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Abstract

Agriculture is facing an expected increase in food production demand, caused by an increased global population of 9 billion people by the middle of this century. At national scale, competitiveness and economic growth issues are at stake. To insure this increase in production, there are two solutions: extend the proportion of agricultural lands at the expense of natural ecosystems; and increase agricultural productivity. Through a review of agronomic and economic articles, we show the importance of considering soil quality in the productivity and sustainability of farms. However, farming practices preserving soil quality are not widely adopted, particularly in France. An economic analysis of these issues provide an understanding of farmers' decision making process, and indicate what the optimal strategies can be to cope with these challenges. We propose an optimal control model that illustrates the links between farming practices and soil quality when soil quality is considered as an endogenous production factor. The interest and originality of this article is to associate different disciplines to investigate the role of soil quality in the sustainability and profitability of farms.

Keywords: soil quality, sustainability, competitiveness, endogenous production factor

JEL Classification: Q10, Q24

Les sols, au cœur des enjeux de compétitivité et de durabilité en agriculture : une approche économique

Résumé

D'ici 2050, l'agriculture devra répondre à une augmentation de la demande alimentaire, due à une augmentation de la population qui devrait atteindre alors les 9 milliards. A l'échelle nationale, cela représente des enjeux de compétitivité et de croissance économique. Par ailleurs, afin d'assurer cette augmentation de la production, il y a deux solutions : augmenter la proportion des terres agricoles au détriment des écosystèmes naturels; et augmenter la productivité agricole. A travers une revue d'articles agronomiques et économiques, nous montrons l'importance de considérer la qualité du sol dans la productivité et la durabilité des exploitations agricoles. Cependant les pratiques agricoles préservant la qualité du sol ne sont pas largement adoptées, ce particulièrement en France. Une analyse économique de ces enjeux permet d'appréhender le processus de décision des agriculteurs, et de déterminer quelles sont les stratégies optimales permettant de répondre à ces enjeux. Nous proposons un modèle de contrôle optimal qui illustre les liens entre les pratiques agricoles et la qualité du sol, quand la qualité du sol est considérée comme un facteur de production endogène. L'intérêt et l'originalité de cet article est d'associer différentes disciplines pour étudier le rôle de la qualité du sol dans la durabilité et la rentabilité des exploitations.

Mots-clefs : qualité du sol, durabilité, compétitivité, facteur de production endogène

Classification JEL : Q10, Q24

Soil resource, at the core of competitiveness and sustainability issues in agriculture: an economic approach

1 Introduction

Agriculture is facing an expected increase in food production demand, caused by an increased global population of 9 billion people by the middle of this century (Tilman *et al.*, 2002; Goulet, 2012) and changing diets requiring more meat production. To insure the necessary increase in production, there are two solutions: extend the proportion of agricultural land, at the expense of natural ecosystems; and increase agricultural productivity.
However, agricultural activities have strong environmental impacts, some of them irreversible and detrimental. With an increase in food production, one could expect an increase in these detrimental effects on natural resources that are scarce. Hence, in addition to being productive, agricultural practices have to be sustainable, or equivalently to ensure the possibility to produce agricultural goods in the long run (Tilman *et al.*, 2002). Furthermore, increasing prices of energy and fertilizers are observed, and there are pressures at the World Trade Organization (WTO) to reduce agricultural support. In this context, concerns related to the competitiveness and sustainability of agriculture, even in developed countries, are particularly important and necessary to consider. Soil resource quality and productivity, as supporting and contributing to agricultural production and productivity, are determinant elements to be taken into account when considering competitiveness and sustainability issues in agriculture.
This article focuses on farms competitiveness, sustainability and productivity issues, within the current international context. In this article, we aim at demonstrating the importance of the soil resource in the productivity and sustainability of farms, and through a theoretical model, at proposing an economic approach of the integration of soil resource as an endogenous production factor in the farmer's decision making process. The interest of the article is to adopt an agronomic approach within an economic analysis framework. Using an optimal control model at the farm level, we illustrate the links between farming practices and soil quality and how soil quality can be taken into account while maximizing the farm profitability in the long run. The article is organized as follows.
First, we expose the competitiveness, productivity and sustainability issues the agricultural sector is facing, and we demonstrate the importance of considering soil resource in agriculture, as being at the core of competitiveness and sustainability issues in agriculture. The Ecologically Intensive Agriculture (EIA) concept is also presented, which is a particular answer to these issues: the EIA concept is based on the intensive use of natural and ecosystem processes and gives to soil a particular importance. In a second part, the interactions between soil quality and farming practices are presented. Then, a theoretical farm-level model is proposed that takes into

account the linkages between soil quality, farm productivity and sustainability. This model is confronted to the related literature in economics, both theoretical and empirical, but also to the agronomic literature.

2 Competitiveness, productivity and sustainability of farms: the role of soil quality

The concept of competitiveness refers to the contribution of one sector to the economic growth of a nation through its ability to face competition successfully: a competitive sector is able to sell products that match market demand (in terms of price, quality and quantity), and to make profits allowing firms to thrive (Latruffe, 2010). The competitiveness of a sector or a firm is a relative measure, and can be done at several levels (national or international).

The agricultural sector is a critical and a sensitive sector since it is related to national food security and safety (Hervieu, 2001). Hence, in a context of globalization and market liberalization, the agricultural sector is a strategic sector with respect to competitiveness. In addition, since this sector is highly supported, and not only in the European Union, it has been at the origin of multiple frictions during Word Trade Organisation (WTO) negotiations (Ball *et al.*, 2010). Therefore, being under both external and internal pressures (Petit, 1999) to reduce the support to agriculture, the European (and French) agriculture has to be able to face the global market with a decreasing agricultural support. In other words, it has to be (more) competitive (Hervieu, 2001).

The competitiveness of a sector or a farm can be understood in terms of strategic management. In this case, competitiveness is illustrated by performance indicators such as costs measures, productivity, efficiency and profitability. Competitiveness is to be considered in the long-run and is associated with the objective of sustainability. Sustainability can be considered at a global or local scale. For instance in the French case, one can consider the contribution of French farms to the sustainable development of the country (global scale), or consider the sustainability of the farm itself (local scale). In this article, we focus on farmers' decisions and practices, thus sustainability is defined at the farm scale.

Soil resource quality has an important role in the competitiveness of farms and agriculture through the aspects of productivity and sustainability. Actually, one parameter of the effective productivity of a farm is related to the potential capacity of agricultural production, which is determined by the interactions of the chemical, physical and biological properties of the soil, which can be referred as soil quality (Parr *et al.*, 1992). For a soil to provide all its functions, among which its production function, its quality has to be preserved (Lal, 1998).

In this article, soil is understood as being the superficial layer of the earth's crust considered with respect to its productive nature or characteristics (Larousse; Société Pédologique de Suisse, 1999); it is *"the primary environmental stock that supports agriculture"* (Wood, Sebastian and

Sheer, 2000). Soil quality is defined by Lal (1998) as *"a soil inherent capacity to produce economic goods and perform environmental regulatory functions"*, and by Parr *et al.* (1992) as *"an inherent attribute of a soil that is inferred from its specific characteristics and observations (e.g., compactability, erodibility, and fertility)"*. Letey *et al.* (2003) propose to define soil quality as *"the chemical, physical, and biological properties of soil that affect its use"*.

In the definitions of soil and soil quality, the notion of production is always mentioned, explicitly or implicitly; and actually in agriculture, land (and thus soil) can be considered as a production factor (Balabaré and Lifran, 2011). Soil is considered to have four principal functions (Lal, 1998): (i) sustain biomass production and biodiversity, (ii) regulate water and air quality, (iii) preserve archaeological, geological and astronomical records and (iv) support socio-economic structure, cultural and aesthetic value and provide engineering foundation. Agricultural productivity can thus be considered as one of the functions of a soil, and will depend on the soil quality. However, it is important to acknowledge that the impact of soil quality on land productivity can be confounded by other factors (such as the use of fertilizers or irrigation). In some cases, though the soil quality is degraded, one can observe constant or even increasing yields (Lal, 2001). Nonetheless, even in these cases, long-term reduction in soil productivity is to be expected (Dregne, 1995).

In agriculture, sustainability is related to the maintenance of the productivity and profitability of farms; and soil quality can be seen as the ability of a soil to sustain plant and animal productivity (Herrick, 2000). Additionally, soil quality is commonly used to assess the sustainability of agricultural land management (Carter, 2002). For example in the *Indicateur de Durabilité des Exploitations Agricoles* (IDEA) method, soil quality indicators are part of what the authors call *"elementary units of sustainability"* (Briquel *et al.*, 2001). In a study led by Gòmez-Limòn and Sanchez-Fernandez (2010) about the empirical evaluation of agricultural sustainability for two agricultural systems in Spain, two of the composite indicators used are soil quality criteria (minimization of soil loss and maintenance of chemical quality of soil).

Hence, it appears that for French farms to be competitive, performing sustainable farm productivity and profitability is required. These are the objectives EIA offers to achieve. EIA proposes to break with a conventional agriculture intensive in chemical inputs (fertilizers and pesticides) and instead, to use intensively natural processes and ecosystem functionalities in a sustainable way (Chevassus au Louis and Griffon, 2008). In addition, EIA proposes a holistic view of farming over decades, at the farm scale and not only the parcel scale (Hochman *et al.*, 2013).

EIA offers farmers a way to re-appropriate the ecosystem functionalities optimization. However, having a constant or increasing production while respecting the environment, implies more complex agricultural practices than in conventional agriculture and requires farmers to adopt an innovation and research logic (Ghali, 2013).

In France, EIA seems to develop from the West of France, where in 2010 a group of professional stakeholders and scientists have created the international association for an ecologically intensive agriculture. There is a large diversity of stakeholders in the association management

board, including researchers, farmers, local elected officials, heads of Chamber of Agriculture, and the sponsors are agricultural suppliers, food retail firms, or agricultural cooperative groups (Goulet, 2012; AEI website). Among the latter, a multi-purpose cooperative has a deep interest in EIA, which is now part of its strategy (Ghali, 2013), for the elaboration of an innovative agriculture (Terrena website). The Chambers of Agriculture of Brittany have also developed a strong interest in EIA (see *Chambres d'agriculture de Bretagne* website).
Actually, EIA development also relies on the support of firms and politics, in the same way as conservation agriculture has. Conservation agriculture consists in farming practices that protect soil from erosion and other forms of degradation (Griffon, 2013) and is frequently named as an example of EIA techniques. In fact, the importance given to soil quality by EIA is revealed by numerous references made to conservation agriculture (Goulet, 2012). Conservation agriculture requires the simultaneous use of three principles: less soil disturbance, soil cover and crop rotation to control for weeds, pests and diseases. Reduced-tillage, direct seeding and cover crops are examples of practices associated with conservation agriculture (Lahmar, 2010) and by extension with EIA.

3 Soil quality: negatively and positively affected by farming practices

Agriculture is acknowledged as being one of the principal causes of soil degradation (Stoate *et al.*, 2001), along with natural causes (erosion by wind and water and other soil formation processes) and urban and industrial use (Lal, 1998; Wood *et al.*, 2000).
Soil degradation or deterioration is the inability of a soil to fulfil its principal functions (Wood *et al.*, 2000). The principal soil degradation processes linked to agriculture are (Lal, 1998): (i) chemical processes, related to soil nutrient depletion, acidification and salinization; (ii) physical processes, related to structural decline, compaction, crusting and erosion; (iii) biological processes, related to the loss of soil biodiversity and soil organic carbon (SOC) decline.
Moreover, soil degradation is a relative concept (Gis Sol, 2011) and has to be defined from a reference point. However, the problem with soil deterioration is that under a critical threshold it may not be possible for the soil to recover (Lal, 1993), so that soil can be considered as a non-renewable resource at the human time scale (Arrouays *et al.*, 2003). In this case, soil degradation would be considered as irreversible. Nevertheless, when this critical threshold is not reached, it is possible for the soil to be restored, and soil degradation in this case is reversible. The soil resilience, or the soil ability to recover from degradation, is based on the restoration process and depends on a critical threshold, along with the rate of recovery to the initial state, and the path of recovery (to be opposed to the path of degradation) (Lal, 1993).
In France, soil physical degradation is mainly due to water erosion (Muxart, Guerrini and Auzet, 1992) and soil compaction (Gis Sol, 2011). In metropolitan France, 18 % of soils are concerned

by a medium to very strong erosion hazard (Gis Sol, 2011). Soil compaction has strong impacts on several processes, including water erosion and production, through a modification of soils properties. However, soil compaction can be reversible in some circumstances (Roger-Estrade *et al.*, 2011). Other soil degradation can be considered as irreversible, such as contamination by toxic elements; or salinization, especially in areas that were influenced by marine water, such as the Camargue and marhses of western France (Stengel and Gelin, 1998).

As for the impacts of farming practices on soil quality, it appears that they can be either positive or negative (see Table 1). For instance, in a study led by Lal (1993) about tillage impacts on soil quality, soil degradation and soil resilience, tillage has both negative and positive effects on soil quality. In addition, these effects are confounded by land use, farming, cropping system, management and other environmental factors. Hence it seems that tillage itself is not detrimental to soil quality, but an inappropriate one can be: according to Chitrit and Gautronneau (2011), inappropriate and chemical-intensive farming practices are the main cause of soils deterioration in France. Wood *et al.* (2000) provide some examples of farming practices that are detrimental to soil quality: intensification on irrigated land can cause salinization, and the inappropriate use of mechanized farming in high-quality rain-fed lands can induce compaction. Reciprocally, some agricultural practices are known to be favourable to soil quality.

Chitrit and Gautronneau (2011) propose an indicative list of farming practices that are beneficial to soil quality, such as long crop rotations, regular organic matter supply, mixed crops, or minimum tillage application.

Hence, there are evidence that farming practices can impact positively or negatively soil quality, itself playing a role in farms productivity. In the next part, we examine how these relationships are taken into account and modeled in an economic framework.

Actually, when investigating the role of soil quality in the profitability and sustainability of farms, it is essential to consider the interactions between farming practices, soil quality and soil productivity (trough crop production). Our objective is to use the information relative to these interactions that are available in the agronomic literature within an economic framework describing schematically a farmer's decision making process. Doing so, it is possible to identify what are the levers of action with respect to farmers' choices when maximising the profitability and sustainability of his farm.

The theoretical model proposed in the next section, though simplified compared to reality, integrates and clarifies the relationships and interactions between crop yield function, soil quality motion function, soil endogenous and exogenous characteristics. While the analysis framework is an economic one, an agronomic approach is used when characterizing the nature of the interaction between soil quality attributes, farming practices and crop yield production. Indeed, the interest and originality of this article lies also in the association of different disciplines to investigate the role of soil quality in the sustainability and profitability of farms. The model proposed is discussed with respect to the existing theoretical economic models and agronomic studies.

Table 1: Examples of the impacts of agricultural practices on soil quality

Agricultural practices	Impact of practices on soil quality	Impact of soil quality on productivity	References	Remarks
Tillage practices	Erosion (+)	(-)	Richard *et al.* (2001)	Reduced tillage, under appropriate cropping systems, decreases water erosion
	Soil porosity (-)	(+)	Carter M.R. (1992), Ekeberg and Riley (1997), Richard *et al.* (2001)	The impact of tillage on porosity can be confounded by other factors or practices, and by an inter- and intra-annual variability (Richard *et al.* (2001).
	Soil Organic Carbon (-)	(?)	Blevins *et al.* (1983), Astier *et al.* (2006)	On Andisols representative of highlands conditions of Mexico and Latin America, during a 2 years period, in spite of higher SOC under no-tillage (twice the amount of conventional tillage), maize yield was higher in conventional tillage compared to no-tillage. Results might have changed in longer term experiments (Astier *et al.*, 2006). In the long run, Blevins *et al.* (1983) observe equivalent or higher corn yield under no-tillage compared to conventional-tillage, under appropriate N fertilization.
	Decrease in soil fauna and flora	(-) pests ; (+) auxiliaries	Kladivko (2001), Verhulst *et al.* (2010)	General result, the impact of tillage on soil micro and meso fauna depends on the organism considered. As for soil microflora, the impact of tillage is detrimental, but usually small (Kladivko, 2001). Under no-tillage, the positive impact on various categories of earthworms affects positively soil structure and aggregation (Kladivko, 2001; Verhulst *et al.*, 2010). Kladivko (2001) suggests the existence of a control of soil-borne pests by other soil organisms, although such dynamics would require time.
Crop rotation	Decrease in pests and diseases pressure	(+)	Cook and Haglund (1991)	Cook and Haglund (1991) have shown that the poor wheat growth and yields under conservation tillage or mulch compared to “clean tillage” was due to root pathogens, favoured by a continuous wheat crop.
	Soil structure (?)	(?)	Glab, Scigalska and Labuz (2013)	Particular crops have a positive impact on soil structure, however in the study led by Glab *et al.* (2013), they were short-term effects.
	Soil Organic Carbon (+)	(+)	Miglierina *et al.* (2000)	In particular rotations including legume (Miglierina *et al.*, 2000).
Crop residue	Erosion (-)	(-)	Cutforth and McConkey (1997), Malhi and Lemke (2007)	
	Soil structure (+)	(+)	Denef *et al.* (2002)	Increase both stable and unstable macroaggregates, while the relative proportion of stable and unstable macroaggregates depends on the weathering status and clay mineralogy of soils (Denef *et al.*, 2002).
	Soil porosity	(+)	Verhulst *et al.* (2010)	
	Soil nutrient availability (+)	(+)	Kumar and Goh (2002)	Kumar and Goh (2002) focus their study on soil nitrogen and the impact of antecedent leguminous and non-leguminous crop residues on winter wheat yields. It appears that leguminous crop residues are more beneficial than non-leguminous crop residues.
	Increase in soil fauna and flora	(-) pests ; (+) auxiliaries	Cook and Haglund (1991)	In the case study of Cook and Haglund (1991), root pathogens activity was increased by the straw residues, which were providing energy to the pathogens.
Fertilizers	SOC (+)	(+)	Verhulst *et al.* (2010)	
	Soil acidity (+)	(-)	Verhulst *et al.* (2010), Shukla, Lal and Ebinger (2006)	

Note: the different impacts have to be considered with respect to the location of the parcels, soil type and crop produced.

4 A theoretical soil resource optimal control model at the farm level

This article focuses on farmers' management decisions related to soil quality, when soil quality is considered as an endogenous production factor, or similarly as a production factor the farmer can have an impact on through management decisions. Since the problematic is related to the optimal use of a natural resource, it seems relevant to use a dynamic farm-level optimization model. Our focus is on farmers' decisions, hence we do not consider off-site consequences of soil quality degradation.

To do so, our approach takes over the optimal control models used in McConnell (1983), Saliba (1985), Hediger (2003), Segarra and Taylor (1987), Smith *et al.* (2000) and Yirga and Hassan (2010), while considering both exogenous and endogenous soil attributes, similarly to Smith *et al.* (2000). An optimal control model is an economic model where a dynamic system is considered.

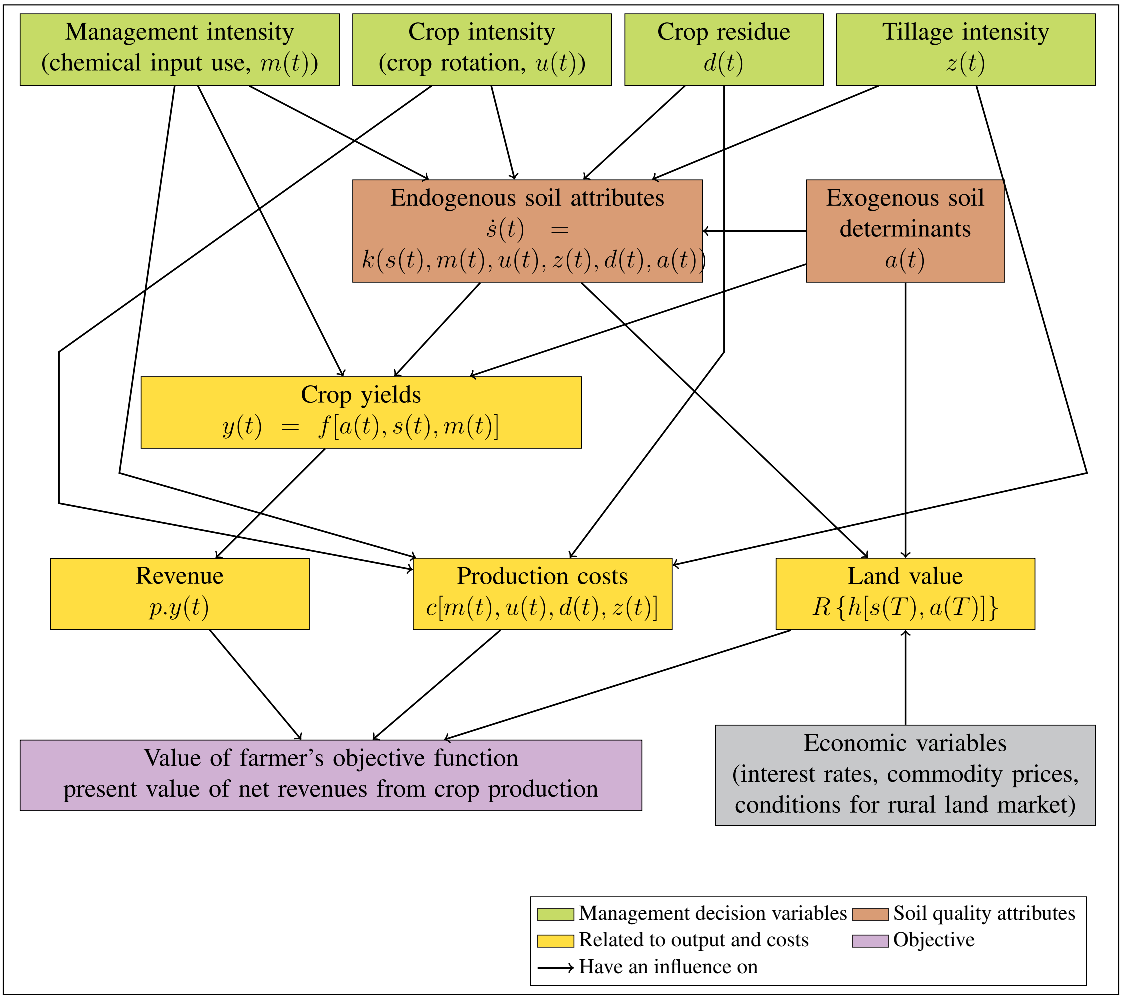
Optimal control models have been used (i) to understand farmers' motives to invest or not in conservation practices (Saliba, 1985; Barbier, 1998), since there can be a conflict between profitability and sustainability objectives (Segarra and Taylor, 1987; Barbier, 1990; Quang, Schreinemachers and Berger, 2010); (ii) to analyze the difference between farmers private optimal rate and the social optimal rate of soil degradation (McConnell, 1983; Hediger, 2003). Actually, it has been observed that soil degradation rate induced by farmers' practices decisions is not always optimal, both privately and socially. This can be due to: (i) imperfect land markets where land prices do not reflect potential land productivity; (ii) local substitutes to soil quality, whereas at a global level this may not be the case; or (iii) unexpected and detrimental public policies effects on soil degradation rates (Barbier, 1998). Non-optimal levels can be corrected through appropriate public policies and investments. Policies design and implementation necessitate to measure on-site and off-site soil erosion costs (Magrath and Arens, 1989; Bandara *et al.*, 2001), soil erosion being one form of soil degradation, and to determine farm-level incentives for soil conservation (Barbier, 1990; Nakhumwa, 2004). Policies can then be evaluated (Louhichi *et al.*, 1999; Quang *et al.*, 2010).

The objective of this theoretical model is to highlight the role of soil quality in the farm profitability and sustainability.

A comprehensive farm-level soil quality model should (Saliba, 1985; Brown, 2000): (i) be dynamic; (ii) be recursive; (iii) contain functional relationships which capture the impact of farm management choices (the control variables) on soil quality characteristics (the state variables); (iv) include variables which reflect changes in soil quality; (v) include crop yield functions that incorporate soil attributes, substitution possibilities and management variables.

Our theoretical model illustrates the trade-offs and inter-dependences between conservation and conventional practices, included as decision variables (see Figure 1). Soil quality is incorporated in the model through endogenous and exogenous soil attributes. Soil quality impact on soil

Figure 1: Variables and functions in the farm-level soil quality model



Sources: adapted from Saliba (1985) and Smith et al. (2000)

productivity is captured through the relationships between soil attributes and crop yields.

4.1 Production function

4.1.1 Concavity assumptions and the choice of the production factors

Our crop production per hectare $y(t)$ is a function of production factors $s(t)$, $m(t)$ and $a(t)$:

$$y(t) = f[s(t), m(t), a(t)] \tag{1}$$

This function satisfies the following assumptions [1]:

$$f_s > 0, f_m > 0, f_{ss} < 0, f_{mm} < 0 \tag{2}$$

$$f_{sm} \gtreqless 0 \tag{3}$$

The production function f is $C^{(2)}$ (twice continuously differentiable) and assumed to be strictly concave. These mathematical assumptions relative to the crop production function are classic in economy. Such assumptions can be found in McConnell (1983), Saliba (1985), Barbier (1990), Hediger (2003) and Yirga and Hassan (2010). These are convenient assumptions when analysing a maximisation problem requiring the use of first and second derivatives. Such assumptions are not inconsistent with what can be observed in reality. For instance in their empirical study, Smith *et al.* (2000) use a concave production function obtained from long term agronomic field experiments.

For the concavity properties to be easier to encompass, two production factors are considered here: soil quality (endogenous s and exogenous a) and chemical inputs (m). This is the approach that McConnell (1983), Saliba (1985), Barbier (1990) and Hediger (2003) have also adopted. Considering only two production factors is a simplification for theoretical computations which is not meaningless empirically since the chemical inputs, that can also be named as productive (McConnell, 1983) or conventional (Barbier, 1990) inputs or considered as the intensity of cultivation (Hediger, 2003), can be disassembled in several inputs (nitrogen fertilizers, phosphorus fertilizers...).

In their empirical studies, Segarra and Taylor (1987), Smith *et al.* (2000), Kim *et al.* (2001) and Yirga and Hassan (2010) use concave production functions. Segarra and Taylor (1987) and Yirga and Hassan (2010) only consider one aspect of soil quality, respectively soil depth and soil nutrients. Only considering one aspect of soil quality is quite reductive with regard to the many characteristics of soil quality that can impact soil productivity, either physical, chemical or biological. In Segarra and Taylor (1987), crop yield depends on variables inputs of production and soil depth. The production function proposed in Yirga and Hassan (2010) is a Cobb-Douglas function of stock of soil nutrients, labor and capital (*i.e.* services of a pair of oxen). The Cobb-Douglas functional form is convenient for estimating and interpreting parameter estimates. However, using this function can have some drawbacks relative to the substitutability of the production factors. In their particular case it is not irrelevant to assume that inorganic nitrogen and natural soil nitrogen are perfect substitute, but it is a strong assumption.

Other empirical studies have considered several characteristics of soil quality. For instance, Smith *et al.* (2000) model crop yield as a quadratic function of soil mineral and applied nitrogen and phosphorus, soil organic carbon, inorganic carbon, precipitations, soil pH, and electrical conductivity. In Kim *et al.* (2001), the production function depends on previous soil quality, the

[1] We denote by $f_{x_i} = \partial f(\ldots, x_i, \ldots)/\partial x_i$ the partial derivative of any function f with respect to x_i and by $f_{x_i x_j}$ the partial derivatives at the second order.

level of nitrogen fertilizer application, the average precipitation, the growing degree days and the rotation index variables.

To describe the production function, some have chosen to use biophysical models, that are then included in an economic framework. Such integrated models allow for a more complex and accurate modeling of natural processes while taking into account motives, constraints and institutional context determining human decisions (Vatn *et al.*, 1999). For instance, Schreinemachers (2006) and Quang *et al.* (2010) use the Tropical Soil Productivity Calculator (TSPC), where the crop yield function depends on the crop yield potential, management, nitrogen, phosphorus and potassium available in soil, soil organic carbon and pH. In Belcher, Boehm and Fulton (2004), crop production is a function of climate and soil quality, while soil quality is influenced by previous crop management. It is estimated by the crop growth component of the Sustainable Agroecosystem Model (SAM) the authors use to assess the sustainability of a regional agroecosystem.

In this study, we assume that crop production increases with soil endogenous quality ($f_s \geq 0$) and the amount of chemical input ($f_m \geq 0$), however the higher soil quality is, the slower the increase in production ($f_{ss} \leq 0$), and chemical input effect is decreasing with higher chemical input level ($f_{mm} \leq 0$).

4.1.2 About the cooperation of the production factors

The cross partial derivative, that is the marginal cross impact of soil quality and chemical inputs use on the marginal productivity, is not discussed in McConnell (1983) and Saliba (1985). It is not detrimental to their results, but they miss an interesting discussion. Barbier (1990) considers it, and assume that the cross partial derivative between soil depth and the traditional input package is positive: he considers that an increase in one additional unit of soil depth increases the productivity of the traditional input, and reciprocally, one additional unit of the traditional input increases the productivity of the current soil depth. However, although considering similar production factors (soil depth and cultivation intensity), Hediger (2003) assumes that the cross partial derivative of the two production factors can be both positive and negative, depending on whether they are "competitors" or not.

Here is proposed a deeper and more satisfying discussion of the sign of the cross partial derivative, using the concept of cooperating production factors.

In some cases, application of chemical inputs and soil quality are cooperating, when the latter is low or in transition from conventional to conservation practices ($f_{sm} > 0$) (Mekuria and Waddington, 2002). Cooperating inputs can be considered as inputs working as a team (Alchian and Demsetz, 1972). The output is yielded by this team, in our case intensive practices m and soil quality s. Hence, stating that intensive practices and soil quality are cooperating means that the production f is not separable, that is, the production obtained is not the sum of the production yield respectively by the use of intensive practices and the benefits of soil quality. Formally, the production function is said to be separable if the cross partial derivative is zero,

i.e. when $f_{x_i x_j} = 0$ (Alchian and Demsetz, 1972). In the case of agricultural production, the non separability assumption is relevant and consistent with what can be observed. For instance, in the empiric production function used by Smith *et al.* (2000), soil quality variables (for instance organic and inorganic carbon) and management variables (N fertilizers for instance) are cooperating. In the original framework of Alchian and Demsetz (1972), team production is used in the case when inputs produce a higher output together than separately, and such that the increase in production overs the costs of organizing this cooperation. Soil quality and chemical inputs can be substitutes if the marginal productivity of chemical inputs decreases with higher soil quality ($f_{sm} < 0$).
In addition, while we consider soil quality, McConnell (1983), Barbier (1990) and Hediger (2003) consider soil erosion. This has an impact on the assumptions made with respect to the soil quality dynamics function.

4.2 Soil quality function

Endogenous soil attributes motion over time depends on management practices $u(t)$, $z(t)$ and $d(t)$:

$$\dot{s} = k(s(t), m(t), u(t), z(t), d(t), a(t)), \tag{4}$$

for which the following assumptions are made:

$$k_s < 0, k_m \gtreqqless 0, k_u > 0, k_z \gtreqqless 0, k_d > 0, \tag{5}$$

$$k_{ss} > 0, k_{mm} > 0, k_{uu} < 0, k_{zz} < 0, k_{dd} < 0, \tag{6}$$

$$k_{du} \geq 0, k_{zu} \geq 0, k_{zd} \geq 0, k_{zm} < 0, k_{um} \gtreqqless 0, k_{uz} \geq 0, k_{dm} < 0, \tag{7}$$

$$k_{sm} \gtreqqless 0, k_{su} > 0, k_{sd} > 0, k_{sz} \gtreqqless 0 \tag{8}$$

The soil quality dynamics function is $C^{(2)}$. As for the crop production function, this is a convenient assumption for computational purposes that is not inconsistent with reality.

4.2.1 Choice of variables that impact soil quality dynamics

In the model proposed by Hediger (2003), soil depth dynamics depends on soil depth and the intensity of cultivation, and the potential impact of practices that could decrease soil erosion are not considered. While in McConnell (1983) and Barbier (1990) two farming practices packages are considered, one positively impacting soil erosion, one negatively. In addition, since McConnel (1983), Barbier (1990) and Hediger (2003) do not consider soil quality but soil depth, they do not mention the soil resilience in their model, which here is represented by k_s.
In empirical studies, soil quality dynamics can be captured by the dynamics of soil organic carbon (SOC), as in Smith *et al.* (2000), Belcher *et al.* (2004). In Yirga and Hassan (2010), it is soil nitrogen dynamics that are considered. Through the use of biophysical models, some authors

have considered soil dynamics in a more comprehensive way. For instance, in Schreinemachers (2006) and Quang *et al.* (2010), the Tropical Soil Productivity Calculator (TSPC) is used to simulate soil nutrient dynamics, soil nutrients being stocks of nitrogen, phosphorus, potassium and soil organic matter.

In addition, it is also relevant to include a recursion feature to the model, and to express soil quality and management choices such that the resulting outcomes can feed back into the biological processes in a dynamic manner (Brown, 2000). In their empirical studies, Smith *et al.* (2000), Kim *et al.* (2001) and Quang *et al.* (2010) use recursive models.

Management practices have an impact on soil quality dynamics. Depending to the issue analysed, the farming practices considered differ from one study to another.

Here, four management variables are considered. These management practices are the basic principles of conservation agriculture (Verhulst *et al.*, 2010): tillage intensity $z(t)$, expressed as a percentage, where the maximum tillage intensity corresponds to a deep tillage and the minimum to no-tillage; use of crop residues $d(t)$, and crop rotations $u(t)$ expressed as the percentage of green manures and legume in the rotation; and management intensity $m(t)$ encompasses substitution possibilities [2] : the larger $m(t)$, the more chemical inputs are applied. The explicit mention of each of the main conservation practices allows a more accurate description of the marginal impact they can have taken separately or together.

4.2.2 Assumptions made on the impact farming practices have on soil quality dynamics

The assumptions made here differ from what can be found in McConnell (1983), Barbier (1990) and Hediger (2003). Indeed, they describe the dynamics of soil erosion, and in addition, do not consider as many farming practices in their theoretical models. Though their assumptions are not irrelevant and though simplified, consistent with can be observed otherwise, they do not confront explicitly their assumptions with the existing agronomic literature, while we do.

Hence, it is assumed that the higher the proportion of green manures and legume in the rotation, the more soil quality is improved ($k_u > 0$) (Cook and Haglund, 1991, Miglierina *et al.*, 2000), but decreasingly ($k_{uu} < 0$). When properly implemented, soil quality is improved when crop residues are left ($k_d > 0$) (Denef *et al.*, 2002), but more slowly when the amount of crop residue is higher ($k_{dd} < 0$). Crop residues and legume rotation are cooperating ($k_{ud} > 0$) in terms of nutrient availability (Kumar and Goh, 2002) or pest control (Kladivko, 2001). Crop rotations and crop residue are assumed to be cooperating with the current soil quality ($k_{su} > 0$ and $k_{sd} > 0$).

Tillage have positive and negative impacts on soil quality ($k_z \gtrless 0$) (Lal *et al.*, 1993). Indeed, while stable aggregation and high level of organic matter are favored by no or superficial tillage (Barthès *et al.*, 1998), the impact of tillage alone on soil quality depends on various factors,

[2] Integration of management intensity in the soil quality function can be discussed. Indeed, one could consider chemical input impact only through the production function (Kim *et al.*, 2001). Smith *et al.* (2000) take into account fertilizer inputs both in the production and organic carbon equilibrium functions.

including climate, seasons and soil structure, and in some cases tillage is recommended (Heddadj *et al.*, 2005; Verhulst *et al.*, 2010). Hence, it is assumed that a decrease in tillage intensity slowly increases soil quality ($k_{zz} < 0$). Reduced tillage has a positive impact on soil quality, when associated with green manures ($k_{zu} > 0$) and crop residues ($k_{zd} > 0$) (Barthès *et al.*, 1998; Verhulst *et al.*, 2010). When tillage is intensive, we assume that its impacts on soil quality are not influenced by green manures ($k_{zu} = 0$) or crop residues ($k_{zd} = 0$).
Management intensity can have a negative or positive impact on soil quality ($k_m \gtrless 0$). Management intensity, in terms of crop protection products, is increasing with the reduction in tillage intensity ($k_{mz} < 0$), so that it can be considered as a substitute to tillage. Tillage and management intensities can be considered as cooperating or not with soil quality ($k_{sm} \gtreqless 0$ and $k_{sz} \gtreqless 0$), depending on the level of soil quality. When done appropriately diversified crop rotations and crop residues can be considered as substitutes to chemical inputs uses ($k_{um} < 0, k_{dm} < 0$). However, during the transition phase (from conventional to conservation practices) chemical inputs and diversification of crop rotations can be seen as cooperating ($k_{um} > 0$).

4.3 Maximisation problem and optimality conditions

In our case, the dynamic system is a farm. The state of system is described by the farm soil quality. Soil quality changes over time depending on the farming practices the farmer decides to use on his farm. Hence, farming practices are the control variables of the system. However the system is controlled to contribute to a given objective: in this study as in most economic studies, the objective that is pursued is the maximisation of the farmer's profit over a given time horizon.
Actually, in the theoretical optimal control models reviewed here, it assumed that the objective of the farmer is to maximise his revenue and the resale value of his land, depending on whether the planning horizon considered is finite or infinite (see McConnell, 1983; Saliba, 1985, Barbier, 1990 and Hediger, 2003). This objective is subject to the soil dynamics constraint. Although not irrelevant, considering that farmers only have the revenue maximisation objective in mind can be seen as restrictive, although widely used also in empirical studies (Smith *et al.*, 2000; Belcher *et al.*, 2004; Yirga and Hassan, 2010). Multi-objective models can be used to take this matter into consideration, as in Louhichi, Flichman and Zekri (1999).
In addition, as in Saliba (1985), crop prices, input prices and interest rates are exogenous and constant. For each activity, costs encompass labour and energy costs. Similarly to Hediger (2003), we denote constant crop prices by p, constant marginal costs of chemical input use by c_1, of tillage by c_2, constant marginal costs associated to the increased complexity of higher crop intensity by c_3 and the opportunity cost of leaving crop residue by c_4. The real net revenue per hectare is then such that:

$$\pi(t) = pf(s(t), m(t), a(t)) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4 d(t) \tag{9}$$

The sustainability objective is accounted for through the dynamic aspect of these models where the farmer's income is maximized over the long run. In addition, a dynamic approach is particularly relevant when studying soil quality changes. Indeed, soil dynamics involve slow processes, and studying the effects of management practices on soil quality requires to take into account cumulative changes (Rhoton, 2000; Malhi *et al.*, 2006).
In our model, the farmer, owner of his land, chooses the levels of the control variables $m(t)$, $u(t)$, $d(t)$ and $z(t)$ at each point in time in order to maximize the net present value of returns plus the market value of the land at the end point in his planning horizon, $R\{h[s(T), a(T)]\}$, such that:

$$\underset{u,z,m,d}{\text{Max}} \int_0^T e^{-rt}[pf(s(t), m(t), a(t)) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4 d(t)]dt + e^{-rT} R\{h(s(T), a(T))\} \tag{10}$$

$$\text{subject to: } \dot{s}(t) = k(s(t), m(t), u(t), d(t), z(t), a(t)) \quad \text{Soil quality motion} \tag{11}$$

$$s(0) = s_0 \quad \text{Initial soil quality} \tag{12}$$

$$0 \leq z(t) \leq 1 \quad \text{Bounds on tillage intensity} \tag{13}$$

$$0 \leq u(t) \leq 1 \quad \text{Bounds on crop intensity} \tag{14}$$

$$0 \leq d(t) \leq d_{max} \quad \text{Bounds on crop residues} \tag{15}$$

$$0 \leq m(t) \leq m_{max} \quad \text{Bounds on management intensity} \tag{16}$$

Assuming an interior solution, this problem can be described through the following Hamiltonian:

$$H(m, u, z, d, s, \lambda) = e^{-rt}[pf(s(t), m(t)) - c_1 m(t) - c_2 z(t)] + \lambda(t)\,(k(s(t), m(t), u(t), d(t), z(t), a(t))) \tag{17}$$

According to the maximum principle, the optimal paths of m, u, z, d, s and λ satisfy [3]:

$$H_m = e^{-rt}[pf_m - c_1] + \lambda k_m = 0 \Leftrightarrow e^{-rt}[pf_m - c_1] = -\lambda k_m \tag{18}$$

$$H_z = e^{-rt}(-c_2) + \lambda k_z = 0 \Leftrightarrow e^{-rt} c_2 = \lambda k_z \tag{19}$$

$$H_u = e^{-rt}(-c_3) + \lambda k_u = 0 \Leftrightarrow e^{-rt} c_3 = \lambda k_u \tag{20}$$

$$H_d = e^{-rt}(-c_4) + \lambda k_d = 0 \Leftrightarrow e^{-rt} c_4 = \lambda k_d \tag{21}$$

$$\dot{\lambda} = -H_s \Leftrightarrow \dot{\lambda} = -e^{-rt}[pf_s] - \lambda k_s \tag{22}$$

$$\lambda(T) = e^{-rT} \frac{\partial R\{h(s(T), a(T))\}}{\partial s(T)} \tag{23}$$

[3] For reading simplicity and clarity, soil quality attributes are presented here as a single variable in the theoretical model.

These optimal conditions are the conditions that must always be verified in order to be on a path leading to the equilibrium point - provided that there is one.
Condition (18) states that the foregone benefits of using more chemical inputs in terms of net revenues have to be balanced with the opportunity costs of using more chemical inputs in terms of soil quality marginal value. Condition (19) states that, at the optimum, tillage intensity is such that the foregone costs of tillage are balanced with tillage benefits in terms of soil quality marginal value. Similarly, at optimum, the farmer adds legume or green manure in his rotation such that the foregone costs associated with a more complex crop intensity are equal to its benefits in terms of soil quality marginal value (condition (20)). In addition, the farmer leaves crop residues on the parcel such that the foregone costs associated with crop residue management are balanced with the benefits from leaving crop residues in terms of soil quality marginal value (condition (21)). The costate equation (22) introduces the rate of change of the costate variable λ, the soil quality shadow price. It implies that changes in soil quality marginal value $\dot{\lambda}$ depend on the discount rate r, crop prices p, the influence of soil quality on crop yield f_s, on the current value of the costate variable λ and the influence of current soil quality on soil quality (k_s). For the changes in soil quality marginal value to be positive, the soil contribution to profits has to be lower than soil resilience benefits in terms of soil quality marginal value. Equation (23) is the transversality condition according to which, in the final period T, the marginal value of soil quality corresponds to soil quality impact on land market value.
The optimality conditions obtained here are consistent with what can be found in the literature. These optimality conditions can be used to discuss for example a scenario where a policy intervention can induce actions that are at the opposite of what was intended, especially when the importance of the value farmers attribute to their soil is misconstrued. From (18), when the value of marginal product of chemical inputs use is higher than its costs, then chemical inputs are used in higher amount that optimum would require and induce soil quality deterioration. One could compensate this effect of on soil quality by subsidizing soil quality beneficial farming practices such as crop residue use d, thus reducing the cost of this practice c_4. However, according to (21), such a decrease in c_4 would also reduce the implicit value of soil quality λ. Farmers would associate a lower value to their land quality which would favor soil quality detrimental practices such as intensive tillage and chemical inputs use.

5 Conclusion

From the economic and agricultural sciences literature reviewed, we demonstrate that soil resource is an important parameter in the productivity and sustainability of farms. We have seen that the expected increase in global population seems to require a considerable increase in global food production. At a country-scale, this agricultural production challenge is related to competitiveness and economic growth issues. To be competitive, French agriculture has to be productive

and sustainable, and soil quality appears to play an important role, as a lever for both productivity and sustainability. Nonetheless, farming practices that contribute to the maintenance or enhancement of soil quality are not always adopted by farmers.
There is a real economic issue of soil degradation that needs to be addressed. While there is an established interest in maintaining soil quality in order to sustain agricultural production in the long run, it requires investment costs in the short run; together with imperfect land markets, short run substitutes to soil fertility and unexpected consequence of some agricultural policies, this can lead to a non-optimal rate of soil degradation. This can have detrimental impacts on farms productivity, profitability and competitiveness.
In the comprehensive farm-level optimal control model proposed in this article, these various interactions between soil quality and farm productivity, profitability and sustainability are modeled based on the agronomic literature. In this model, soil quality is considered as an endogenous production factor in the farmers' decision making process, and is not reduced to only one characteristic. Indeed, in economic models, soil quality is usually reduced to soil depth and soil degradation to soil erosion. The main elements to consider in an empirical application of this model are presented, and the discussion related to the impacts of farming practices on soil quality shows how complex these relationships are, even when simplified.
Nonetheless, for simplified as it is, the model accurately represents the substitution and complementary relationships between the various variables and in particular on the cooperating relationship between soil quality and chemical inputs. Deeper and further theoretical analysis of the stationary equilibrium and its dynamics would require a simpler model, in which decision management variables that respectively negatively and positively affect soil quality could be grouped together. In such a simplified model, prices and policy effects could be more easily considered, trough qualitative analysis of the equilibrium situation.

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