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Sébastien Foudi

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Exploitation of soil biota ecosystem services in agriculture: a bioeconomic approach

Sébastien Foudi*

Abstract

This paper analyzes the interactions between soil biota and agricultural practices in the exploitation of soil ecosystem services. A theoretical bioeconomic model stylized this set of interactions and combined a production function approach with optimal control theory. In the model, a farmer decides his optimal use of external input and land use given that (i) land uses modify soil biota composition, (ii) the external input reduces soil biota population. The results show how the combination of ecological interactions, farmer's expectations on the evolution of the stock of soil biota and the technology of production determines the optimal decisions. The interpretation of the results helps to understand why and under which circumstances a sustainable or a non-sustainable use of soil ecosystem services may be optimal for farmers. A particular emphasis given to the role of property rights and time preferences in the use of soil biota services reveals the ambiguity of their role on the conservation of soil ecosystem services generated by soil biota.

Keywords: Ecosystem services, land uses, agriculture, heterogeneous environment, time preferences.

JEL classification : Q15, Q20, Q57.

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*Basque Centre for Climate Change (BC3), Alameda Urquijo 4, 48008 Bilbao, Spain. Email: sebastien.foudi@bc3research.org

1 Introduction

A wide variety of ecosystem services and more particularly soil ecosystem services are exploited and in the case of some agricultural systems over-exploited. The main reasons for the degradation of these services lies in some agricultural practices: the massive diffusion and excessive use of chemical fertilizers and xenobiotic compounds, the fragmentation and simplification of habitats (Tilman et al., 2001). Moreover, the degradation of the natural habitat causes a reduction of biodiversity, firstly in the number of individuals, then in the number of populations and finally in the number of species (Teyssèdre, 2005) implying a loss of ecosystem services. If these practices increased the agricultural production and yields to feed a growing human population, its sustainability is now questioned. Having a better understanding of farmers's incentives to exploit or conserve soil ecosystem services would help to design soil conservation policies. This article proposes to understand the interactions of agricultural practices and soil biota services generation.
Soil biota plays an important role in the generation of soil ecosystem services and land productivity (Barrios, 2007). Soil biota provides intermediate services in agriculture (Fisher et al., 2008). Indeed, it supplies nutrient to plant (Fragoso et al., 1997), maintain soil structure, improve water infiltration, and participates in soil organic matter decomposition (Swift et al., 2004; Barrios, 2007). The preservation of soil ecosystem services would then depend upon the preservation of soil biota. Yet the functions and services provided by resource biota in the agroecosystem are poorly recognized and documented. Furthermore, they are rarely quantified and valued by either life scientists or economists.

The identification of soil biodiversity, its functions in the ecosystems, and the quantification of the interactions between agricultural production and the soil biota is being referenced by scientists. The understanding of how agroecosystems function is then challenging for the design of bioeconomic approaches to the use of agroecosystem services. However, the differences of scales between economists and biologists investigations, the latter work at the laboratory or micro-plot levels and the former at the farm or regional level, makes it difficult to base natural resource conservation policies on only one of these two groups. The integration of biology and economics is then challenging for the design of policies aiming at promoting the sustainability of agroecosystem (Shogren et al., 2003; Watzold et al., 2006). This article integrates the biological literature on soil biota in the modeling in order to tend to a more complete design of soil ecosystem services.

The economic valuation of ecosystem services allos for the measurement of the dependance and relationship between economic activity and the ecosystem services (MEA, 2005; TEEB, 2010; EPA, 2009). Swinton et al. (2007) review these techniques for agricultural services. More generally, valuation techniques assume that the linkages between the function of ecosystem services, the net benefits derived by society and their values can be identified and quantified (Fisher et al., 2008; Turner and Daily, 2008). For agricultural services generated by soil biota, the identification of services is very recently addressed and understood in the field of economic ecosystem services. Quantification of the services is even more rare. (Barrios, 2007; Omer et al., 2010). Moreover, there are very few economic valuation studies on the relationship between soil biota and agricultural services (Huguenin et al., 2006). To contribute to the understanding of the interactions between soil biota and agricultural ecosystem services exploitation, this paper combines a production function approach to ecosystem services (Barrios, 2007) with optimal control theory. This would help understand the drivers of the exploitation of soil biota services. The contribution of the paper remains theoretical and conceptual since the model can not be calibrated for lack of data and knowledge on quantified/estimated functions. However, the bioeconomic model derived is based upon the identification of soil biota typology and functions in the provision of services or dis-services that can be interpreted in economic terms.

In the model the farmer manages both the space (land) and the intensity of his harvesting effort. The model departs thus from the literature on renewable resources exploitation that are largely applied to (de facto) open access resources. The effects of property rights and long term preferences on agricultural practices is then questioned. It is common knowledge that secure property rights favor natural resource conservation compared to the (de facto) open access situation. However, the model will show that depending on the bioeconomic state of the agroecosystem, property rights and long term preferences can induce more exploitation of soil resources than myopic preferences.

The article is organized as followed. Section 2 describes the generation of services and dis-services generated by soil biota in agroecosystems and its interactions with agricultural practices. Section 3 proposes a bioeconomic model of soil biota exploitation and derives optimal agricultural practices in terms of land use and use of external inputs. Section 4 studies the role of property rights and long term preferences on the bioeconomic system. Section 5 concludes and discusses the main hypothesis and results.

2 Soil biota ecosystem services and dis-services to agriculture

At the scale of an agroecosystem, the preservation of soil services depends upon the preservation of soil biota. Soil biota include productive biota (crops, livestock), resource biota (decomposers) and destructive biota (pests) (Swift and Anderson, 1993). These resources generate supporting and regulating services to agricultural production at the field and farm scales. Soil biota support the nutrient cycle, and they structure, retain, and fertilize the soil, participate in the biological control of pests and diseases (Zhang et al., 2007; Dominati et al., 2010)

2.1 The provision of services

At the field scale, soil biodiversity is a complex system of interactions among species, interactions between species function and agricultural production (Beare et al., 1997; Barrios, 2007). The function of soil biota in the ecosystem is heavily ecosystem and species specific. Various interactions are being discovered: interactions among decomposers, between plants and microorganisms, influence of decomposers density and diversity on soil properties (Zaller, 1999; Tian, 2001; Fragoso et al., 1997; Chauvel et al., 1999; Black and Okwakol, 1999; Joshi et al., 1999). These organisms participate in the synthesis of soil organic matter and its decomposition (Swift et al., 2004).
Among these fauna, earthworms might be the most studied species (Lavelle et al., 1992; Stinner et al., 1997; Zaller, 1999; Feller et al., 2003). It is known among biologists that many earthworms species contribute to nutrient cycling through the production of nutrient-rich casts. Their production is estimated around 50-100 kg ha^{-1} in humid tropical pastures. It has also been shown that earthworms casts contain more organic carbon, total nitrogen, available phosphorus from which the casts are derived. The casts produced by the earthworms are rich in organic matter and the higher rates of mineralization found in these casts implicate and enhanced availability of nutrients ($NH4^+$ and $NO3^-$) to roots growing in this zone and to superficial roots which can absorb these nutrients after they leach from the litter layer (Fragoso et al., 1997). In tropical grasslands around 25-150 kg ha^{-1} of mineral nitrogen may be released annually by a species of earthworm (Lavelle et al., 1992).

The quantification of the role of soil biota on soil fertility is poorly known and even less known is the effect of soil biota on agricultural productivity. Lavelle et al. (1992) have shown that for the earthworm species they studied, this species enhanced maize yields. Gilot (1994) observed an increase of 18% and 12% in maize grain and stalk production respectively, when earthworm species was introduced into microplots. But the survival rates of the species after the harvest was very low, which indicates a low robustness of the experience and suggests that an integrated conservation of soil biota and agricultural practices should be preferred.

2.2 The dis-services

The classification of soil biota between productive, resource biota and destructive biota by Swift and Anderson (1993) helps to understand that the use of pesticide in agriculture is designed to manage and regulate the destructive biota. The effect of pests on productivity may be non negligible. It is estimated for example that foliar pest attacks were responsible for a 12% reduction in eucalypt plantation productivity (Pinkard et al., 2010). The grazing effect of mice would lead to a mean yield loss of 12.4% (Brown et al., 2007). Other studies based on a questionnaire reveals that Ethiopian farmers estimate the losses in sorghum yield to 50% due to insect damage during the storage period (Mendesil et al., 2007). However the use of convenient techniques to reduce the space occupied by the destructive biota has several effects on the ecosystems and modify the equilibrium between species. The use of insecticides decimates natural enemy population and exacerbates the problem generated by the destructive biota (Zhang et al., 2007). Furthermore, Christiaans et al. (2007) shows that pest eradication is a non optimal strategy for farmers. Modelling approaches should thus integrate both the services and the dis-services generated by soil biota.

2.3 The impact of agricultural practices on soil biota

The impacts of agricultural practices on soil biota and on soil properties have also been studied but quantification of this impact is more rare. Beare et al. (1997) identify three factors associated with agricultural intensification that affect soil biota production: '(*i*) an increase in the frequency and magnitude of perturbations that result from land-use changes and site preparation, (*ii*) a reduction in the quantity of organic resources returned to the soil; (*iii*) the use of xenobiotic compounds such as industrial fertilizers and pesticides'. For example, land-use changes consisting in converting native forest or grassland systems to arable cropping results in a decline of soil biodiversity (Lavelle et al., 1992).

On the effects of agrochemical herbicides on soil biodiversity, it is known that non-selective agrochemicals can be detrimental for long run soil management and for maintaining soil fertility. Moreover insecticides and herbicides reduce also the abundance of invertebrates (Mesléard et al., 2005). The use of chemical fertilizers and pesticides by farmers also modify the soil properties either directly trough chemical effects or indirectly trough the modification of the soil biota composition. Consequently, fertilizers deplete the organic matter of the soil and speed up the disappearance of humus via mineralization processes (Swift et al., 2004; Dominati et al., 2010).
Hole et al. (2005) analyze the impact on biodiversity of agri-environmental schemes aim at promoting organic farming practices. They review the effects of organic farming on flora, soil microbes, invertebrates (earthworms, butterflies, spiders, beetles) and vertebrates (birds, mammals). They reveal that in almost all the 76 studies they refer to, organic farming benefits to a larger abundance and/or species richness.

Based upon this description of the interactions between soil biota functions and agricultural practices, optimal control theory would help to derive optimal practices and use of soil ecosystem services by farmers. A bioeconomic model following this description of soil biota and agricultural practices interactions is proposed the following section. A production function approach is introduced in an optimal control problem of soil ecosystem services and dis-services.

3 A bioeconomic model of soil ecosystem services and disservices

3.1 A model of agricultural and soil biota interactions

The farm is a heterogenous environment of C patches α_{ikt} representing the share of land devoted to landuse $i = 1, ...C$ at time t while under landuse k at the preceding period. Let B_{it} be the stock of soil biota on patch i at time t. Soil biota is here considered as a metapopulation representing both the destructive and the resource biota of the soil.

At the scale of a patch, the interactions between soil biota and agricultural practices presented in the preceding section are summarized in figure 1.

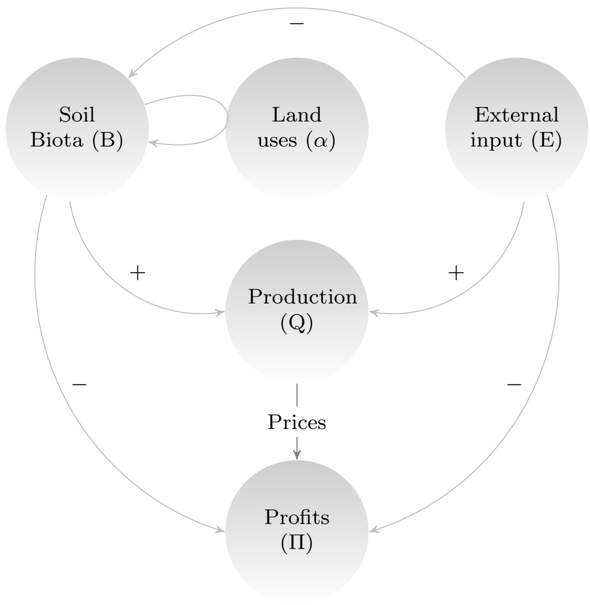

Figure 1: An optimal control model of soil biota and agricultural practices interactions

Land uses They influence the renewing of the resource through its carrying capacity. Indeed, as the farmer changes his land uses he changes the habitat the resource is living in and thus changes the carrying capacity[1]. The effective carrying capacity κ_{it} is thus specific to plot i and to time t and it can be written as a linear function of a potential intrinsic carrying capacity, κ_i:

[1]Swanson (1994) considers that the carrying capacity in the logistic growth function must be a function of the habitat available for the resource.

$$\kappa_{it} = \sum_{k=1}^{C_2} \alpha_{ikt}\kappa_i = \alpha_{i.t}\kappa_i \tag{1}$$

As the share of the habitat increases, the effective carrying capacity reaches its potential intrinsic carrying capacity.

In a patchy environment, the population is subject to migration processes from one patch to another. The dispersal process is represented as a multiple sources dispersal process: "many patches contribute biomass to one common pool" (Sanchirico and Wilen, 1999). In this model, the dispersal is assumed to be a function of land uses since when the farmer assigns a particular crop to a patch he modifies the specific soil biota. The patch specific resource is then:

$$B_{it} = \sum_{k=1}^{C_2} \alpha_{ikt} B_t = \alpha_{i.t} B_t \tag{2}$$

The damage to soil biota The use of external inputs (E) for production such as chemical fertilizers generates a damage to soil biota. A Schaefer function $H_i(E_{it}, B_{it})$ represents this damage. A multiplicative damage is relevant for random damage of a randomly distributed population (Clark, 1979). This function is convenient to capture the non linearity in the damage of the agricultural practices onto the soil biota.

$$H_i(E_{it}, B_{it}) = \varphi_i B_{it} E_{it} \tag{3}$$

where φ_i is a catchability or mortality coefficient due to the use of chemical inputs.

The renewing of soil biota The patch specific growth of the resource is decomposed in a natural growth function G and the harvest or damage function H. It is given by:

$$B_{i,t+1} = G_i(B_{it}) - H_i(E_{it}, B_{it}) = B_{it}\left[1 + r_i\left(1 - \frac{B_{it}}{\kappa_{it}}\right)\right] - H_i(E_{it}, B_{it}) \tag{4}$$

where r_i is the intrinsic growth rate of the patch and κ_{it} is the effective carrying capacity of the patch i at time t.

Using equations 1 to 4, the evolution of the pool soil biota (the stock of resources over all patches) can be written as:

$$B_{t+1} = \sum_{i=1}^{C_2} B_{i,t+1} = \sum_{k=1}^{C_2}\sum_{i=1}^{C_2} \alpha_{ki,t+1} B_t \left[1 + r_i\left(1 - \frac{B_t}{\kappa_i}\right) - \varphi_i E_{it}\right] \tag{5}$$

where r_i is the intrinsic growth rate of the patch, κ_i is the carrying capacity of the field i and φ_i the catchability or mortality coefficient of the inputs.

The agricultural production The production function approach of the valuation of soil ecosystem services considers soil biota (B) as an input to the production of agricultural goods (Q). Other input for the production is the external input (E) such as chemical fertilizer. The yields $Q_{it} = Q_i(B_{it}, E_{it})$ are assumed to be concave.

The costs The external input has a financial cost $C_i(E_{it})$. Soil biota as a metapopulation is also composed by destructive biota (pests) that generate a cost of nuisance $C_i(B_{it})$ (Skonhoft, 1999, 2007). The damage function is modeled in the literature on damage control as a fraction of a potential production (Hennessy, 1997; Fox and A., 1995). In the bioeconomic and biological literature, the damage function is often density dependent and directly modeled as a function of the resource (Skonhoft, 1999, 2007; Omer et al., 2010; Choquenot and Parkes, 2001). The former approach allows the nuisance to evolve with the evolution of the resource.

The profits The total profit function at time t, with decoupled subsidies S_{it} is then:

$$\Pi_t = \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ikt} \left[P_{it} Q_i(B_{it}, E_{it}) + S_{it} - C_i(E_{it}) - C_i(B_{it}) \right] \tag{6}$$

3.2 Soil biota valuation and optimal practices

A risk neutral farmer decides the level of input E and the land uses α such that he maximizes the expected discounted total profit, in a finite horizon under the law of evolution of soil biota described in equation 5:

$$\max_{\alpha, E} E_t \left[\sum_{s=t}^{T} \frac{\Pi_s(B, E, \alpha)}{(1 + \tau_s)^{s-t}} \right]$$

where τ_s is the interest rate of the period $s = t, t+1, ..., T$. Let $V(B_t)$ be the maximum value function. According to Bellman dynamic programming, this value satisfies the Bellman's equation:

$$V_t(B_t) = \max E_t[\Pi_t + \frac{1}{1 + \tau_t} V_{t+1}(B_{t+1})]$$

The resolution of the problem is proposed in A.

The future marginal value of soil biota It is given by:

$$\frac{dV_{t+1}}{dB_{t+1}} = \sum_{k=1}^{C_2}\sum_{i=1}^{C_2} \alpha_{ik,t+1}[\alpha_{i.,t+1}(P_{i,t+1}Q^B_{i,t+1} - C^B_{i,t+1}) + \Phi_{i,t+1}(P_{i,t+1}Q^E_{i,t+1} - C^E_{i,t+1})] \tag{7}$$

where $\Phi_{i,t+1} = \frac{G^B_{i,t+1} - H^B_{i,t+1}}{H^E_{i,t+1}}$.

The sign of this value is determined by the combination of three factors: ecological interactions with soil biota, farmer's expectations on the stock of resources and farming technical orientations. Table 1 summarizes this sign given the different states of the agroecosystem.

The *ecological interactions* describes the nuisance that soil biota can generate to the agricultural activity (Skonhoft, 1999, 2007). The interaction is qualified as 'Normal' when the marginal cost of the input does not exceed the marginal benefits it generates. The interaction is defined as a 'Nuisance' situation otherwise[2]. The *farmer's expectations* on the evolution of the stock determines the sustainability of the exploitation of soil biota according to the level of input used. These expectations are 'Sustainable' as long as the term $\Phi_{i,t+1}$ is positive. Otherwise they are 'Non Sustainable'. The *farming technical orientations* provide information on the productivity of the inputs. The technology is said to be 'Natural Resource Orientated' (NRO) when the marginal productivity of soil biota is larger than the one of the external input. Otherwise the technology is 'Agricultural Effort Orientated' (AEO).

Table 1: Sign of the marginal value of the resource

	Normal	**Nuisance**
Sustainable	$+$	$-$
Non-Sustainable and NRO	$+$	$-$
Non Sustainable and AEO	$-$	$+$

The optimal level of external input The farmer chooses the optimal level of input E that equates the instantaneous marginal benefit of the external input to its discounted future value:

$$P_{it}Q^E_{it} - C^E_{it} - \beta_t H^E_{it} E_t \left\{ \frac{dV_{t+1}}{dB_{t+1}} \right\} = 0 \tag{8}$$

if $E_{it} > 0$ and with $\Phi_{i,t+1} = \frac{G^B_{i,t+1} - H^B_{i,t+1}}{H^E_{i,t+1}}$, $\beta_t = \frac{1}{1+\tau_t}$.

Otherwise, if $E_{it} = 0$, this expression is strictly negative.

[2]The terms under the parentheses in equation 7 are positive under the normal situation and negative under the nuisance situation.

The optimal land uses The optimal choice of land use α_{ikt} is driving by the arbitrage between the instantaneous benefit generated by a land use and the discounted future value of this land use:

$$P_{it}Q_{it} + S_{it} - C_i(E_{it}) - C_i(B_{it}) + [G_k - H_k] \left(\sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ikt}(G_{it}^B - H_{it}^B) \right) \beta_t E_t \left\{ \frac{dV_{t+1}}{dB_{t+1}} \right\} = 0 \quad (9)$$

if $\alpha_{ikt} > 0$, with $\Phi_{i,t+1} = \frac{G_{i,t+1}^B - H_{i,t+1}^B}{H_{i,t+1}^E}$, $\beta_t = \frac{1}{1+\tau_t}$.

These two optimal decisions on land use and external input are thus influenced by the bioeconomic states of the agroecosystem defined by the three factors described previously but also driven by farmers preferences and property rights regime.

4 The role of property rights and time preferences

In the economic literature on natural resource exploitation, the conservation of natural resources depends on the growth of the resource, on harvesting technology and on the economy's institutions and property (Clark, 1973; Gordon, 1954; Coase, 1960; Swanson, 1994). Linking conservation of resources to property is an old issue in economics (Gómez-Baggethum et al., 2010). Gray (1913) wondered if "...private property in natural objects [is] favorable or unfavorable to the realization of the ideals of the conservationists?" Property rights create incentives to invest in natural resources since secure property rights are a necessary condition for being able to have long-term management perspectives and invest in wildlife conservation (Smith, 1975; Swanson and Barbier, 1992; Skonhoft and Solstad, 1998; Kiss, 2004).
This section shows that if property rights are a necessary condition for conservation they are not a sufficient condition for investing in natural resources. Indeed Gray's own response to the issue of private property was: "This depends upon the extent to which the individual will find it profitable to employ methods of conservation in the utilization of the natural resources under his control." The following sections address the issue of the profitability in the investment in soil biota conservation practices at the farm scale and identifies cases where the intensification of agricultural practices and the land expansion increase the damage to soil biota because of property rights combined with time preferences and symmetrically cases where these practices lead to the conservation of soil biota.

When an agent is the owner of a resource, he has access, can withdraw, manage, exclude others and alienate the resource (Ostrom, 2000) and can make long term decisions. But when this agent cannot monitor the use of the resource, because of imperfectly protected property rights he has short-term preferences (Skonhoft and Solstad, 1998). This results in a de facto open access situation (Ostrom, 2000). In the model, this situation arises when the discounted terms of the first order conditions tends to zero, in equations (8) and (9). Consider this myopic time preferences has a benchmark.

4.1 Property rights, time preferences and the optimal use of external inputs

Table 2 identifies the combinations of states of the agroecosystem that lead a farmer with long term preferences to use lower levels of external inputs than under myopic time preferences[3]. These situations correspond thus to an investment in the soil biota through a reduction of the use of detrimental external inputs and occurs when: (*i*) the soil biota is costless and its exploited stock is increasing (Normal-Sustainable case), (*ii*) the resource does not harm the benefits it generates and the technology is natural resource oriented so that the resource is positively valued and justifies any investments in it even if its stock is declining (Normal-Non Sustainable and NRO), (*iii*) both inputs are relatively costly and since the technology of the farm is agricultural effort oriented it justifies the disinvestment in the effort and the investment in the natural resource (Nuisance-Non Sustainable and AEO).

Table 2: The variations of the agricultural effort

	Normal	**Nuisance**
Sustainable	-	+
Non Sustainable and NRO	-	+
Non Sustainable and AEO	+	-

When secure property rights on the resource are given to the farmer, in Johannesen and Skonhoft (2004), the nuisance and the normal case always result in respectively lower and higher investment in the resource than in the myopic case, while in this model, it is clear that farmers do not always play the same strategy in the two ecological situations (normal and nuisance). The farmer's expectations concerning the level of the resource are then another determinant of his strategy.[4]

4.2 Property rights, time preferences and the optimal land uses

In a long-term perspective, the optimal land use choice is driven by the principle of equalizing the instantaneous benefit from a given land use with the expected discounted value of that land use. This arbitrage[5] is driven by equation 9.

[3]" the −" in table 2.

[4]Johannesen and Skonhoft (2004) studied conservation at the steady state equilibrium so that expectations concerning the evolution of the stock of resources could not be identified.

[5]to account for the land availability constraint, one should interpret this condition in land use relative terms. For reasons of clarity in notation, this constraint is not formalized but relatively easily accounted for.

To analyze land use decisions, assume that land use expansion does not drive the soil biota to total extinction[6].

Table 3 presents the variation in land uses compared to the benchmark myopic case. It shows that three states of the agroecosystem justify the expansion of a given land use when the farmer is not myopic[7]: (*i*) when the resource located in that land does not harm the benefits it generates and when the stock of the resource is increasing. Uses of that land is justified in order to exploit and manage the soil resources concerned (Normal-Sustainable). (*ii*) When the resource is not costly, the farmer expands this land use because the technology is agricultural effort oriented so that it will be profitable to exert this effort on more land (Normal-Non Sustainable and AEO). (*iii*) The resource is costly, its stock is in decline, and as the technology is natural resource oriented then the expansion of the land is a tool to capture and exploit more soil biota (Nuisance-Non sustainable and NRO). Symmetrically, one can find three reasons to justify a reduction in land use when agents have secured property rights and long term preferences.

Table 3: The variations of landuses

	Normal	**Nuisance**
Sustainable	+	-
Non Sustainable and NRO	-	+
Non Sustainable and AEO	+	-

4.3 Property rights, time preferences and agricultural practices

Looking at the arbitrage between intensive and extensive farming when the agent is not myopic, (Table 2 and Table 3), it appears that the farmer substitutes external inputs for the land only when the exploitation of the resource is sustainable: the choice between intensive and extensive farming is then not ambiguous and depends upon the level of the nuisance. Indeed, when the exploitation of the resource is sustainable and when the resource is not harmful, the farmer chooses an extensive farming (reducing the use of external input and increasing the land use). Otherwise when the resource is costly, he prefers intensive farming. In all other cases, the choice is undetermined since the effort and the land uses fluctuate in the same direction.

Therefore, it appears that the effect of property rights and time preferences on soil ecosystem services remain ambiguous in this heterogenous ecosystem. For some bioeconomic states, long term preferences might create their own incentive on farmers' decisions

[6] $G(.) - H(.) = \frac{dB_t}{d\alpha_{ikt}} > 0$

[7] $+$ means that the farmer who has long term preferences expands the share of land under land use i compared to a myopic case and $-$ means he reduces this share.

to conserve soil biota services. For other bioeconomic circumstances, they justify the disinvestment in the natural services.

5 Conclusions

The paper analyzed the determinants of the exploitation of soil ecosystems services and dis-services in managed lands. To that end, it uses optimal control theory and proposes a bioeconomic model applied to soil biota exploitation. In this model, a farmer manages both the space and the intensity of his harvest effort as he decides land uses and use of external inputs.

Results show how the optimal determination of the external input use and of the land use is driven by the combination of three determinants: an ecological determinant that defines the nuisance of the resource, the farmer's expectations on the evolution of the resource and the farming technical orientations. The farmer's expectations for the stock are either sustainable or not. A sustainable use means that the level of agricultural effort is low enough to maintain a growing resource. The farming technical orientations describe the technology of production. This technology can be natural resource oriented or agricultural effort oriented. In the latter case the productivity is dominated by the productivity of the external inputs while in the former case it is dominated by the productivity of the soil biota. The combination of these determinants will then define six bioeconomic states of the system. These states enable to understand how farmers derive long-term profitability and under which circumstances sustainable or non-sustainable use of ecosystem services can be optimal.

The role of property rights and long term preferences on agricultural practices and thus on soil biota has been highlighted. The results show that they are another determinant of soil ecosystem services exploitation. Indeed, the interpretation of the optimal practices, both land use and use of external inputs, revealed that for some bioeconomic circumstances, a farmer can find it profitable to conserve soil biota for the services it provides for production. Under long term preferences, he then has the incentive to use optimal practices that do not reduce soil biota services in the long run. For other bioeconomic circumstances, the model shows that soil biota can be exploited at level associated with low ecosystem services. This non-homogeneity that characterizes the bioeconomic system can explain why the role of tenancy on soil conservation practices remain ambiguous (Lichtenberg et al., 2010).
The difference in the bioeconomic state of farms can illustrate the differences between farmers using eco-friendly practices like organic farming with conventional farmers. Therefore, under some bioeconomic circumstances a farmer can find incentives for soil biota conservation in the services delivered by soil biota (thought the production function) and in his time preferences. Mechanisms designed to promote soil ecosystem services conservation

should thus be able to reveal a farmer's preferences in the time and reveal the bioeconomic state of the soil (Perrings et al., 2006; Pascual and Perrings, 2007).

A determinant of soil biota management left aside in this model is the role of risk aversion. The farmer is assumed to be risk neutral in this model. The consensus on farmers' risk aversion is not established in the literature, the role of external input on production risk is still ambiguous (Groom et al., 2008; Koundouri et al., 2009; Foudi and Erdlenbruch, 2011) and methods to measure risk aversion are debated (Just and Just, 2011; Lence, 2009). The production function approach accounting for production risk should give more emphasis on the role of risk in agricultural practices and soil ecosystems services conservation.

The presence of soil biota, more particularly destructive biota could have exacerbated farmers' risk aversion and be a reason for pesticide use that generate undesirable effects on the resource biota. Since Christiaans et al. (2007) it is known that pest eradication is not optimal. Managing both type of soil biota in integrated manner would reveal some benefits to farmers, either in terms of production or risk management. In this sense, more recently, insurance value of natural resources are being addressed as a motive to maintain the resilience of the system (Derissen et al., 2011; Simonit and Perrings, 2011; Quaas and Baumgartner, 2008). Addressing the insurance value of soil biota would be a challenging issue and an argument for its conservation in the long run.

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A Marginal value of soil biota and optimal decisions

Nota: the subscripts correspond to land uses and time and the superscripts to the first derivative with respect to E or B.

Recall the set of equations describing the relation between soil biota and agricultural practices:
Equation 2 becomes equation 1

$$B_{it} = \sum_{k=1}^{C_2} \alpha_{ikt} B_t = \alpha_{i.t} B_t \tag{1}$$

Equation 4 becomes equation 2

$$B_{i,t+1} = G_i(B_{it}) - H_i(E_{it}, B_{it}) = B_{it} \left[1 + r_i \left(1 - \frac{B_{it}}{\kappa_{it}}\right)\right] - H_i(E_{it}, B_{it}) \tag{2}$$

Equation 5 becomes equation 3

$$B_{t+1} = \sum_{i=1}^{C_2} B_{i,t+1} = \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ki,t+1} B_t \left[1 + r_i \left(1 - \frac{B_t}{\kappa_i}\right) - \varphi_i E_{it}\right] \tag{3}$$

Subject to the constraint of evolution of the soil biota, the problem of the farmer is:

$$\max_{\alpha, E} E_t \left[\sum_{s=t}^{T} \frac{\Pi_s(B, E, \alpha)}{(1 + \tau_s)^{s-t}}\right]$$

where τ_s is the interest rate of the period $s = t, t+1, ..., T.$.

Let $V(B_t)$ be the maximum value function. According to Bellman dynamic programming, this value satisfies the Bellman's equation:

$$V_t(B_t) = \max E_t[\Pi_t + \frac{1}{1 + \tau_t} V_{t+1}(B_{t+1})]$$

The marginal value of the renewable resource is:

$$\frac{\partial V_t(B_t)}{\partial B_t} = \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ikt} [P_{it} \frac{\partial Q_{it}}{\partial B_{it}} \frac{\partial B_{it}}{\partial B_t} - \frac{\partial C_i}{\partial B_{it}} \frac{\partial B_{it}}{\partial B_t}] + \beta_t E_t \left\{ \frac{dV_{t+1}}{dB_{t+1}} \frac{dB_{t+1}}{dB_t} \right\} \tag{4}$$

$$= \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ikt} \left[P_{it} \alpha_{i.t} Q_{it}^B - \alpha_{i.t} C_{it}^B\right] + \beta_t E_t \left\{ \frac{dV_{t+1}}{dB_{t+1}} \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ki,t+1} (G_{it}^B - H_{it}^B) \right\} \tag{5}$$

with $\beta_t = \frac{1}{1 + r_t}$.

The first order condition with respect to the agricultural effort E_{it} is:

$$\frac{\partial V_t(B_t)}{\partial E_{it}} = 0 \Leftrightarrow \sum_{k=1}^{C_2} \alpha_{ikt} \left\{ P_{it} \frac{\partial Q_{it}}{\partial E_{it}} - \frac{\partial C_i}{\partial E_{it}} \right\} + \beta_t E_t [\frac{dV_{t+1}}{dB_{t+1}} \frac{dB_{t+1}}{dE_{it}}] = 0 \qquad (6)$$

if $E_{it} > 0$.

Multiplying equation 6 by $\frac{G_{it}^B - H_{it}^B}{H_{it}^E} \equiv \Phi_{it}$ and summing over $i = 1, ..., C_2$, we have:

$$\sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ikt} \Phi_{it} \left[P_{it} Q_{it}^E - C_{it}^E \right] - \beta_t E_t \left\{ \frac{dV_{t+1}}{dB_{t+1}} \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ki,t+1} (G_{it}^B - H_{it}^B) \right\} = 0 \qquad (7)$$

The right last terms of equation (7) and equation (5) are the same so that the marginal value of the renewable resource taken at time $t+1$ is:

$$\frac{dV_{t+1}}{dB_{t+1}} = \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ik,t+1} [\alpha_{i.,t+1} (P_{i,t+1} Q_{i,t+1}^B - C_{i,t+1}^B) + \Phi_{i,t+1} (P_{i,t+1} Q_{i,t+1}^E - C_{i,t+1}^E)] \qquad (8)$$

where $\Phi_{i,t+1} = \frac{G_{i,t+1}^B - H_{i,t+1}^B}{H_{i,t+1}^E}$.

The land use rotation condition states that $\sum_{k=1}^{C_2} \alpha_{ikt} = \sum_{k=1}^{C_2} \alpha_{ki,t+1}$ (Thomas, 2003), i.e. the areas i at time t with land use origin k are equals to the areas k with origins i at time $t-1$ the optimal level of agricultural effort E_{it} is determined by the first order condition:

$$P_{it} Q_{it}^E - C_{it}^E = \beta_t H_{it}^E E_t \left\{ \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ik,t+1} [\alpha_{i.,t+1} (P_{i,t+1} Q_{i,t+1}^B - C_{i,t+1}^B) + \Phi_{i,t+1} (P_{i,t+1} Q_{i,t+1}^E - C_{i,t+1}^E)] \right\} \qquad (9)$$

if $E_{it} > 0$ and with $\Phi_{i,t+1} = \frac{G_{i,t+1}^B - H_{i,t+1}^B}{H_{i,t+1}^E}$ and $\beta_t = \frac{1}{1+\tau_t}$. Otherwise, if $E_{it} = 0$, this expression is strictly negative.

The first order condition with respect to the land use α_{ikt} is:

$$\frac{\partial V_t(B_t)}{\partial \alpha_{ikt}} = 0 \Leftrightarrow P_{it} Q_i(B_{it}, E_{it}) + S_{it} - C_i(E_{it}) - C_i(B_{it}) + \beta_t E_t \left[\frac{dV_{t+1}}{dB_{t+1}} \frac{\partial B_{t+1}}{\partial B_t} \frac{\partial B_t}{\partial \alpha_{ikt}} \right] = 0$$

if $\alpha_{ikt} > 0$.

Given the land use rotation condition and equation 8, the optimal land use is determined by the first order condition:

$$P_{it} Q_{it} + S_{it} - C_i(E_{it}) - C_i(B_{it}) + [G_k(B_{t-1}) - H_k(E_{k,t-1}, B_{t-1})] \left(\sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ikt} (G_{it}^B - H_{it}^B) \right)$$

$$\times \beta_t E_t \left\{ \sum_{k=1}^{C_2} \sum_{i=1}^{C_2} \alpha_{ik,t+1} [\alpha_{i.,t+1} (P_{i,t+1} Q_{i,t+1}^B - C_{i,t+1}^B) + \Phi_{i,t+1} (P_{i,t+1} Q_{i,t+1}^E - C_{i,t+1}^E)] \right\} = 0 \qquad (10)$$

if $\alpha_{ikt} > 0$, with $\Phi_{i,t+1} = \frac{G_{i,t+1}^B - H_{i,t+1}^B}{H_{i,t+1}^E}$ and $\beta_t = \frac{1}{1+\tau_t}$.

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