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

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A R T I C L E I N F O

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A B S T R A C T

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 modelling and a basis for policies to enhance sustainable soil management.

1. 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 and decreasing availability of land because of competition for space (Alexandratos and Bruinsma, 2012). 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 (Kik et al., 2021). 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;

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Koch et al., 2013).

There is a strong call for the implementation of sustainable soil management (SSM): 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 SSM 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 McConnell (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 SSM.

The aim of this paper 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 paper is structured as follows. Section 2 provides the economic conceptualization of SSM. Section 3 includes a framework for SSM in the context of arable farming. Section 3.1 and Section 3.2 provide technical and agronomic knowledge on soil quality and crop production respectively to implement SSM in arable farming. Both sections address knowledge gaps for implementation of SSM. The paper ends with a Discussion, including an illustration of the framework and implications for further use.

2. Economic conceptualization of sustainable soil management

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

PM can be categorized in one of the following three strategies:

(1) Unsustainable *PM*: *PM* consists of unsustainable practices causing a decline in soil quality, particularly in the mid-long run.
(2) Sub-optimal *PM*: the soil's potential is not fully utilized. *PM* can be intensified without affecting soil quality.
(3) Sustainable *PM*: 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 *PM* in such a way that long-term farm income is maximized in a sustainable way. This section defines the economic range for sustainable *PM*. The upper bound of this range is when *PM* becomes too intensive and subsequently soil quality starts to decline. The lower bound is the *PM* 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 *PM*. However, they operate in a context with other actors that can influence their decisions (Kik et al., 2021).
- 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.
- *PM* can consist of many options that will be elaborated in Section 3. For illustration purposes we assume that the whole set of production management options can be integrated into a vector *PM* intensity, ranging from an extensive *PM* to very intensive *PM*.[1] Defining *PM* as a vector allows us to illustrate the range of sustainable management. When PM is sub-optimal, more intensive *PM* results in a higher yield. Beyond the point where *PM* is sustainable, a higher *PM* 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 *PM* 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

[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.

organic matter content) responds dynamically to the applied management. Therefore, *SQ* refers to the manageable part of soil quality.

Under these assumptions, *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 Eqs. (1) to (3). Subsequently replacing *SQ* by Eq. (1) in Eqs. (2) and (3) shows that in the long-term the output level of *Y* and *E* is dependent on *PM*.

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

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

Eqs. (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*.

Depicting the above graphically, Fig. 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 Fig. 1A: Area 1 represents unsustainable soil management, Area 2 represents sub-optimal management.

Fig. 1B introduces the hypothetical response curves for ecosystem services. As follows from Eqs. 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. Providing E_c at an optimal level requires a different level of *PM* than the optimum level of *PM* for yield. Whereas *Y* in Fig. 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.

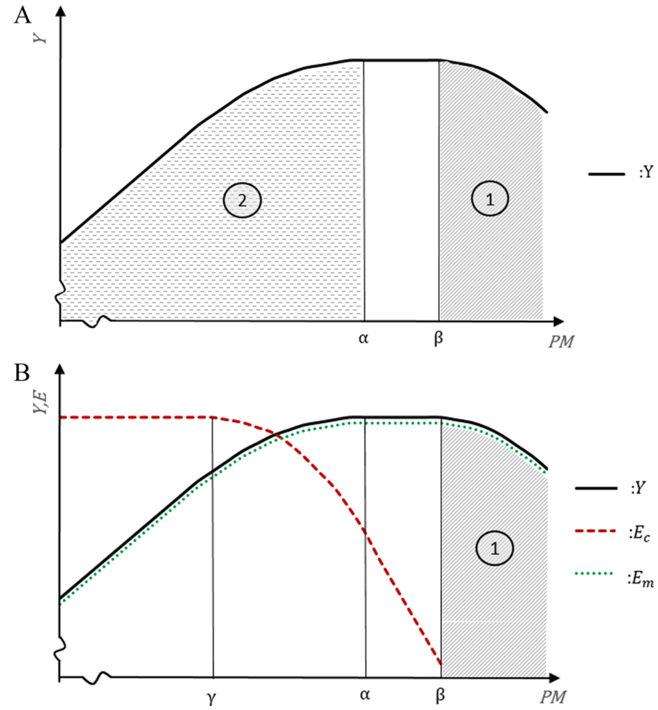

Fig. 1. (A) Yield (Y) response to an increasing production management (PM) intensity in an arable production system. Area 1 represents the area with unsustainable PM. Area 2 represents the area with sub-optimal PM. (B) Response of Y and ecosystem services E to an increasing PM intensity. E can be competing with Y (E_c) or_mutual (E_m).

Similarly to Fig. 1A we can define an area of unsustainable management in Fig. 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*: 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 Eqs. 4 and 5 into Eq. 6 shows that one can derive a steady state optimal *PM* and thus *SQ* by maximizing *EVL* through the choice of *PM*.

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

Fig. 2A builds upon Fig. 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*.

Until point α, the *EVL* curve in Fig. 2A has a similar pattern as the *Y*

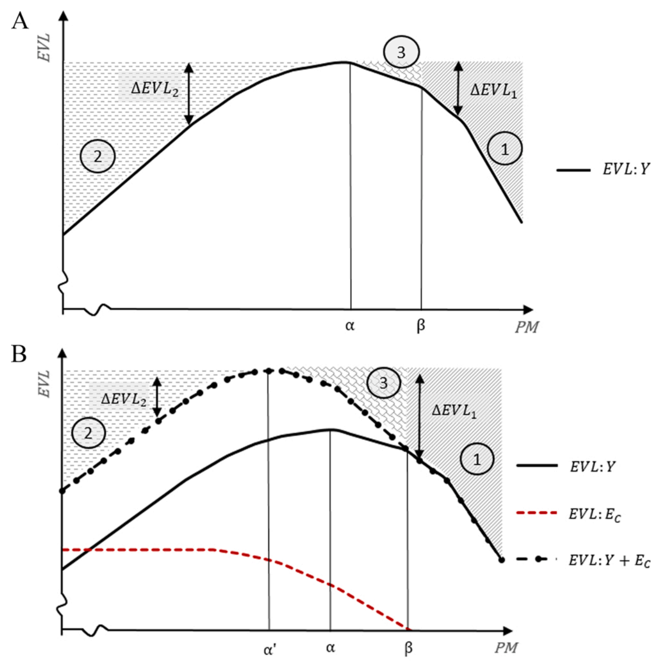

Fig. 2. (A) Total returns from agricultural land (EVL) in relation to Production Management (PM) intensity. ΔEVL_1 in the area of unsustainable management 1 represents the economic loss of soil quality degradation due to too intensive production. ΔEVL_2 in the area of sub-optimal management represents the economic loss of sub-optimal PM. (B) 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'.

curve in Fig. 1A. Maximum yield and therefore maximum *EVL* is achieved at point α.[2] 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 (Fig. 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*. Fig. 2A 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 Fig. 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'.

Fig. 2B shows that farmers can be stimulated by financial incentives to adopt a *PM* intensity which is beneficial for the delivery of ecosystem services. Fig. 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 Fig. 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*.

EVL response curves for mutual ecosystems services in Fig. 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 following 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 *PM* 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 *PM* 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 *PM* so *EVL* stays maximal?
(2) If *EVL* is not maximal, how to choose *PM* so that *EVL* is maximized?
(3) If soil quality declines, how to change *PM* 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.

3. 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 Fig. 3 illustrates that farmers manage *EVL* within a context with other actors.

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*). Fig. 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* 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*, 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 *LU* over multiple growing

[2] Compared to Fig. 1A, the position of alpha (α) can shift to the left if costs of production management increase and subsequently marginal returns decrease.

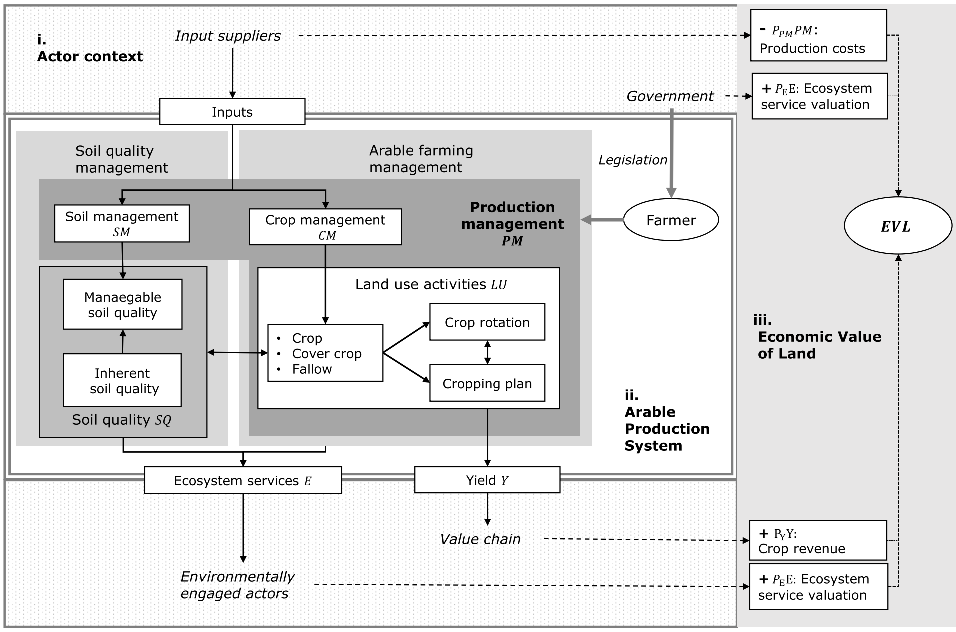

Fig. 3. Framework integrating the Economic Value of Land (EVL) in an arable farming system.

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 *PM* and (2) Arable farming management: How to organize *PM* in such a way that *EVL* is maximized?

3.1. Soil quality management

In Section 2, 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.

Fig. 4 illustrates soil quality management by explaining the relation between the production management and the main chemical, physical and biological components of soil quality.

The soil properties in Fig. 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

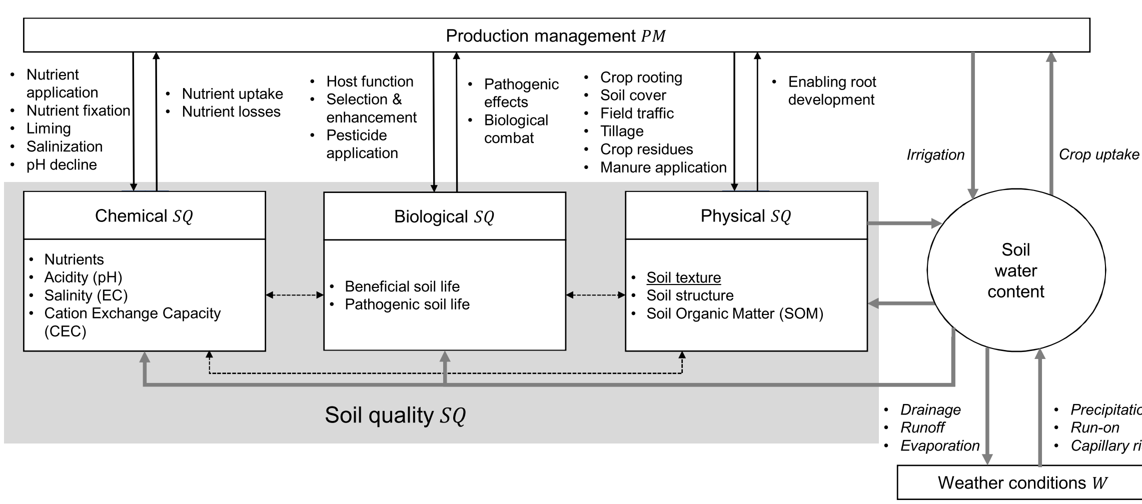

Fig. 4. Illustration of the various factors determining soil quality management. Underlined Soil Quality (SQ) properties are inherent and thus hardly influenced by production management.

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 and 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 *PM* on soil quality is not fully understood and quantifiable. For example the effect of field traffic on soil structure is hard to quantify (Hamza and 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 *PM* 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. This not only applies for SOM, but for all aspects of soil quality.

3.2. Arable farming management

Fig. 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 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. Fig. 5 provides an illustration of the spatial and temporal allocation of *LU* and *CM* in an arable farming system.

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 Fig. 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). Fig. 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. Fig. 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

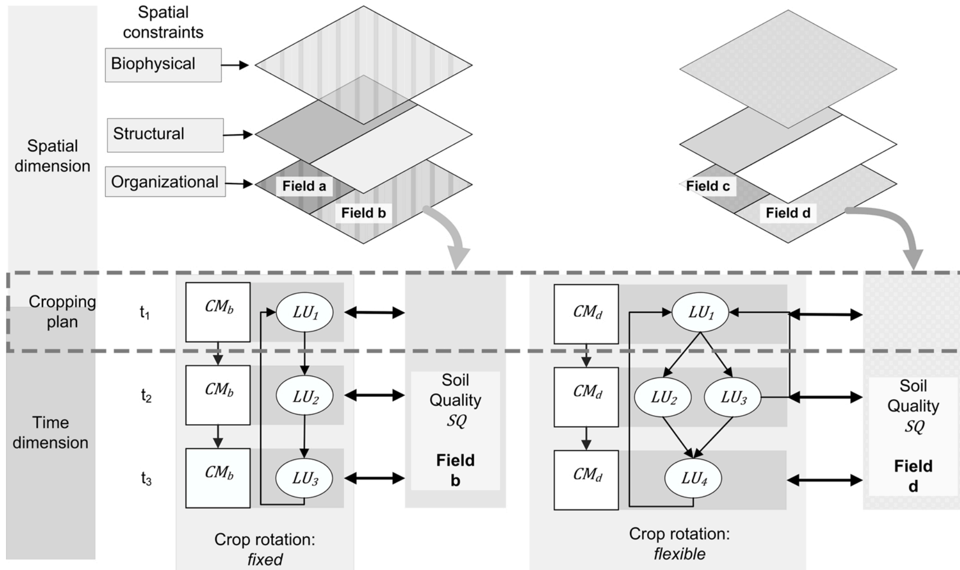

Fig. 5. Illustration of factors determining arable farming management. In the spatial dimension, spatial constraints determine allocation of land use activities (*LU*) and crop management (*CM*) to a certain field. The time dimension represents the sequence of *LU* and *CM* over the year. Figure adapted from Dury (2011).

modelling 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 Fig. 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 and 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.

4. Discussion

This paper 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.

4.1. 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.

4.2. 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). Our 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 delivery of ecosystem services can be an integrated part of sustainable development. In Section 2, 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.

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 *SSM* 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.

4.3. Conclusions

This paper 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.

CRediT authorship contribution statement

M.C. Kik: Conceptualization, Writing - original draft. **G.D.H. Claassen:** Conceptualization, Writing - review & editing. **M.P.M. Meuwissen:** Writing - review & editing. **A.B. Smit:** Writing - review & editing. **H.W. Saatkamp:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors report no declarations of interest.

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

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