Sustainable Soil Management ($EVSM$) at farm level requires quantitative relationships between management and soil quality. Therefore, our aim is to build on Schreefel et al.'s (2022) approach by using the FARManalytics bio-economic modelling approach.

The aim of this study is to optimize the economic value of sustainable soil management on existing farms using FARManalytics. We define three sub-objectives:

1. Describe nine existing case farms in the Netherlands and calculate the impact of their current PM on soil quality and farm economics.
2. Optimize $EVSM$ on the case farms, based on the major challenges for implementation of sustainable soil management at farm level.
3. Explore $EVSM$ on the case farms for: (1) policy scenarios implementing stricter water quality regulations, and (2) field beans as an alternative crop in the protein transition.

We selected the Netherlands as a case study region. The Netherlands is a suitable case study region to evaluate potential sustainable farm management strategies because of its high demand for agricultural products and its intensive land use due to high land prices. We assume the farmer to be the primary actor and decision-maker with regard to sustainable soil management (Kik et al., 2021b). In this study, we focus solely on agricultural productivity and do not consider other ecosystem services as a potential additional source of farm income.

5.3 Methods

5.3.1 Model description FARManalytics

FARManalytics is a bio-economic modelling approach that combines soil quality with farm economics to preserve long-term soil quality while achieving a financially robust strategy. Figure 5.1 provides a conceptual outline of the model.

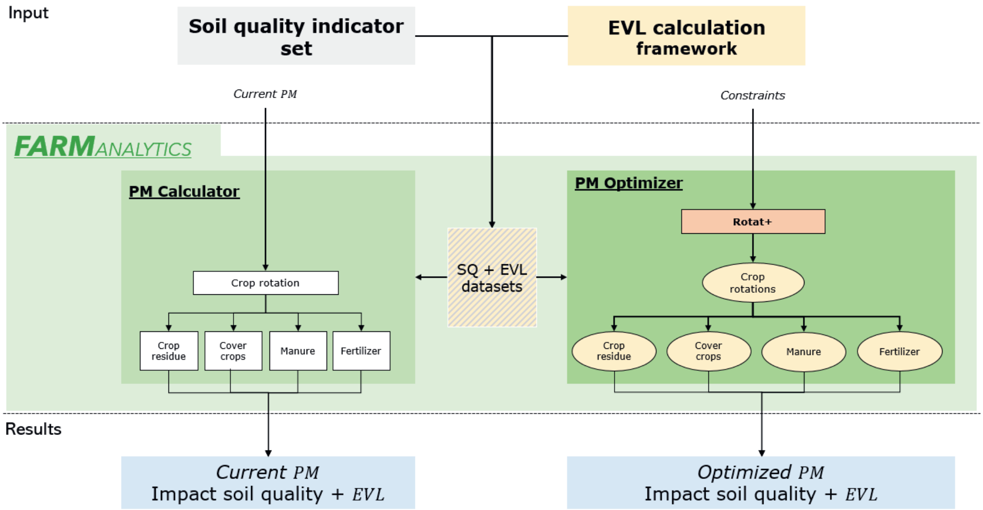


Figure 5.1 - Conceptual outline of the FARManalytics bio-economic modelling approach to optimize farmers' production management (PM) *towards maximum farm income, expressed as Economic Value of Land* (EVL) *(Kik et al., 2023)*

The two main inputs of FARManalytics are: (1) a set of soil quality indicators, and (2) an economic calculation framework. The soil quality indicator set consists of 15 chemical, physical, and biological indicators and threshold values based on studies by de Haan et al. (2021) and Ros et al. (2022). Quantitative rules of how indicators develop over time as a response to farmers' production management are a pivotal aspect of the indicator set. The economic calculation framework calculates the contribution of different production management decisions regarding farm income, expressed as Economic Value of Land (EVL). The Activity-Based-Costing (ABC) method is used to accurately assign indirect costs (e.g., for mechanizations) to production management decisions. The final results are a net EVL (consisting of potential revenues, direct costs, and indirect costs) for all production management decisions. The soil quality indicator set and economic calculation framework result in datasets that describe the impact all production management decisions covered in FARManalytics have on soil quality and economics. Table 5.1 provides an overview of the production management decisions in FARManalytics and definitions.

Table 5.1 – Definition and examples of farmers' production management decisions in FARManalytics.

Production management	Definition	Example
Cropping plan[1]	Acreage of crops and their spatial distribution within a particular year	• 50 ha winter wheat (WW) • 25 ha sugar beet (SB) • 25 ha ware potatoes (WP)
Crop rotation[2]	The sequence of crops grown on a field	• WW-SB-WW-WP • WW-WW-SB-WP
Cover crop[3]	A close-growing crop that provides soil protection, seedling protection and soil improvement between periods of main crop production	• Yellow mustard planted after winter wheat (1-Aug) and terminated before potato planting (1-Apr).
Manure	Organic matter originating from livestock husbandry or composting	• 30 ton ha^{-1} pig slurry applied 1-Mar • 20 ton ha^{-1} compost applied 1-Oct
Fertilizer	Application of plant nutrients through natural or synthetically produced fertilizer	• 200 kg Calcium Ammonium Nitrate (27% N) application on 1-May
Crop residue management	Decision to sell crop residues to generate revenue or keep them on the field to enhance soil quality	• Sell wheat straw • Keep wheat straw and incorporate it in the soil

[1]: Dury et al. (2012) [2]: Castellazzi et al. (2008) [3]: Ramesh et al. (2019)

FARManalytics consists of two modules, as outlined in Figure 5.1: PM *calculator* and PM *optimizer*. PM *calculator* is a module that calculates the impact of a pre-defined set of production management decisions on soil quality and economics. This is useful to gain insight into current soil quality and economic status. PM *optimizer* is a module that optimizes production management in terms of EVL while fulfilling soil quality constraints. To optimize the different production management decisions (Table 5.1), first, all feasible crop rotations are generated using ROTAT+ (Dogliotti et al., 2003). After this, the subset of rotations with the highest crop EVL is selected. For these selected rotations, the choices for cover crops, manure, fertilizer, and crop residue management are optimized using Mixed-Integer-Linear Programming (MILP). The MILP model maximizes EVL at farm level subject to agronomic, legal and soil quality constraints. The final outcome of PM *optimizer* is an optimized set of production management decisions and their impact on soil quality and EVL. For an extensive description of FARManalytics, we refer to Kik et al. (2023).

5.3.2 Case farms & data collection

The case farms are nine farms participating in the "Farmers Network for Soil Sampling (FNSS)" initiated by Wageningen Plant Research. The nine farms are heterogeneous with regard to key characteristics, such as location, soil type, size, and cropping plan. Table 5.2 presents the detailed farm characteristics and current production management. For each farm, we collected: (1) soil samples, (2) current production management decisions, and (3) economic data of current production management. Soil samples were retrieved for all fields and the nutrient status (of nitrogen, phosphorus, sulfur), pH, Soil Organic Matter (SOM) content, soil texture, Cation Exchange Capacity (CEC) value, were recorded. In the Netherlands, regular soil sampling is performed once every four years as part of good agricultural practice. Current production management choices – such as the cropping plan, manure, and fertilizer application (type, dose, timing, application technology) – and types of cover crops were retrieved from farm management systems or via interviews with the farmers. Economic data of current production management choices were collected using templates with pre-defined questions. To a large extent, these templates were filled with estimations made in consultation with the farmers, as a lot of the required economic data was not readily available. For example, in order to calculate the costs of field operations, we needed to collect data on the task time and fuel demand of field operations, which farmers rarely register. For the economic data such as costs of inputs, crop prices, and crop yields, we used averages from 2019, 2020, and 2021. Table 5.2 presents an extensive overview of current farm characteristics and production management decisions.

Table 5.2 – Farm characteristics and current production management decisions for nine arable case study farms from the Netherlands. For acronyms, see below.

Nr. Farm Acronym	1 **Sand** S	2 **Sand - River clay** S-CR	3 **Loess** L	4 **Clay organic** CO	5 **Clay Nord** CN	6 **Clay River** CR	7 **Clay polders** CP	8 **Clay southwest 1** CSW1	9 **Clay southwest 2** CSW2
General characteristics									
Soil type	Sand	Sand/River clay	Loess	Sea clay	Sea clay	River clay	Sea clay	Sea clay	Sea clay
Farm type	conventional	conventional	conventional	organic	conventional	conventional	conventional	conventional	conventional
Tillage system	Plowing/Spading	Non-inversion tillage	Non-inversion tillage	Non-inversion tillage	Plowing/Subsoiling	Plowing/Subsoiling	Plowing/Subsoiling	Non-inversion tillage	Non-inversion tillage
Size	Large	Middle	Middle	Middle	Middle	Middle	Small	Middle	Middle
Crop rotation									
Crop rotation	STP-SPB-SB-SP-SC-SB-	WP-SB-KC-WW	WP-SO-SB-WW-WP-SPB	GC-CA-WB-SPI	SP - WW - WB	WP-WW-SB-WW-	SP-SB-GS-SO	WP-WW-SO-WW-WP-WW-	WP-WW-SB-WW-SP-WW
Crop rotation (continued)	STP-SC-SB-SP-SC-SPB	WP-KC-KC-WW	SB-WW-WP-SO-SB-WW	GC-SO-PE-GB		WP-WW-SO-WW	SP-SB-WW-TU	GS-PE-WP-WW-SB-SC	SO-WW-WP-WW-CA-W
Cover crops	SPB : Winter radish SC : Rye	WW : White radish KC -> KC : Avena Strigosa	WW : Yellow mustard SPB : Yellow mustard	GC : Rye WB/SPI/PE : mix 3 SO : mix 4	WW -> SB : mix 1 WW/WB -> SP : mix 2	WW: yellow mustard	SO : yellow mustard WW : grass TU : mix 5	WW : mix 2 PE : mix 2 GS : GS	WW : mix 3
Manure (ton ha^{-1})	STP$_s$: 25 PS SPB$_a$: 35 CS SB$_s$: 35 CS SB$_s$: 3 NKM SP$_s$: 20 CS SP$_s$: 2 KF SC$_s$: 40 CS SC(8 : 20 GRC	WP$_s$: 40 CS SB$_s$: 40 CS KC$_s$: 40 CS WW$_a$: 30 CS	WP$_s$: 30 PS WW$_a$: 40 CS SPB$_a$: 40 CS SC$_s$: 40 CS	GC(1) : 20 GSM$_O$ CA$_a$: 20 GSM$_O$ WB$_a$: 20 GSM$_O$ SPI$_a$: 20 GSM$_O$ SPI$_s$: 5 VKA GC(5) : 15 GSM$_O$ SO$_a$: 12 GSM$_O$ PE$_a$: 20 GSM$_O$ GB$_a$: 15 GSM$_O$	SP$_a$: 15 CSF WW$_a$: 20 CS WB$_a$: 3.5 PM	WW$_s$: 30 PS WW(5)$_a$: 30 CH	GS$_a$: 30 CH SO$_a$: 22.5 CH TU$_a$: 30 CH	WP(1)$_s$: 20 PS WW$_s$: 30 CS WW(2) : 20 CS WW(4) : 20 CS WW(9) : 20 CS GS$_a$: 20 CS SC$_s$: 30 CS	WW$_s$: 37.5 CS WW$_a$: 22.5 CSM
Liming (ton ha^{-1})	SB$_s$: 5 BET		WP$_a$: 5 BET			WP$_a$: 5 BET	SP$_a$: 5 BET		
Crop residue management	SPB : keep	WW : keep	WW : keep SPB : keep	WB : sell	WW : sell WB : sell	WW : sell	GS : keep WW : sell	WW : keep GS : sell	WW : keep
Fertilizer (kg N/P/K/S/Mg ha^{-} (cluster *a*)	N : 54 P : 3 K : 20 S : 2 Mg : 3	N : 71 P K S Mg : 5	N : 99 P K : 67 S Mg	N P K S Mg	N : 108 P : 20 K : 58 S : 26 Mg	N : 108 P K : 74 S : 31 Mg	N : 93 P : 8 K : 9 S Mg	N : 84 P : 6 K : 33 S : 45 Mg : 6	N : 118 P K : 61 S : 31 Mg : 19

Crops						**Manure**				**Cover crops**	
CA	: Carrots	SC	: Silage corn	SPI	: Spinach	BET	: Betacal	KF	: Kaliflow	mix 1	DSV Betasola
GB	: Green beans	SO	: Seed onions	STP	: Starch potato	CH	: Champost	NKM	: NaKaMag	mix 2	DSV Solarigol
GC	: Grass clover	SP	: Seed potato	WB	: Winter barley	CS	: Cattle slurry	PS	: Pig slurry	mix 3	Oats/Vetch/Phacelia
GS	: Grass seed	SB	: Sugar beets	WP	: Ware potato	CSF	: Cattle slurry solid fraction	PM	: Protamylasse	mix 4	Oats/Yellow mustard
KC	: Corn (kernel)	SPB	: Spring barley	WW	: Winter wheat	GRC	: Greencompost	VKA	: Vinasse potassium	mix 5	DSV WarmSeason
PE	: Peas					GSM$_O$	: Goat Solid Manure (organic)				

5.3.3 Scenarios

We assess $EVSM$ in four farm-specific scenarios (Section 5.3.1). Subsequently, we study the impact of two policy developments on $EVSM$ at farm level (Sections 5.3.2 and 5.3.3).

Farm scenarios

The selected farm scenarios consist of a baseline scenario, a soil quality tactical scenario, and soil quality strategic scenario, which were all the same for all farms. The farm strategic scenario consists of a farm-specific challenge. The precise definition of the farm scenarios is as follows:

- *Baseline*: Continuation of current production management during one complete rotation. Calculated with the FARManalytics module PM calculator.
- *Soil quality tactical*: Maximize farm level EVL with soil quality constraints applied. Decision variables are cover crops, manure, fertilizer, and crop residue management because these are typical production management choices that can changed in the tactical dimension.
- *Soil quality strategic:* Additional decision variables compared to "*soil quality tactical*" are cropping plan and crop rotation.
- Farm strategic: Maximize farm-level EVL with soil quality constraints applied for a farm-specific challenge. Decision variables are equal to the *soil quality strategic*" scenario. Inputs and constraint settings ware made in consultation with the farmers. Table 5.3 details the farm-specific challenges for each farm.

Table 5.3 - Challenges to be modelled with bio-economic modelling approach FARManalytics in the farm strategic scenarios, which includes a farm-specific challenge to maximize the economic value of sustainable soil management.

Farm	*Farm challenge*
Sand	Optimize crop rotation with 1:3 break crops and ware potatoes as alternative for starch potatoes
River clay - sand	Explore potential of land exchange with dairy farmers
Loess	Optimize position of onions in rotation
Clay organic	Explore potential of cut-and-carry fertilizers[1]
River clay	Maximize farm income with labor extensive crops
Clay nord	P and K fertilization from manure and explore potential of seed onions as alternative crop
Clay polders	Explore potential of land exchange with dairy farmers
Clay SW1	Optimize cropping plan and crop rotation with celeriac as alternative crop for seed onions
Clay SW2	Optimize crop rotation by increasing share of sugar beets

[1]: Cut-and-carry fertilizers are a crop of grass-clover that is cut, collected, and spread on another crop to serve as organic nitrogen fertilizer.

Stricter water quality regulations

The first policy scenario is the stricter water quality scenario. In it, we explore the impact of two recent policy measures aimed at improving surface and ground water quality in agricultural ecosystems in the Netherlands. We only chose to implement this scenario on the farms *S, CR, S-CR, L* and *CSW-1* because these farms represent different soil types and are considerably different in their current production management. The studied policy measures are: (1) the Dutch 7th Nitrate Directive Action Program, which intends to achieve the objectives formulated in the European Union (EU) Nitrate Directive; and (2) the EU Derogation Grant for 2023–2025, which includes a gradual phasing out of the exemption for the Netherlands to use more animal manure than 170 kg N ha^{-1}. Both policy measures have been implemented because the current water quality is below the standard defined in the EU Water Framework Directive, despite efforts made in the past to achieve this objective. The combined measures specified in the 7th Action Nitrate Directive Program and the EU Derogation Grant have a major impact on farmers' production management and subsequently EVL. Changes made to the current production management might be required to comply with legislation, especially for farms on sandy and loess soil. Various measures will be implemented gradually, with full implementation by 2027. For this scenario, we selected the full implementation outlined for 2027 because farmers will ultimately have to comply with these requirements farmers.

Table 5.4 presents the exact measures implemented in the water quality scenario.

Table 5.4 - Measures resulting from the 7th Action Nitrate Directive Program (ND) and Derogation Grant 2023-2025 (DER) and their implications on farmers' production management. N = Nitrogen, P = Phosphorous.

Measure	Source	Implementation	Soil types
Break crops	ND	- Compulsory break crop[1] every 3 years at field level	sand, loess
Catch crops	ND	- Recommended catch crop[2] after all crops except winter crops[3]	sand, loess
		- Discount on N norm if harvest after 1 Oct and no catch crop	
		- Compulsory catch crop after corn	all
		- No N fertilization space for cover crops (except non-legimunious cover crops after wheat, grass seed and rapeseed)	all
P norms	ND	- P in compost counts 25% for legal P norm	all
		- P in solid manure/champost counts 75% for legal P norm	all
N autumn	ND	- After August 1st, not more than 60 kg N-total via slurry	all
Buffer zones	ND/DER	- Uncultivated buffer zones next to water streams (implemented as 4% of total area)	all
Nutrient norms	DER	- 20% discount on fertilization norms in "nutrient polluted areas" (implemented as 20% discount on total N fertilization)	all

[1]: Break crops are crops with an expected positive impact on soil quality and water quality. A list of break crops is available from RVO (2022).
[2]: Catch crops are cover crops that take up residual N after cultivation of a main crop to prevent N leaching. A list of allowed catch crops is available from RVO (2023).
[3]: Winter crops are crops that do not require planting a catch crop because they have a low amount of residual N. A list of winter crops is available from RVO (2023).

In the water quality scenario we used the cropping plan, crop rotation, cover crops, manure, fertilizer, and crop residue management as decision variables. The measures resulting from stricter water quality regulations as presented in Table 5.4 were implemented as additional constraints. The detailed description of the implementation of these constraints in the model can be found in Appendix A-1.

Field beans as part of protein transition

In this scenario, we explored the potential of a protein-rich crop like field beans as an alternative in the cropping plan. Field beans are a crop that can meet the demand for a high-quality protein source as part of the protein transition towards more plant-based protein consumption (Augustin & Cole, 2022; Ofoedu et al., 2022). Compared to other crops, such as soybeans, peas, lentils, and lupin, field beans currently have the highest potential in the Netherlands for three reasons:
(1) Field beans have the highest yield potential in the cooler and humid climate (Timmer & Toren, 2022).
(2) The harvest time of field beans (early August for winter field beans and early September for spring field beans) fits better in the crop rotations than the late and therefore risky harvest of soy (late September/early October).
(3) There is currently a lot of research being done on field beans. As such, better crop cultivators with higher yield and better quality can be expected in the near future (Augustin & Cole, 2022).

Field beans are already being cultivated in the Netherlands, however, only on a limited scale (Statistics Netherlands, 2020). Therefore, information on inputs, crop yield, and output prices are not readily available. There are two types of field beans: winter field beans (planted in autumn) or spring field beans (planted in spring) (Jensen et al., 2010). We assume that spring field beans are cultivated on sandy soil and winter field beans are cultivated on clay soil. Winter field beans have higher yield potential but are susceptible to foraging during winter (Van Overveld, Limagrain Netherlands, personal communication 25 May 2023).

We calculated the costs, yields, and prices for field beans in the following way:

1. *Crop costs:* Crop costs consist of direct costs and field operation costs. Direct costs include costs for seeds and crop protection. Insights into these costs were provided by Limagrain Netherlands, one of the leading companies in the breeding of field beans (Roothaert, personal communication 25 May 2023). We assumed that direct costs were the same for all farms. Field operation costs consist of costs of mechanization, energy, labor, and contractor work for the required field operations in field beans. These costs were calculated for every farm individually.
2. *Crop yield:* To determine the crop yield, we studied results of recent trials with field beans in the Netherlands (Prins et al., 2018, 2019; Prins & Timmer, 2017; Timmer & Toren, 2022). For spring field beans, we chose to use an average yield of 5,000 kg ha^{-1}. For winter field beans, we used an average yield of 7,000 kg ha^{-1}.
3. *Crop output price*: Average prices of field beans are not registered. Therefore, we have chosen to estimate the price for field beans based on the average feed prices in the 2019–2022 period. Average feed prices expressed in EUR (€) per unit of energy (kVEM) and in EUR per kg rumen degradable protein (DVE) are registered monthly by Wageningen Livestock Research (2023). In the 2019–2022 period, the average feed price was € 0.21 kVEM^{-1} and € 0.90 kg DVE^{-1}. For the energy content of field beans, we use a value of 1,009 VEM kg product^{-1} and, for the protein content, a value of 118 g DVE kg product-1 (Limagrain Nederland, 2023). Multiplying these values with the specific average feed price results in a field bean price of € 0.32 kg^{-1}.

We multiplied the average yield and average price to get the standard revenue. Because the adaptation of a new crop in the cropping plan strongly depends on the returns, we performed a sensitivity analysis on the crop revenue. We applied changes of -25%, +25% and +50% compared to the standard revenue.

Both spring field beans and winter field beans were implemented with a minimum period of return between the crop of five years, as this is considered the upper limit for cultivation of field beans (Limagrain Netherlands, 2023) (Van Overveld, Limagrain Netherlands, personal communication 25 May 2023). Because field beans are a leguminous crop, no N fertilization is required. Moreover, we assume field beans supply 75 kg N ha^{-1} to the subsequent crop (Limagrain Netherlands, 2023).

5.4 Results

The results for the defined scenarios in the Sections 5.3.2 to 5.3.3 are structured as follows. First, we discuss the results of the four farm-level scenarios (5.4.1). Next, the results of stricter water regulations and of field beans as an alternative crop are discussed in the Sections 5.4.2 and 5.4.3, respectively.

5.4.1 Results: Farm scenarios

Figure 5.2 shows the results of the soil quality indicators in the baseline scenario.

Figure 5.2 - Results of soil quality indicators in the baseline scenario for nine case farms. "x" indicates a lower limit for the indicator. "-" indicates an upper limit for the indicator.

N = Nitrogen, P = Phosphorous, K = Potassium, S = Sulfur, Mg = Magnesium, CRA = Crumbling Ability, SV = Slaking Vulnerability, WEV = Wind Erosion Vulnerability, SCI = Subsoil Compaction Index

Overall, the case farms demonstrate commendable performance, with only a few indicators showing limitations. Moreover, most of these limitations can be addressed through simple and practical production management decisions, such as increasing sulfur fertilizer or lime application. Figure 5.2 shows that P input is a limiting factor on multiple farms due to the upper bound P norm being lower than the lower bound P fertilization advise. This implies that farmers cannot apply P according to the agronomic recommendations, because it will exceed the legal norm. Input of K is insufficient on the farm with clay soil (*CP*), which can easily be resolved by applying more K fertilizer or by opting for manure types with higher K content. Sulfur fertilization requires attention in the case of farms on sandy and loess soil (*S, S-CR, L*). A solution that is easy to implement is to apply sulfur-containing fertilizers. Farms on sand, loess, and old marine clay (*S, S-CR, L,CO*) need to their increase lime application rates to reach the target value. All farms exceed the target set by the subsoil compact index, although farms with extensive cropping plans (*CN, CO, CSW1*) come close to the target value. Input of organic matter is a limiting factor primarily due to the required increase in SOM for improving CEC on sandy soils (*S, S-CR*), or due to the reduced slaking vulnerability on loess and clay soil (*L, CR,CSW1,CSW2)*. The minimal requirement for organic matter input is to match decomposition, typically around 2,000 kg effective SOM ha^{-1} year. All farms meet this target.

Figure 5.3 shows the current cost revenue ratio and total EVL for the baseline scenario on all farms.

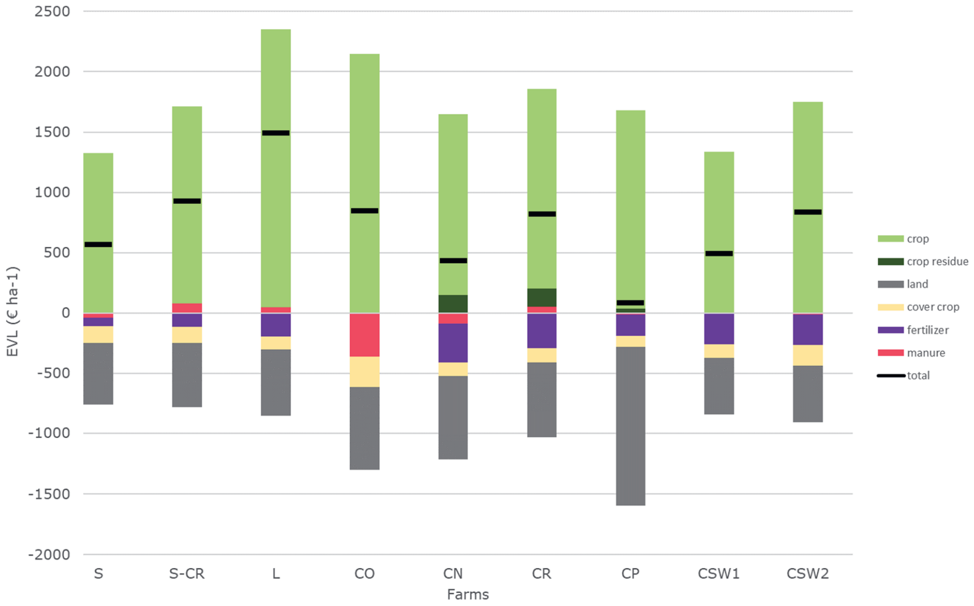


Figure 5.3 – Farm revenues and costs of current PM decisions (baseline scenario) expressed as Economic Value of Land (EVL). All components above the x-axis represent revenues, all components below represent costs. Total EVL (revenue – costs) is indicated with a black line.

Figure 5.3 shows considerable differences in total EVL between the farms in the baseline scenario. Total EVL of farm *loess* (*L*) is € 1,493 ha^{-1} whereas this is € 79 ha^{-1} for farm *clay polders* (*CP*. the differences between these farms are mainly caused by crop returns and land costs. For example, land costs on *clay polders* are €1,318 ha^{-1} while land costs on loess soil are only € 557 ha^{-1}. Additional variation in the baseline scenario is caused by differences in EVL of cover crops, manure, crop residues and fertilizers. For example, on farm *clay rivers* (*CR*) the sum of EVL all these production management decisions is € 125 ha^{-1}, compared to € 612 ha^{-1} for farm *clay organic* (*CO*). Figure 5.3 illustrates that manure can either be a cost or a revenue. Because of the high manure surplus in the Netherlands, slurry is often available at a premium. Therefore, farms that mainly apply slurry show a positive EVL for manure, which implies profit is generated by applying manure (*S, S-CR, L, CR*). Manure costs on farm *clay organic* (*CO*) are high because this farm is required to buy expensive organic manure.

Figure 5.4 shows the total EVL for the baseline, soil quality tactical, soil quality strategic, and farm strategic scenarios. A detailed overview of all production management decisions in all scenarios can be found in Appendix A-2.

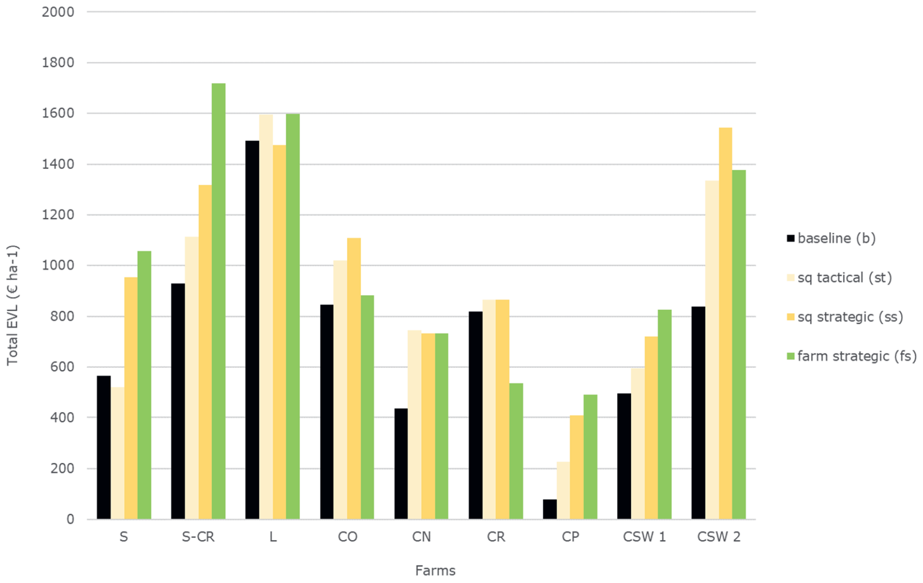


Figure 5.4 - Total Economic Value of Land (EVL) as an economic indicator resulting from optimization with bio-economic model FARManalytics for different scenarios on arable farms in the Netherlands.

For almost all farms, we observe an increase in total EVL when production management is optimized, subject to all soil quality constraints. There are substantial differences in the potential of EVL increases between farms, varying from € 47 ha^{-1} for the farm on river clay (*CR*) up to € 704 ha^{-1} for an extensive farm on clay (*CSW2*). For most of the farms, switching to other crops in the cropping plan leads to an increase in EVL (Figure 5.5A). For farm on loess soil *(L*), the soil quality strategic scenario results in a decline in crop EVL, which implies the crop rotation in the baseline scenario does not match with the agronomic constraints in the soil quality strategic scenario. The clay farm in the North (*CN*) and farm on river clay (*CR*) already have an optimal crop rotation, as evidenced by the fact that a further increase in EVL in the soil quality strategic scenario compared soil quality tactical scenario is not possible.

Aside from cropping plan changes, the main cause of increased EVL in soil quality tactical and soil quality strategic scenarios compared to the baseline scenario come from: (1) reduction in fertilizer costs; (2) increase in revenue from crop residues and; (3) lower manure costs. A decrease in fertilizer costs ranging from € 19 ha^{-1} to € 182 ha^{-1} is possible on all farms, with the exception of farm *CO*, which does not use fertilizer. In the soil quality strategic scenario, crop residues (cereal straw) are sold on all farms that do not sell crop residues in the baseline scenario (*S, S-CR, L, CO, CSW1 and CSW2*). EVL decreases in the soil quality tactical scenario for farm *S*, because in order to meet soil quality target, more cover crops have to be grown than in the baseline scenario. However, in the soil quality strategic scenario, EVL increases compared to baseline scenario: by optimizing the cropping plan with more silage corn instead of starch potatoes, soil quality targets can be met while increasing EVL.

Figure 5.5A and Figure 5.5B show how the different production management decisions contribute to a change in EVL for the soil quality strategic and farm strategic scenarios compared to the baseline scenario.

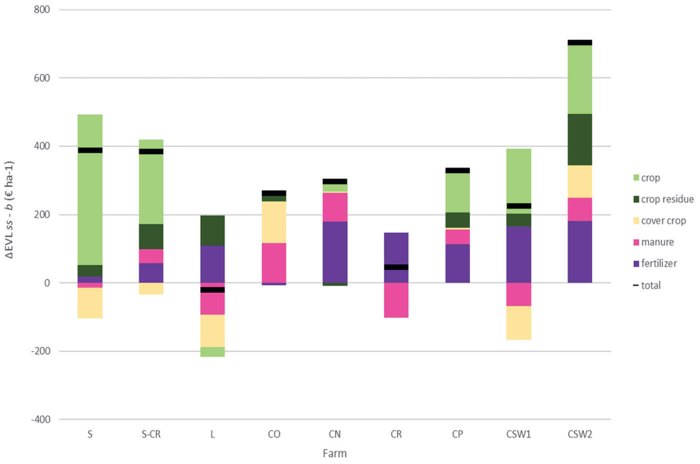


Figure 5.5A - Change of Economic Value of Land (EVL) components in "soil quality strategic scenario compared to the baseline scenario for nine arable farms in the Netherlands.

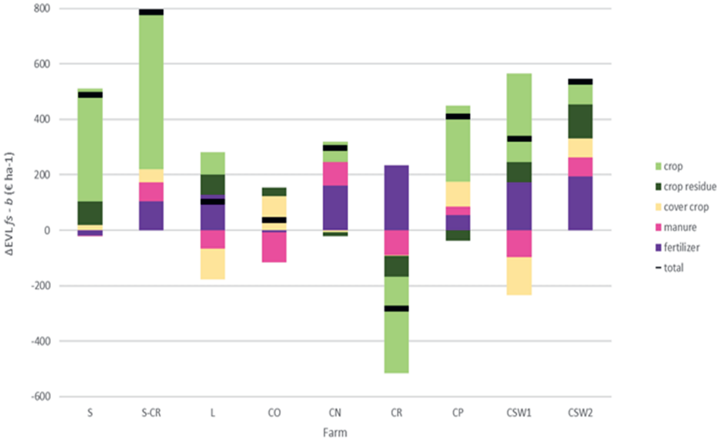


Figure 5.5B – Change of Economic Value of Land (EVL) components in the farm strategic scenario compared to the baseline scenario for nine arable farms in the Netherlands.

For most, the farm strategic scenario implied changes in the cropping plan: compared to results of soil quality strategic scenario in Figure 5.5A, Figure 5.5B shows larger changes in crop EVL. The changes in EVL for cover crops, manure, fertilizer and crop residues management in the farm-strategic scenario are similar to the changes in the soil quality strategic scenario". For the farms *sand* (*S*), *sand-river-clay* (*S-CR*), *loess*, *clay polders* (*CP*) and *clay southwest* 1 (*CSW1*) the farm strategic scenario resulted in a larger increase in total EVL than the soil quality strategic scenario. Exchanging land with dairy farmers, which was a challenge studied in the farm strategic scenario for farms on sandy soil and *clay polders (S, S-CR, CSW1*) resulted in a considerable increase in EVL compared to the baseline scenario. Switching from low-yielding seed onions to better yielding plant onions and celeriac on clay farm southwest 1 (*CSW1* increased the EVL with € 250 ha^{-1} year^{-1} compared to the baseline scenario. Growing seed onions in the farm strategic scenario on the farm clay nord (*CN)* only resulted in a minor increase in EVL compared to the baseline scenario. On farm *CSW2*, a higher share of sugar beets in the rotation, at the expense of the more profitable crops carrots and onions, resulted in lower total EVL compared to soil quality strategic scenario. The implementation of cut-and-carry fertilizer as an alternative for expensive organic solid manure on clay organic *(CO)* resulted in higher costs, decreasing EVL compared to the soil quality strategic scenario. On the farm *clay river* the farm strategic scenario centered on potential EVL without ware potatoes in the cropping plan due to labor constraints. This resulted in a decrease of EVL compared to the baseline and soil quality strategic scenarios, as ware potatoes are profitable for this farm.

Detailed model input, model settings and results of the farm scenarios are available in the digital appendix.

5.4.2 Results: Stricter water quality regulations

Figure 5.6 shows the total EVL for the scenario where production management is optimized subject to stricter water quality regulations. In addition to the "baseline" results, this figure also presents the outcomes of the "soil quality strategic" scenario, which represents total EVL in an optimized situation without stricter water quality regulations.

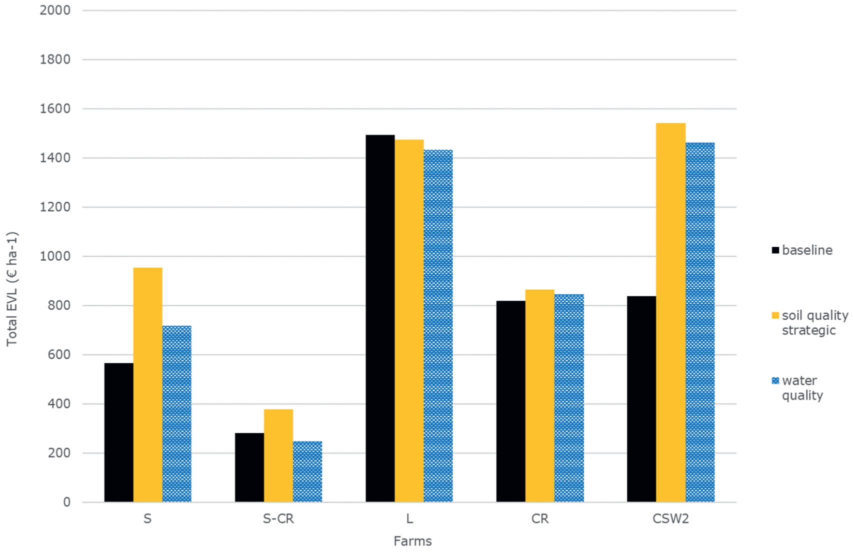


Figure 5.6 – Total Economic Value of Land (EVL) *for the water quality scenario (scenario in which production management is optimized subject to policy measures to improve water quality. For comparison, the total* EVL *from the baseline situation and total EVL for the soil quality strategic scenario in which production management is optimized without water quality restrictions is included.*

Implementing the water quality restrictions is feasible for every farm included in this analysis. From Figure 5.6 follows that for all farms the implementation of water quality restrictions results in a decline in EVL compared to the soil quality strategic scenario, a scenario without water quality. However, by optimizing their production management, farms *S*, *CR* and *CSW2* can increase their total EVL compared to the baseline scenario while meeting both soil quality targets and implementing water quality restrictions. Despite the drastic measures (such as compulsory break crops) for the farm on sandy soil (*S*, the farmer can increase EVL due to land exchange with dairy farmers. On clay soil (*CR, CSW2*), the impact of water quality restrictions is substantially less compared to sand and loess. On farms *S-CR* and *L*, EVL decreases compared to the baseline scenario. This implies that despite the optimization of production management, implementation of water quality restrictions goes at the expense of income.

Both farms have to comply with all water quality measures (Table 5.4). Farm *S-CR* has to grow more rest crops, which are not very profitable. On farm *L*, the main driver for the loss in EVL are the non-cultivated buffer zones.

Detailed model input, model settings and results of the water quality scenarios are available in the digital appendix.

5.4.3 Results: Field beans as part of protein transition

Figure 5.7 presents the total EVL for the field bean scenario and the results of the sensitivity analysis. For comparison also the results of the baseline and the soil quality strategic scenarios: the optimized scenario without field beans (soil quality strategic scenario) is included. The production management decision in the field bean scenario can be found in Appendix A-3.

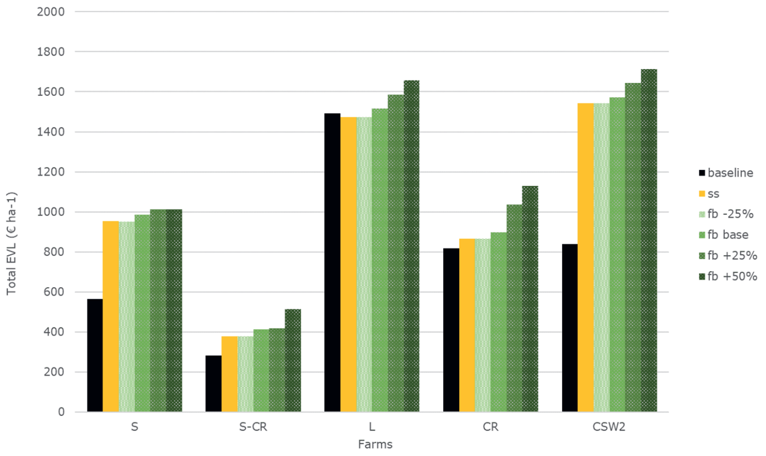


Figure 5.7 – Total Economic Value of Land (EVL) for scenarios that explore the potential of field beans as an alternative crop on arable farms in the Netherlands. In the field bean base, field beans are added with their EVL based on their current revenue. fb -25%, fb+25% and fb+50 are results of a sensitivity analysis with -25%, +25% and +50% of the revenue compared to the base. The total EVL from the baseline scenario and the soil quality strategic scenario (cropping plan optimized without field beans) is included for comparison.

From Figure 5.7 follows that based on current yield and current prices of field beans in the field beans baseline, field beans can be considered as a serious alternative crop in the cropping plan of all considered farms since EVL increases compared to an optimized scenario without field bean (soil quality strategic scenario). However, if the revenue of field beans decreases with 25%, total EVL does not increase compared to the soil quality strategic scenario, which implies that based on that revenue field beans are not an interesting alternative. Based on the sensitivity analysis fb+25% and "fb+50%" the share of field beans in the rotation increases on farms *S*, *S-CR* and *CR*. On farms *S* and *CR*, the crop frequency of field beans approaches the maximum of 0.2. On farms *L* and *CSW2* the share of field beans remain equal compared to the field been baseline.

Detailed model input, model settings and results of the field bean scenarios are available in the digital appendix.

5.5 Discussion

The objective of this study was to optimize the economic value of sustainable soil management ($EVSM$) on nine case farms in the Netherlands in future scenarios using the bio-economic modelling approach FARManalytics. We studied $EVSM$ in (1) farm-level scenarios, (2) a scenario on the implementation of stricter water quality regulations (3) a scenario in which we studied the potential of field beans as part of the protein transition.

5.5.1 Outcomes of the study

Soil quality bottlenecks and economic performance in the baseline

The evaluated farms perform relatively well regarding their impact on soil quality: most of the soil quality indicators are above critical thresholds needed for sustainable crop growth. Ros et al. (2022) report similar findings when they applied their Open Soil Index framework on all agricultural fields in the Netherlands. The main current soil quality bottlenecks are organic matter input, subsoil compaction and nutrients. These findings are confirmed by Mandryk et al. (2014) who found that improving SOM was one of farmers' the most important goals. Van den Akker & Hoogland (2011) confirm this too; they found subsoil compaction was a major bottleneck in soil quality in the Netherlands. Finally, Ros et al. (2022) found insufficient sulfur availability on 49% of the Dutch agricultural fields. In the baseline, there are considerable differences in current economic performance between farms. This is supported by the annual farm income estimate derived from national monitoring networks (Wageningen Economic Research, 2022). For example, in 2021, it was found that the difference in farm income between the 20% best performing farmers and the 20% worst performing farmers was € 74,000 at farm-level.

Improving production management in the tactical dimension

In the soil quality tactical scenario, choices of cover crops, manure, fertilizer, and crop residue management were optimized within the farms' current crop rotations. For seven out of nine farms, farm income increased substantially while achieving all soil quality targets except subsoil compaction, due to the appropriate selection of production management decisions. Cover crops are planted to the same extent as currently done by all farmers. Preferred cover crops are *avena strigosa*, yellow mustard, and winter radish. These cover crops fit best in requirements regarding frost vulnerability, regrowth, rooting, and plant-parasitic nematode development. The most preferred manure type includes cattle slurry and compost due to their economic value and composition. Cattle slurry is available for free or at a price premium, has a high content of nutrients (in appropriate proportions), and the amount of effective organic matter per unit phosphorus is amongst the highest of the different types of manure available. Compost is applied as a source of organic matter because it fits best in the limiting application space for phosphorous (P). On average, the allowed P dose applied through compost is twice that of animal manure due to the low plant availability of P in the compost. Solid manure is not preferred because of its higher costs and lower levels of plant available nutrients. This is contradictory to the general "feeling" of farmers that solid manure is the best type of manure for the soil (Van Eekeren et al., 2009). In the literature, there is no consensus about the best manure type. However, a general conclusion is that application of any type of manure is beneficial for soil quality compared to no manure being applied (Zavattaro et al. 2017) due to the addition of carbon and base cations. P and potassium (K) fertilizers are not applied anymore. According to the P & K recommendations made in the CBAV, (2022), in FARManalytics, P & K recommendations can be fulfilled with the application of manure and compost alone, which is supported by findings of de Vries et al. (2023). These findings show that, at the national scale of the Netherlands, P and K input is achieved almost entirely with manure. Model results show a substantial decrease in nitrogen (N) fertilizer use compared to current practices. Possible reductions in N fertilization are also indicated by Oenema et al. (2009), Silva et al. (2017), and Silva et al. (2021).

There are large differences between farms in terms of current nitrogen use. A potential solution to more effectively applying N fertilizer might be by implementing best practices from peers (Lamkowsky et al., 2021). Based on Van Der Burgt et al., (2006), the FARManalytics model accounts for all possible sources of N, such as N supplying capacity from the soil, previous crops, and cover crops; this is not always done in practice due to the uncertainty surrounding the magnitude of these sources. Losses like volatilization, leaching, and denitrification during the seasons are partly ignored in FARManalytics; this might lead to an overestimation of plant available N by FARManalytics. On all farms that currently do not sell crop residues, crop residues can be used to generate additional income. Although crop residues have a widely acknowledged beneficial impact on soil quality (Klopp & Blanco-Canqui, 2022; Turmel et al., 2015), alternative sources of nutrients and SOM are widely available at low prices in the form of animal manure.

Improving production management in the strategic dimension
In the soil quality strategic scenario, changes in cropping plan and crop rotation were allowed. For three farms, EVL did not increase compared to "soil quality tactical." This implies that current cropping plan is already optimal from the model perspective. For five out of nine farms, changing the cropping plan resulted in a substantial increase in income. The basic principle behind cropping plan optimization is to maximize the share of the most profitable crops. It is therefore of vital importance that crop EVL is calculated accurately (Mattetti et al., 2022). This is illustrated by excluding seed onions from the cropping plan on three farms because the crop was not profitable. However, in Kik et al. (2023), seed onions were found to be a very profitable crop in hypothetical farms. This illustrates that the bio-economic optimization of farms is case dependent.

In the farm strategic scenario, farm-specific challenges were studied. For three farms, the farm strategic scenario included land exchanges with dairy farmers. On these farms, farm income could be increased, even more than in the soil quality strategic scenario. This indicates that land exchange might be an interesting means to increase farm income while achieving soil quality targets. The joint land use of arable and dairy farmers approaches an integrated crop-livestock system where land is use for both arable and feed production for livestock. The benefits of such systems on farm income, soil quality and environmental performance have been acknowledged in literature (Lemaire et al., 2014; Sekaran et al., 2021)

Impact of stricter water quality regulations
In the water quality scenario, we optimized farmers' production management with additional restrictions resulting from policy to preserve water quality. Implementation of these restrictions comes at a cost since potential total EVL in the soil quality strategic scenario: an optimized scenario without the water quality restrictions, is always higher. However, when compared to the baseline scenario, three out of five farms could increase farm income while meeting soil quality targets and water quality restrictions by optimizing their production management. This implies that, for these farms in the baseline scenario, there is considerable room for improvement. Belhouchette et al. (2011) studied the impact of implementation of the EU Nitrates Directive for French arable farming. They found that farm income was not negatively affected, but substantial changes in production management were required. However, Dellink et al. (2011) state that the economic performance of agriculture will suffer from more stringent water quality regulations.

Impact of field beans as alternative crop
Based on current yields and expected prices, field beans are an interesting alternative crop to replace part of cereals in the crop rotation. Jensen et al. (2010) conclude that there is field beans have a great deal of potential but, first, major limitations surrounding crop yield have to be overcome. Moreover, production yield and the host-status of field beans for some soil-borne diseases are a point of concern. As a nitrogen-fixing crop, field beans can fixate their own nitrogen demand. Subsequently, they can provide a certain amount of N to the following crop. These agronomic benefits are acknowledged in the literature (Ditzler et al., 2021; Jensen et al., 2010; Palmero et al., 2022). Preissel et al. (2015) state that incorporation of these benefits is crucial to the profitable cultivation of grain legumes. From the results of the sensitivity analysis on field bean revenue follows that a substantially higher revenue (i.e., 50%) that only has a limited impact on the optimal cropping plan. The share of field beans is close to the maximum (i.e., once every five years) and despite higher revenues, other crops are more profitable, such as potatoes and onions.

5.5.2 Limitations and opportunities for on-farm decision support

In this study, we tried to optimize the economic value of sustainable soil management on nine arable in the Netherlands farms using the bio-economic modelling approach FARManalytics. In this section, we discuss the main challenges that need to be addressed before this kind of models can be applied for on-farm decision support.

Limited number of case farms
Case farms were selected from the Farmers Network for Soil Sampling (FNSS). Farmers in this network are more interested in sustainable soil management on average, which might explain why performance on soil quality indicators in the current situation is already good. The studied number of farms is relatively small; however, the current case farms are fairly heterogenous in terms of soil type and farm set-up thereby providing a fair picture of arable farms in the Netherlands. In practice, there is huge variation in terms of soil type and management styles, highlighting the needs for tailormade solutions. Despite the network bias and small sample size, this study illustrates the added value of integrated bio-economic modelling of soil quality and farm economics. This is because, even for a network consisting of front-runners, a substantial increase in farm income seems to be achievable while preserving soil quality. We recommend that, in future research, studies like this use larger samples of randomly selected farms. When extrapolating the findings of this study to arable farming in the Netherlands as a whole, we hypothesize that more intensive farms may present fewer opportunities to increase farm income while adhering to soil quality restrictions. In comparison to the farms in this study, the current production management of these intensive farms may push soil quality closer to the limit, leaving less room for improvement.

Spatial variability within farms
The current level of detail concerning the spatial allocation is at the farm-level. Soil quality and field characteristics are assumed to be homogenous across the farm. Based on finding a right balance between required input, model complexity, and quality of results, we argue that this is a justifiable decision. However, two aspects have critical consequences. First, at the farm level, soil quality can be fairly heterogeneous. This implies that not every management decision is appropriate for every field. A field with low SOM content might require more SOM input and, hence, other management decisions than a field with high SOM content. This is illustrated by Lessmann et al. (2022) and Moinet et al. (2023) who state that the potential of soil to sequester carbon is deeply dependent on the initial situation. Second, we assume that available farmland can be flexibly allocated to different crops whereas, in reality, field size and location are key drivers of crop allocation. For example, on four 10 ha fields each, implementing a 12-year crop rotation implies that every field has to be split into three parts, resulting in 12 fields of 3.33 ha. Castro et al. (2018) and Dury et al. (2012) recognize that these many bio-economic models fail to sufficiently address spatial issues.

Validation
Output validation and end-user validation are key concepts in model validation (Bockstaller & Girardin, 2003). Output validation concerns whether model results are realistic and reliable (Groot et al., 2012). An output validation can be done by comparing modelled results with measured data. End-user validation concerns usefulness and whether the model's results can be used for decision support (Bockstaller & Girardin, 2003).

We discussed results in an iterative way with the farmers, which contributed to both output and end-user validation. Farmers perceived the results as useful and confirmed the added value of integral decision support on soil quality. The most prevalent reasons for not adopting model suggestions concerned risks (e.g., of soil compaction when applying manure in spring) and changing circumstances (e.g., higher prices for crops in recent years than averages used in this study). However, both of these validations can be extended. A more thorough output validation can be achieved by comparing modelled results regarding soil quality indicators with the output from long-term trials, such as described by Korthals et al. (2014) and Schrama et al. (2018).

Currently, the impact of soil quality is calculated based on calculation guidelines and standard input tables (e.g., from CBAV, 2022). For example, development of SOM is calculated based on a calculated decomposition rate and on calculated input based on standard tables. Regarding end-user validation, the current bio-economic modelling approach allows for the economic evaluation of scenarios, which provides decision-support for farmers. However, when optimizing their production management, farmers take more economic aspects into account than just average profit, risk, and uncertainty. Therefore, we recommended doing a structured end-user validation in which farmers reflect on solutions provided by the model and indicate their reasons for implementing these suggestions or not. Information from this kind of validation can then be used to extend the model with more economic indicators, if necessary.

Resource availability & product market
In our optimization at the farm level, factors like market prices, product demand, climate factors, and regional impact are assumed to be exogenous (Dogliotti et al., 2005). However, production management decisions cannot be considered outside of their socio-economic context (Castro & Lechthaler, 2022). For example, cattle slurry and compost are the preferred manure types in the majority of the scenarios. A crucial assumption is that these manure types are available, and the price will remain constant despite potentially higher demands. Another example is found in the field beans scenario: based on current yields and expected prices, we assume a demand, but it is unclear if this demand exists.

5.5.3 Implications of the study

This study shows that management advice derived from the bio-economic modelling of soil quality and farm economics can increase farm income while improving soil quality. We first discuss the implications of our results at the farm-level. Second, we outline the implications for two groups of actors around the farmers (Kik et al., 2021a).

Implications at farm-level
Even for the nine farmers that are actively concerned with sustainable soil management, the results from our study suggest that farm income can be substantially increased while improving soil quality. Accordingly, it is plausible that similar results can also be achieved for a large proportion of the other arable farms in the Netherlands. Moreover, results from this study show the potential of FARManalytics to provide suggestions for alternative production management decisions to anticipate changing legislation (e.g., water quality) and changes in product demand (e.g., field beans). These developments require a change of current PM and FARManalytics can help to make the right decisions. Ultimately, this ensures the long-term preservation of soil quality in a financially robust strategy. In order to achieve useful and reliable results, it is of vital importance that the FARManalytics model is tailored to farm-specific conditions. This is particularly important for cropping plan decisions, as there is considerable variation in crop profitability in terms of the same crop between farms. It is, therefore, of the utmost importance that FARManalytics is provided with accurate cost and revenue data. Besides average profits, various important aspects (including production risk, robustness of choices, spatial allocation of activities, and variation in fields) are not covered by the model yet and thus rely on farmers' skills.

Implications for policy makers
Current insights from this study provide valuable information for policy makers and illustrate the added value of policy impact analysis. Broader application of the methods used in this study on a larger and less biased sample of farms will provide more insights. This study goes beyond existing studies like those by de Haan et al. (2021) and Ros et al. (2022) because we assess the status quo of the soil and link it with production management as well. This enables the prediction of what problems with soil quality will arise under various combinations of soil quality and production management. However, rolling this out on a larger scale, we recommended a thorough validation of the quantification of soil quality development using FARManalytics.

The FARManalytics model can be extended with environmental performance indicators to perform policy impact analyses on policies aiming at improving environmental quality. For example, for the water quality scenario in this study, policy impact analysis would be of added value to assess the effects of measures on water quality indicators (e.g., nitrate leaching). The FARManalytics model is also able to calculate economic returns based on production management decisions. Calculating the expected increase in costs and revenues for farmer to reach environmental targets could be useful for policy makers. Subsequently, this information could be used to increase financial incentives for farmers so they actually change their production management.

Implications for value chain actors
Insights and further application of this study could provide valuable information for actors in the farm value chain. For post farm value chain actors like agricultural processors and purchasers, the results are expected to create cropping plan choices for farmers. Cropping plan choices affect product availability differently for post-farm value chain actors. For example, the cultivation of field beans will result in a higher supply of field beans but a likely lower supply of wheat and barley. Value chain actors can use this information to create financial incentives for farmers to steer their product supply, such as by setting higher prices for wheat than for field beans to incentivize wheat cultivation.

5.5.4 Conclusions

This study explores the economic value of sustainable soil management in different future scenarios on nine existing arable farms in the Netherlands, using the bio-economic modelling approach FARManalytics. The main conclusions that can be drawn from this study are as follows.

- Nutrient management, subsoil compaction vulnerability, and soil organic matter input are currently bottlenecks to soil quality.
- Even for front-runners of sustainable soil management, model results show that farm income can be increased substantially while meeting soil quality targets, except for subsoil compaction.
- Implementation of water quality regulations limits management options, which reduces potential farm income. Nevertheless, depending on the initial situation, farm income and soil quality can still be improved compared to current management while complying with water quality regulations.
- According to model results, field beans have the potential to replace part of the cereals in cropping plans in the Netherlands. The positive effects of field beans' nitrogen-fixing properties are an interesting additional find.

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Appendices

A5-1 Model implementation water quality scenario

The objective of this scenario study is to study the impact of two major changes in agricultural policy and legislation relating to preservation of water quality. These changes are the results of the implementation of:

1: 7th EU Nitrate Directive. Implemented from 1-1-2023 onwards in different phases.

2: Loss of derogation: Implemented from 1-1-2023 onwards in different phases.

In both policies, a transitions from the current situation toward the desired situation if formulated. We choose to study the impact of the final/desired situation because that's in the end the legislation farmers have to comply with

A short overview of the proposed measures can be found in the Table below

Overview

Table A5-8 – Overview of proposed measured from EU Nitrate Directive (ND) and loss of derogation (DER)

Theme	Source		Measure	Soil types
Rest crops	ND	**1**	Compulsory 1:3 rest crop from 2027	sand, loess
Catch crops	ND	**1**	Recommended catch crop after all crops except winter crops Discount on N norm if harvest after 1 Oct and no catch crop	sand, loess
		2	Compulsory catch crop after corn	all
		3	No N space for cover crops (except non-legimunious cover crops after wheat, grass seed and rapeseed)	all
P space	ND	**1**	P in compost counts 25% of legal P norm	all
		2	P in solid manure/champost counts 75% legal P norm	all
N application autumn	ND	**1**	After august 1st not more than 60 kg N via slurry	all?
Buffer zones	ND/DER	**1**	Buffer zones next to water streams	all
Total N norms	DER	**1**	20% discount on fertilization norms in "nutrient polluated areas"	south sand, loess

For each of the measures, the precise model implementation is explained below:

1. Rest crops

A list with rest crops has been published by the Dutch government: https://www.rvo.nl/onderwerpen/mest/rustgewassen

The rest crop requirement is implemented as additional code that filters the ROTAT+ output. All rotations not matching the rest crop requirement are removed from the list with feasible rotations. The rationale is as follows:

- Counter for rest crops start in 2023.
- Result of counter is evaluated every three years, so first evaluation is over the years 2023, 2024 and 2025.
  - If one or more rest crops found -> pass and continue to next cycle.
  - No rest crops found: -> fail.
- This procedure is repeated until the end of the rotation. If no complete number of 3-year cycles fits in the rotation, at least one rest crop has to be found in the incomplete cycle.
  For example, the rotation:

Non-rest – Rest – Non rest – Non rest

is not feasible: on average only once every four years a rest crop is implemented.

Examples of rotations can be found below:

2023	2024	2025	2026	2027	2028	Result
NRC	RC	NRC	NRC	RC	NRC	pass
NRC	RC	NRC	NRC	NRC	RC	pass
NRC	NRC	RC	RC			pass
NRC	NRC	RC	NRC			fail
NRC	RC	NRC	NRC	RC	RC	fail

NRC = Non rest crop, RC = rest crop

2. Catch crops

The catch crop measures consists of (1) a **recommend** catch crop after all crops and (2) a **compulsory** cover crop after corn.

2a: Recommended catch crops

On sandy and loess soil a catch crop planted before October 1st is recommend to avoid nitrate leaching. This implies that crop harvest also has to be done before October 1st. An exemption is made for crops that are considered "winter crops". A list with winter crops and allowed catch crops can be found on https://www.rvo.nl/nieuws/vanggewassen-winterteelten-en-korting-gebruiksnorm

If no catch crop is planted, the farmer gets a lower N norm next year. This implies that the farmers are allowed to use less nitrogen in the next year. The N discount is as follows:

Table A5-11 Nitrogen discount dependent on plant date of catch crop (RVO 2023).

Catch crop plant date	Nitrogen discount (kg ha-1)
2 Oct until 14 Oct	5
15 Oct until 31 Oct	10
From 1 Nov onwards	20

Despite the N discount, it is unlikely that farmers start harvesting crops that are not matured before 1st of October to be able to plant a catch crop. Most prevalent example will be the harvest of ware potatoes. The model implementation therefore is as follows:

- Winter crop (e.g. sugar beets, starch potatoes) -> Don't plant catch crop without consequences
- No winter crop and "standard" harvest before 1st of October (e.g. wheat, barley, seed onions) → Required to plant a catch crop and avoid N discount.
- No winter crop and "standard" harvest after 1st of October (e.g. ware potatoes) -> Do not plant catch crop and incur N discount.

2b: Compulsory catch crops

On all soils, planting of a catch crop after corn becomes compulsory. The following options exist:

- Under sowing of catch crop, no final harvest date.
- Plant catch crop after harvest: harvest before October 1st and plant catch crop.
- Plant subsequent main crop serving as catch crop: harvest before October 31st and plant winter rye, winter barley or winter wheat.

3. Phosphorous space

The nitrate direct wants to stimulate the use of compost and solid manure. Therefore the P in compost only counts for 25% in the calculation of the legal P application, this was 50%. The P in solid manure and champost counts for 75% in the legal P application, this was 100%.

For compost, this was already implemented as only filling in 50% of the P of compost in the manure table. For example the P content of GFT compost is 2.2 kg ton-1 but in the manure table we used a value of 1.1 kg ton-1. However, this implies that the P in compost also only counts for 50% in the calculation of the P advice. This is justified as not all P in compost is plant available, as can be found on https://edepot.wur.nl/54182.

Implementation:

- We calculate the "Legal P" application apart from the "actual P" application that is used in the P advices.
- For compost, for the legal P application we count 50% of the P application (which is already 50%) of the total P content, see above. So, we calculate 50% of the P content in compost for the actual P application and 25% of the total for the legal P application.
- For solid manure and champost we count 75% of the total P application for the legal P application but we count 100% of the total application for the actual application.

4. Nitrogen application autumn

The nitrate directive want to limit the application of slurry in autumn. Therefore the application of more than 60 kg N-total ha-1 via slurry is forbidden after August 1th.

Implementation

- Added agronomic constraint that forbid autumn slurry application after 1st of august with more than 60 kg N-total.

5. Buffer zones

Buffer zones have a considerable financial impact because they result in a substantial loss of productive area. However, in the current scenario, the impact of buffer zones is not implemented as buffer zones are not management variable included in the model.

6. Total nitrogen norms

As a result of the loss of derogation, the following measure applies:

" In nutrient polluted areas, the total fertilization with organic manure and mineral fertilizers is decreased gradually in such a way the percentages from January 1st 2025 are 20 percent point lower than the percentages published in the Nitrate Directive.

Until further notice, the central and south sandy soils and loess soils are nutrient polluted areas.

Implementation:

- On farms on sandy soil (south) or loess soils, 20% discount on total N application space.

A5-2 Production management decisions scenarios

Table A5-2. Production management choices made by the bio-economic modeling approach FARManalytics for scenarios on arable case farm in the Netherlands

		Crop rotation												Rest crops	Cover crops		Crop residues	Manure & lime (*avg. kg ha⁻¹ y⁻¹*)					Fertilizer (*avg. kg ha⁻¹ y⁻¹*)				
		1	2	3	4	5	6	7	8	9	10	11	12	*(%)*	*(% cc)*	*types*	*(keep/sell)*	*PS*	*CS*	*solid*	*compost*	lime	N	P	K	S	Mg
S	b	STP	SPB	SB	SP	SC	SB	STP	SC	SB	SP	SC	SPB	16.7	42.0	WR, RY	keep	4.2	27.9	0.0	1.7	1.3 BET	43	0	0	0	0
	ss	SP	SC	SB	SP	SC	SB	SC	SPB	SC	SPB	SC	SB	16.7	75.0	AV, YM,WR	sell		33.3	7.5	7.4		21	0	0	13	0
	fs	SP	SC	WB	WP	SC	WB							33.3	33.3	WR	sell	5.3	16.7	5.0	10.0	2.2 BET	50	0	0	9	0
S-CR	b	WP	SB	KC	WW	WP	KC	KC	WW					25.0	37.5	WR,AV	keep		38.8				71	0	0	0	5
	ss	WP	SB	KC	WW									25.0	50.0	YM,AV	sell	18.0	8.0		6.8	3.7 BET	34	0	0	3	0
	fs	WP	SC	GC	GC	WP	SC	SC	GC					37.5	25.0	AV	NA	20.1	9.0		3.8	4.5 BET	0	0	0	3	0
L	b	WP	SO	SB	WW	WP	SPB	SB	WW	WP	SO	SB	WW	33.3	33.3	YM	keep	7.5	13.3			1.3 BET	11	0	67	0	0
	ss	WP	WW	SB	SPB	WP	SPB	SB	SO					37.5	62.5	YM,AV	sell	5	22.9		9	2.5 BET	45	0	0	10	0
	fs	WP	SB	SPB	SO	WP	SPB	SB	WP	SPB	SO	SB	WW	25.0	75.0	AV, YM	sell	6.7	17		6.5	2.2 BET	34	0	0	10	0
CO	b	GC	CA	WB	SPI	GC	SO	PE	GB					37.5	75.0	MIX, RY, YM	keep			17.1			0	0	0	0	0
	ss	WB	PE	SO	GC	SPI	GB	GC	CA					37.5	37.5	MIX, AV	sell		30.0		4.2	4.3 BET	0	0	2	1	1
	fs	GC	CA	WB	SPI	GC	SO	PE	GB					37.5	37.5	MIX, AV	sell		22.9		7.4	4.8 BET	0	0	2	1	1
CN	b	SP	WW	WB	SP	WW	WB	SP	SB	WB				55.5	33.3	MIX	sell		4.5	5.0			108	20	58	26	0
	ss	SP	WW	WB	SP	SB	WW							50.0	33.3	AV	sell		32.0	2.1			87	0	0	2	0
	fs	SP	WW	SB	WW	SP	WW	SO	WW	SP	SB	WW		45.0	36.3	AV	sell		38.6	2.2			98	0	0	2	0
CR	b	WP	WW	SB	WW	WP	WW	SO	WW					50.0	37.5	YM	sell	15.0		4.7		1.3 BET	108	0	74	31	0
	ss	WP	WW	SB	WW	WP	WW	SO	WW					50.0	37.5	YM	sell	4.8	36.3	0.6	8.6	3.0 BET	87	0	0	2	0
	fs	WW	SO	WF	SB	WW	FL	WF	SB					62.5	37.5	YM, WR	sell	5.0	22.5	2.7	8.5	2.6 BET	32	0	0	4	0
CP	b	SP	SB	WW	TU	SP	SB	GS	SO					25.0	50.0	MIX,YM,GR	sell, keep			11.3		1.3 BET	93	8	9	0	0
	ss	SP	SB	GS	SP	WW	TU	SB	SP	GS	SB	WW	TU	33.3	58.3	GR	sell	6.7	19.6			2.6 BET	41	0	0	0	0
	fs	GR	SP	GR	GR	SB	SP	GR	TU					50.0	0	NA	NA	3.5	30			3.0 BET	78	0	1	0	0
CSW-1	b	WP	WW	SO	WW	WP	WW	GS	PE	WP	WW	SB	SC	50.0	41.6	MIX, GR	keep	2.1	17.3	1.3			82	0	33	45	6
	ss	WP	WW	SB	PE	WP	GS	SB	SC					37.5	62.5	AV, WR	sell, keep		30.2		8.9		52	0	0	7	0
	fs	WP	GS	PO	PE	WP	GS	CE	SC					37.5	62.5	AV	sell, keep		28.8		8.9		25	0	0	5	0
CSW-2	b	WP	WW	SB	WW	SP	WW	SO	WW	WP	WW	CA	WW	50.0	50.0	MIX	keep		18.8	11.3			118	0	61	31	19
	ss	WP	WW	SB	WW	SP	WW	CA	WW					50.0	25.0	YM	sell	15	19.6		0.6		41	0	0	2	0
	fs	WP	WW	SO	SB	WP	WW	CA	WW	SP	WW	SB	WW	41.7	33.3	YM	sell	16.4	14.5		0.4		34	0	0	3	0

Crops						**Manure**		**Cover crops**	
CE	: Celeriac	KC	: Corn (kernel)	SPI	: Spinach				
CA	: Carrots	PE	: Peas	STP	: Starch potato	BET	: Betacal	WR	: Winter radish
FL	: Flax	SC	: Silage corn	TU	: Tulips	PS	Pig Slurry	RY	: Rye
GB	: Green beans	SO	: Seed onions	WB	: Winter barley	CS	: Cattle slurry	AV	: Avena Strigosa
GC	: Grass clover	SP	: Seed potato	WF	: Winter field beans			YM	: Yellow mustard
GR	: Grass	SB	: Sugar beets	WP	: Ware potato			GR	: Grass
GS	: Grass seed	SPB	: Spring barley	WW	: Winter wheat				

A5-3 Production management decisions field beans

Table A5-3. Crop rotations, share of rest crops & field beans and average nitrogen (N) fertilizer application for baseline scenario, field beans with base revenue, and field beans with +50% revenue Green highlights indicate the position of field beans in the rotation.

Farm	Scenario	Crop rotation 1	2	3	4	5	6	7	8	9	10	11	12	Rest crops *(%)*	Field beans (%)	N fertilizer *(avg. kg ha-1 y -1)*
S	b	STP	SPB	SB	SP	SC	SB	STP	SC	SB	SP	SC	SPB	16.7	0	43
	fb base	**SF**	SC	SB	SP	SC	SB	SP	SC	SB	SC	SPB	SC	16.7	8.3	14
	fb + 50%	**SF**	SC	STP	SB	SC	**SF**	SC	SB	SP	SC	SB	SP	16.7	16.7	13
S-CR	b	WP	SB	KC	WW	WP	KC	KC	WW					37.5	0	71
	fb base	WP	SB	KC	WW	WP	SB	KC	WW	WP	SB	KC	**SF**	25	8.3	54
	fb + 50%	WP	SB	KC	WW	WP	SB	**SF**	WW	WP	SB	KC	**SF**	25	12.5	40
L	b	WP	SO	SB	WW	WP	SPB	SB	WW	WP	SO	SB	WW	33.3	0	99
	fb base	WP	SPB	SB	SPB	WP	**WF**	SB	SO					37.5	12.5	24
	fb + 50%	WP	SPB	SB	SPB	WP	**WF**	SB	SO					37.5	12.5	24
CR	b	WP	WW	SB	WW	WP	WW	SO	WW					50	0	108
	fb base	WW	SB	WW	WP	WW	SO	**WF**	WP					50	12.5	62
	fb + 50%	WW	SB	WW	WP	**WF**	SO	WW	WP	WW	SB	**WF**	WP	50	16.7	50
CSW-2	b	WP	WW	SB	WW	SP	WW	SO	WW	WP	WW	CA	WW	50	0	118
	fb base	WP	WW	CA	WW	SP	WW	SB	**WF**					50	12.5	21
	fb + 50%	WP	WW	CA	WW	SP	WW	SB	**WF**					50	12.5	21

SF = Spring field beans, WF = Winter field beans

Digital appendix

Digital appendices of this chapter are available via:

https://wageningenur4-my.sharepoint.com/:f:/g/personal/maarten_kik_wur_nl/Eoi4II9BpfNDugqoKLliwigBOayXKyCtFckTzxmvat9nog?e=FYlmgt

In case access to this shared folder does not work, please contact maarten.kik@wur.nl for access.

6

General Discussion

6.1 Introduction

Soil quality plays a crucial role in agricultural productivity, farm resilience, and the environmental quality of arable farming systems (Karlen et al., 1997; Stevens, 2022). The increasing demand for agricultural products coupled with the declining availability of agricultural land places greater pressure on arable farming systems (Alexandratos & Bruinsma, 2012). However, if this growing demand is managed unsustainably, it can lead to soil degradation. Soil degradation encompasses issues such as erosion, soil compaction, loss of soil organic matter, nutrient leaching, and pesticide emissions (Koch et al., 2013; Squire et al., 2015). To address these threats, sustainable soil management is crucial, as it allows us to meet current productivity needs without compromising the soil's capacity to meet the needs of future generations (adapted from Smith & Powlson, 2007).

Sustainable soil management is of key importance for farmers who operate and often own the land. Their primary objectives are to achieve a sufficient yearly income and ensure the long-term continuity of their farms. Sustainable soil management can be considered as an economic problem (Stevens, 2018; Kik et al., 2021a): an investment that aims to improve and/or maintain *long-term* soil quality and consequently farm income, which however may reduce *short-term* profits. Currently, there is a lack of understanding regarding the trade-off between short-term and long-term economic impacts, hindering the implementation of sustainable soil management at the farm level. However, sustainable soil management extends beyond the farm level: it is crucial for food production within the agricultural value chain and the environmental quality of regional ecosystems (McBratney et al., 2014; Greiner et al., 2017). Therefore, the implementation of sustainable soil management at the farm level cannot be viewed in isolation from its socio-economic context surrounding the farmers.

The aim of this thesis was to assess the economic value of sustainable soil management in arable farming systems. The following sub-objectives were defined:

1. Define the Economic Value of Sustainable Soil Management (EVSM) and develop a conceptual framework for sustainable soil management in an arable farming context.
2. Provide an analysis of the actors involved in sustainable soil management in the Netherlands.
3. Develop and illustrate a bio-economic modeling approach to optimize EVSM at farm-level.
4. Explore EVSM on existing Dutch arable farms in future scenarios.

This General Discussion is structured as follows. Section 6.2 provides a synthesis of the main outcomes for the four cross-cutting themes in this thesis. Section 6.3 discusses the main limitations of this thesis. Main conclusions of this thesis are presented in Section 6.4. In Section 6.5 I generalize the findings beyond the scope of this thesis and discuss the role of the economic value of sustainable soil management in sustainable food systems.

6.2 Synthesis: towards sustainable soil management in arable farming

This synthesis highlights the importance of the economic value of sustainable soil management based on four cross-cutting themes.

6.2.1 Soil quality

To maximize economic returns expressed as Economic Value of Land in a sustainable way, it is essential to have a fundamental understanding of soil quality. This includes insights into soil quality parameters, their interrelations, and how they are influenced by production management (Chapter 2). In the bio-economic modeling approach called FARManalytics, soil quality is represented by seven chemical, six physical, and five biological indicators (Chapter 4). These indicators were studied on arable farms in the Netherlands (Chapter 5). Chapter 2 identified five knowledge gaps related to soil quality, which are necessary to address in order to quantify the Economic Value of Sustainable Soil Management ($EVSM$). These knowledge gaps can be utilized to assess the contribution of the soil quality indicators as used in the bio-economic modeling as discussed below.

First, soil quality cannot yet be fully described by a comprehensive set of quantitative and measurable indicators. Although two soil quality indicator sets were available for the Netherlands, the Open Soil Index of Ros et al. (2022) and the Soil Quality Indicators Agricultural Soils Netherlands of De Haan et al. (2021), none of these indicator sets were suitable for the goal of this study in its current form. Main reasons were that some indicators were costly and cumbersome to measure, such as bulk density and earthworm population in De Haan et al. (2021), or did not respond to production management, such as current subsoil compaction index in Ros et al. (2022). Therefore, in Chapter 4, I made a selection of indicators from the set of De Haan et al. (2021) and Ros et al. (2022). Main criteria for inclusion of indicators were (1) required data must be available at large scale and at acceptable costs (Rinot et al., 2019), (2) response to production management has to be quantifiable (Stevens, 2018), and (3) availability of target values (Rinot et al., 2019). Selected indicators in Chapter 4 align with selections made in the literature, such as those by Stevens (2018) and Bünemann et al. (2018). Considering the Dutch context, Chapter 4 includes indicators that have been identified as pivotal. These indicators encompass nutrient management (Groot et al., 2012; Ros et al., 2022; Silva et al., 2021), subsoil compaction (Akker & Hoogland, 2011; Hanse et al., 2011), and soil organic matter (Hijbeek et al., 2018; Mandryk et al., 2014).

Second, interrelations between indicators must be considered Bouma (2014). Chapter 4 addressed these interrelations to select the appropriate target values for indicators. For instance, on soils with higher soil organic matter content, the target pH value is lower (CBAV, 2022). Moreover, interrelations were considered when calculating modeling constraints to achieve the target values. For example, the required yearly input of organic matter to compensate for decomposition depends on the pH level (Janssen, 1984). Rinot et al. (2019) argue that examining the correlations between indicators can help minimize the number of required indicators. Based on the findings in Chapter 4, it is evident that indicators such as cation exchange capacity, crumbling ability, slaking vulnerability, and plant available water are largely influenced by the soil organic matter content (Ros et al., 2022). The results from Chapter 5 support this dependency as in many cases the target values for soil organic matter are determined based on one of these indicators. However, it should be noted that these indicators cannot be solely replaced by soil organic matter if one would like to reduce the number of indicators. Other production management decisions like crop cover, can also influence performance of indicators like slaking vulnerability and crumbling ability (Ros et al., 2022).

Third, current soil quality measurement can be costly thereby hampering large-scale application (Bünemann et al., 2018; Stevens, 2018). In Chapter 4, one of the criteria for selecting indicators was their availability at a large scale and acceptable cost (Rinot et al., 2019). The application of these indicators to the farms studied in Chapter 5 was feasible without incurring additional expenses, as the required information was readily available on all farms. However, it is important to note that some indicators, such as the subsoil compaction index and the score for plant parasitic nematodes, are based on risk assessments related to current production management practices rather than direct measurements of soil quality.

Fourth, the quantification of the impact of production management on soil quality remains a challenge (Bhardwaj et al., 2011; D'Hose et al., 2014). While many studies, including Bünemann et al. (2018), suggest that selected soil quality indicators should respond to changes in the environment and production management, for many indicators this is not yet possible. Soil quality indices such as those proposed by Ros et al. (2022) often overlook the impact of management practices and the subsequent evolution of soil quality indicators. While these indices can assess the overall soil quality at a specific point in time, they do not provide insights into how the indicators may develop over time. The FARManalytics bio-economic modeling approach goes one step further, i.e. all the indicators included contain quantitative rules that describe how they are influenced by production management (Chapter 4). However, it should be noted that this also was used as a criterion for their inclusion in Chapter 4. Based on this criterion, certain indicators such as bulk density were not included but were replaced by other indicators like the subsoil compaction vulnerability index.

Fifth, the unknown response of future yield and ecosystem services to soil quality. Despite the identified knowledge gap outlined in Chapter 2, I did not incorporate the potential impact of increased soil quality on crop yield in the bio-economic modeling approach described in Chapter 4. The primary reason for this omission is the limited availability of data and subsequent uncertainty in estimations. My approach considered soil quality as an integrated concept comprising eighteen distinct indicators. Evaluating the yield response would require a comprehensive understanding of how the interplay between these indicators affects crop productivity. Although studies have been conducted on this topic, such as those by Bhardwaj et al. (2011), D'Hose et al. (2014), and Korthals et al. (2014), the lack of available data presents a major challenge in bridging this knowledge gap. Chapter 2 emphasized the achievement of maximum Economic Value of Land through production management practices that yield maximum economic returns while preserving soil quality. The bio-economic modeling approach in Chapter 4 and 5 accomplishes this objective by optimizing scenarios that satisfy soil quality constraints. However, incorporating the benefits of increased crop yield could potentially further enhance the maximum Economic Value of Land. If higher levels of soil quality result in higher crop yields, the maximum sustainable Economic Value of Land may surpass the current optimum level.

The application of FARManalytics on the case farms (Chapter 5) involved in this study revealed that these farms demonstrate relatively good performance in terms of their impact on soil quality, as bottlenecks are observed in only four out of the eighteen indicators. Similar findings are reported by Ros et al. (2022) when they applied their Open Soil Index framework to all agricultural fields in the Netherlands. Two recurring bottlenecks, namely sulfur input and pH, can be easily addressed without major impact on economic returns through the application of sulfur fertilizer and lime. However, it is important to note that the farms examined in Chapter 5 have a bias towards sustainable soil management, potentially leading to better performance compared to the average Dutch farmer. The intensive farm types in Chapter 4 that prioritize short-term profit contrast to the case farms of Chapter 5, however assessing the impact on soil quality in the clay-intensive farm type also revealed limited bottlenecks, primarily subsoil compaction and input of potassium. While subsoil compaction remains a challenging issue and poses a serious threat to soil quality in this farm type, the potassium target can be easily achieved through the application of fertilizer or alternative manure types. On the sand-intensive farm type, more bottlenecks were identified, including input of sulfur, magnesium, and lime. However, these limitations can also be resolved easily. Larger concerns involve the required input of organic matter and potential damage from plant-parasitic nematodes. The latter are particularly problematic on sandy soils (Molendijk, 2022). Although the presence of plant-parasitic nematodes was not confirmed as a bottleneck on the sandy soil farms studied in Chapter 5, the results from Chapter 4 indicate their potential to become a limiting factor. This finding is supported by Korthals et al. (2014), who highlight the challenges faced by intensively managed ecosystems in relation to these pests.

The main bottlenecks identified in terms of soil quality, as observed in both Chapter 4 and Chapter 5, involve nutrient management, subsoil compaction vulnerability, and organic matter input. These findings align with existing literature: Ros et al. (2022) report insufficient sulfur availability in 48% of Dutch agricultural fields, and phosphorus and potassium availability are identified as bottlenecks, albeit to a lesser extent. Subsoil compaction is recognized as a major and widespread threat to soil quality in the Netherlands by Van Den Akker (2004) and Van den Akker & Hoogland (2011). The importance of organic matter input is emphasized by Hijbeek et al. (2018) and Mandryk et al. (2014) as a key objective for farmers engaged in sustainable soil management.

While not all indicators are limiting factors, the inclusion of an integrated set of soil quality indicators demonstrates to be highly relevant. Many existing studies recommend production management decisions for single aspects of soil quality based on statistical analysis or field experiments, such as Hanse et al. (2011), Hijbeek et al. (2018) and Silva et al. (2021). However, at the farm-level all soil quality aspects must be taken into account (Schreefel et al., 2022). Although this may not always be evident from the individual scores of soil quality indicators, it becomes apparent through the model's behaviour (Chapter 4). For instance, the choice of cover crops on sandy soils highlights the added value of the comprehensive approach to soil quality. *Avena strigosa* and resistant cultivars of winter radish, despite being more costly, are preferred as cover crops over cheaper alternatives like winter rye due to their non-host status for the nematodes *Pratylenchus Penetrans* and *Meloidogyne Chitwoodi*, respectively. This example underpins the benefits of the integrated approach to soil quality.

6.2.2 Bio-economic modeling

Chapter 2 defines four knowledge gaps for quantification of $EVSM$ by means of bio-economic modeling. These knowledge gaps can be used to synthesize the bio-economic modeling approach FARManalytics in Chapter 4.

First, time dimension and temporal interaction of production management decisions. The bio-economic modeling approach FARManalytics utilizes ROTAT+ to generate feasible crop rotations (Dogliotti et al., 2003). In these rotations, crops are assigned to fixed positions in time, enabling accurate modeling of other production management decisions, such as cover crop allocation. The allocation of cover crops depends on the harvest date of the preceding crop and the planting date of the subsequent crop. The current version of the model offers flexibility in the considered time frame, which depends on the selected crop rotation. If the optimal crop rotation is eight years, the time frame considered is eight years; if it is twelve years, the time frame is twelve years. This approach provides an advantage and a drawback compared to setting a fixed planning horizon for modeling, such as twenty years. The advantage lies in the model's flexibility, as it can always select the optimal crop rotation based on the given time frame. For instance, if the time-period is set to ten years, a five-year or ten-year crop rotation will be preferred over a six-year rotation that does not fit within a ten-year time horizon. Results from Chapter 4 and Chapter 5 support this advantage, as the rotation length is chosen to maximize the share of the most profitable crops. However, this flexible rotation length has an unintended effect on soil quality constraints. With longer rotation lengths, more time is available each year to achieve the soil quality targets, thus reducing the yearly efforts required to reach those targets. For example, if an additional 10,000 kg ha^{-1} of organic matter input is needed to meet the target, it translates to 2500 kg ha^{-1} year^{-1} over an eight-year rotation and 2000 kg ha^{-1} year^{-1} over a ten-year rotation. This highlights the drawback of the flexible approach in terms of soil quality constraints.

Second, spatial variability of production management: The limitation of oversimplifying the spatial aspects of production management is highlighted in Chapter 2. In Chapter 4, spatial variability is addressed at the farm cluster level, where a group of fields with homogeneous management is assumed. Dealing with spatial aspects involves a trade-off between complexity and accuracy, which applies to both modeling and practical production management by farmers. While fields can exhibit substantial differences, they are rarely managed individually. This observation is supported by the overview of current production management at real-life case farms (Chapter 5). In addition to assuming homogeneity in production management at the farm level, I also assumed homogeneity in soil quality. However, it is important to note that substantial differences in soil quality may exist between fields. Furthermore, as highlighted in Chapter 2, the spatial and temporal planning of production management are interconnected. This relationship is confirmed in Chapter 5 where farmers take crop allocation decisions based on available field sizes, impacting the temporal allocation of production management activities. For instance, let's consider a scenario where a farmer owns four non-adjacent fields, each spanning ten hectares. Implementing a twelve-year crop rotation on this set of fields would require dividing each field into three parts. This division negatively impacts operability and economies of scale.

Third, cropping plan decisions as a dynamic concept. The need for a dynamic approach in cropping plan decisions has been emphasized by Dury et al., (2012) due to the inherent uncertainty associated with these decisions. However, in this study, cropping plan decisions are approached in a static manner. This choice was made for two main reasons. First, a static approach currently allows for accurate modeling of temporal interactions, as highlighted in the previous knowledge gaps. This becomes considerably more complex when crops do not have fixed positions in the rotation. Therefore, I preferred an accurate static approach over a dynamic approach that might be a better representation of the farmer decision-making process (Dury et al., 2012). Second, time constraints played a role in selecting the approach. The ROTAT approach proposed by Dogliotti et al. (2003) was chosen due to its availability and up-to-date nature. In contrast, more dynamic approaches, such as those proposed by Castellazzi et al. (2008), Detlefsen & Jensen, (2007) and Klein Haneveld & Stegeman, (2005) pose greater implementation challenges because the availability and status of these models was unknown.

Fourth, target-oriented-approach of modeling. Despite the call in Chapter 2 to include the impact of soil quality on crop yield via e.g., a production function (Van Ittersum & Rabbinge, 1997), the bio-economic modeling approach used a target-oriented approach, as also discussed in Section 6.2.1.

Based on the results of the bio-economic modeling approach, it can be observed that farm income can be increased while meeting all soil quality targets except for subsoil compaction on both the standard farm types (Chapter 4) and the case farms (Chapter 5). This finding prompts a critical examination of the hypothesis presented in Chapter 2, which posits that the implementation of sustainable soil management is an investment that may reduce short-term farm income but enhance long-term soil quality and overall farm income. The study's findings necessitate a nuanced evaluation of this hypothesis. On the one hand, the analysis in Chapter 3 revealed that short-term income is consistently higher in scenarios that do not consider soil quality constraints (profit scenarios) compared to scenarios where soil constraints are considered too, indicating the existence of a trade-off between short-term farm income and long-term soil quality. On the other hand, the examination of the current production management of the case farms in Chapter 5 demonstrated that there are ample opportunities to increase short-term income while still achieving soil quality targets (except for subsoil compaction vulnerability). This suggests that the current management approaches adopted by the farmers may be sub-optimal, as discussed in Chapter 2. The main production management decisions farmers can take to increase their EVL are changes in cropping plan, switching to other manure types, lower the application of fertilizer and sell crop residues. However, it is important to acknowledge that farmers may have valid reasons for their current choices. When results were discussed with farmers, a primary reason to not adopt for example spring application of manure or selling crop residues is the risk involved in these decisions. The bio-economic modeling approach FARManalytics is a static and deterministic model and does not consider the impact of weather variations on suggested production management, whereas these conditions may have a major impact. For example, spring application of manure under unfavourable conditions can cause severe soil compaction. Removal of crop residues in a season with changeable weather can take a while, thereby postponing the planting of a cover crop and leading to a risk of soil compaction. Another reason for farmers to deviate from model results are risks e.g., risks in production and price. This is further discussed in the synthesis on the role of the farmer and the limitations of this study. It should be noted that the case farms analyzed in Chapter 5 were biased towards sustainable soil management, which might explain their relatively good performance in terms of soil quality. However, from an economic perspective, their production management practices may still be considered sub-optimal. When extrapolating the findings of this study to Dutch arable farming in general, I hypothesise that more intensive farms have less opportunities to increase farm income while adhering to soil quality restrictions compared to less intensive farms. In comparison to the case farms discussed in Chapter 5, the current production management of intensive farms may be closer to the maximum sustainable level of production management as defined in Chapter 2.

Based on the findings in Chapter 4, it can be observed that in scenarios where changes in the cropping plan were allowed, the cropping plan was always altered. This change entailed an increased share of onions, as they are the most profitable crop across all farm types. Similarly, on the case farms discussed in Chapter 5, adjustments to the cropping plan were made to contribute to higher economic returns. These results align with previous studies by Alfandari et al. (2015) and Capitanescu et al. (2017), emphasizing the impact of cropping plan decisions on agronomic and economic performance. In terms of cover crops, no major changes were observed compared to the current situation, reaffirming the known agronomic benefits of cover crops as demonstrated by Adetunji et al. (2020) and Hao et al., (2023). Throughout the model outcomes in both Chapters 4 and 5, cattle slurry and compost emerged as the preferred manure types. These choices are well-founded: cattle slurry is often available at no cost or at a premium price and is rich in organic matter, nitrogen, phosphorous and potassium. While compost may be more expensive than slurry, it serves as a valuable source of nutrients and organic matter, particularly in situations with high requirements for organic matter input and limited space for phosphorus application. Substantial reductions in the use of fertilizers were observed in both Chapters 4 and 5. This raises questions about whether farmers are currently over-fertilizing their crops. However, several important nuances should be considered. Firstly, fertilizer use is reduced due to a shift towards more spring application of manure, although caution is warranted due to the risk of subsoil compaction and potential negative impacts on crop quality. Secondly, the implemented approach assumes 100% availability of applied nutrients, whereas in practice, availability will always be lower due to soil processes and weather events which retards the availability of nutrients. Nevertheless, I argue that these results are too important to be ignored. By implementing integrated nutrient management strategies that encompass fertilizers, organic manure, and cover crops while closely following the recommendations of relevant guidelines (CBAV, 2022), substantial reductions in fertilizer use can be achieved. Furthermore, I found that it is always preferable to sell crop residues on both standard farms and case farms. Selling crop residues generates additional revenue, and the associated loss of organic matter and nutrients can be compensated by applying manure at lower costs. Reflecting on the model's behaviour, I conclude that not only crop choices but also the inclusion of cover crops, manure, fertilizer, and crop residue management are of added value. These choices are essential for achieving soil quality targets and have a substantial impact on increasing returns compared to the current situation, as demonstrated in Chapter 5.

6.2.3 Role of the farmer

The results of power-interest grids (Chapter 3) demonstrated that farmers are prime actors in sustainable soil management as they had a high degree of power and high degree of interest. This finding corresponds with the conceptualization in Chapter 2: Farmers are the actors that have to implement decisions and have a key interest in sustainable soil management since it is a pivotal factor for short-term and long-term farm income. Strauss et al., (2023) also defined farmers as prime actors in sustainable soil management.

Chapter 2 made a critical assumption that farmers are financially rational decision-makers who aim to sustain their businesses in the long term, either through inheritance or takeover. This assumption was then implemented in the bio-economic modeling approach in Chapter 4, where the objective was to maximize returns while respecting soil quality constraints. However, the results from Chapter 5 reveal that substantial differences in economic returns already exist between farms in the current situation, not only within the small sample but also within Dutch arable farming in general (Wageningen Economic Research, 2022). Several key factors can explain these differences: (1) Farmers may exhibit risk aversion rather than risk neutrality, which challenges the implicit assumption of maximum economic returns as the sole consideration. Rounsevell et al., (2003) confirm that farmers are risk-averse profit maximizers and identify risk attitude as a key factor contributing to differences in farmers' choices. (2) Farmers may have non-economic objectives and are financially able to execute them, such as biodiversity preservation, public appreciation of agriculture or job satisfaction. Chapter 3 indicates that while farmers prioritize economic aspects of sustainable soil management, they also assign some priority to environmental and social aspects. (3) Farmers may lack awareness of current opportunities to improve their production management from an economic perspective. Similar findings are reported by Lamkowsky et al. (2021) for dairy farms in the Netherlands. The fact that substantial effort was required to analyze the current economic performance of the farm (Chapter 4) further supports this hypothesis, because this underpins farmers are not always actively concerned about current economic performance (4) Inherent farm characteristics, including different soil types, resource availability (e.g., irrigation water), and climatic conditions, have a substantial impact on production potential. (5) Larger-scale farms may benefit from economies of scale, providing them with a competitive advantage compared to smaller-scale farms.

Chapter 5 encompassed a small yet heterogeneous group of farmers, and for almost all of them, it was possible to improve farm income while enhancing soil quality. Generalizing these results to arable farming in the Netherlands as a whole, my hypothesis is that farm income can be increased while improving soil quality. To achieve this, I suggest two approaches: (1) peer feedback learning and (2) improved knowledge transfer. Through discussions on production management decisions and their outcomes, farmers can learn from their peers and implement best practices. The potential of interaction and feedback from peers in Dutch agriculture has been recognized by Lamkowsky et al. (2021) and Schneider et al., (2021). While sustainable soil management already receives considerable attention in Dutch arable farming, I hypothesize that arable farmers would benefit from improved knowledge transfer. Acknowledging the farm context and tailor-made advices is a prerequisite for successful knowledge transfer. In the Netherlands, extension services have been privatized (Lamkowsky et al., 2021), meaning that advice comes at a cost for farmers. Considering that the benefits of enhanced soil quality are uncertain and manifest in the long term (Brady et al., 2015), this may hinder farmers from seeking costly advice. As emphasized in this thesis, the implementation of sustainable soil management requires an integrated approach to soil quality embedded in the socio-economic context of the farm. Current extension services mostly specialize in individual aspects of production management, such as fertilization, often neglecting the broader aspects of soil quality. Both in scientific research and practical application, the economic aspects of sustainable soil management have not received sufficient attention. Advancements in this field require efforts of actors beyond farmers such as extension services, knowledge institutions, and the government to place greater emphasis on providing integral advice on the implementation of sustainable soil management within the farmer's business model.

Farmers were initially assumed to be the owners of the land. However, it is important to recognize that various situations exist where the land is owned by non-operating landowners and rented to farmers (Chapter 3) (Ranjan et al., 2019). For farmers who own the land, it is in their long-term interest to preserve soil quality (Chapter 2) (Stevens, 2018, 2022). This long-term interest in soil quality may also apply to farmers who rent land for extended periods, as it aligns with their long-term goals. However, farmers who rent land for short durations do not directly benefit from long-term soil quality and thus tend to prioritize short-term profits (Stevens, 2022). Previous research indicates that farmers who rent land are less likely to adopt sustainable soil management practices (Deaton et al., 2018; Ranjan et al., 2019). To implement sustainable soil management on rented land, additional incentives for farmers are necessary. One potential solution is to encourage long-term lease contracts, as they align the incentives of both landowners and farmers (Stevens, 2022). If land tenure primarily relies on short-term contracts, monitoring soil quality can serve as a possible solution to prevent farmers from overexploiting rented land. The Open Soil Index developed by Ros et al. (2022) is being applied for this purpose by the largest private landowner in the Netherlands.

6.2.4 Role of other actors

The farmer is the operator and often owner of the land and the actor directly involved in operating the land. However the farmer is operating in a context of other actors (Chapter 2) (Bünemann et al., 2018). Chapter 3 confirmed that beyond farmers the main actors are input suppliers, post-farm value chain participants, environmental actors, and policy makers. These results align with existing literature such as Bampa et al. (2019), Bouma et al. (2012), Strauss et al. (2023) and Vanino et al. (2023) but Chapter 3 went in much more detail about the role of actors than existing literature. Using the Analytical Hierarchy Process (Saaty, 1990), I found that farmers and value chain actors have a strong priority for economic criteria. This is in line with results from a survey of Strauss et al. (2023) where farmers identified economic factors as the main obstacle for implementation of sustainable soil management measures. This provides additional underpinning for the approach of sustainable soil management as an economic problem (Chapter 2). I studied actors' self-assessment of power-interest and power-interest assessment by other actors: actors with a low degree of self-perceived power but high power perceived by other actors might face a locked-in situation where actors wait for each other to undertake action (Chapter 3). In a study on implantation of water quality measures, Wuijts et al. (2023) argue that better understanding of locked-in situations is necessary.

A key question regarding the role other actors beyond farmers is: "How and by whom can farmers be motivated to act not only in their own interest but also in the interest of other actors in sustainable soil management (Chapter 3). Common actor priorities for sustainable soil management combined with actor power-interest can be used to build coalitions and incentive structures around the farmer (Chapter 3). Such information is of key importance as according to Strauss et al. (2023) "Governance for more sustainable soil management is easiest to implement and most effective where proposed measures meet with approval across a wide set of stakeholder groups". Actor coalitions and incentive structures can be particularly useful to stimulate farmers not to focus solely on primary productivity but also on the provision of ecosystem services. The benefits of ecosystem services manifest outside the farm-level for the public at large (Chapter 2). However, as Chapter 2 illustrated, provisioning of ecosystem services might go at the expense of the farmer's ability to produce crop yield, thereby negatively impacting farm income. However, through financial incentives, farmers can be stimulated to adopt a production management strategy that is beneficial for ecosystem services (Chapter 2).

The focus of the bio-economic modeling approach is on the farmers as key decision makers, however from the results of the scenario analysis at the case farms (Chapter 5), interesting implications for other actors beyond the farmer can be derived. The water quality scenario in which the impact of more stringent water quality regulations is studied (Chapter 5) is an example of a powerful actor, i.e. the national government (Chapter 3), applying top-down measures on the farmer. Measures enforcing more break crops, lower fertilization rates and buffer zones result in a loss of potential income (Chapter 5). These findings confirm the mechanism explained in Chapter 2: Farmers have to decrease their production management intensity, resulting in a lower income. In such a situation, the bio-economic model FARManalytics (Chapter 4) can be used to calculate the estimated income loss for the farmer. A financial compensation by other actors equal to the estimated income loss can be an alternative to legal enforcement. Beyond farmers and governments, other actors have a key interest in water quality, such a water boards and drinking water companies (Chapter 3). In the water quality scenario in Chapter 5, these actors with a high interest in water quality but a low power to enforce decisions see a contribution to their priorities for sustainable soil management enforced by a powerful actor, the government. The water quality regulations also have a major impact on post-farm value chain actors (Chapter 3). The break crop requirement enforces farmers to plant a break crop once every three years, which decreases the ability to grow crops such as sugar beets and potatoes. Processors of these products face a reduction in their potential volume and are likely to undertake action to maintain their processed volume of products.

6.3 Limitations and opportunities for further research

This section discusses main limitations and the opportunities to overcome these limitations. These include (1) lack of physical and biological indicators, (2 exclusion of yield effects, (3) static & deterministic modeling approach, (4) exclusion of ecosystem services in bio-economic modeling, (5) assumed unlimited availability of resources and demand for products, and (6) exclusion of regional & farm collaboration aspects.

Lack of physical and biological indicators

Originally, this thesis aimed to consider soil quality as an integral concept, including chemical, physical, and biological indicators (Chapter 1 and Chapter 2). However, the bio-economic modeling approach only incorporates a limited number of physical indicators and even fewer biological indicators compared to those described in the literature (Dominati et al., 2010; Greiner et al., 2017; Jónsson & Davídsdóttir, 2016). The primary reasons for not including more physical or biological indicators are: (1) the inability to assess their changes over time in response to production management, (2) unavailability or high cost of indicators, and (3) absence of target values (Chapter 4). Bünemann et al. (2018) and Ros et al. (2022) reach a similar conclusion regarding physical and biological indicators. Currently, the assumption is that soil quality will be preserved if the targets of the current indicators are met. However, in practice, farmers and other stakeholders consider a broader set of indicators. This becomes evident when comparing the current farm management practices in Chapter 5 with the optimized management. Production management choices that benefit soil quality, such as extensive crop rotation, retention of crop residues, and application of solid manure, which are implemented in the current management of multiple farms, are not preferred by the model. Ultimately, this suggests that farmers have additional constraints on soil quality and are willing to accept lower economic returns in exchange for perceived soil quality benefits. Including more physical and biological indicators could serve as a means to address this limitation. A comprehensive overview of additional physical and biological indicators can be found in Bünemann et al. (2018) and Dominati et al. (2010). Advancements in this field primarily pose a challenge for soil scientists and ecologists to come up with quantifiable indicators and target levels which can be implemented against reasonable costs.

Exclusion of influence of soil quality on yields

Throughout this thesis, I adopt a target-oriented approach to soil quality, where the desired value of soil quality indicators is based on a target yield and remains static despite changes in soil (Van Ittersum & Rabbinge, 1997). This limitation implies that even if soil quality indicators reach their targets, the yield remains unchanged. From a modeling perspective, this means that the model's behaviour is solely focused on achieving soil quality targets without considering possible impacts on additional outcomes such as enhanced yield. For instance, in the optimized scenario of a clay farm in Chapter 5, the model does not prioritize the cultivation of more cover crops because the soil quality targets can be met without the added expenses of cover crops. However, considering the well-established agronomic benefits of cover crops (Adetunji et al., 2020; Hao et al., 2023), it is plausible that they could have a positive impact on yield, although the model currently does not account for this factor. Despite its significance, integrating yield benefits into the bio-economic modeling approach remains challenging. A key reason for this challenge is my comprehensive perspective on soil quality, which encompasses numerous heterogeneous indicators, each of which can exert a substantial influence on crop yield. This phenomenon, referred to as "Von Liebig's law of the minimum" by Stevens (2018), is recognized as a limitation in current multidimensional soil quality approaches. To address this limitation, one potential approach is to introduce crop response levels corresponding to different soil quality levels. Long-term trials investigating crop yield in response to changes in soil quality can provide the necessary information to establish these crop responses (Bhardwaj et al., 2011; D'Hose et al., 2014). For broader application, crop growth models that estimate yields using production functions could be a valuable approach (Jones et al., 2003; Stockle et al., 2003). However, a critical factor for successful implementation of such an approach is ensuring that both field trials and crop models incorporate an adequate number of soil quality indicators, which may pose a challenge, particularly for crop models. Alternatively, more readily implementable solutions that still offer valuable insights include (1) expert estimations of crop responses to soil quality improvements and (2) expert estimations based on relevant literature regarding the yield effects of "good practices" like additional cover cropping.

Static & deterministic modeling

I employed a static and deterministic modeling approach, despite the recommendation for a dynamic and stochastic approach as discussed in Chapter 2. The current approach assumes a certain level of predictability in long-term decisions. However, farmers' decisions are subject to continuous changes in their operating environment, leading to potential deviations from the model's suggestions (Dury et al., 2012). This limitation calls for the implementation of production management as a more dynamic process that allows farmers to continuously adapt to changing circumstances. Furthermore, farmers are assumed to be financially rational decision-makers who are risk-neutral. However, risk attitude plays a significant role in farmers' decision-making processes. Farmers may be willing to adopt strategies that result in lower average returns but also lower risks and uncertainties (Dury et al., 2012). To account for risk and variability, a first and simple approach would be to conduct sensitivity analyses on model inputs and evaluate different worst- and best-case scenarios (Kleijnen, 1994). Alternatively, a more comprehensive solution involves exploring options for stochastic or robust modeling (Najafabadi et al., 2019; Yue et al., 2022). However, such approach comes at the costs of higher model complexity and more data requirements. Stochastic programming requires for instance that probability distributions of e.g. crop yields and crop prices are known. For economic data, the Farm Accountancy Data Network might provide useful insights.

Exclusion of ecosystem services in bio-economic modeling

Ecosystem services, alongside crop yield, are valuable outputs in agriculture that can generate additional income (Chapter 2) (Stevens, 2018). Farmers may accept lower crop yields if they can benefit economically from ecosystem services. However, due to time constraints, the bio-economic modeling approach eventually did not account for ecosystem services (Chapter 4). Therefore, the optimization efforts in Chapter 4 and Chapter 5 focused solely on maximizing primary productivity. This means that the alternative production management strategies identified may be optimal in terms of production, but not necessarily in terms of ecosystem services and the beneficiaries of those services. Considering the high societal demand with regard to agriculture (Schulte et al., 2019) and the recognized potential of ecosystem services (Dominati et al., 2014; Robinson et al., 2013), it would be beneficial to further include ecosystem services in the model (Dale & Polasky, 2007). Implementing these services can be relatively straightforward, either as constraints that need to be fulfilled or by encouraging specific production management decisions (as exemplified in the new European Common Agricultural Policy). Furthermore, embedding ecosystem services within a broader socio-economic context is essential, considering uncertainties in markets and prices. Bio-economic modeling can help determine the required level of returns, as demonstrated in scenarios related to water quality.

Assumed unlimited availability of resources and demand for products

The bio-economic modeling approach employed in this thesis primarily focused on the farm-level analysis, thus overlooking important factors beyond the farm boundary. Notably, key aspects currently disregarded include resource availability and the dynamics of product markets. Rounsevell et al. (2003) state that "farm-level decisions mediate the impact of market and policy change on land use". Concerning resource availability, the findings highlight the significant role of manure application as a vital source of nutrients and organic matter, often at low prices or even generating revenues. The underlying assumption in the bio-economic modeling is that there is an unlimited availability of all manure types. While this assumption may hold true for the present situation in the Netherlands, societal developments such as a reduction in livestock populations can potentially have a profound impact on the availability of these resources. This consideration extends to the broader upstream value chain as well. The modeling approach assumes an unlimited demand for products. However, changes in cropping plans on an individual farm are unlikely to exert a major influence on the overall value chains. Conversely, if a substantial number of farms were to alter their cropping plans, the situation could change significantly. Supply may exceed demand, leading to a subsequent decline in prices and ultimately resulting in reduced economic returns at the farm-level. This mechanism is particularly pertinent for crops with a relatively small acreage in the Netherlands. For instance, in Chapter 5, one farmer raised the question of whether celeriac would be a viable alternative crop. Celeriac is a specialized non-commodity crop occupying an area of 1850 ha in 2022 (CBS, 2023). However, if only 20 farmers were to cultivate 10 ha of celeriac each, the total area would already increase by 10.8%.

Exclusion of regional & farm collaboration aspects

Besides the optimization at farm level, regional structures and possible collaborations between farms can have a major impact on production management decisions - but these are not considered in the thesis. From Chapter 5 it follows that land exchange with a dairy farmer has the potential to improve farm income for the arable farmer: the area of cash crop could be increased by planting part of these crops on the land of the dairy farmer while feed crops are cultivated as break crops on the land of the arable farmers. As usually an exchange rate is applied, e.g. 1.5 ha of feed crops (e.g. grass or maize) for 1 ha of cash crops (e.g. potatoes or onions), the dairy farmers benefit from a larger area of feed crops. Additional benefits in arable-dairy collaboration can be achieved by exchange of manure. In the Netherlands, a manure surplus exists and many dairy farmers have to dispose manure at high costs. Collaboration with a neighbouring arable farmer to apply manure on the fields of the arable farmers might result in lower manure disposal costs for the dairy farmer. However, arable-dairy collaboration has to be considered at the system-level of the collaboration. Although the land exchange includes high potential benefits, it also includes the risk of the overall land-use in the system becoming more intensive, which if managed in an unsustainable way can threaten soil quality. Besides land exchange, collaborations between arable and livestock farmers can also be based on the exchange of produce, e.g. feed produced on arable farms for neighbouring livestock farmers and the other way around manure of livestock farms for arable farms. Multiple bio-economic farm models consider mixed farming systems such as Britz et al., (2014) and Groot et al., (2012), however none of these models allow for regional optimization in which farms are considered as separate entities.

6.4 Conclusions

The main objective of this thesis was to assess the economic value of sustainable soil management in arable farming systems. The main conclusions of this thesis are:

- Production management i.e., the complete set of physical and non-physical inputs made by the farmer is the primary determinant of long-term soil quality and hence future economic returns. (Chapter 2).
- The Economic Value of Sustainable Soil management ($EVSM$) can be defined as the difference in economic returns between sustainable management and unsustainable or sub-optimal management. Sustainable management can be defined as obtaining highest economic returns without compromising long-term soil quality (Chapter 2).
- Beyond farmers, a diverse group of other actors, such as value chain participants, environmental actors and policy makers, is involved in sustainable soil management (Chapter 3).
- Farmers are the prime actors in sustainable soil management due to their high power and high interest (Chapter 3).
- Bio-economic modeling at farm-level allows to make production management decisions with an integral view on soil quality, which ensures long-term preservation of soil-quality in a financially robust strategy (Chapter 4)
- The FARManalytics bio-economic modeling approach can be used for policy support when combined with standard farm types. FARManalytics can be tailored to an individual farm to support decision making at the farm-level (Chapter 4 and Chapter 5).
- Nutrient management, subsoil compaction vulnerability and soil organic matter input are the current soil quality bottlenecks in Dutch arable farming (Chapter 4 and Chapter 5).
- Even for a group of front runners, farm income can be increased with up to €700 ha^{-1} year^{-1} while preserving or improving soil quality (Chapter 5).
- $EVSM$ can be effectively evaluated by integrating soil quality into a bio-economic model, considering the interrelations between indicators and the influence of production management on soil quality. Furthermore, implementing this approach on a large scale at reasonable costs is achievable. However, a significant challenge that remains is the incorporation of crop yield response to improved soil quality (Chapters 2-5).
- The bio-economic model FARManalytics enables the assessment of current $EVSM$ at the farm-level and provides alternative production management strategies. To enhance decision support at the farm level, it is essential to better incorporate spatial aspects and consider farmers' attitudes towards risk and uncertainty (Chapters 2-5).
- While farmers play a pivotal role in sustainable soil management decisions, their actions are influenced by interactions with other actors. Therefore, assessing $EVSM$ at the farm-level requires considering its broader socio-economic context (Chapters 2-5).

6.5 Outlook: Soil management in sustainable food systems

The aim of this outlook is to illustrate how insights from this thesis can contribute to improved decision-making on sustainable soil management. Therefore I first highlight what kind of information can be obtained from the bio-economic modeling approach and how this can contribute to enhanced decision support at farm-level. Second, I provide an overview the challenges agriculture is facing in the transition towards a sustainable food system based on the ambition of the EU Green Deal. Third, I illustrate how methods from this thesis can be used to address research questions at the level of the food system.

6.5.1 Implications of economic decision making for sustainable soil management

The aim of this thesis was to assess the economic value of sustainable soil management, which was done by development and application of the bio-economic modeling approach FARManalytics. FARManalytics consists of two modules, PM calculator and PM optimizer, which both address specific issues of decision support at farm-level.

The PM calculator module uses *ex-post data* from current production management to make an *ex-ante assessmen*t of the impact on soil quality and farm economics. The key outcomes of this module are: (a) Impact of production management on a diverse set of soil quality indicators, expressed as performance compared to target. (b) The expected economic performance, expressed as total Economic Value of Land and (3) The calculated environmental impact, for example nitrogen surplus. Key outcomes of this module are particularly useful for decision support in the following areas: (1) Identification of soil quality bottlenecks under the combination of initial soil quality and current production management. The PM calculator assesses current soil quality by comparing indicators to targets (e.g. compare target phosphorus availability to actual phosphorus availability) and predicts future soil quality by comparing current production management to soil quality constraints (e.g. compare required phosphorus input per year to actual phosphorus input per year); (2) Explore the impact on soil quality and economics of user-defined changes in production management, e.g. replace pig slurry by cattle slurry; and (3) Prioritizing of production management decisions based on their impact on soil quality and economics, e.g. explore which manure type allows highest input of organic matter against lowest costs.

The PM optimizer module optimizes production management decisions, considering agronomic and soil quality constraints to maximize economic value of land and provides ex-ante insight in the impact on soil quality and farm economics of future alternative strategies. The PM optimizer produces the same key outputs as the PM calculator, calculated for alternative sets of production management decisions. An additional key output of the PM optimizer is the alternative set of production management decisions themselves. They provide valuable information on which decisions famers can optimize their management in such a way their income is maximized while preserving soil quality. An interesting cross-link between the PM calculator and PM optimizer is to use the PM optimizer module for suggestions of alternative production management decisions that subsequently are implemented in the PM calculator. This is especially useful if one wants to change part of the current production management and wants to keep certain other decisions. An area where the PM optimizer can provide information for decision support is for example to study the potential of alternative production management decisions at the farm level, i.e. to explore the potential of an alternative crop in the cropping plan. Moreover, this module contributes to decision support if the production management has to be reorganized as a result from changing circumstances outside the farm-level, for example changing legislation, changes in resource availability or changing product demands. For these type of questions the PM optimizer has added value over the PM calculator since the PM optimizer module ensures best implementation based on the agronomic and soil quality restrictions whereas with the PM calculator implementation of alternative decisions has to be done manually, which can result in an infeasible solution or overlooking promising alternatives.

6.5.2 Soil management in the transition to sustainable food systems as outlined in the EU Green Deal

Farms are part of food systems, which are defined as "the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture forestry or fisheries, and parts of the broader economic, societal and natural environments in which they are embedded" (FAO, 2023). The current food system is unsustainable: "It negatively affects the environment by generating significant emissions and pollutants affecting air, water and soil quality, as well as our own health" (Davies, 2020). Therefore, there is a need to transform to a sustainable food system. In this section, I aim to illustrate how the transition to a sustainable food system impacts farmers' implementation of sustainable soil management.

The Food and Agricultural Organisation of the United Nations (FAO) has the following definition of a sustainable food system: "A sustainable food system is one that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generation are not compromised. This means that it is profitable throughout, ensuring economic sustainability, it has broad-based benefits for society, securing social sustainability, and that it has a positive or neutral impact on the natural resource environment, safeguarding the sustainability of the environment." (FAO, 2023)

At the EU level, the guiding principles for the transition towards sustainable food systems are included in the EU Green Deal. The EU Green Deal is an ambitious package of measures for Europe to become the first climate-neutral continent by 2050. As part of the proposed EU Green Deal ambitious measures for sustainable soil management are presented in the Biodiversity Strategy 2030, the Farm to Fork strategy and the EU Climate Law (Montanarella & Panagos, 2021).

Table 6.1 – EU Green Deal targets (Montanarella & Panagos, 2021). F2F = Farm to Fork strategy, CL = EU Climate Law, BD = EU Biodiversity Strategy 2030.

	Theme	*Goal*	*Package*
1	Neutral or positive environmental impact	50% reduction in pesticide use by 2030	F2F
		20% reduction in fertilizer use by 2030	F2F
		50% reduction in nutrient leaching while maintaining soil quality levels	F2F
2	Mitigate climate change and adopt to its impacts	Maintain wetlands as carbon sink	CL
		Reduce CO2 emissions from agriculture: climate neutral by 2050	CL
		Use full potential of soil for carbon sequastration	CL
3	Reverse loss of biodiversity	Legally protect 30% of EU land area by 2030	BD
		10% of agricultural area under high diversity landscapes by 2030	BD
		25% organic farming by 2030	BD
		Plant three billion threes	BD
4	Food security	Ensure food security, nutrition and public health, making sure that everyone has access to sufficient, safe, nutrititious, sustainable food	F2F
5	Food affordability	Preserve affordability of food while generating fairer economic returns, fostering competetiveness of the EU supply sector and promoting fair trade	F2F

The implications of the Green Deal for individual farmers have been identified by Boix-Fayos & de Vente (2023) and Montanarella & Panagos (2021). Most important implications are:

Lower crop yields: The restricted use of fertilizer and pesticides is expected to result in an average decrease in crop yield of 7 – 12% (Beckman et al., 2020). Schneider et al., (2023) state that without adapting food systems a 50% reduction in pesticides may result in sizable crop yield reductions. The ambition of 25% of organic farming in 2030 can have an even bigger impact, since for organic agriculture yield losses of 20% to 35% compared to conventional agriculture are reported (Boix-Fayos & de Vente, 2023).

Higher production management costs: Due to the restriction of fertilizer and pesticides use, farmers may need to switch to other production management options. For example, as an alternative to fertilizer, introducing legumes can be an alternative (Boix-Fayos & de Vente, 2023). Alternatives for pesticides are for example wider crop rotation to break pest and disease cycles or mechanical weeding as alternative for herbicides. The alternative production management decisions are likely to be more expensive than input of fertilizer and pesticides, thereby negatively impacting the business model of the farmer.

Higher competition for land: The conversion of 10% of the agricultural to high biodiversity landscapes combined with the ongoing process of rural development, results in a lower area of land available for farming. On the other hand, the ambition for 25% organic farming and need for extensification to meet Green Deal targets ask for more agricultural land (Boix-Fayos & de Vente, 2023). Ultimately, higher demand and lower availability might increase the prices of agricultural land.

Increasing demands on agriculture: Despite discussion about the exact number, future food production must increase to feed a growing world population. Simultaneously, agriculture also needs to become an important supplier of food and fuel putting even more pressure on the food system. Although the Green Deal also aims to reduce food demand by reduction of food waste and switching to more sustainable diets, future demands from agriculture will remain high.

6.5.3 Economic-based decision support for the transition towards sustainable food systems

The implications of the EU Green Deal on sustainable soil management likely force farmers to reconsider their current production management, in which the relation between soil quality and economic sustainability is a key issue. Therefore, this section includes three examples of how FARManalytics can be a valuable tool for decisions support in the transition to a sustainable food system.

(1) *The impact of EU Green Deal ambitions on farmers' business models and soil management*

As a result of the EU Green Deal ambitions, input use is increasingly restricted. By applying correction to crop inputs and crop yields in the PM calculator, some first explorations can be done to estimate farm income as a result of lower input use. Such results are not only relevant for farmers, but also for other actors such as value chain participants, who have a prime interest in expected production volumes. The ambitions of the Green Deal are a typical example of policy that requires farmers to revise their current production management. Using the PM optimizer, farmers and their advisors can explore how they can re-arrange their production management in such a way that it meets the policy targets while achieving maximum farm income and preserving soil quality. For such an application, policy targets can be implemented as additional constrains in the model, e.g. a constraint enforcing 20% lower fertilizer use or a 50% reduction in N surplus. If the input restrictions require a more fundamental revision of the farm set-up, e.g. a wider crop rotation to break pest & disease cycles, this can be modelled by applying stricter crop rotation constraints. Beyond farmers, results of such an exploration are also useful for policy makers: using the model, they can explore expected changes in production management by farmers to avoid changes in an unwanted direction, i.e. more intensive cropping plans as a result of higher land prices and higher product demands.

(2) *The potential of alternative business models including ecosystem services*

The ambitions of the EU Grean Deal put large emphasizes on agriculture to deliver a wide variety of ecosystem services, such as water purification and regulation, carbon sequestration and provisioning of a habit for biodiversity. This development might require de-intensifying some production management. As de-intensification is likely to result in lower yields and hence lower farm income, a key question is: How can the farmer be (financially) incentivized to deliver ecosystem services. Using the PM calculator, one can calculate current farm income and the current provisioning of ecosystem services (e.g. N surplus as proxy indicator for water quality). Subsequently, provisioning of ecosystem services can be modelled with the PM optimizer as more stringent constraints. Results of the optimization are useful for policy makers and environmentally engaged actors such as water boards and managers of natural areas to assess the expected loss of income and hence required financial compensation to create an incentive for farmers to deliver ecosystem services. In turn, farmers and their advisors can use the PM optimizer to find the optimal combination of production management decisions that result in highest returns from crop yield and ecosystem services.

(3) The potential of technical developments

Technical developments have the potential to contribute to achieving Green Deal targets while simultaneously contributing to farm income. Examples of such technical developments are precision application of inputs which allows a reduction in input without harming effectiveness and better crop cultivators, i.e. crop cultivars with lower fertilizer requirements or resistance against pests and diseases. Precision application of inputs often requires higher investments, resulting in higher costs of field operations as better crop cultivators might be more expensive compared to traditional varieties. Both precision application and better crop varieties can be implemented in FARManalytics. The impact of precision fertilization can for example be implemented as a lower constraint for crop fertilization, e.g. 20% lower nitrogen need if applied in the root zone on the right time. The impact of better crop cultivars can be implemented by adding them as separate crops with a different impact on soil-borne diseases compared to traditional varieties. Using the PM optimizer, farmers and their advisors can explore how these technological developments contribute to policy targets, soil quality and farm economics. For example, using crop cultivars with better resistance against soil-borne diseases, it might be possible to cultivate the crop with 50% reduction in pesticides but without the need for a wider crop rotation to break the pest cycle. Outcomes of such analyses provide interesting insights for providers and developers of technology. Based on the model outcomes, they can explore which properties have most impact and at which price their technology becomes profitable for the farmer.

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Summary

Soil quality is a pivotal factor influencing crop productivity, farm resilience, and the overall environmental quality of arable farming systems. The increasing global population and the need to ensure food production worldwide have placed high demands on agricultural land, while the available land area is diminishing due to factors like urbanization. This is particularly the case in densely populated areas such as The Netherlands. Here, these developments put an immense pressure on agricultural land, which can lead to the degradation of soil quality through issues such as subsoil compaction, organic matter loss, and erosion. Soil quality is not only crucial for farmers as operators and often owners of the land but also for agricultural value chains and regional ecosystems. Consequently, there is a pressing need for the implementation of sustainable soil management. However, the implementation of sustainable soil management is not straightforward due to the uncertain long-term impacts of farmers' production management on soil quality, the trade-offs between soil functions, and conflicts between short-term income and long-term soil quality. Although this implies that the implementation of sustainable soil management is an economic problem, an integrated economic approach to the problem has largely been neglected so far i.e., insight in the economic value of sustainable soil management is lacking.

The objective of this thesis is to assess the economic value of sustainable soil management ($EVSM$) which is split in four sub-objectives: (1) Define $EVSM$ and develop a conceptual framework for sustainable soil management in an arable farming context. (2) Provide an analysis of actors involved in sustainable soil management in the Netherlands. (3) Develop and illustrate a bio-economic model to optimize $EVSM$ at farm-level. (4) Explore $EVSM$ on existing Dutch arable farms in future scenarios.

Chapter 2 develops an inter-disciplinary conceptual framework based on extensive literature review in which $EVSM$ is defined as the difference in returns between long-term sustainable and sub-optimal or unstainable production management. Sustainable production management results in highest economics returns while preserving long-term soil quality. Chapter 2 integrates disciplinary knowledge on agronomy and soil quality with economics in a conceptual framework. Farmers' production management i.e., the complete set of physical and non-physical inputs made by the farmers is the primary determinant of soil quality and hence future farm income. The conceptual framework provides a basis for integrated bio-economic modeling and policy development to enhance sustainable soil management.

Chapter 3 focuses on all actors involved in sustainable soil management in The Netherlands. Main actors are value chain participants, environmentally engaged actors and policy makers. Analytical Hierarchy Process is used to elicit priorities of actors for soil sustainability criteria. Results show a complex and heterogenous network of actors with famers and value chain participants prioritizing economic criteria. Power-interest grids based on a survey underscore the prime role of the farmers due to their high power and high interest. The self-assessment of power-interest compared to assessment by others reveals noticeable differences, especially for environmentally engaged actors. Results from this chapter provide an overview on which actors to involve in decision-making on sustainable soil management.

The insights obtained from Chapters 1 and 2 provide the basis for the development of the FARManalytics bio-economic modeling approach, described in *Chapter 4*. Inputs for FARManalytics are a comprehensive set of chemical, physical and biological soil quality indicators and quantitative rules on how these indicators respond to farmers' production management over time. Secondary inputs are the economic contributions of different production management decisions towards farm income which were calculated with Activity-Based-Costing. FARManalytics consists of (1) PM Calculator, a module that calculates the impact of current production management on soil quality and farm economics and (2) PM Optimizer, a module that uses Mixed-Integer-Linear Programming to maximize farm income within soil quality constraints. Decision variables are cropping plan, crop rotation, cover crop, manure & fertilizer application and crop residue management. FARManalytics was applied on four standard farm types in the Netherland derived from the Farm Accountancy Data Network, demonstrating farm income can be increased with up with up to €940 ha-1 year-1 on clay soil and up to €683 ha-1 year-1 on sandy soil, while meeting all soil quality targets except subsoil compaction vulnerability. The latter is among the most limiting soil quality indicators for the farm types in this study, together with soil organic matter input, wind erosion vulnerability and plant-parasitic nematodes. FARManalytics integrates the impact of production management decisions on soil quality and economics at farm-level, which can provide useful information for policy support and decision support for individual farms.

Chapter 5 assesses $EVSM$ on nine Dutch arable farms and explores the impact of various production management strategies using scenario analysis. Using the FARManalytics bio-economic modeling approach, first the current performance of the farms regarding soil quality and farm economics is studied. Second, $EVSM$ is optimized in farm-specific scenarios addressing specific challenges. Third, the impact of stricter water quality regulations and field beans (*Vicia faba*) as an alternative crop is explored. Nutrient management, subsoil compaction, and organic matter input were found to be the major soil quality bottlenecks. By implementing the right production management decisions farm income could be increased with up to €704 ha^{-1} while meeting all soil quality targets except subsoil compaction. Stricter water quality regulations severely limit production management options, thereby reducing potential farm income. Field beans have a potential to replace part of the cereals in the cropping plan and contribute positively to soil quality and farm income. However, field beans are not yet able to compete with cash crops like potatoes and onions. Through sustainable soil management, farm income can be increased while improving soil quality. The FARManalytics model can be applied at farm level to solve local and regional challenges regarding agronomic and environmental targets.

This thesis shows the potential for improved decision support on $EVSM$ by integrating the impact of production management on soil quality indicators embedded in an economic context. The main limitations are the lack of physical and biological soil quality indicators, the difficulty to include yield effects of enhanced soil quality and the static and deterministic modeling approach. *Chapter 6* provides an outlook on the implications of this thesis and addresses future developments for sustainable soil management based on the European Union Green Deal. This chapter illustrates how insight in $EVSM$ can contribute to better economic based decision making in the transitions towards a sustainable food system, not only for farmers but also for other actors like value chain participants and policy makers.

The main conclusions of this thesis are:

- The Economic Value of Sustainable Soil management ($EVSM$) can be defined as the difference in economic returns between sustainable management and unsustainable or sub-optimal management. Sustainable management can be defined as obtaining highest economic returns without compromising long-term soil quality.
- Production management i.e. the complete set of physical and non-physical inputs made by the farmer is the primary determinant of long-term soil quality and hence future economic returns.
- Farmers are the prime actors in sustainable soil management due to their high power and high interest.
- Besides the farmer as prime actor, a diverse group of other actors including value chain participants, environmental actors and policy makers is involved in sustainable soil management.
- Bio-economic modeling at farm-level allows to support production management decisions with an integral view on soil quality, which ensures long-term preservation of soil-quality in a financially robust strategy.
- The FARManalytics bio-economic modeling approach optimizes key production management decisions: cropping plan decisions, crop rotation design, cover crop, manure application, fertilizer application and crop residue management.
- FARManalytics be used for policy support when combined with standard farm types. Furthermore, FARManalytics can be tailored to an individual farm to support decision making at the farm-level.
- $EVSM$ can be effectively evaluated by integrating soil quality into a bio-economic model, considering the interrelations between soil quality indicators and the influence of production management on soil quality. Furthermore, implementing this approach on a large scale at reasonable costs is achievable. However, significant challenges that remain are the incorporation of crop yield response to improved soil quality and farmers' attitudes towards risk & uncertainty.
- Nutrient management, subsoil compaction vulnerability and soil organic matter input are the current soil quality bottlenecks in Dutch arable farming.
- Even for a group of front runners, farm income can be increased with up to €700 ha^{-1} year^{-1} while preserving or improving long-term soil quality. Although farmers play a pivotal role in sustainable soil management decisions, their actions are influenced by interactions with other actors. Therefore, assessing $EVSM$ at the farm-level requires considering its broader socio-economic context.

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About the author

Martinus Cornelis (Maarten) Kik was born on July 20th 1994 in Zierikzee, the Netherlands. Since an early age he was already working together with his father on the arable-dairy farm of family members, which triggered his passion for agriculture. Following this passion, Maarten started the bachelor's degree of Biosystems Engineering at Wageningen University in 2012. In 2015, he started the master program of Biosystems Engineering at Wageningen University where his thesis on the economic feasibility of innovative arable farming systems triggered his interest in economics. To further expand his knowledge on economics, he also enrolled in the master program of Management and Economics where he did a thesis on cropping plan optimization in Dutch arable farming and an internship at Royal Agrifirm Group on optimization of land use in Dutch dairy farming.

In 2019, Maarten started his PhD Research at the Business Economics Group and Operations Research and Logistics Group of Wageningen University. In this PhD research, Maarten continued to work on his thesis and internship project by optimizing the economic value of sustainable soil management in Dutch arable farming. Since September 2023, Maarten is working as a researcher specialized in arable and dairy farming at Wageningen Economic Research. In this position, Maarten hopes to further contribute to the sustainable development of land-based agricultural systems by building upon the work he did in his PhD.

Besides his profession as a researcher, Maarten works as a freelance farm assistant at various Dutch farms where his main tasks are tractor and forklift driving during the planting and harvest season. If Maarten is not conducting research or driving a tractor, he can be found renovating his 1930's house, working in the garden or in an Austrian ski resort.

Education certificate

Maarten Kik

Wageningen School of Social Sciences (WASS)

Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
A1. Managing a research project			
WASS introduction course	WASS	2019	1.0
Scientific writing	Wageningen in'to languages	2019	1.8
Efficient writing strategies	Wageningen in'to languages	2019	1.3
Writing research proposal	WUR	2019	6
'A conceptual bio-economic approach to soil quality'	IGLS Forum, Garmisch Partenkirchen	2019	1
'Optimization of gross margin and soil quality in Dutch arable and dairy farming – towards the economic value of soil quality'	Wageningen Soil Conference, Wageningen	2019	1
'Stakeholder involvement in sustainable soil management - A case study from the Netherlands'	IGLS Forum, Garmisch Partenkirchen	2020	1
'The economic value of sustainable soil management in arable farming system – A conceptual framework'	EAAE Conference Prague	2021	1
'Bio-economic modelling to establish the economic value of sustainable soil management'	IGLS Forum, Garmisch Partenkirchen	2023	1
A2. Integrating research in the corresponding discipline			
MOOC Soil4Life Sustainable Soil Management	WUR	2019	3
Research internship soil quality	NMI/ WUR	2023	6
Learn Python 3	Codecademy	2020	5
Analyse data with Python			

B) General research related competences			
B1. Placing research in a broader scientific context			
MOOC Sustainable Food Security: Crop production	WUR	2019	1.5
Economic Perspectives for a Circular Food System, APS51303	WUR	2020	3
Co-organisation of inter-disciplinary symposium on socio – economics of soil quality	BEC/ORL/WEcR	2019	2

B2. Placing research in a societal context			
Consultation and reflection with arable farmers in the Dutch network “Bedrijvennetwerk Bodemmetingen”	BEC/ORL/Wageningen Plant Research	2020-2023	2
Consultation and reflection with cooperating arable-livestock farmers in Drenthe	BEC/ORL	2021-2023	1
Invited presentations for Wageningen Plant Research and Duurzaam Praktijknetwerk Akkerbouw	BEC/ORL	2021-2023	1
C) Career related competences			
C1. Employing transferable skills in different domains/careers			
Supervising BSc and MSc students	BEC/ORL	2019-2022	2
Lecturing courses	BEC	2019-2022	2
Total			**43.6**

*One credit according to ECTS is on average equivalent to 28 hours of study load

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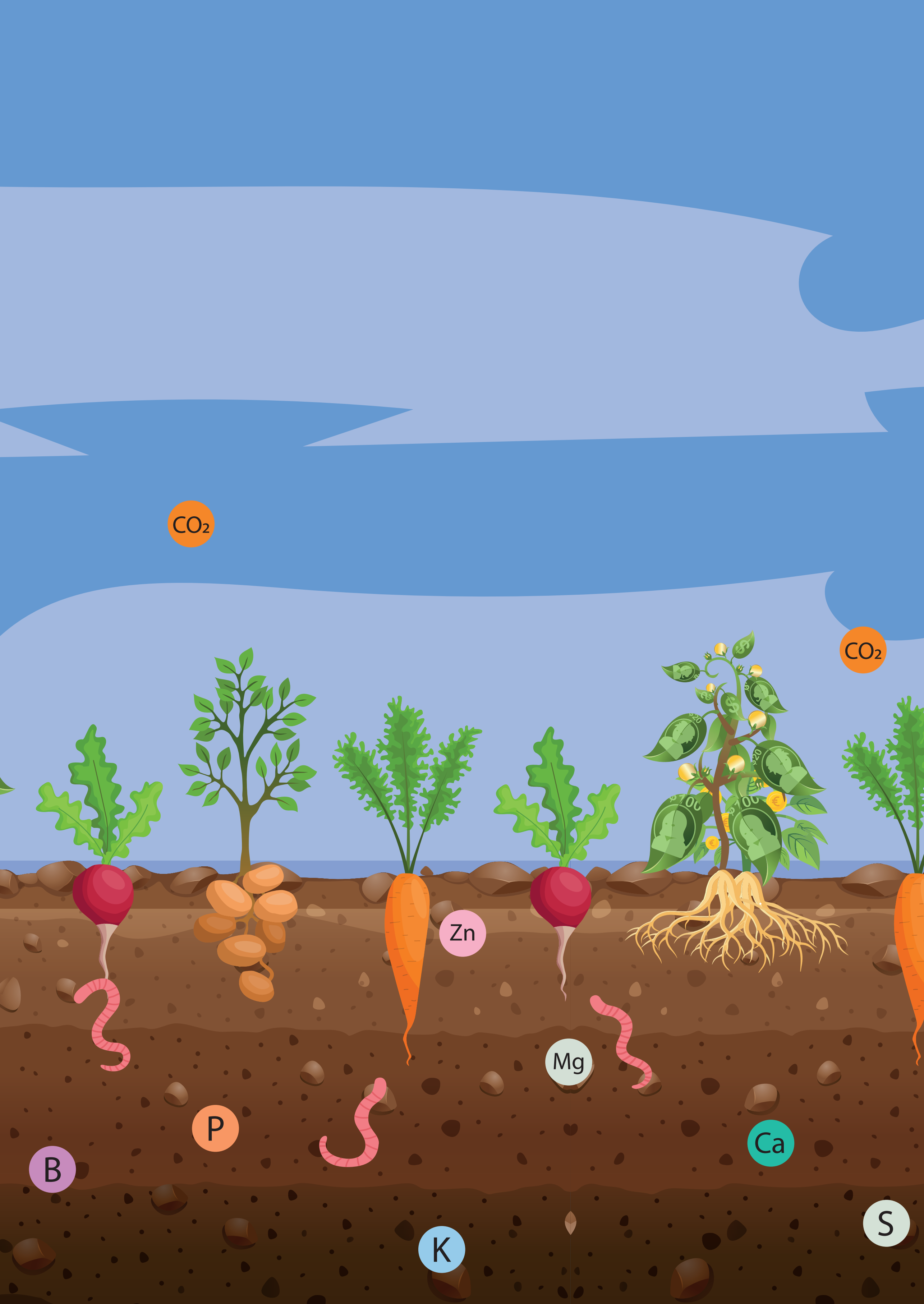
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