Intertemporal soil management: revisiting the shape of the crop production function

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Soil resources play a role in food security and climate change mitigation. Through their practices, farmers impact the physical, biological and chemical quality of their soil. However, farmers face a trade-off between the short-term objectives of production and profitability and the long-term objective of soil resource conservation. In this article, we investigate the conditions under which farmers have a private interest in preserving their soil quality. We use a simplified theoretical soil quality investment model, where farmers maximize their revenues under a soil quality dynamic constraint. Here, soil quality is an endogenous production factor of the crop production function. We show that the existence of an equilibrium depends on the cooperation between soil quality and productive inputs. The results are confronted to a statistical illustration in France. In this case, nitrogen fertilizers are not cooperating with soil organic carbon. Incentives to reduce nitrogen fertilizers would not trigger a negative feedback effect.

\textbf{Keywords:} optimal control; soil quality management; crop production function; profitability; sustainability

1. Introduction

The importance of soil resources is increasingly recognized and is at the center of the “4/1000 Initiative: Soil for Food Security and Climate”, an international, multi-stakeholder voluntary action plan presented at the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in Paris on 1 December 2015 (Ministry of agriculture, agrifood and forestry website). In fact, soil and soil quality play important roles in food security and climate mitigation issues, as both a production and regulation factor, for instance, through carbon sequestration (Lal 2004). Soil resources management generates positive and negative externalities, and the issues faced are of public interest, which explains the resurgence of public and political interest in soil.

However, soil resources are mainly managed by private agents such as farmers. Soil resources management is a good example of the multifunctionality of agriculture and of the external costs and benefits derived from this activity (Pretty \textit{et al.} 2001). The existence of such externalities can justify public intervention, especially when private agents’ management of soil resources is not socially optimal.

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Indeed, through their farming practices, farmers affect the physical, chemical and biological quality of soil. These impacts can be positive or negative, depending on how farming practices are implemented with respect to the location of the land, the climate and the initial soil quality. However, some farming practices are more likely to be beneficial to soil quality than others (Chitrit and Gautronneau 2011). For instance, agroecology practices related to soil resources aim at maintaining or increasing soil quality. The concept of agroecology used here refers to the intensified use of natural processes and resources, including soil resources, by implementing conservation practices (such as reduced tillage or cover crops).

Soil quality can be defined as “a soil inherent capacity to produce economic goods and perform environmental regulatory functions” (Lal 1997, 18) and can be described through “the chemical, physical, and biological properties of soil that affect its use” (Letej et al. 2003, 182). Degrading soil quality can have detrimental impacts on the performance of soil environmental regulatory functions and generate negative externalities. Nonetheless, even when disregarding the externalities in terms of climate change mitigation, preserving the quality of their soil can be interesting, even from the private perspective of farmers, to achieve a productive and sustainable agriculture.

Actually, agricultural productivity can be considered as one of the functions of soil, and it depends on the soil quality (Lal 1998). 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, although 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). Here, we consider that the sustainability of the agricultural system is relative to the maintenance of the productivity and profitability of farms. Hence, maintaining or increasing soil quality seems to be one of the requirements for a sustainable (and thus competitive) agriculture.

However, farming practices that aim at maintaining or increasing soil quality imply more complex agricultural practices than those of conventional agriculture and require farmers to adopt an innovation and research logic (Ghali et al. 2014). Hence, there can be a trade-off between the short-term production and profitability objectives and the long-term soil conservation objective in a tense economic context, where energy, fertilizer and crop production costs are expected to increase.

Some studies have approached farmers’ motivations in soil conservation using econometric methods, as in Ryan, Erickson, and De Young (2003) and Aregay, Minjuan, and Tao (2018). Here, the focus is on the farmer’s individual decision-making process, and our approach is theoretical. To translate these questions in economic terms, we use a model where the farmer seeks to maximize his farm profitability, while considering long-term soil quality dynamics. It consists of estimating the optimal level of soil quality when the farmer controls this resource. Actually, in the economics literature, optimal control models have been used to explain farmers’ motives to invest in conservation practices (Saliba 1985; Barbier 1998), since there can be conflicts between profitability and sustainability objectives (Segarra and Taylor 1987; Barbier 1990; Quang, Schreinemachers, and Berger 2014).

Our work is based on the theoretical optimal control models of McConnell (1983), Saliba (1985), Barbier (1990) and Hediger (2003). In these theoretical dynamic models, although soil quality is mentioned, the dynamics considered are those related to soil erosion (soil loss) and soil depth (McConnell 1983; Saliba 1985; Barbier 1990; Hediger 2003). Indeed, soil resource management issues were first addressed with
respect to soil erosion and soil loss until the 1990s (Karlen, Ditzler, and Andrews 2003).

However, considering only one aspect of soil quality is quite reductive with regard to the many characteristics of soil that can impact soil productivity, which can be physical, chemical or biological. Besides, soil loss due to water and wind erosion can be considered irreversible (Scherr 1999) and one can only reduce soil loss; while other soil degradation processes can be reversible, such as nutrient depletion, organic matter loss and eutrophication (Scherr 1999). Considering other aspects of soil quality allows us to take into account soil degradation and restoration processes that occur at the human scale.

In addition, most crop production functions in agronomy sciences are defined as the relationship between crop yield and water use, which is determined by experiments and crop models (Saseendran et al. 2015; Zhang et al. 2018). In these models, although soil characteristics are taken into account, soil quality is not considered as an endogenous production factor. In these economic and agronomic articles, the production function and the cooperation between the productive inputs and the soil quality parameter considered are not discussed. McConnell (1983) and Saliba (1985) do not mention the cross-effect of productive inputs and soil. Barbier (1990) considers that soil depth and productive inputs are cooperating, while Hediger (2003) does not specify the cooperation relationship between productive inputs and soil depth in terms of crop production. However, the cooperation relationship between soil quality and productive inputs is critical to establish the existence of an equilibrium and to design desired public policies. These are the missing elements to which this article aims to contribute.

The objective of this article is to determine the conditions under which farmers have a private interest in maintaining or increasing soil quality when they maximize their revenue under a soil quality dynamic constraint. Particular attention is given to the cooperation relationship between productive inputs and soil quality. The theoretical approach allows us to study all types of cooperation relationship. The results obtained are illustrated by a statistical analysis.

To do so, we propose a soil quality investment model wherein soil quality dynamics are considered and applied to a crop production system. From this model, the equilibrium and the dynamics of this equilibrium are discussed with respect to soil quality and productive inputs cooperation. Soil quality is considered here with respect to the physical, chemical and biological attributes that are affected by farming practices, such as soil depth, acidity, flora and fauna. The results obtained are discussed with a statistical study of the regional crop production functions in France.

The functional relationships between soil quality, agricultural practices and crop production are presented in Section 2. In Section 3, we analyze the optimal soil quality investment model, with respect to the cooperation relationship between soil quality and productive inputs. Section 4 is devoted to the statistical analysis of the main crop production functions in France. In Section 5, the results of the statistical illustration are discussed with respect to our theoretical results.

2. Soil quality, agricultural practices and crop production

In the soil quality investment model proposed, two types of practices are identified: (1) productive inputs $m$ (corresponding to chemical inputs) and (2) conservation
practices $u$ (considered here as an investment in soil quality). Investments in soil quality correspond to extra costs incurred, for instance, by implementing green manure within crop rotation, leaving crop residues, or adopting superficial tillage or no-tillage farming. The extra costs encompass the costs induced by the more complex management of the system.

There are two production factors, soil quality and productive inputs. The crop production function is represented by $y = \phi(q, m)$. Similarly to McConnell (1983), Barbier (1990) and Hediger (2003), soil quality $q$ is composed of endogenous attributes $s$ and exogenous attributes $a$. Exogenous attributes, such as soil type or other site-specific attributes, are fixed. Endogenous attributes are affected by farming practices. When the farmer is investing in soil quality, he is investing in his soil’s endogenous quality. Contrary to McConnell (1983), Barbier (1990) and Hediger (2003), the endogenous quality of soil is considered here not only with respect to soil depth (a physical dimension) but also with respect to the chemical and biological dimensions of soil quality, such as soil acidity or soil fauna and flora auxiliaries. These three soil characteristics are chosen as examples because all three have positive impacts on soil quality, are positively affected by conservation practices $u$ and cooperate with productive inputs $m$.

There are numerous dimensions of soil quality (physical, chemical or biological) with positive or negative impacts on crop production. Further, a single soil quality characteristic can be affected positively by one practice and negatively by another that is implemented at the same time. Hence, these are complicated relationships. This is a simple model, where the effects of so-called productive inputs and conservation inputs are simplified in order to focus on a qualitative discussion.

Crop production per hectare $y(t)$ depends on soil quality $q$ and productive input intensity $m$, and $t$ denotes time. The production function is $C^{(2)}$ (twice continuously differentiable). Since the soil quality exogenous attributes $a$ are fixed, the crop production function can be written as:

$$y(t) = \phi(q(s(t), a), m(t)) = f(s(t), m(t))$$  \hspace{1cm} (1)

$$f_s > 0, f_m > 0, f_{ss} < 0, f_{mm} < 0,$$  \hspace{1cm} (2)

$$f_{sm} = f_{ms} \leq 0, f_{ss} f_{mm} - (f_{ms})^2 > 0$$  \hspace{1cm} (3)

$$f(s, m(t)) = 0$$  \hspace{1cm} (4)

It is assumed that crop production $f$ increases with soil quality ($f_s > 0$) and productive inputs ($f_m > 0$). However, the higher the soil quality, the slower the increase in production ($f_{ss} < 0$). Besides, the more productive inputs are intensively used, the smaller their positive impact ($f_{mm} < 0$). Here, we consider the two situations of cooperation between inputs ($f_{sm} \leq 0$). For instance, 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 ($f_{sm} > 0$) (Smith et al. 2000; Mekuria and Waddington 2002). Soil quality and chemical inputs can also be substitutes if the marginal productivity of chemical inputs decreases with higher soil quality ($f_{sm} < 0$).

Soil is considered as essential for production. The critical threshold under which soil quality is degraded irreversibly is denoted $s$. Below this threshold, it is assumed that input use is not sufficient to ensure agricultural production.

Soil quality changes over time depend on a soil natural degradation factor $\delta$ and on a soil natural formation function $g$. Indeed, soil quality parameter changes (e.g. soil
depth, soil organic carbon [SOC]) are the results of formation and degradation processes that are distinct (Kögel-Knabner 2002; Morgan 2009). McConnell (1983) and Hediger (2003) also consider and distinguish the aspects of soil degradation and formation. However, McConnell (1983) reduces soil degradation to soil loss, and Barbier (1990) and McConnell (1983) focus on the soil degradation rate, which is reduced to the soil erosion rate. Here, we consider soil physical, chemical and biological quality.

The soil quality dynamics function we propose is based on the pollution stock dynamics equation of Van Der Ploeg and Withagen (1991). In Van Der Ploeg and Withagen (1991), the dynamics of the stock of pollutant increases with inevitable pollution generated by the activity, independent of the stock of pollutant, and that can be reduced by investment in clean technology, and decreases with the rate at which pollutant dissolves in the environment, which rate is timed by the stock of pollutant and depends on the amount devoted to clean-up activities.

Similarly here, the detrimental effects of productive inputs and the positive impacts of conservation practices on soil quality changes are both considered. The soil degradation factor $\delta$ depends on the productive inputs $m$, which are also considered to be soil quality-degrading practices. For instance, pesticides can have non-desirable, detrimental effects on auxiliaries, and fertilizers can increase soil acidity (Verhulst et al. 2010), thus decreasing soil productivity. Following Bellamy et al. (2005), we consider that this soil degradation factor is timed with soil quality at $t$. The farmer can invest in the quality of his soil through the adoption of conservation practices $u$, which have a positive impact on the soil regeneration function $g$. The soil quality dynamics function is $C^{(2)}$ such that:

$$
\dot{s}(t) = -\delta(m(t))s(t) + g(u(t)) \quad (5)
$$

$$
\delta_m > 0, \delta_{mm} > 0, g_u > 0, g_{uu} < 0 \quad (6)
$$

It is assumed that the natural soil formation function $g$ positively depends on conservation practices $u$, which increase soil quality ($g_u > 0$). For instance, leaving crop residues on the soil surface reduces erosion (Cutforth and McConkey 1997; Malhi and Lemke 2007) and increases the number of auxiliaries, while more complex crop rotation reduces pest and disease pressures (Cook and Haglund 1991). The more conservation practices are implemented, the lower their positive impact on soil quality ($g_{uu} < 0$).

It is assumed that soil quality is all the more degraded as productive inputs are used ($\delta_m > 0$). Moreover, the detrimental impact of productive inputs on soil quality is increasing in the use of productive inputs ($\delta_{mm} > 0$).

3. Optimal soil quality investments

The farmer, owner of his land, maximizes his profits. It is assumed that the farmer has a long-term objective of land capitalization, through his soil quality. Soil dynamics processes evolve in a continuous manner, so our model is continuous. Besides, soil dynamics are slow, and for changes to be significant, have to be considered with a large time horizon. Since solutions between an infinite-horizon problem and a large but finite-horizon problem do not differ significantly (Léonard and van Long 1992), for mathematical convenience it is also assumed that the farmer maximizes his profits through an infinite time horizon.
His profits depend on crop yield, crop prices and farming practice costs. The constant marginal cost of productive input use $m$ is denoted $c_1$, and the constant marginal cost associated with conservation practices $u$ is denoted $c_2$. The marginal costs encompass the labour cost and the energy cost associated with each activity. The price of the crop $p$ is constant. The farmer’s profits can be written as:

$$\pi(t) = pf(s(t), m(t)) - c_1 m(t) - c_2 u(t)$$ (7)

In addition, the farmer is constrained by the dynamics of his soil. Hence, he has the following optimization problem:

$$\max_{m,u} \int_0^{T-\infty} e^{-r t} [pf(s(t), m(t)) - c_1 m(t) - c_2 u(t)] dt$$ (8)

subject to: $s(t)$ (9)

The current value Hamiltonian of this problem can be written as:

$$\tilde{H}(m, u, s, \mu) = pf(s(t), m(t)) - c_1 m(t) - c_2 u(t) + \mu s$$ (10)

According to the maximum principle, the optimal paths of $m, u, s$ and $\mu$ satisfy:

$$\tilde{H}_m = pf_m - c_1 - \mu \delta_m s = 0$$ (11)

$$\tilde{H}_u = -c_2 + \mu g_u = 0$$ (12)

$$\dot{\mu} - r \mu = -\tilde{H}_s \iff \dot{\mu} = r \mu - pf_s + \delta(m) \mu = \mu (r + \delta(m)) - pf_s$$ (13)

Condition (11) states that the marginal revenues obtained from using more productive inputs must be balanced by their marginal damage to soil quality, expressed as the marginal value of soil quality. Condition (12) states that conservation practices $u$ should be implemented, such that the costs of conservation inputs $c_2$ are equal to the additional benefits generated in terms of the marginal value of soil quality. The co-state variable $\mu$, which is the implicit value of soil quality, has a rate of change that depends on the interest rate $r$, the degradation rate $\delta$, the current soil quality implicit value $\mu$, the crop price $p$ and the the influence of soil quality on crop yield $f_s$ (condition (13)). The implicit value of soil quality grows at a rate of discount and degradation minus the contribution of soil quality to current profits. In addition, the rate of change of the co-state variable $\dot{\mu}$ depends on productive inputs through their aggravating impact on the soil degradation rate.

Conditions (11) and (12) are related to productive inputs and conservation practices, respectively, and are always true in equilibrium and on the optimal path leading to the equilibrium (when both exist).

When (11) and (12) are combined, they can be rewritten such that:

$$\frac{pf_m - c_1}{\delta_m s} = \frac{c_2}{g_u} = \mu$$ (14)

Equation (14) states that in equilibrium and on the optimal path, the marginal value of soil quality is equal to the ratio of the marginal revenues obtained from the use of productive inputs to their marginal damage to soil quality. This ratio must be equal to the ratio between soil conservation costs over the marginal restoration.
Along the optimal time paths of the state and co-state variables $s$ and $\mu$, management intensity must continuously be adjusted to satisfy, at any time for each case, the first-order condition (11), and similarly, soil quality investment must satisfy (12).

Consequently, management intensity and soil quality investment must be represented as implicit functions of soil quality $s$ and marginal soil rent $l$:

$$\frac{\partial m}{\partial s} = -\frac{\tilde{H}_{ms}}{\tilde{H}_{mm}} = -\frac{pf_{ms} - \mu \delta_m}{pf_{mn} - \mu \tilde{\delta}_{mm} s} \geq 0$$ (15)

$$\frac{\partial m}{\partial \mu} = -\frac{\tilde{H}_{mu}}{\tilde{H}_{mm}} = -\frac{-\delta_m s}{pf_{mn} - \mu \tilde{\delta}_{mm} s} < 0$$ (16)

$$\frac{\partial u}{\partial s} = -\frac{\tilde{H}_{us}}{\tilde{H}_{uu}} = -\frac{0}{\mu g_{uu}} = 0$$ (17)

$$\frac{\partial u}{\partial \mu} = -\frac{\tilde{H}_{mu}}{\tilde{H}_{uu}} = -\frac{g_u}{\mu g_{uu}} > 0$$ (18)

According to Equation (18), soil conservation practices implementation increases with the marginal soil rent. However, a change in soil quality does not trigger a change in soil conservation practices (Equation (17)).

When productive inputs negatively impact soil quality, productive input use decreases with the marginal soil rent (Equation (16)). When the production factors are not cooperative, Equation (15) is negative, and the productive inputs use decreases with soil quality. However, when production factors are cooperative, the sign of Equation (15) is ambiguous. Indeed, on one hand, productive inputs and soil quality are cooperative production factors, and on the other hand, the use of productive inputs deteriorates soil quality. Hence, the sign of the implicit function of $m$ is undetermined.

When production factors are cooperative, two cases can be distinguished:

1. The case where $H_{ms} > 0$, which can also be written as $pf_{ms} > \mu \delta_m$. This is the case where the use of productive inputs gives more benefits in terms of revenues than losses in terms of the marginal value of soil quality.

2. The case where $H_{ms} < 0$, which can also be written as $pf_{ms} < \mu \delta_m$. It corresponds to a situation where the marginal damage to soil quality caused by productive inputs is higher than the marginal benefits in terms of productivity.

In fact, when deciding the amount of productive inputs to be used and soil quality to be restored, one has to consider the costs and benefits of organizing such cooperation. In the case where $H_{ms} > 0$, the situation is favorable to cooperation between productive inputs and soil quality. It is a situation where $\frac{p_l}{p_{ms}} > \frac{\delta_m}{f_{sw}}$, that is, where the ratio of the crop price to soil quality value is higher than the ratio of the damages of $m$ on soil quality to the cooperating effect. However, in the opposite case, the situation is more difficult to assess. In this case, $\frac{p_l}{p_{ms}} < \frac{\delta_m}{f_{sw}}$.

In addition, $H_{ms}$ can be rewritten using condition (11), such that:

$$pf_{ms} - \mu \delta_m \leq 0$$ (19)

$$pf_{ms} \leq \mu \delta_m$$ (20)

$$pf_{ms} \leq \frac{pf_{m} - c_1}{s}$$ (21)
where, $P_m/s$ is the marginal profit of productive inputs $m$ per unit of soil quality, and $\partial P_m/\partial s$ is the marginal profit of productive inputs $m$ for one additional unit of soil quality.

There can be a threshold value of soil quality $s$ below which soil quality is sufficiently low that the cooperating marginal productivity of $m$ and $s$ exceeds the marginal damage of $m$. However, above this threshold, the marginal damage is more important than the marginal cooperative productivity. In this case, the shadow values of soil quality $\lambda$ are higher (see Figure 1).

The solution to our optimal control problem is characterized by a long-term optimum only when $H_{ms} > 0$.

When $H_{ms} < 0$, the existence of the equilibrium is not ensured. This corresponds to two situations: (1) the situation wherein soil quality and productive inputs are not cooperative; (2) the situation wherein production factors are cooperative, but with benefits in terms of marginal crop production lower than the marginal damage caused by productive inputs on soil quality. The existence of a stable steady-state equilibrium point depends on the crop production and soil quality dynamic function specifications and calibrations. In other words, this situation requires an empirical analysis to determine whether an equilibrium exists for a given situation.

However, some observations can be made with respect to such a situation. Irrespective of the value of $H_{ms}$, the trace of the Jacobian matrix of our problem is positive. Hence, for a saddle point to exist, the determinant of the matrix has to be negative. In addition, the slopes of the curves are likely to have the same sign, irrespective of the value of $H_{ms}$. The conditions under which such a situation occurs do not contradict themselves. Thus, a stable steady state equilibrium point can exist when $H_{ms} < 0$. However, such conditions are arithmetic and do not have economic interpretations.

When $H_{ms} > 0$, the long-term equilibrium can be represented in a phase diagram (see Figure 2). It is a steady state, where $m = \dot{u} = \dot{s} = \dot{\mu} = 0$. The steady state is attained through a stable transition path, departing from an initial state $s_0$ toward the

Figure 1. Soil quality threshold and the marginal productivity of productive inputs.
steady state \((s^*, \mu^*)\). The stability properties of the problems and the determination of the long-term equilibrium are described in Appendix 2 (online supplemental data).

The phase diagram (see Figure 2) corresponds to the situation where soil quality is below some soil quality threshold \(s\). It corresponds only in the case where the damage caused by the use of productive inputs is more than offset by its cooperating benefits for soil quality in terms of revenue (see Figure 2). Above the threshold \(s\), one can neither determine the existence of an equilibrium nor represent the situation in a phase diagram.

The steady state can only be achieved by pursuing one of the optimal trajectories. The optimal trajectories are represented in the phase diagrams by the two directed lines moving toward the steady state \((s^*, \mu^*)\) (see Figure 2).

When the initial soil quality is low \((s_0 < s^* < s)\), the optimal trajectory is located in region I. On this path, soil quality increases, while the marginal soil quality value decreases. In addition, the productive input intensity increases with soil quality (from (15)), and the conservation practices decrease with the marginal value of soil quality (from (18)). This is a situation where the soil is of low productivity. To improve this situation, investments in soil conservation are made, which diminish while soil quality is improved and its value decreases. Indeed, on this optimal path, the higher the soil quality, the lower its marginal value, and the more effective conservation practices become. Thus, as soil quality increases, less investment in conservation practices is required to increase soil quality (see condition (12)). Since productive inputs and soil quality are cooperative production factors, the farmer adjusts his productive inputs to improve the soil quality.

When the initial soil quality is high \((s^* < s_0 < s)\), the optimal trajectory is located in region III. Along this path, soil quality decreases while the marginal soil quality value increases. Additionally, from (15) and (18), when soil quality decreases, the use of productive inputs decreases, and when the marginal soil quality value increases, conservation practice implementation increases. In this situation, the quality of the soil is “too” high compared to the equilibrium and is of high soil productivity. Hence, the optimal strategy for the farmer is to let his soil deteriorate until he attains the equilibrium level of soil quality. To do so, the farmer diminishes his use of productive inputs.
while implementing conservation practices. Indeed, at some point, the impact of soil deterioration on productivity is such that soil quality investments become necessary. All strategies differing from these two optimal strategies move away from the steady-state equilibrium. For instance, the initial conditions \((s_0, \mu_0)\) can be such that the farmer is initially located in region I, with a \(\mu_0\) placing him above the unique optimal path of region I. Recall that \(\mu_0 = \frac{c_2}{g_u(u_0)}\). Hence, such a case may correspond to a situation where \(g_u(u_0)\) is small and \(u_0\) is large. Since we are not on an optimal path, this is a case where \(u_0 > u^*\), that is, where investments in soil conservation are higher than optimal. At first, the strategy followed by the farmer would be similar to the optimal strategy. However, at some point, the path followed by the farmer will cross \(\mu = 0\) and enter region II. In region II, the trajectory followed is to increase both the soil quality \(s\) and marginal value of soil quality \(\mu\) by using more and more productive inputs \(m\) and increasingly investing in soil quality conservation practices \(u\). Thus, in this region, the paths followed correspond to overproduction, a strategy that is clearly unsustainable.

The initial conditions \((s_0, \mu_0)\) can also be such that the farmer is in region I but with a small \(\mu_0\). In this case, \(g_u(u_0)\) is high; hence, \(u_0\) is small, and investment in soil conservation is lower than optimal \((u_0 < u^*)\). Once again, at first, the strategy followed corresponds to the optimal one, except that in following this non-optimal path, \(s = 0\) is crossed. The farmer is now located in region IV, where it is no longer optimal to maintain soil quality. In region IV, both soil quality and the marginal quality of soil decrease along with management intensity and soil quality investments. This corresponds to a situation of underproduction, where soil quality is depleted until it is totally degraded.

A similar discussion can be provided for initial conditions placing the farmer in region III.

The optimal levels and strategies to attain a steady-state equilibrium have been described. The next sections propose an illustration of our problem through a statistical analysis of the crop production functions in France.

4. Empirical relationships between soil quality, crop yield and farming practices: Illustration from France

This statistical analysis is performed for France, for which we can have homogeneous data. The objective is to examine statistically the cooperative relationship between productive inputs and soil quality. To do so, we have specified a production function that satisfies the conditions of our theoretical model. Due to data limitation, the productive inputs considered here are nitrogen (N) fertilizer inputs. SOC is used as a proxy for soil quality. SOC pool is a reliable indicator of soil quality changes (Lal 2015). In addition, SOC is considered in public policies as a promising regulation factor through carbon sequestration (Lal 2004).

SOC is expected to have a positive marginal effect on crop production. The second-order effect is expected to be negative, with a smaller impact as the soil organic carbon level is high. It also translates relationship thresholds, especially since a given soil has a finite storage capacity. N fertilizers are expected to have a positive marginal impact on crop production. The second-order effect is expected to be negative: the more N fertilizers are applied, the lower their positive marginal effect on production. Following Smith et al. (2000), their interaction is expected to be positive. The
cooperative relationship between fertilizers and SOC is the one to be closely examined here.

To estimate our crop production regressions, we performed a multiple linear regression using the software R. These regressions are done for the two main crops grown in France: soft wheat and maize grain.

The explained variable is the level of crop production in quintal per hectare. The explanatory variables are SOC (COOH), N fertilizers (NFERTI), the amount of soil clay and sand, as well as binary regional variables.

The proportions of soil clay and sand are considered as constant throughout time. Data relative to N fertilizers are available for years 2001 and 2006, but not for the year 2011. Since it is not enough to perform a time series analysis, we have proceeded to the same regression on data for both 2001 and 2006.

For both crop production regressions, the production function is such that:

\[
YIELD(CROP)_t = \beta_0 + \beta_1COOH_t + \beta_2COOH^2_t + \beta_3NFERTI(CROP)_t
+ \beta_4NFERTI(CROP)_t^2 + \beta_5NFERTI(CROP)_t*COOH_t
+ \beta_6CLAY + \beta_7SAND + \beta_8REGIONSO + \beta_9REGIONGEO
+ \beta_10REGIONSE
\] (23)

Following Singh et al. (2003) and Hatirli, Ozkan, and Fert (2006), since in our theoretical model we make the assumption that when soil quality is critically low the crop yield is also equal to zero, that is, the constant term \( \beta_0 \) is equal to zero, the crop production regressions can also be reduced to:

\[
YIELD(CROP)_t = \beta_1COOH_t + \beta_2COOH^2_t + \beta_3NFERTI(CROP)_t
+ \beta_4NFERTI(CROP)_t^2 + \beta_5NFERTI(CROP)_t*COOH_t
+ \beta_6CLAY + \beta_7SAND + \beta_8REGIONSO + \beta_9REGIONGEO
+ \beta_10REGIONSE
\] (24)

Data relative to crop yield, N fertilizers are available for the years 2001 and 2006. Crop yield data are from the Annual Agricultural Statistics surveys for 2001 and 2006. Crop yield data are available at the department scale. However, farming practices (N fertilization) are only available at the regional scale, from farming practices surveys conducted for years 2001 and 2006, by the French Ministry of Agriculture and Alimentation. They are available on the DISAR online platform. To take into account the specificities of each major agricultural production bassin, four regional binary variables are built: Region Sud Ouest, Region Grand Ouest, Region Sud Est, Region Nord Est.

Data relative to soil quality parameters are obtained from the BDAT website (2014). It is a network of soil analysis measures, provided voluntarily by laboratories of soil analysis. Data are available at the departmental scale, and by 5-year period. In fact, data are collected for a period of 5 years.

The years 2001 and 2006 have not been particularly good in terms of yields for soft wheat and maize grain crops. In 2001, climatic conditions were not favorable to annual crops, with important rainfall in autumn, and climatic irregularities in the spring. It has caused a decrease in crop yield, more important for cereals than maize grain (Rabaud and Cesses 2004). In 2006, soft wheat yields were 2% below the average yield for the past 5 years, while maize grain yields were 9% lower than the good
yields of 2002 and 2004. This is due to the hot and dry climatic conditions in the summer (Chapelle-Barry 2008).

From the farming practices survey (DISAR website 2016), we have the average amount of N fertilizers applied on parcels that have been treated, and the percentage of surface having been fertilized in each region. However, the average level of crop yield encompasses both treated and non-treated parcels. Hence, we have adjusted the amount of fertilizer with the ratio of parcels treated, such that:

\[
NFERTI(CROP)_t = \frac{NFERTIAPPLIED(CROP)_t}{FERTISURF(CROP)_t} \times 100
\]  

(25)

Since these regressions are estimated for each crop, the amount of N fertilizers is considered for each crop individually, and is not aggregated at the scale level. This is done for the years 2001 and 2006, for each crop. Data relative to the amount of fertilizer applied are available for the years 2001 and 2006; while the surface fertilized data are only available for the year 2000. Crop yield data are available at the department scale, and N fertilizers at the regional scale. Since the regressions are made with respect to crop yield, the number of observations is limited by the number of departments in France.

We have first performed a multiple linear regression, using the program “lm” of the statistical software R. We performed two tests on these regressions, to ensure that they verify the homoscedasticity condition and that there are no correlations between residues (see Table 1).

According to our results, our regressions respect the homoscedasticity condition, and they do not exhibit auto-correlation between residues.

The results of our regressions are displayed in Table 2.

As expected, soil organic carbon has a significant positive impact on crop yields for both soft wheat and maize grain. For soft wheat, there is a significant and negative second-order effect of SOC on yields, while this second-order effect is not statistically significant for maize grain. N fertilizers have a statistically significant positive impact on soft wheat and maize grain yields together with a significant and negative second-order effect. This is consistent with our assumptions.

Regarding the cooperation relationship between productive inputs and soil quality, it appears that the cooperative effect between N fertilizers and SOC is statistically significant and negative for both crops.

There is potential bias in the results presented. This is due to the fact that farmers make choices: they are likely to choose to grow crops in their high quality soils. This

Table 1. Tests on the crop production regressions: non-constant variance test and Breusch–Godfrey test.

| Regressions                  | Soft wheat/N inputs | Maize grain/N inputs |
|-----------------------------|---------------------|----------------------|
| Non-constant variance test  | \( p = 1.465473e-08 \) | \( p = 0.5072266 \) |
| Breusch–Godfrey test        | \( p = 0.0001617 \) | \( p = 0.001107 \) |
| Interpretation of the non-  |                     |                      |
| constant variance test      | When \( p > 0.05 \), it means that the null hypothesis according to which variances are constant cannot be rejected. |                      |
| Interpretation of the       |                     |                      |
| Breusch–Godfrey test        | When \( p < 0.05 \), it means that the null hypothesis according to which there is no serial correlation up to 1 can be rejected. |                      |
could explain why crop yields are so positively correlated to soil quality. However, we are using crop yield data for two different years, with a 5-year gap. Since farmers have an interest in practicing crop rotations, even short ones, we are likely to also observe crops allocations that reflect that phenomenon, thus reducing this bias.

Another potential bias could be the impact of farmers’ practices and choices on soil organic carbon – which is the hypothesis in our theoretical models. Hence, at the farmer’s scale, soil quality and thus soil organic carbon is endogenous. This could mean that soil organic carbon is endogenous in our regressions. However, here, we use soil quality parameter data, respectively, from 1995 to 1999 and from 2000 to 2004, to be regressed on crop yield data from, respectively, 2001 and 2006, furthermore at regional and department scale. Hence, soil quality data are not impacted by the farming practices or crop allocation for the years considered – although it is impacted by a succession of crop allocation choices and farming practices. As such, we can consider here that the soil quality parameters used in our regressions are not endogenous.

Another bias not addressed here is related to the spatial autocorrelation. Neighboring cantons may have functional relationships between one another, for instance due to a particular spatial organization of activities. For instance, a canton with a high proportion of maize grain is likely to also present a high proportion of cattle, with a relative high amount of spreading that can impact on neighboring parcels located in different cantons.

Table 2. Crop production regression results.

| Explaining variables | Soft wheat yield | Maize grain yield |
|----------------------|------------------|------------------|
|                      | Estimate         | p-value          | Estimate         | p-value          |
| Soil organic carbon (SOC) | 6.075e+00 | 8.45e-16*** | 2.0910756 | 0.013037* |
| SOC second-order effect | -1.116e-01 | 3.65e-09*** | -0.0204809 | 0.395858 |
| N fertilizer inputs | 5.443e-01 | 1.33e-05*** | 1.1517996 | 1.37e-13*** |
| N fertilizer inputs second-order effect | -1.320e-03 | 0.01127* | -0.0039216 | 8.80e-11*** |
| Cross impact of SOC and N fertilizer inputs | -1.665e-02 | 2.91e-08*** | -0.0118219 | 0.000558*** |
| Clay content in soil | -1.328e-02 | -0.645 | -0.0014330 | 0.953208 |
| Sand content in soil | -2.102e-02 | 0.02288* | 0.0128613 | 0.196664 |
| Region Sud Ouest | -1.463e+01 | 8.38e-07*** | 6.9048500 | 0.025745* |
| Region Grand Ouest | -3.975e+00 | 0.13934 | 10.0837000 | 0.003623** |
| Region Sud Est | -1.024e+01 | 0.00477** | 9.4998358 | 0.010900* |
| Number of observations | 147 | 125 |
| Multiple R-squared | 0.97 | 0.98 |

Signif. codes: 0.001***, 0.01**, 0.05*, 0.1
5. Cooperative and non-cooperative inputs: what does it change?

The statistical analysis illustrates one of the possible cooperative relationships described by our theoretical model. Here, N fertilizer inputs and SOC are not cooperative inputs and $H_{ms} < 0$ and $m_s < 0$. This is also a case where, theoretically, we cannot determine the existence of an equilibrium. Yet, the non-cooperative inputs N and SOC could also lead to an equilibrium without violating our mathematical conditions.

Although we cannot perform a dynamic analysis of the equilibrium that may occur in this case, using comparative static analysis, we can compare the situation where productive inputs and soil quality are cooperating and when they are not.

A comparative static analysis of this problem allows us to determine how the endogenous variables in our model would differ from the steady-state equilibrium with different values for the exogenous parameters (Léonard and van Long 1992). In our case, the endogenous variables that characterize the optimal steady state are productive inputs $m$, conservation practices $u$, soil quality $s$ and the soil quality implicit value $\mu$. In what follows, we present the change in the optimal values for a change in a given parameter, with all other parameters remaining constant. The computation of such impacts highly depends on the cooperative relationship between production factors.

The comparative static analysis that corresponds to the theoretical equilibrium we computed, where production factors are cooperating and the damage caused by the use of productive inputs are more than offset by its cooperating benefits with soil quality in terms of revenue ($H_{ms} > 0$), yields the following results (see Appendix 2 [online supplemental data] for the computation details):

$$ m = m\left(\frac{c_1}{c_2}, \frac{p}{r}, r\right) \quad (26) $$
$$ u = u\left(\frac{c_1}{c_2}, \frac{p}{r}\right) \quad (27) $$
$$ \mu = \mu\left(\frac{c_1}{c_2}, \frac{p}{r}\right) \quad (28) $$
$$ s = s\left(\frac{c_1}{c_2}, \frac{p}{r}\right) \quad (29) $$

The comparative statics for an equilibrium where production factors are not cooperating, as in our empirical illustration, with respect to N fertilizers and SOC are presented below. For this second case, we do not consider the impact of parameter changes in conservation practices $u$ and soil quality implicit value $\mu$, for they are of undetermined sign.

$$ m = m\left(\frac{c_1}{c_2}, \frac{p}{r}\right) \quad (30) $$
$$ u = u(c_1, c_2, p, r) \quad (31) $$
$$ \mu = \mu(c_1, c_2, p, r) \quad (32) $$
$$ s = s\left(\frac{c_1}{c_2}, \frac{p}{r}\right) \quad (33) $$

An increase in the cost associated with productive inputs $c_1$ leads to an expected decrease in productive inputs and to a decrease in the equilibrium soil quality and the marginal value of soil, when the two production factors are cooperative. Since the value attributed to soil quality is lower, smaller investments are made in conservation practices. However, when production factors are not cooperative, the expected decrease in productive inputs is compensated by an increase in soil quality.
When productive inputs are cooperative, an increase in the cost associated with soil conservation and non-productive practices $c_2$ reduces investment in soil conservation. As a consequence, the optimum soil quality is lower, and the associated marginal value increases. Since productive inputs and soil quality are cooperating, the use of productive inputs associated with lower soil quality is smaller than in our original equilibrium.

An increase in the crop price $p$ leads to an increase in soil quality and productive inputs. Indeed, the farmer faces the possibility of increasing production to attain an equilibrium where the marginal benefits of using more productive inputs equal the costs of these practices. When there is cooperation between these two variables, soil quality in equilibrium also increases. To maintain this level of soil quality, higher investment in soil conservation techniques is required. With a higher price and a higher productivity of soil quality at this optimum, the marginal soil quality is also higher. When production factors are not cooperative, the increase in crop price also leads to an increase in both production factors.

An increase in the discount rate $r$ can correspond to a higher preference for the present. Hence, in his maximization problem, the farmer values present revenue more than future revenue. As a consequence, soil quality will be either more depleted or less restored by the farmer, who will be less willing to invest in soil conservation measures since the marginal value attributed to soil quality has decreased in this equilibrium. The level of productive inputs also decreases due to the cooperation with soil quality. However, when production factors are not cooperative, productive input use increases, while soil quality decreases. The $r$ values range between 0 and 1. An $r$ equal to 0 corresponds to the time preferences of a benevolent state, where future revenues are considered as valuable as current revenues. Conversely, an $r$ equal to 1 corresponds to the time preference of a selfish short-termist private agent who values only present revenue.

Figure 3 provides a graphical representation of how the steady-state equilibrium can be modified by an increase in the cost $c_1$ of productive inputs. In this example, the former optimal path that was located in region I is now in region II. Whereas in the previous situation, a farmer located on this path would have reached the steady
state, now this farmer is in a situation of overproduction with a total depletion of his soil quality. Conversely, farmers previously located in region IV, which was characterized by non-sustainable underproduction, may either be on the optimal path or on a path that does not immediately lead to either over- or underproduction.

6. Conclusion

This article examines whether farmers have a private interest in maintaining or increasing soil quality. Particular attention is given to the cooperative relationship between productive inputs and soil quality. It explores and discusses the different optimal strategies for achieving long-term equilibrium. In addition, the dynamic elements of soil resource management problems have been characterized. An illustrative statistical analysis is proposed for the French case, to establish which sort of cooperative relationship can be observed at a regional level between N fertilizers and SOC.

The investment model proposed highlights some favorable situations for the maintenance and enhancement of soil quality. The model shows the importance of cooperation between the two production factors (soil quality and productive inputs). When production factors are cooperative and when the marginal cooperative productivity is higher than the marginal damage of productive inputs to soil quality, there exists a long-term optimal equilibrium with strategies that can be followed by the farmer to reach the optimum. However, when production factors are not cooperative, or when the marginal productivity of the cooperating inputs is lower than the marginal and detrimental impact of productive inputs on soil quality, one cannot draw conclusions about the existence of an equilibrium.

These ambiguities show that we are, indeed, facing empirical questions that depend on technical interactions that are difficult to discover and control. Actually, our statistical analysis shows that empirically, N fertilizer inputs and SOC are not cooperating. This has consequences in terms of policy. From our comparative statics, when production inputs are not cooperating, it is relevant to tax productive inputs costs, such as N fertilizer costs in our example. No feedback would be observed, it could even trigger a positive snowball effect. However, such a strategy applied for a cooperative input would have a negative feedback effect. Farmers might reduce their use of this input, but they would not invest in soil quality either, leading to a decrease in soil quality.

Other productive inputs, such as irrigation, should be considered. According to our approach, irrigation would be a productive input with a potential detrimental impact on soil quality. As a consequence, its cooperative relationship with soil quality should be assessed, as we did for nitrogen fertilizers.

In addition, at a larger geographical scale, such as the watershed rather than the parcel, water management can be considered similarly to soil quality management in this study, where farming practices can have positive and negative impacts on the water resources.

Notes

1. For simplicity, soil quality endogenous attributes will be referred to as soil quality throughout the rest of this article.

2. Cooperative inputs can be considered inputs that work as a team (Alchian and Demsetz 1972). The output is yielded by this team, here, productive inputs \( m \) and soil quality \( s \). In the original framework by Alchian and Demsetz (1972), team production is used in the
case when inputs produce a higher output together than separately, such that the increase in production exceeds the costs of organizing this cooperation.

3. Appendix 1 (online supplemental data) considers the particular case where farmers do not consider soil quality dynamics in their decision-making process, which leads to the unsustainable long-term degradation of their soils.

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