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Alice Issanchou, Pierre Dupraz, Carole Ropars-Collet, Karine Daniel

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

Issanchou A.[12], Dupraz P.[3], Ropars-Collet C. [2] and Daniel K.[14]

[1] Ecole Supérieure d'Agriculture d'Angers, LARESS, Angers, France
[2] Agrocampus Ouest, UMR 1302 SMART, F-35000, Rennes, France
[3] INRA, UMR 1302 SMART, F-35000, Rennes, France
[4] INRA, UR 1134 LERECO, F-44000, Nantes, France
a.issanchou@groupe-esa.com

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Summary

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. 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 codes: Q24

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[4] INRA, UR 1134 LERECO, F-44000, Nantes, France

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 agricultural 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 impacts on the state of the environment, 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 relative 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 a 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. The Ecological 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, through the review of economic articles that have considered soil quality, we show the importance and interest of adopting a bio-economic approach when considering soil quality and we present the limits of the approaches used and the improvements

required. Finally, a theoretical farm-level model is proposed, that takes into account the linkages between soil quality and farm productivity and sustainability.

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 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 relative 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, 1998); 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 relative 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, 2002). 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 Ecological Intensive Agriculture (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 than 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. Actually, the importance given to soil quality by EIA is revealed by numerous references made to conservation agriculture (Goulet, 2012). Conservation agriculture requires the simultaneously 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 is reversible in this case. 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 marshes 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.

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

Agricultural practices	Impact of practices on soil quality	Impact of soil quality parameters 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).
	SOC (-)	(?)	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 organ-ism 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 aff ects 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 eff ects.
	SOC (+)	(+)	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.				

Source: own elaboration

Chitrit and Gautronneau (2010) 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 evidences 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 modelled in an economic framework.

4. ECONOMIC APPROACH OF SOIL QUALITY: A REVIEW

Soil quality is mentioned in economic studies covering a wide range of topics (see Table 2): land use and cover options (Chomitz and Gray, 1996; Brown et al, 2004; Verburg et al, 2006), agrosystems sustainability (Belcher et al, 2004), or farms productivity determinants (Bhalla and Roy, 1988; Schreinemachers, 2006). Actually, there are two reasons for studying soil quality changes in agriculture: (1) 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 (Barbier, 1990; Quang, Schreinemachers and Berger, 2010); (2) to analyze the difference between farmers private optimal rate and the social optimal rate of soil degradation (McConnell, 1983; Hediger, 2003).

Soil degradation rate induced by farmers' practices decisions is not always optimal, both privately and socially. This can be due to: (1) imperfect land markets where land prices do not reflect potential land productivity; (2) local substitutes to soil quality, whereas at a global level this may not be the case; or (3) 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).

4.1. Soil resource optimization: basic theoretical models highlighting the main trade-offs

When considering soil quality and agriculture, optimization models are relevant since they address the issue of a resource optimal use (Nakhumwa, 2004; Lobo Pereira et al, 2013).

McConnell (1983) is widely referred to in studies addressing soil degradation or conservation issues (*e.g.* Saliba, 1985; Barbier, 1990; Smith et al, 2000; Yirga and Hassan, 2010). In his study, the author seeks to determine when the private rate of soil erosion of a farmer's land differs from the socially desired one. He uses a private decision model where crop choices and soil quality are considered as unique and constant and crop production is a function of soil loss, soil depth and an index of variable inputs, weighted by a neutral technical change. The farmer maximizes the present value of the stream of profits and the farm real estate values, which depend on soil depth (assimilated to soil fertility). From this model, McConnell concludes that an increase in soil loss does not mean that farmers ignore physical production relations. In addition, when soil depth affects farm resale value, farmers are likely to conserve it.

Table 2: Studies considering soil quality: a wide range of topics and models.

References	Type of study	Subject of the study	Method used
Land degradation optimal control			
McConnell (1983)	Theoretical	Determine when the private and the socially optimal paths of erosion differ	Farm-level dynamic optimal control model
Saliba (1985)	Theoretical	Provide a theoretical model to guide empirical research	Farm-level dynamic optimal control model
Hediger (2003)	Theoretical	Evaluation of sustainability at the farm-level considering both on- and off-farm effects of erosion	Farm-level dynamic optimal control model
Segarra and Taylor (1987)	Empirical (United States)	Apply a general farm-level dynamic model of soil conservation to narrow the linkages among variables which affect soil use to the Piedmont Area of Virginia	Optimal erosion control model / use of a representative farm
Smith et al (2000)	Empirical (Canada)	Determine optimal cropping systems for dryland grain production in the northern Great Plains	Soil quality dynamic optimal control model / solved using GAMS/MINOS modelling system
Yirga and Hassan (2010)	Empirical (Ethiopia)	Analyze trade-offs between short and long-term objectives of soil use by smallholders teff farmers in Ethiopia	Static and dynamic farm-level optimal control model- parametric estimation
Costs of erosion			
Magrath and Arens (1989)	Empirical (Indonesia, Java)	Estimating benefits and costs of alternative soil conservation policies	Change in productivity approach / Estimations using transfer method
Barbier (1990)	Review and theoretical	Review the soil conservation packages offered to upland farmers in Java and the factors influencing their adoption	Farm-level dynamic optimal control model (adapted from McConnell (1983))
Bandara et al (2001)	Empirical (Sri Lanka)	Analyze the economy-wide impact of changes in soil erosion induced by a range of policy reforms, distinguishing between and quantifying the on-site and offsite effects	Computable general equilibrium model / estimation of costs using the replacement cost approach and the change in productivity approach
Policies			
Vatn et al (1999)	Methodological and empirical (Norway)	Policy analysis of environmental problems	Mathematical modelling framework
Louhichi, Flichman and Zekri (1999)	Empirical (Tunisia)	Quantitative evaluation of the impact of water and soil conservation techniques on crop yield, production system, erosion and expected economic returns	Dynamic multi-period recursive model, using nonlinear mathematical programming
Quang, Schreinemachers and Berger (2010)	Empirical (Vietnam)	Explore ex-ante the effect of selected policy options on the adoption of soil conservation techniques and the sustainability of agriculture in the northern highlands of Vietnam	Dynamic simulation using a mathematical programming-based multi-agent system (MP-MAS)
Farm productivity			
Bhalla and Roy (1988)	Empirical (India)	Evaluate whether the inverse relationship between farm size and productivity is due to difference in soil fertility	Reduced form equation of a production function
Schreinemachers (2006)	Empirical (Uganda)	Study the relationship between width of crop-yield gap and farm households food security	Dynamic simulation using a MP-MAS
System sustainability			
Belcher, Boehm and Fulton (2004)	Empirical (Canada)	Evaluate regional agrosystem sustainability	Simulation model (SAM)
Land use			
Chomitz and Gray (1996)	Empirical (Belize)	Explore the trade-off between rural road building (economic development) and deforestation (environmental preservation)	Static spatially explicit multinomial logit model of land use

Source: own elaboration

In a study related to farm-level conservation decisions in the Uplands of Java, Barbier (1990) provides a simple variant of McConnell (1983), where crop production is a function of conventional crop production inputs and topsoil depth. Soil depth depends on the balance between conventional and conservation inputs, the former being detrimental and the latter beneficial to soil depth. Actually in this case, farmers did not have incentives to invest in conservation measures: the impact of erosion on crop productivity was perceived as negligible compared to conservation practices costs, and some governmental policies were detrimental to the adoption of conservation measures, such as fertilizers subsidization, that decreased conventional inputs costs.

Saliba (1985) uses a dynamic framework when studying soil erosion, arguing that it is soil loss cumulative effects on both soil quality and crop yields that are of importance, and that it is to these cumulative effects that the farmer potentially accommodates his management practices. Hediger (2003) submits an extension of Saliba's model by proposing an “agricultural Hartwich rule”, where when investing soil rents into alternative capital to insure a constant level of income, both on-farm and off-farm effects of soil erosion are addressed.

4.2. Applications of soil quality optimal control models

Segarra and Taylor (1987) provide an application of a farm-level dynamic optimal control model to the Piedmont area of Virginia, where soil conservation is an important policy issue. Four farming practices are separately considered: up-and-down-the-slope cultivation, contourning, stripcropping and terracing. Decision variables are crop rotations, and the state variable is topsoil depth. According to their results, a change of practice from up-and-down-the-slope cultivation to other practices leads to sizeable reductions in gross topsoil loss. Adopting contouring increases the net present value of returns and leads to outcomes both privately and socially desirable. Stripcropping and terracing are socially desirable, but induce a lower net present value of returns compared to traditional practices.

Kim et al (2001) use a recursive approach in a dynamic structural model aiming at explaining current soil productivity in terms of previous management choices and predicting its evolution. They consider soil quality changes as recursive, since soil quality is not only determined by the chosen farming practices, but also by the previous state of soil.

Smith et al (2000) explicitly model soil quality as a production factor, and soil quality attributes are a function of past level of soil quality attributes plus the outcome of the soil quality attribute function, which depends on previous soil quality attributes and inputs per activity that impact on soil quality.

Yirga and Hassan (2010) provide a soil nutrients optimal control model where the farmer maximizes the sum of discounted streams of future net returns, subject to soil nutrient dynamics. Control variables are fertilizer levels, production and conservation labour, and capital inputs for production and soil conservation activities. They consider only one crop (teff), with no rotation, which is not representative of small-holder farmers' practices. From their results, current small-holder farmers practices appear to over-exploit soil nutrient stock.

A more sophisticated way to associate economic objectives and natural resources constraint is to integrate to the economic model a biophysical model describing soil dynamics. Integrated models allow for a more complex and accurate modelling of soil processes while taking into account motives, constraints and institutional context determining human decisions (Vatn et al, 1999).

4.3. Integrating biophysical models within an optimization model

When studying the relationship between the width of the crop yield gap[1] and farm household food security, Schreinemachers (2006) integrates to his model a biophysical component simulating crop yields and soil property dynamics, using the Tropical Soil Productivity Calculator (TSPC), where crop yield depends on various complementary factors (management, available nitrogen, phosphorus and potassium in the soil, soil organic carbon and acidity). It seems that in the case of Uganda, it is population dynamics rather than soil fertility decline that determine maize yields, land productivity and labour productivity.

Belcher et al (2004) use the Sustainable Agroecosystem Model (SAM) to assess the sustainability of a regional agroecosystem. The model simulates land use decisions and dynamically integrates an economic model with a maximization profit objective and a soils and crop growth model. Crop production is a function of climate and soil quality, while soil quality is influenced by previous crop management. According to their simulations, the agroecosystem biophysical characteristics are critical determinants of the system economic performance and sustainability, two aspects that can be conflicting.

This conflict can be addressed using a multi-objective model, as in Louhichi, Flichman and Zekri (1999): in their model, there are two weighted objectives, economic and environmental. The economic objective is to maximize the expected net actualized revenue while minimizing its deviation with respect to nature and price states. The environmental objective is to minimize soil loss due to erosion, using the Erosion Productivity Impact Calculator (EPIC). EPIC simulates the impacts of soil, climate, crop practices and rotations on soil erosion as well as the long-term impact of soil erosion on crop yield.

Quang et al (2010) do not use a farm-level model but a multiple agent system (MAS), and they consider individual farmers' private decisions, recursively at an annual time step. They analyze the effect of an environmental tax on the unsustainable use of sloping lands in Vietnam. Soil fertility dynamics is modelled and estimated using the Tropical Soil Productivity Calculator (TSPC).

4.4. Limits and interest of the economics approaches reviewed

The articles of McConnell (1983) and Barbier (1990) are interesting as simplified theoretical models that illustrate the possible trade-offs between soil conservation practices and conventional ones. Hediger (2003) goes further and also considers the off-farm effects of soil erosion. The optimal control approach is consistent with our investigation concerning the role of soil quality in the productivity, profitability and sustainability of farms. Such approaches should allow us to determine whether soil conservation practices, *i.e.* practices that aim at preserving or increasing soil quality, are indeed optimal when maximizing the farm profitability and sustainability. 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 taking into account cumulative changes (Rhoton, 2000; Malhi et al, 2006).

However, McConnell (1983), Barbier (1990) and Hediger (2003) are only considering soil depth in their optimal control model. Similarly, in their empirical studies, Segarra and Taylor (1987) and Yirga and Hassan (2010) only consider one aspect of soil quality (respectively soil depth and soil nutrients). These

[1] The difference of actual average yield level and yield obtained under optimum management practices.

approaches are reductive with respect to the various dimensions of soil quality. Other studies have considered several aspects of soil quality: Saliba (1985) considers soil depth and other soil characteristics affecting soil productivity, Smith et al (2000) take into account different aspects of soil quality through various physical and chemical soil attributes. Kim et al (2001) adopt another approach: they estimate soil quality using a non-linear function depending on past management choices and soil quality, in order to obtain a relative measure of soil quality through two coefficient estimates. Hence, they implicitly consider the different dimensions of soil quality through their contribution to soil productivity.

Models that integrate an economic model and a biophysical model do not necessarily considerate much more soil quality attributes than simpler models. The EPIC model used by Louhichi et al (1999), which primary purpose is to evaluate the impact of soil erosion on soil productivity and crop yield, includes various soil quality attributes and determinants, such as nutrients, soil temperature, weather and hydrology (Gassman et al, 2005). In the SAM framework used by Belcher et al (2004), soil quality is represented by soil nitrogen, soil phosphorus, available soil water, soil erosion and soil organic matter, all attributes influenced by climate and soil type. Schreinemachers (2006) and Quang et al (2010) use the TSPC model that considers chemical soil attributes (available N, P and K in the soil, soil organic carbon and soil acidity). In these last two studies, erosion is also taken into account.

It may be 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). Smith et al (2000), Kim et al (2001) and Quang et al (2010) use recursive models. In these studies, soil quality attributes are considered as endogenous variables, that is variables that both determine and are determined by other variables in the models. Sometimes, authors consider both exogenous (*e.g.* soil texture) and endogenous soil quality attributes (*e.g.* SOC). In addition, they all consider the interactions between soil quality, crop yield and farming practices.

Actually, when investigating the role of soil quality in the profitability and sustainability of farms, it is essential to consider these interactions. Doing so, it is possible to identify what are the levers of action with respect to farmers' choices considering profitability and sustainability objectives.

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).

The originality of our approach lies more in the purpose for which the soil quality optimal control model is used than in the development of the model as such. Our study and the one conducted by Smith et al (2000) have some similarities; however, the objectives are different. The objective of Smith et al (2000) is to determine the optimal cropping systems for dryland grain production in the northern Great Plains. Ours is to determine what is the role of soil quality in the farm profitability and sustainability, and whether it is optimal for farmers to maintain or increase their soils quality to maximize their farms profitability in a sustainable way, and if so in which extend. Hence, although considering similar variables, relationships and interactions in our models, the results obtained are not displayed nor analysed in the same way.

In addition, the theoretical model proposed, 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 as well as climatic conditions. 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.

In the following section, the theoretical model is proposed.

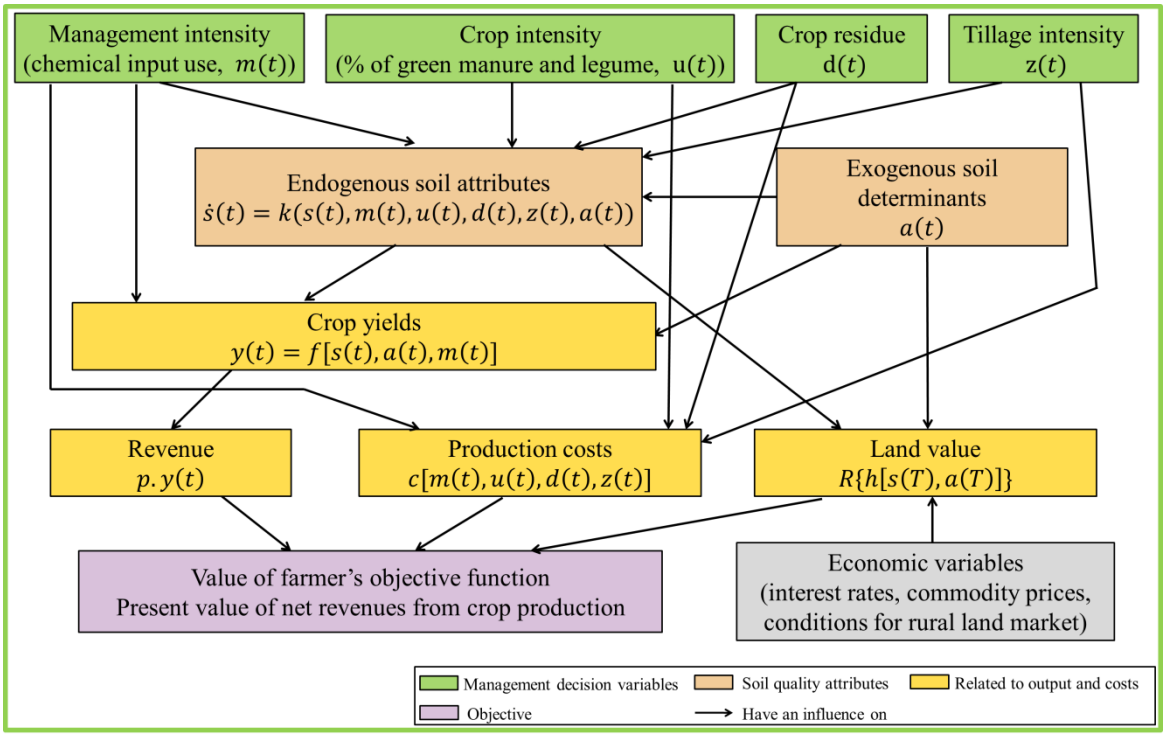
5. A THEORETICAL SOIL RESOURCE OPTIMAL CONTROL MODEL AT THE FARM LEVEL

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. 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): (a) be dynamic; (b) be recursive; (c) contain functional relationships which capture the impact of farm management choices (the control variables) on soil quality characteristics (the state variables); (d) include variables which reflect changes in soil quality; (e) include crop yield functions that incorporate soil attributes, substitution possibilities and management variables.

Our theoretical model is built on the works of McConnell (1983), Saliba (1985), Smith et al (2000), Hediger (2003) and Yirga and Hassan (2010). It 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 productivity is captured through the relationships between soil attributes and crop yields.

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



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

5.1. Production function

Crop production per hectare $y(t)$ is such that:

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

This function satisfies the following assumptions[2]:

$$f_s > 0, f_m > 0, f_{ss} < 0, f_{mm} < 0, f_{sm} = f_{ms} \lesseqgtr 0 \tag{2}$$

The production function f is $C^{(2)}$ (twice continuously differentiable) and assumed to be strictly concave. Crop production increases with soil endogenous quality ($f_s > 0$) and the amount of chemical input ($f_m > 0$), however the higher soil quality is, the slower the increase in production ($f_{ss} < 0$), and chemical input effect is decreasing with higher chemical input level ($f_{mm} < 0$). 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). Soil quality and chemical inputs can be substitutes if the marginal productivity of chemical inputs decreases with higher soil quality ($f_{sm} < 0$).

5.2. Soil quality function

Endogenous soil attributes motion over time depends on management practices:

$$\dot{s} = k\big(s(t), m(t), u(t), z(t), d(t), a(t)\big), \tag{3}$$

For which the following assumptions are made:

$$k_s < 0, k_m \lesseqgtr 0, k_u > 0, k_z \lesseqgtr 0, k_d > 0, \tag{4}$$

$$k_{ss} > 0, k_{mm} > 0, k_{uu} < 0, k_{zz} < 0, k_{dd} < 0, \tag{5}$$

$$k_{du} \geq 0, k_{zu} \geq 0, k_{zd} \geq 0, k_{zm} < 0, k_{um} \lesseqgtr 0, k_{uz} \geq 0, k_{dm} < 0, \tag{6}$$

$$k_{sm} \lesseqgtr 0, k_{su} > 0, k_{sd} > 0, k_{sz} \lesseqgtr 0, \tag{7}$$

The soil quality dynamics function is $C^{(2)}$. Four management variables are considered: the basic principles of conservation agriculture (Verhulst et al, 2010): tillage intensity z, 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, and crop rotations u expressed as the percentage of green manures and legume in the rotation; and management intensity m that encompasses substitution possibilities[3]: the larger m, the more chemical inputs are applied. k_s is the soil resilience.

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

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

[3] 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.

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 ($k_{du} \geq 0$) 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 has positive and negative impacts on soil quality ($k_z \lesseqgtr 0$) (Lal et al, 1993). Indeed, while stable aggregation and high level of organic matter are favoured by no or superficial tillage (Barthès et al, 1998), the impact of tillage alone on soil quality depends on various factors, 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 ($k_m \lesseqgtr 0$). Management intensity, in terms of crop protection products, is increasing with the reduction in tillage intensity ($k_{zm} < 0$), 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 ($k_{sm} \lesseqgtr 0$ and $k_{sz} \lesseqgtr 0$), 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 ($k_{um} < 0$).

5.3. Maximisation problem

As in Saliba (1985), crop prices, input prices and interest rate are exogenous and constant. For each activity, costs encompass labour and energy costs. Similarly to Hediger (2003), assuming constant crop price p and constant marginal costs of chemical input use c_1 and tillage c_2, and the constant marginal costs associated to the increased complexity of a higher crop intensity c_3, the opportunity cost of leaving crop residue c_4 and the real net revenue per hectare is such that:

$$\pi(t) = pf\big(s(t), m(t), a(t)\big) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4\, d(t) \tag{8}$$

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:

$$\max_{u,z,m,d} \int_0^T e^{-rt}\big[pf\big(s(t), m(t), a(t)\big) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4 d(t)\big]dt + e^{-rT} R\{h[s(T), a(T)]\} \tag{9}$$

$$\textit{subject to:} \quad \dot{s} = k(s(t), m(t), u(t), d(t), z(t), a(t)) \qquad \textit{Soil quality motion} \tag{10}$$

$$s(0) = s_0 \qquad \textit{Initial soil quality} \tag{11}$$

$$0 \leq z(t) \leq 1 \qquad \textit{Bounds on tillage intensity} \tag{12}$$

$$0 \leq u(t) \leq 1 \qquad \textit{Bounds on crop intensity} \tag{13}$$

$$0 \leq d(t) \leq d_{max} \qquad \textit{Bounds on crop residues} \qquad (14)$$

$$0 \leq m(t) \leq m_{max} \qquad \textit{Bounds on management intensity} \qquad (15)$$

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

$$H(m,u,z,d,s,\lambda) = e^{-rt}\left[pf\big(s(t),m(t),a(t)\big) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4\, d(t)\right] + \lambda(t)\left(k\big(s(t),m(t),u(t),d(t),z(t),a(t)\big)\right) \qquad (16)$$

According to the maximum principle, the optimal paths of m, u, z, d, s, and λ satisfy[4]:

$$H_m = e^{-rt}[pf_m - c_1] + \lambda k_m = 0 \iff e^{-rt}[pf_m - c_1] = -\lambda k_m \qquad (17)$$

$$H_z = e^{-rt}(-c_2) + \lambda k_z \iff e^{-rt}c_2 = \lambda k_z \qquad (18)$$

$$H_u = e^{-rt}(-c_3) + \lambda k_u \iff e^{-rt}c_3 = \lambda k_u \qquad (19)$$

$$H_d = e^{-rt}(-c_4) + \lambda k_d \iff e^{-rt}c_4 = \lambda k_d \qquad (20)$$

$$\dot{\lambda} = -H_s \iff \dot{\lambda} = -e^{-rt}[pf_s] - \lambda k_s \qquad (21)$$

$$\lambda(T) = e^{-rT}\frac{\partial R\{h[s(T),a(T)]\}}{\partial s(T)} \qquad (22)$$

Condition (17) 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 (18) 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 (19)). 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 (20)). The costate equation (21) 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 price 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 (22) 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.

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 (17), 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

[4] For reading simplicity and clarity, soil quality attributes are presented here as a single variable in the theoretical model and time dependency is dropped.

practice c_4. However, according to (20), 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.

Deeper and further theoretical analysis of the stationary equilibrium and its dynamics would require a simpler model, in which decision management variables could group together variables that respectively, negatively and positively affect soil quality. In such a simplified model prices and policy effects could be more easily considered.

6. CONCLUSIONS

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.

Actually, through the literature reviewed, it appears that the adoption of soil conservation measures depends on whether soil quality or potential soil productivity are linked to the farm resale value; on the costs incurred by adopting such measures compared to its benefices in terms of productivity; and on the possibility of substitution between soil fertility and conventional inputs. The problem is that farmers might not induced an optimal soil degradation rate, because of a lack of information, market imperfections and political distortions. Indeed, we have seen that soil degradation effects can be not detected at first when using fertilizers inputs for instance, while at some point, the soil will be irreversibly degraded. Besides, the empirical studies related to soil conservation or soil degradation are usually limited by data availability and quality (Barbier, 1998). In addition, in economic models, soil quality is usually reduced to soil depth and soil degradation to soil erosion. Integrated models allow for a more precise and accurate modelling of soil quality and the interactions between soil quality, crop productivity and farming practices.

Overall, it appears that there is a real economic issue of soil degradation that needs to be addressed. While there is an established interesting 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 consequences 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.

The second objective of this article was to propose an economic approach of soil quality issues in agriculture, when soil resource is considered as an endogenous production factor in the farmers' decision making process. The theoretical model provided here highlights the relationships between farming practices, soil quality and farm productivity, profitability and sustainability. The main elements to consider in an empirical application of this model are present, and the discussion relative 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. This model provides a useful basis for future empirical applications.

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