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Mireille Chiroleu-Assouline

Sébastien Roussel

Payments for Carbon Sequestration in Agricultural Soils: Incentives for the Future and Rewards for the Past

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Mireille Chiroleu-Assouline, Paris School of Economics - Université Paris 1 Panthéon-Sorbonne,
Centre d.Economie de la Sorbonne, 106-112 Bd de l.Hôpital, 75647 Paris Cedex 13, France.
E-mail: Mireille.Chiroleu-Assouline@univ-paris1.fr

Sébastien Roussel, Université Montpellier 1, UMR5474 LAMETA, F-34000 Montpellier, France.
E-mail:roussel@lameta.univ-montp1.fr

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Payments for Carbon Sequestration in Agricultural Soils: Incentives for the Future and Rewards for the Past

Mireille Chiroleu-Assouline* Sébastien Roussel‡

Abstract

According to several studies, agricultural carbon sequestration could be a relatively low cost opportunity to mitigate greenhouse gas concentrations. However the potential for storing additional carbon quantities in agricultural soils is critical, and depends on the past behavior of agricultural firms with regards to land heterogeneity. In this paper, we set incentive mechanisms to enhance carbon sequestration as a principal-agent relationship between a regulator and agricultural firms. The potential for additional carbon sequestration is treated as an exhaustible resource, under the assumption that the sequestration costs increase with the amount of carbon already stored. We specify contracts in order to induce truthful revelation by firms regarding the characteristics of their intrinsic behaviour towards carbon sequestration, while analytically characterizing the optimal path to sequestering carbon as an exhaustible resource. Firstly, we take into account the impact of the co-effects on the sequestration path, due to carbon sequestering practices. Secondly, we show that incomplete information slows the sequestration process and increases the unexploited potential of carbon sequestration. Thirdly, our paper provides a sound basis for differentiated per-hectare subsidies, dynamically defined for the entire duration of the contract. A type-dependent participation constraint acknowledges the previous efforts of the farmers who have previously accepted policy to incur some sequestration costs, and this constraint prevents them from deciding to switch back to less sequestering practices. The proposed contract has the advantage of avoiding the inefficiency of per-hectare subsidies, as well as the excess costs of a uniform per-tonne subsidy. In addition, it does not penalize early adopters of practices with more intensive sequestration.

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[*] Corresponding author. Address: Paris School of Economics - Université Paris 1 Panthéon-Sorbonne, Centre d'Economie de la Sorbonne, 106-112 Bd de l'Hôpital, 75647 Paris Cedex 13, France, E-mail: Mireille.Chiroleu-Assouline@univ-paris1.fr

[†] Université Montpellier 3 Paul Valéry

[‡] Université Montpellier 1, UMR5474 LAMETA, F-34000 Montpellier, France. E-mail: roussel@lameta.univ-montp1.fr

1 Introduction

Agricultural carbon sequestration could be a relatively low cost opportunity to mitigate GHG concentrations and a promising means that could be institutionalized (McCarl and Schneider, 2000). While comparing different countries, the position given to carbon sequestration in their strategies to reduce GHG emissions has been very diverse. As stressed by Young *et al.* (2007), the US has not ratified the Kyoto Protocol but has been encouraging the use of agricultural and forestry carbon sequestration, whereas the EU ratified the Protocol as soon as 2002, but without using agricultural soil carbon sequestration in its strategy. Sperow *et al.* (2003) have estimated that agricultural carbon sequestration could account for 40% of the US reduction of GHG emissions needed to reduce US emissions relative to their level in 1990. In Europe, Freibauer *et al.* (2004) has estimated that carbon soil sequestration could have provided 9% of the reductions required in 2005. Schulze *et al.* (2009) show that Europe should consider the development of land management policies which aim at reducing GHG emissions as a priority. Within the preparation of the next European Common Agricultural Policy (CAP) for the period 2014-2020, after almost two years of negotiations between the Commission, the European Parliament and the Council, a political agreement on the reform of the CAP was reached on 26 June 2013 announcing that agri-environmental measures will be stepped up to complement specific greening practices. These programmes will have to set and meet higher environmental protection targets, even though carbon sequestration was not explicitly mentioned. The main objective of our article is therefore to analyse and provide theoretical justification to designing incentive mechanisms to enhance carbon sequestration in agricultural soils.

Additional storage of carbon in agricultural soils can be achieved by the use of new crops or new management practices. According to Feng, Zhao and Kling (2002) (referring to Lal *et al.*, 1998), the potential for carbon sequestration of US cropland through improved management could be set at 75–208 MMTC/year. Significant illustrations of these practices are conservation tillage and mineral fertilization. However, farmers do not switch spontaneously to costly practices that increase social benefits and the adoption rate is likely to be lower than the socially optimal one. They do indeed assess their private costs whilst ignoring the positive externalities of higher sequestration that enhances social benefits. Schneider (2002) states that these costs include adjustment costs, opportunity costs, stickiness, market changes, and environmental and international co-effects. The great heterogeneity that can be observed between countries regarding the use of different management practices is reflected in the heterogeneity of sequestration costs. For instance, Weersink *et al.* (2005) state that the profitability of reduced tillage is not significantly different compared to the profitability of conventional practices, which is consistent with the observed common use of both tillage methods in Canada. Kurkalova, Kling and Zhao (2006) notice that switching to conservation practices does not always imply a monetary sacrifice for farmers; indeed they observe that even without any subsidy, on average more than one third of the US acres are in conservation tillage. Nevertheless, in Europe the practices that have the highest sequestration rates are also the least profitable (Pendell *et al.*, 2007) as is also true in many developing countries, such as in West Africa, according to Gonzalez-Estrada (2008). As a consequence, policymakers usually have to counteract direct costs while inducing sustainable sequestering practices to increase carbon sequestration in soils. To this end, they have the opportunity to offer monetary transfers as subsidies to bring about suitable land management systems. Two kinds of subsidies are mainly available to policymakers: a per-tonne subsidy and a per-hectare or lump-sum subsidy.

According to the soil-science literature, the role of history (past crops and practices) and the nature of agricultural soils do indeed lead to a great spatial heterogeneity about the potential of additional carbon sequestration (Stavins, 1999; Antle *et al.*, 2003) which prevents from implementing standard regulation policies (Pautsch *et al.*, 2001). This heterogeneity involves high monitoring costs if the regulator is concerned about rewarding farmers accordingly to their results. Kurkalova, Kling and Zhao (2004) point out the difficulties encountered by a regulator willing to differentiate payments between farmers in the absence of field-scale measurement technologies. Moreover, one important effect of switches toward more sequestering practices is that they generally bring about other external effects. Plantinga and Wu (2003) point out the important environmental co-benefits provided by an afforestation program in Wisconsin. Nevertheless, there is still an ongoing debate about assessing if the positive externalities are greater than the negative ones. Another view which encompasses this range of issues consists in considering agriculture as a provider of various ecological services (Dale and Polasky, 2007), such as the preservation of landscape that should be paid as Payments for Environmental Services (PES). Even if Elbakidze and McCarl (2007) consider that the valuation of the numerous co-effects from various GHG mitigation activities might prove to be too expensive in order to determine the socially optimal combination of emission mitigation strategies, we follow Antle and Diagana (2003) who insist on the need to consider co-benefits of carbon sequestration.

The question we are looking at may be framed as follows: how can the policymaker induce more carbon sequestration in agricultural land whilst taking into account heterogeneity in potential for additional carbon sequestration? We bear in mind that the regulator cannot observe this heterogeneity among plots of land without prohibitive costs, even in the same region (or even among plots belonging to the same farmer). This asymmetric information with private information on the farmers' side depicts a so-called hidden information or adverse selection setting. Furthermore, picking sequestering practices could imply changes in the use of fertilizers and pesticides and could generate positive or negative externalities such as variations in groundwater pollution. This generates another kind of failure and requires a more sophisticated regulation policy whilst taking into account the positive externality of sequestering carbon as well as the joint co-effects. Asymmetric information indeed prevents a regulator from using first-best economic instruments as long as farmers get information rents. In this paper, we set incentive mechanisms to enhance carbon sequestration as a principal-agent relationship between the regulator and agricultural firms. The originality of our paper is that we build a model on two different streams of the theoretical literature: on the one hand, optimal exploitation of the exhaustible resource represented by the potential of additional carbon sequestration (Dasgupta and Heal, 1974, 1980), and on the other hand, mechanism design (Myerson, 1979; Baron and Myerson, 1982; Baron, 1989; Laffont and Martimort, 2002). Our contribution is to specify differentiated contracts in order to induce truthful revelation by the firms regarding their intrinsic characteristics towards carbon sequestration (following Wu and Babcock (1996) or Canton, De Cara and Jayet (2009)), and to analytically characterize the optimal path to sequester carbon.

Several important results emerge from our theoretical framework. Firstly, we show that even with complete information, it is not always economically rational to exhaust the potential for carbon sequestration and that incomplete information slows the sequestration process and decreases the quantity of carbon stored at the end of the contract (which increases the unexploited potential for carbon sequestration). Secondly, we take into account the further co-benefits or the potential negative externalities due to carbon sequestering practices, and we highlight the need to slow down or to accelerate sequestration, depending on the paramount externality in a given geographical area. Thirdly, our paper provides a sound basis for differentiated dynamic per-hectare subsidies. We introduce a participation type-dependent constraint, in order to acknowledge the previous effort of the farmers who have accepted before policy incurring some sequestration costs, and to prevent them from deciding to switch back to less sequestering practices. Our dynamic setting allows us to show that the subsidy path must be dynamically defined for the entire contract duration and not as a sequence of static independent yearly subsidies. The proposed contract has the advantage of avoiding the inefficiency of the per-hectare subsidy, as well as the excess cost of the uniform per-tonne subsidy; it is defined as a combination of a per-hectare subsidy with an output subsidy. In addition, by taking account of a type-dependent participation constraint, it overcomes the unfairness of the incentive mechanism mentioned by Kurkalova, Kling and Zhao (2004) by not penalizing early adopters of more sequestering practices. After the end of the sequestration process, the contract must entail a non-decreasing subsidy in order to deter any moral hazard and induce conservation.

The remainder of the paper is organized as follows. In Section 2, we describe our assumptions and the model design. In Section 3, we analyse the regulator's objective, and we detail the benchmark case of perfect information while Section 4 considers the environmental externalities caused by the sequestering process. In Section 5 we set out the menu of contracts under asymmetric information. Section 6 concludes and provides a few extensions of our analysis and public policy proposals.

2 The Model

2.1 The crucial role of the potential for additional carbon sequestration

The potential for additional carbon sequestration is at the core of our analysis. It depends on land quality as well as on past and upcoming crops and management practices by agricultural firms. Plots of land (one hectare each) can be of different qualities (McCarl *et al.*, 2000).[1] The heterogeneity among plots of land is therefore twofold: partly observable and partly unobservable (or imperfectly observable and at a cost). Let us define the maximal soil carbon capacity, denoted by M (for *maximal*) of a given plot of land as the maximal amount of carbon that can be sequestered in it. It corresponds to the saturation level reached with the highest sequestration combination of a crop and land management system. The heterogeneity in M is exogenous and observable because it only depends on the land quality.

But even in case of equal quality, the quantity of carbon already sequestered in plots of land can differ, according to the past crops and practices. By carbon sequestration activities in agricultural soils, we refer to changes in land management of cropland, soil restoration and grassland or pasture that can in particular alter the input quantities of organic matter going into the soils. In Table 1, we state these sequestration practices.

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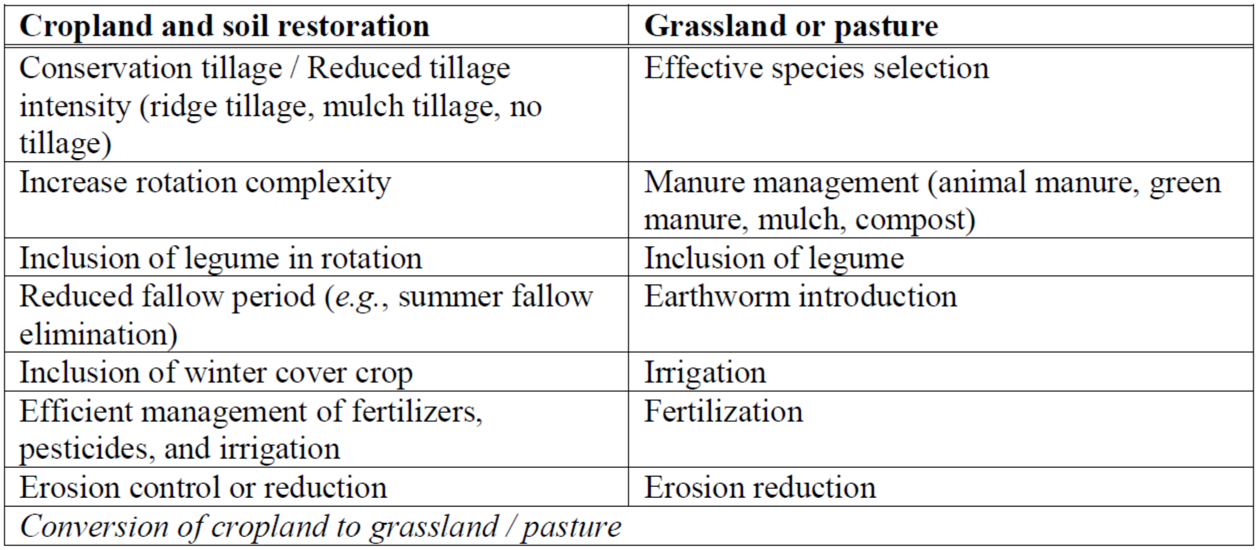
[1] By land quality we mean the natural bio-physical properties of soils.



Cropland and soil restoration	**Grassland or pasture**
Conservation tillage / Reduced tillage intensity (ridge tillage, mulch tillage, no tillage)	Effective species selection
Increase rotation complexity	Manure management (animal manure, green manure, mulch, compost)
Inclusion of legume in rotation	Inclusion of legume
Reduced fallow period (*e.g.*, summer fallow elimination)	Earthworm introduction
Inclusion of winter cover crop	Irrigation
Efficient management of fertilizers, pesticides, and irrigation	Fertilization
Erosion control or reduction	Erosion reduction
Conversion of cropland to grassland / pasture	

Table 1. Land management categories in agriculture and their corresponding practices which can increase carbon sequestration
(Adapted from West *et al.* (2004) citing Paustian, Collins and Paul (1997), West and Post (2002), Conant, Paustian and Elliott (2001), and from Post *et al.* (2004))

Let us now define for any plot of land, its potential for additional carbon sequestration, denoted by A (for *additional*), as the difference between its maximum soil carbon capacity M and the amount of carbon already sequestered at time T_0 of the policy's implementation. The unobservable heterogeneity between two plots of land due to the dynamics of carbon sequestration is illustrated by the following figure (Figure 1), according to most empirical studies (INRA, 2002) which demonstrate that the sequestration process is essentially non-linear. After a move toward more sequestration management practices, carbon sequestration increases rapidly, then slows down to reach a maximum level depending on the nature of the soil, the crops and on the practices themselves. Studies show that it is not possible to sequester an infinite quantity of carbon on a given plot of land. The adoption of particular practices for a given crop enables a finite quantity of carbon to be sequestered, which is the saturation level for carbon sequestration associated with these crop and practices.

The time over which sequestration is effective refers to the duration of sequestration, while reaching this maximal soil carbon capacity that refers to carbon or soil saturation (West and Six, 2007). [2] In case of any move back to less sequestering practices, carbon release is even faster

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[2] West and Six (2007) distinguish sequestration flow duration and sequestration stock duration. Flow duration is the time period with active sequestration (with annual changes), whereas stock duration is the time period following this active sequestration; stock duration allows the previously-sequestered carbon to remain effectively sequestered. The stock duration, also called passive sequestration, is a steady state and is different from sequestration saturation as changes in management practices can once more provide new flow and stock durations with a new steady state (closer to the saturation level when soil carbon can no longer increase regardless of changes in production inputs or management).

than was carbon sequestration. Taking these specific dynamics into account, Ragot and Schubert (2008) show that the only optimal policy is to encourage permanent carbon storage as far as future carbon prices do not decrease. We will consider this point explicitly later.

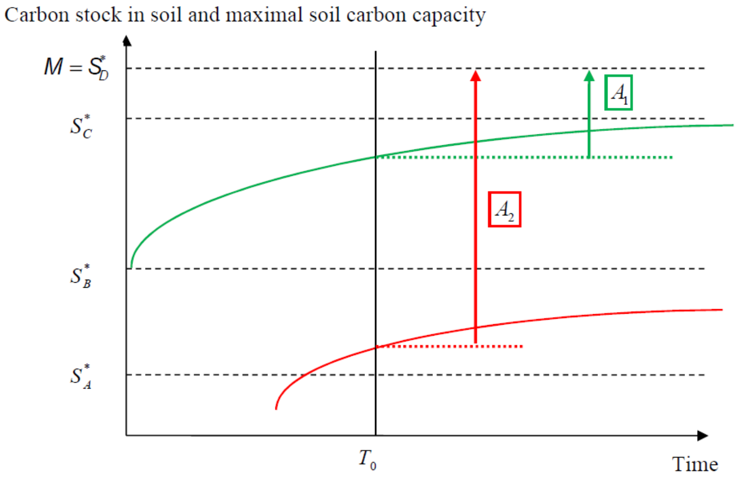

Figure 1: Carbon stock in soil, potential for additional carbon sequestration and maximal soil carbon capacity

To illustrate the mechanism, let us assume that there are four kinds of practices or crops (A, B, C, D), each of them allowing a maximum potential $S_A^* < S_B^* < S_C^* < S_D^*$ to be sequestered (Figure 1). Under the assumption that the maximal soil carbon capacity M is the same (reachable only with practice D, i.e. $S_D^* = M$) for two plots of land, suppose that more sequestering practices had been adopted on plot 1 sooner than on plot 2. On plot 1, the farmer decides to switch from practice B to practice C and engages on a new dynamics of sequestration from S_B^* to S_C^*. On plot 2, the decision is taken later to switch from practice A to practice B and then to sequester carbon progressively until S_B^*. At the date T_0 of implementation of the policy, the potential for additional carbon sequestration of plot 1 (A_1) is less than the potential for additional carbon sequestration of plot 2 (A_2).

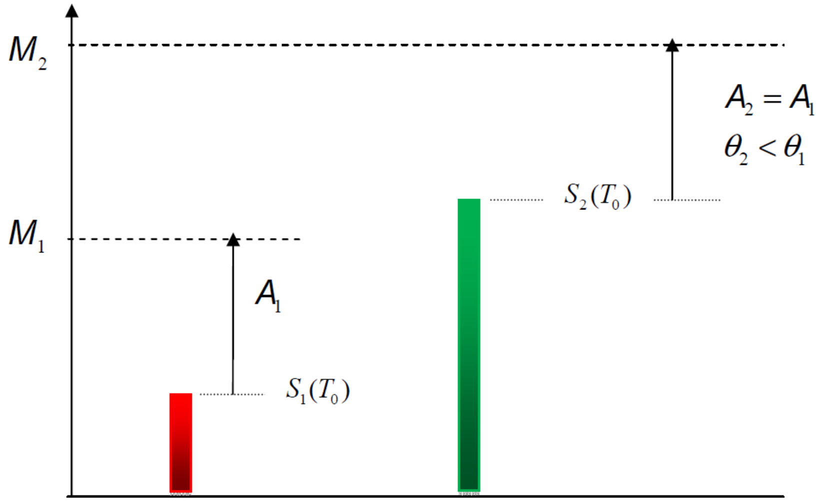

Figure 2: Carbon stock in soil and potential for additional carbon sequestration for different maximal soil carbon capacities

Given the available practices and crops, any plot of land can be entirely characterised by its observable maximal soil carbon capacity M, that depends on its soil nature and its location and - more specifically, by its unobservable potential for additional carbon sequestration A depending on its history of crops and practices. This history is generally not known by the regulator at the beginning of the contract (in most countries farms are not required to document land use history). Two plots of land with different M could be characterized by the same A depending, on their crop history, as shown by Figure 2. But the proportion of the maximal soil carbon capacity that has already been exploited is both a measure of the effort previously done and, because sequestration becomes more difficult and costly when reaching the maximal capacity, a measure of the future efficiency in sequestering. From now on, we denote θ the ratio A/M: the higher θ and the less sequestering in the past together with the more efficiency in the future.

By relying on this statement, we assume that the economy is composed by a continuum of competitive agricultural firms characterized, at the date of implementation of the policy, by their observable land's quality, featured by their maximal soil carbon capacity M and by their potential for additional carbon sequestration, A, or equivalently by their future sequestering efficiency that is the firm's type θ determined by their crop and practices history. We assume that, for any given M, the real type of the firm is distributed according to θ in a continuous manner such that $\theta \in \left[\underline{\theta}, \overline{\theta}\right]$. $\underline{\theta}$ therefore accounts for the firm with the lowest additional potential for carbon sequestration (more sequestering in the past but the least efficient type for the future) while $\overline{\theta}$ accounts for the firm with the highest potential for additional carbon sequestration (the most efficient type). θ is the unobservable intrinsic characteristic of the plot of land and $f(\theta)$ represents the probability density function on $\left[\underline{\theta}, \overline{\theta}\right]$; $F(\theta)$ is the cumulative distribution function of the firms' types, which is assumed to be known by the policymaker. The following assumption accounts for monotone hazard rate and inverse hazard rate properties.

$H1 : \dfrac{d}{d\theta}(\dfrac{F(\theta)}{f(\theta)}) \geq 0$ non-decreasing (resp. non-increasing) in θ (or equivalently $\dfrac{d}{d\theta}(\dfrac{1-F(\theta)}{f(\theta)}) \leq 0$).

As far as the potential for additional carbon sequestration can be considered as an imperfectly known stock of a valuable resource, i.e. possible carbon sequestration, the regulator's objective can be treated as an optimal resource extraction problem with adverse selection, similar to Gaudet, Lasserre and Long (1995), Osmundsen (1998), Hung, Poudou and Thomas (2006) or Poudou and Thomas (2000).

2.2 Heterogeneity and subsidies

In order to infer changes in management practices by the agricultural firms, public authorities have to subsidize them to cover induced costs and create incentives. Regarding the subsidies, Antle *et al.* (2003) emphasize that the heterogeneity across plots of lands in terms of sequestration potential implies that per-hectare subsidies should be individualized to reflect this heterogeneity. Kurkalova, Kling and Zhao (2004) highlight the difficulties associated with payments differentiation. Instead of measuring the annual amount of carbon accumulated in each plot of land, one could work to observe the practices employed by the farmer and to estimate the level of the accumulated carbon stock. But in fact, this process would imply quite high monitoring costs too (for example, if the nature of the crops can be monitored with observation satellites, but more usually with on-field inspection) meaning the practices cannot be easily controlled. The same paper examines the related problem of the per-tonne basis for incentive payments. Either the payment is based on the total amount of carbon sequestered in the soil, or the payment rewards carbon stored above an initial baseline, that might be the level of carbon contained in the soil at the beginning of the program, and then early adopters of more sequestering practices would be penalised.

Since monitoring costs are high, a per-hectare subsidy could only be based on average sequestration rates and it could therefore be less efficient than a per-tonne subsidy. However, on-site monitoring costs of the sequestered carbon are high as well, and technical constraints generally prevent the implementation of per-tonne subsidies. Even if the ranking between the two kinds of subsidy depends on the gap between losses of efficiency (per-hectare) and monitoring costs (per-tonne), the choice currently favours per-hectare subsidies. Other instruments are rarely considered, except Pendell *et al.* (2007) who study the incentives to adopt conservation practices provided by marketable carbon credits. The implementation of carbon credits probably raises the same issue about monitoring costs of the effective amount of carbon sequestered. However, Mooney *et al.* (2004) evaluate these costs for the small-grain producing region of Montana and confirm that the costs of measuring and monitoring are greater in the most heterogeneous areas; their amount compared to the value of carbon credit depends crucially on the price of carbon credits. Antle and Diagana (2003) see the main incentive to sequester carbon in the carbon price established by the environmental regulations implied by the Kyoto Protocol and the rising concern about climate change. For their part, Wu and Babcock (1996) develop a payment scheme that overcomes the information asymmetry between farmers and a policymaker and accounts for the deadweight losses of distortionary taxes in the case of an "environmental stewardship" program, whereby farmers receive direct payments for the services they provide.

Instead of any per-hectare or per-tonne subsidies, we propose to define contracts or subsidies depending *ex post* both on the observable land quality that determines the maximal soil carbon capacity M and on the potential for additional carbon sequestration A, in order to take into account the unobservable heterogeneity of the plots of land. We focus on voluntary adoption of sequestering practices promoted by a stewardship contract, relying on Wu and Babcock (1999), who show that voluntary programs can be more efficient than mandatory programs in agriculture when the marginal cost of public funds is zero or small, and if the number of firms involved is large. With incomplete information, the policymaker proposes contracts to farmers in order to induce them to adopt sequestering practices whilst revealing their efficiency level (type), *i.e.*, their knowledge / characteristics towards their private information. We assume that the contract is signed at the beginning of the first period with full commitment between the policymaker (so-called the principal) and the farmers (so-called the agents).

Regarding the time duration of the contract, in our framework, we consider that it entails two stages: the first stage would account for the carbon sequestration process stage while the second stage would represent the stationary carbon level stage.[3] As already shown by Ragot and Schubert (2008) in a different framework, it is never optimal to stop sequestering carbon, since the carbon released into the atmosphere is actually done so more quickly than during the sequestration stage, and the regulator must keep on providing a subsidy to the agricultural firm even if the firm has reached its maximal soil carbon capacity. This subsidy is similar to a maintenance cost as mentioned by Kim, McCarl and Murray (2008). It prevents the firm from going back to practices that sequester less carbon in the second stage.[4] Under the assumption that a maintenance cost will

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[3] This is the stage when the upper bound in carbon sequestration has been reached.

[4] If the carbon value falls under the cost of sequestration, the optimal policy could be different, as it is shown by Ragot and Schubert (2008) who take into account the heterogeneity of land and the dynamics of carbon sequestration and carbon release in a macroeconomic model.

be paid to the farms after the end of the sequestration contract, we acknowledge this permanence issue without explicitly taking it into account in the design of the contract. We will show in the following that it is not always optimal to sequester carbon until the maximal soil carbon capacity and that incomplete information impacts both the sequestration process and its extent.

2.3 The cost function of agricultural firms

On the agricultural firm's side during period t, crops and practices enable carbon sequestration flows denoted by q_t, whereas the accumulated carbon stock during the contract is set as S_t. In our stylized model, firms are assumed to choose their carbon sequestration flows q_t while in fact they minimize their exploitation costs by choosing practices and crops that imply carbon sequestration flows.[5] As the firm is characterized by the ratio θ of its potential for additional carbon sequestration A to its maximal soil carbon capacity M, $C(y_t(\theta), q_t(\theta), s_t(\theta)/M)$ are exploitation costs for an individual firm that result from the firm's aggregated output $y_t(\theta)$, the carbon sequestration flow $q_t(\theta)$, and its remaining gap up to full carbon sequestration $s_t(\theta)$ which is defined as the gap, at time t, between the potential for additional carbon sequestration in this plot of land and the accumulated carbon stock $S_t(\theta)$ from the policy implementation date $T_0 = 0$. This gap can be formally written as $s_t(\theta) = A(\theta) - S_t(\theta)$. Let us recall that $A(\theta) = \theta M$ is given at the beginning of the programm but that $S_t(\theta)$ and consequently $s_t(\theta)$ are endogenous variables. Even if the choice variables will be shown to depend on the firm's type, from now on, we will simplify the notations unless the details become necessary. Our cost function modelling can be explained as follows. It is assumed that the less the crops and the practices were previously sequestering, the less costly it is to switch to better practices (Antle *et al.*, 2002). As a result, the total cost depends negatively on θ because it increases when the remaining gap to full carbon sequestration decreases. Our cost function is thus basically defined in order to capture heterogeneity. Even if farms would likely not use the same technique but a combination of techniques to get to M, we assume here that all farms have essentially the same choice of activities and so that the core variable is the gap to M, which is heterogeneous. To be consistent with the physical sequestration process and the saturation issue illustrated in Figure 1, our cost function exhibits exploitation costs depending on the remaining gap up to full carbon sequestration for each firm s_t normalized by the maximum soil carbon capacity M.[6] We may notice that this cost dependency on the accumulated stock does

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[5] The only convenient assumption here is that q_t is assumed to be continuous, instead of discrete. Instead of a sequential choice of different sequestration practices, our model is more appropriate in representing the farms' decision of increasing the percentage of their land under conservation tillage or other activities.

[6] Like Osmunden (1998), we model the inter-period link arising from the "resource" constraint by using a reserve-based cost function.

raise an asymptotic cost growth (Levhari and Liviatan, 1977). As a result, and as an indirect effect, the cost decreases when the maximum soil carbon capacity M increases, for any given θ.

The cost function $C(y_t, q_t, s_t/M)$ is therefore defined by the following assumptions (where C_i stands for the marginal cost of variable i and $C_{ij} = \partial^2 C/\partial i \partial j$):

- $H2 : C_1 = C_y \geq 0, C_{yy} \geq 0$, convexity in the output y_t;
- $H3 : C_2 = C_q \geq 0, C_{qq} \geq 0$, convexity in the carbon sequestration flow q_t;
- $H4 : C_3 \leq 0$, and $C_{33} \geq 0$; this assumption encompasses the following ones: $C_s = C_3/M \leq 0$; $C_S = -C_3/M \geq 0$; $C_{ss} = C_{33}/M^2 \geq 0$ and $C_{sM} = -C_3/M^2 \geq 0$; moreover $C_\theta = C_3 \leq 0$ i.e. the lower θ is (for a given M), the higher the costs for sequestering practices in the future; and $C_{\theta\theta} \geq 0$; $C_M = SC_3/M^2 \leq 0$ i.e. the lower M is (for a given θ), the higher the costs for sequestering practices in the future, and $C_{MM} = -2SC_3/M^2 \geq 0$
- $H5 : C_{yq} \geq 0$, increasing in both arguments, and $C_{qs} \leq 0$ (equivalently $C_{qS} \geq 0$ and $C_{q\theta} \leq 0$).
- $H6 : C_{ys} = 0$ ($C_{y\theta} = 0$); for simplicity and because there is no clear evidence about a carbon stock effect on the marginal cost of output,[7] we assume that the cost function is separable in y and s, that leads to simplifying the different marginal costs as $C_y(y_t, q_t)$ and $C_s(q_t, s_t/M)$.
- $H7 : C_{qq}(y_t, q_t, s_t/M)C_{yy}(y_t, q_t) - (C_{yq}(y_t, q_t))^2 < 0$ which ensures the Hessian of the cost function is negative definite (for a given level of the remaining gap up to full carbon sequestration).

As mentioned by Osmundsen (1998), the convexity of the single period cost (Assumption *H3*) makes it profitable to spread sequestration over the following periods. The asymptotic costs assumption implies, in our setting also, an interior solution (a non-binding constraint).

2.4 The regulator's objective

As agriculturally sustainable practices raise the quantities of carbon in soils, the accumulated carbon stock in the atmosphere decreases, which raises welfare in the economy. The representative consumer surplus (V) depends on the agricultural output flow y_t and on the amount of carbon stock stored $S_t = \theta M - s_t$ through the avoided damage due to climate change. V is assumed to be

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[7] Gulati and Vercammen (2005) assume that the level of carbon stored in the soil increases the soil's productivity. We consider that this effect is likely to be a second-order effect relative to the negative effect induced by the change in practices and that it can be neglected. If not, there would be no use to contract with the farmer in order to induce him to choose sequestering practices.

separable. We should actually consider that the consumer surplus decreases with the total carbon stock released in the atmosphere $\Sigma = \Sigma_0 - S_t$ where Σ_0 stands for the carbon stock released by the world economy net of sequestration elsewhere (by other farmers, or in forestry, for example). We consider from now on that the government contracts independently with each agricultural firm without taking into account the endogeneity of Σ_0 (that is why we simply assume that the consumer's utility increases with $M - s_t$) but it is worth noting that the marginal utility of the carbon sequestered by the regulated firm is all the lower as Σ_0 is higher.

The regulator seeks to maximize an expected social welfare function W that can then be defined as the discounted sum of the current expected welfare W_t assumed to be the sum of the current consumer expected surplus (EV_t) and the expectancy, according to its type, of the current profits of the agricultural firm $E\Pi_t = \int_{\underline{\theta}}^{\overline{\theta}} \pi(y_t, q_t, s_t, M) f(\theta) d\theta$, that is $EW_t = EV_t + E\Pi_t$. The relationship between the regulator and the agricultural firm can be described as the following game: (1) the regulator offers a contract that specifies a trajectory of monetary transfers $\Lambda_t(\theta)$ and of sequestration flows $q_t(\theta)$, or equivalently of outputs $y_t(\theta)$ during the contract length T exogenously chosen by the government for all firms; (2) the firm accepts the contract and it announces its type θ, or it declines the contract; (3) the government pays $\Lambda_0(\theta)$ and commits to pay $\Lambda_t(\theta)$ during the contract length T, and the sequestration takes place.

Let us assume perfect competition summarized by the exogenous market price p_t of the aggregated agricultural commodity (common to all farms). If $\Lambda_t(\theta)$ is the monetary transfer given during period t by the regulator to the firm to infer carbon sequestration in its plots of lands, the farmer's current profit is $\pi(y_t, q_t, s_t) = p_t y_t - C(y_t, q_t, s_t/M) + \Lambda_t(\theta)$. And because this transfer has to be financed through a distortionary tax policy, λ denotes the marginal cost of public funds or the opportunity cost of the regulation. The current expected welfare EW_t writes then (see the proof in Appendix 7.1):

$$\begin{aligned} EW_t &= \int_{\underline{\theta}}^{\overline{\theta}} U(y_t, \theta M - s_t) f(\theta) d\theta \\ &\quad + \int_{\underline{\theta}}^{\overline{\theta}} \left[\lambda p_t y_t - \lambda \pi(y_t, q_t, s_t, M) - (1+\lambda) C(y_t, q_t, s_t/M)\right] f(\theta) d\theta \qquad (1) \\ \text{with} \quad U_1 &\geq 0,\ U_{11} \leq 0 \text{ and } U_2 \geq 0,\ U_{22} \leq 0 \text{ and } U_{12} = U_{21} = 0 \end{aligned}$$

In the following section, we consider successively the complete information case, as a benchmark, and the incomplete information case to show how the regulatory policy is altered.

3 The Complete Information Case

With complete information, each agricultural firm's potential for additional carbon sequestration denoted by $A = \theta M$ is perfectly known by the regulator whose problem of maximizing social welfare is:

$$\begin{aligned}\max_{y_t, q_t} W \quad \Leftrightarrow \quad \max_{y_t, q_t} & \int_0^T U(y_t, \theta M - s_t) e^{-\rho t} dt \\ & + \int_0^T \left[\lambda p_t y_t - \lambda \pi(y_t, q_t, s_t, M) - (1+\lambda) C(y_t, q_t, s_t/M)\right] e^{-\rho t} dt\end{aligned}$$

$$st \begin{cases} \pi(y_t, q_t, s_t, M) \geq \Pi_t(\theta) \\ \dot{s}_t = -q_t \\ s_t \geq 0 \\ s_0 = A = \theta M, \mu_0 \end{cases}$$

where $\pi(y_t, q_t, s_t, M) \geq \Pi_t(\theta)$ is the type-dependent participation constraint[8]. μ_t is the value of the costate variable at date t. s_0 is the initial value following the implementation of the public policy and equals θM. μ_0 is the initial value of the costate variable associated with the sequestration process. The transversality condition is given by $\mu_T s_T = 0$.

Because farmers may have accepted before the policy to incur some sequestration costs, they will not be happy by accepting a contract that would not acknowledge their previous effort and they could decide to switch back to less sequestering practices if they don't sign the contract. Their participation constraint is thus type-dependent (Jullien, 2000): a low θ comes from a high previous sequestering effort that the firm wants to monetize. $\Pi_t(\theta)$ decreases when θ increases: $\Pi'_t(\theta) = \partial \Pi_t(\theta)/\partial \theta < 0$. This amount stands for the opportunity cost for not releasing all the carbon already sequestered before the policy implementation.[9] By assumption, $\Pi_t(\overline{\theta}) = 0$. Obviously, the participation constraint is binding for all firms: $\pi(y_t, q_t, s_t, M) = \Pi_t(\theta)$ because any extra-profit given to a firm would increase the policy's costs without any efficiency gain.

The assumption of convexity of $C(y_t, q_t, s_t/M)$ in (q_t, S_t), where $S_t = \theta M - s_t$, ensures the existence of an optimum (Farzin, 1992).

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[8] Instead of assuming a non-myopic participation constraint such that $\int_0^\infty \pi(y_t, q_t, s_t, M) e^{-\rho t} dt \geq \Pi(\theta)$ that could be simplified into $\pi(y_0, q_0, s_0, M) \geq \Pi(\theta)$ and $\pi(y_t, q_t, s_t, M) \geq 0$ for $t > 0$, we prefer to assume that the regulator complies to this slightly more restrictive condition. This assumption does not entail any significant qualitative difference in the firm's behavior, but it is empirically more realistic, since it clearly avoids any temptation for the firm to deviate at any time and it is also more compatible with the yearly basis of the regulator's decision about the financing of its current budget.

[9] In our setting, we have assumed that carbon sequestration does not produce any private benefits to the farmer. If not, in order to avoid paying farms for profitable activities already taken (and because they would not choose to reverse sequestration anyway, even without a payment), we should restrict the payment for past action only on accumulated carbon, beyond what the farmer finds unilaterally to be profitable.

When the agricultural firm actually sequesters carbon ($q_t > 0$), the first-order necessary conditions are (see the proof in Appendix 7.2):

$$
\begin{aligned}
p_t &= C_y(y_t, q_t) && (2)\\
\mu_t &= (1+\lambda) C_q(y_t, q_t, s_t/M) && (3)\\
\rho\mu_t &= \dot{\mu}_t + U_2(\theta M - s_t) + \frac{(1+\lambda)}{M} C_s(q_t, s_t/M) && (4)
\end{aligned}
$$

The firm produces the output of perfect competition which equals the market price of its marginal cost (2). As $C_{yq} \geq 0$, any effort of carbon sequestration increases the marginal cost of output. That means that, by choosing some more sequestering practices or crops, the firm must sacrifice some output.

The shadow price of carbon sequestration μ_t is equal to the marginal static cost of sequestration, adjusted by the marginal cost of public funds (3).

The last equation stands for a Hotelling rule regarding the exploitation of the exhaustible resource which is the potential for additional carbon sequestration, $A = \theta M$. It features a cost-benefit analysis which can be explained such that: $\rho\mu_t$ accounts for the marginal cost when the agricultural firm does not sequester at the current time period (with the discount rate ρ). In other words, this is the marginal cost when the agricultural firm does not extract the resource in carbon sequestration, and this is the cost when the flow q_t does not take place. $\dot{\mu}_t$ is the marginal benefit when the firm does not sequester (does not extract the resource in carbon sequestration) at the current time period; the gap up to full carbon sequestration is therefore not reduced for the future. $U_2(M - s_t)$ is the marginal utility of the representative consumer when the accumulated carbon stock S_t increases (respectively when the remaining gap up to full carbon sequestration s_t is reduced); this stands for the avoided damage due to carbon sequestration. $-C_s(q_t, s_t/M)$ accounts for the marginal cost when the agricultural firm increases the accumulated carbon stock S_t (respectively decreases the remaining gap up to full carbon sequestration s_t). This last equation can also be written as:

$$
\dot{\mu}_t = \rho\mu_t - U_2(\theta M - s_t) - \frac{(1+\lambda)}{M} C_s(q_t, s_t/M) \qquad (5)
$$

The shadow cost of carbon sequestration increases at a non-constant rate that is likely to be higher than ρ because $C_s < 0$ and $U_2 > 0$ is likely to be a second-order term relative to C_s (because of the relative weight of the global carbon stock in the atmosphere). As $U_{22} \leq 0$ and $C_{ss} \geq 0$, along the sequestration path, S_t is non-decreasing (resp. s_t is non-increasing), the gap between the growth rate of the shadow value and ρ decreases unambiguously along the sequestration stage (where s decreases): $\partial\left(\dot{\mu}_t - \rho\mu_t\right)/\partial s = U_{22} - \frac{(1+\lambda)}{M^2} C_{ss} \leq 0$. Because of the separability assumption of the cost function (Assumption $H6$)), this growth rate does not depend on the level of output.

Moreover, at $T_0 = 0$, $s_0 = \theta M$ and $\partial\left(\dot{\mu}_0 - \rho\mu_0\right)/\partial\theta = 0$, the shadow cost growth does not depend on θ.

A crucial point is that the observable maximal soil carbon capacity M also matters: for any given θ, the higher M and the lower the marginal utility of an additional unit of carbon added to the sequestered flow; the shadow cost growth is the lowest for the highest M as $\partial\left(\dot{\mu}_t - \rho\mu_t\right)/\partial M = -U_{22} + \frac{(1+\lambda)}{M^2}C_s - \frac{(1+\lambda)}{M^2}C_{ss} \leq 0$.

Under Assumption $H5$, the Spence-Mirlees condition or static single-crossing property (Salanié, 2005) is verified and under Assumption $H4$ ($C_{ss} \geq 0$), the dynamic single-crossing condition is also verified. This ensures that the iso-profit curves of the agricultural firms cross only once in (Λ, q) or equivalently in (Λ, y). It implies that $\partial q_t/\partial\theta \geq 0$ *i.e.* the sequestration effort required from a plot of land increases with its sequestration potential θM.

One can show that, depending on the relative values of the first and second derivatives, the growth rate of the sequestration flow $\dot{q}_t/q_t$ could be either positive or negative (see the proof in Appendix 7.2.1). Moreover, since s_t does not increase during the contract, because of the sequestration process, the growth rate of the sequestration flow decreases. At any date t, $\dot{q}_t(\theta)$ increases with θ, according to the intuition: the highest θ (the lowest sequestration effort before the contract), and the highest the growth of the sequestration flow.

Since the sequestration cost is asymptotic, it may be optimal for the firm not to exhaust its whole maximal soil carbon capacity (as well as for any exhaustible resource with stock dependent exploitation cost, as in Gaudet, Lasserre and Long (1995) or Poudou and Thomas (2000)). At some endogenous date $T(\theta)$, the sequestration flow is equal to zero. From this date on, the remaining gap up to full carbon sequestration remains constant, $s_t(\theta) = s_{T(\theta)} \quad \forall t \geq T(\theta)$ (under the assumption that the appropriate payment is offered to prevent the firm from releasing back the sequestered carbon stock). Because of the discounting, there is no incentive for the farmer to stop sequestering carbon before the end of the contract and $T(\theta) \geq T \quad \forall\theta$. At the end of the contract, the maximal soil carbon capacity M is not exhausted because the sequestration is no more profitable ($s_T > 0$). The necessary condition to determine this level of unexploited resource $s_T(\theta)$ is given by the transversality condition $\mu_T = 0$ and:

$$s_T(\theta) = s_0(\theta) - \int_0^T q_t(\theta)dt = \theta M - S_T(\theta)$$

Since $q_t(\theta)$ increases with θ ($\forall t$), it follows that $S_T(\theta)$ increases with θ, but because the potential for additional carbon sequestration at the beginning of the contract also increases with θ, $s_T(\theta)$ might decrease or increase with θ. We can show however that there is an absolute economic limit to the remaining unexploited carbon potential, denoted by ΘM and that if some plots with an initial low potential may reach it, for others, the remaining unexploited potential is higher than ΘM and increases with θ(proof in Appendix 7.2.2). The intuition behind this result is that, for farms with an already high level of sequestration effort before the contract, it will be too costly to try to store additional carbon in the soil, because of the depletion effect of the 'resource' represented by the maximal soil carbon capacity.

Because of the intertemporal link between sequestration costs due to the depletion effect, the sequestration flows for all periods must be set simultaneously at the implementation date and the subsidy path must be dynamically defined for the entire contract duration and not as a sequence of static independent yearly subsidies.

As a result, we get the following Proposition:

Proposition 1 *With complete information, the potential for additional carbon sequestration is similar to an exhaustible resource and the carbon sequestration process occurs following the optimal path defined by this Hotelling rule with trade-offs:* (i) *for a given* M*, the growth rate of the sequestration flow increases with* θ*;* (ii) *for a given* θ*, the growth rate of the sequestration flow increases with* M*;* (iii) *there exists a threshold* $\hat{\theta} \geq \underline{\theta}$ *such that for* $\underline{\theta} \leq \theta \leq \hat{\theta}$, $s_T(\theta) = \Theta M$ *with* $\Theta < \underline{\theta}$*, and for* $\hat{\theta} < \theta < \bar{\theta}$*, the remaining unexploited potential increases with* θ*.*

4 The Environmental Co-Effects of Carbon Sequestration Activities

Management practices such as reduced tillage or adoption of no-tillage are shown to decrease soil erosion, which in turn can reduce nutrient pollution of groundwater, but negative environmental externalities can also result from increased use of pesticides (Schneider, 2002). Many studies, like Weersink *et al.* (2005), consider that reduced tillage can allow reduced use of nitrogen and phosphate fertilizers, but according to Wu and Babcock (1998) no clear evidence can be found of a link between the adoption of no-tillage and the use of nitrogen fertilizer and even less evidence of reduction in phosphate use. This is an important issue because nitrous oxide emissions are due to fertilizer-induced emissions from the soil and to indirect emissions from nitrous fractions of fertilizers that were translocated by leaching or volatilization and then emitted as N_2O. The physical process of nitrous pollutants is very complex and subject to many uncertainties (depending on weather conditions and soil erosion, the emission coefficients can double). Moreover nitrous oxide is one of the most powerful GHG, with a radient coefficient 310 greater than CO_2. As a matter of fact, Schulze *et al.* (2009) stress that current methane emissions from feedstock and nitrous oxide emissions from arable agriculture are fully compensated in Europe by the carbon dioxide sink provided by forests and grasslands. As a result, the balance for all GHG across Europe's terrestrial biosphere is near neutral, despite carbon sequestration in forests and grasslands. And if the trend towards more intensive agriculture is not reversed, Europe's land surface may become a significant source of GHG. We can therefore consider carbon sequestration as a part of the more general issue of land management, that has been extensively discussed, even if all the characteristics of carbon sequestration have not been taken into consideration.

To take this effect into account, we assume that the production process of the agricultural firms causes different environmental externalities, like polluting emissions. Decisions about the level of agricultural output, the amount of carbon sequestered and the amount of pollution emitted are closely linked and can hardly be considered as separate decisions. When a farmer sets a crop, a level of output and a carbon sequestration target, she faces a few possibilities about the volume of fertilizers and the conservation practices to use.[10] The environmental impacts are then only co-effects of agricultural output y_t and of carbon sequestration q_t. By assumption, they are composed of two separable components: the first one standing for environmental effects that have mainly accumulation effects as soil erosion and which depend more on the sequestering practices than on the output level; the second one standing for the pollution flows as nutrient leaching due to the use of fertilizers to increase output while adopting more sequestering practices that are also less productive. According to Post *et al.* (2004), environmental co-effects are difficult to assess, and they should be inventoried if they cannot be integrated in cost estimates. To keep the model simple and tractable, we suppose that the stock-effect component is strictly proportional to the quantity of stored carbon at each period of time $H_t = \varepsilon S_t = \varepsilon \left(M - s_t \right)$ (with $\varepsilon \geq 0$), keeping in mind the fact that the stock of this environmental externality is actually proportional to the total sequestered carbon stock $\Sigma - \left(1 - \theta \right) M + S_t$ and then, with our notations, implicitly on the otherwise stored carbon. And we suppose that the flow-effect environmental externality e_t may depend both on the level of output and the quantity of sequestered carbon via the conservation practices $e_t = e(y_t, q_t)$ with $e_y = \partial e / \partial y \geq 0$ and $e_q = \partial e / \partial q \lesseqgtr 0$. [11].

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[10] Allowing more flexibility of choice would imply assuming that the farmer also decides about her level of polluting emissions and that she faces a cost function that decreases with pollution. The final results of the paper would be analytically different but their meaning would be unchanged.

[11] These assumptions allow both dealing with a rather simple model but also revealing the different effects at stake. Refining these assumptions (*e.g.*, by assuming more general functional forms and independent externality stocks with a sole dynamic) would impose a far greater analytical complexity without providing dramatically different results.

For example, $e_y > 0$ and $e_q > 0$ if the farmer decides to use more fertilizers to compensate the negative effect of the sequestering practices on output. But the case of reduced tillage which increases soil water-holding capacity and reduces the need for irrigation water would be acknowledged through $e_y = 0$ and $e_q < 0$.

To keep our model as general as possible, in the absence of evidence about the sign of the external effects, we will discuss further the consequences of both the overall negative and positive externalities.[12] Taking these externalities into account yields the following social welfare function, where the representative consumer surplus V_t depends not only on the agricultural output flow y_t and on the total stored carbon stock $M - s_t$ but also on the total environmental externalities, *i.e.*, the stock $H_t = \varepsilon S_t = \varepsilon\left(s_t\right)$ and the flows e_t at each period of time:

$$\begin{aligned}
\max_{y_t(\theta),q_t(\theta)} EW &\Leftrightarrow \max_{y_t(\theta),q_t(\theta)} \int_0^T U(y_t, M - s_t, , e_t, H_t)e^{-\rho t}dt \qquad (6)\\
&\quad + \int_0^T \left[\lambda p_t y_t - \lambda\pi(y_t, q_t, s_t/M) - (1+\lambda)C(y_t, q_t, s_t/M)\right] e^{-\rho t}dt \\
\text{with} \quad U_1 &\geq 0,\, U_{11} \leq 0 \text{ and } U_2 \geq 0,\, U_{22} \leq 0\ ,\, U_E \leq 0 \text{ (or } U_E \geq 0),\, U_H \geq 0 \text{ (or } U_H \leq 0) \\
\text{and} \quad U_{ij} &= 0 \quad \forall i \neq j \text{ (separability assumption of the utility function)} \qquad (7)
\end{aligned}$$

and the corresponding first order conditions, under perfect information:

$$\begin{aligned}
p_t &= C_y(y_t, q_t) - \frac{U_E e_y}{(1+\lambda)} \qquad (8)\\
\mu_t &= (1+\lambda)C_q(y_t, q_t, s_t/M) - U_E e_q \qquad (9)\\
\dot{\mu}_t &= \rho\mu_t - U_2(M - s_t) - \varepsilon U_H - \frac{(1+\lambda)}{M}C_s(q_t, s_t/M) \qquad (10)
\end{aligned}$$

Even in this case of perfect information, the firm does not produce the output of perfect competition which equalises the market price to its marginal cost (equation 8): at the optimum, the output price is greater than its marginal cost C_y if $U_E < 0$ and $e_y > 0$ (8). The plot of land has to produce less in case of negative externality due to the pollution flow caused by the fertilizers used to enhance productivity.

The optimal amount of polluting emissions is indirectly set in (8) and (9) because the regulator takes into account the positive and negative environmental externalities when deciding respectively on the levels of output and carbon sequestration flows: the shadow price of carbon sequestration μ_t is greater than the marginal cost of sequestration (9). Since the regulator takes into account the damage due to the induced pollution, the optimal level of emissions is lower than it would have been in the decentralized equilibrium.

In (10), U is a concave function with a decreasing marginal utility towards the accumulated carbon stock S ($U_S \geq 0, U_{SS} \leq 0$). Intuitively, the two components of the environmental externalities of carbon sequestration might play in opposite directions on the dynamics of carbon sequestration: with $U_E \leq 0$, the flow effect increases the shadow price and, with $U_H \geq 0$, the stock effect increases

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[12] Regarding the applied literature, the most credible assumption appears to be $U_E \leq 0$ and $U_H \geq 0$. but it may depend on the paramount externality at stake in the specific geographical area.

the social benefit of the carbon stock. The first one accelerates the sequestration process while the second one slows it down. In the cost-benefit analysis represented by these first-order conditions, $\varepsilon U_H > 0$ (with $U_H \geq 0$) is the marginal utility of the consumer when, for example, the soil loss due to erosion decreases: this term magnifies the previous one because it adds an indirect benefit of additional carbon sequestration.

Taking into account the environmental externalities due to the sequestering practices induces most likely an acceleration of the optimal process, but this effect crucially depends on the relative sizes of the different negative externalities and co-benefits.

Proposition 2 *The externalities caused by the sequestering practices may affect both the regulated extent and the pace of carbon sequestration:* (*i*) *a negative (resp. positive) flow externality enhanced by the agricultural output reduces (resp. increases) directly only the level of output, and increases (resp. decreases) indirectly the level of carbon sequestration through its impact on the marginal static sequestration cost;* (*ii*) *a negative (resp. positive) flow externality enhanced by the carbon sequestering practices reduces (resp. increases) directly only the level of carbon sequestration, and increases (resp. decreases) indirectly the level of output through its impact on the marginal production cost;* (*iii*) *a negative (resp. positive) stock externality enhanced by the carbon sequestering practices reduces (resp. increases) only the pace of carbon sequestration.*

This theoretical result shows the need for empirical work aimed at evaluating such externalities, or at least, if their extensive and accurate valuation is too costly (Elbakidze and McCarl, 2007), the need of identifying the paramount externality in a given geographical area in order to alter the contract.

5 Information and Incentives: the Case of Incomplete Information

With incomplete information, the planner's objective is to derive the social optimum within an adverse selection setting; private information on the firms' side increases the cost of any regulatory policy. To this end, we lean on the revelation principle (Myerson (1979); Baron and Myerson (1982); Baron (1989)). This direct mechanism means that firms will reveal their real types θ, *i.e.*, their real potential for additional carbon sequestration A, which is unknown by the planner. It is worth noting that our adverse selection issue is a static one (a farm's type does not vary over time and the farm will reveal its type only once) even if the contract concerns a dynamic path of carbon sequestration.

The range of contracts is a range of trajectories of monetary transfer - sequestration flow contracts $\{(\Lambda_t(\theta), q_t(\theta))\}_{t=T_0,\ldots T}$ where $\Lambda_t(\theta)$ is the subsidy depending *ex post* on the potential for additional carbon sequestration A, compared to the maximum soil carbon capacity M of the plot of land. Nevertheless, as $q_t(\theta)$ is unobservable but linked to the observable and verifiable output $y_t(\theta)$, the contract is defined by $\{(\Lambda_t(\theta), y_t(\theta))\}_{t=T_0,\ldots T}$

Assuming that the firm claims $\widetilde{\theta}$, the profit of an agricultural firm is:

$$\pi(y_t, q_t, s_t(\theta)/M, \widetilde{\theta}) = p_t y_t(\widetilde{\theta}) - C(y_t(\widetilde{\theta}), q_t(\widetilde{\theta}), s_t(\theta)/M) + \Lambda_t(\widetilde{\theta})$$

The sole rational type declaration by an agricultural firm is then $\widetilde{\theta} < \theta$. This declaration is close to $\underline{\theta}$ in order to get the highest subsidy.

The Incentive Constraints ($IC1$, $IC2$) account for the conditions under which a given firm will be induced to adopt the intended behavior, and the Participation Constraint (PC) for the reservation profit condition:

$$IC1 : \pi_\theta(q_t, \theta - S_t/M, \widetilde{\theta})\Big|_{\widetilde{\theta}=\theta} = -C_\theta(q_t(\widetilde{\theta}), s_t(\theta)/M) \tag{11}$$

$$\begin{aligned} IC2 \quad &: \quad \pi_{\theta\theta}(q_t, s_t/M, \widetilde{\theta})\Big|_{\widetilde{\theta}=\theta} \leq 0 \\ PC \quad &: \quad \pi(y_t, q_t, s_t/M) \geq \Pi_t(\theta) \quad \text{with } \Pi_t'(\theta) < 0 \end{aligned}$$

Condition (11) gives the positive marginal information rent for the firm: $\pi_\theta(q_t, s_t/M, \widetilde{\theta}) \geq 0$ because $C_\theta \leq 0$. The marginal information rent increases as θ increases. The less sequestering firms will obtain the highest information rent, because they are the most efficient for the future. Since $\Pi_t'(\theta) < 0$, we also have $\pi_\theta - \Pi_t'(\theta) < 0$. In this specific case, the type-dependent participation constraint does not entail countervailing incentives.

A firm close to $\overline{\theta}$ uses practices with initial crops which allow one of the highest total sequestration levels. Accordingly, the higher this potential is ($\theta \rightarrow \overline{\theta}$), the less expensive the sequestration practices are for a given quality of agricultural soils. A firm of type $\widetilde{\theta}$ will announce the type of the less efficient firm (or close to the less efficient one), $\underline{\theta}$, in order to get the highest available subsidy $\Lambda_t(\widetilde{\theta})$. The less efficient firm is the only one that cannot understate its potential and therefore that is unable to extract any information rent.

The information rent is then:

$$\pi(y_t(\theta), q_t(\theta), s_t(\theta)/M) = \pi(y_t(\underline{\theta}), q_t(\underline{\theta}), s_t(\underline{\theta})/M) + \int_{\underline{\theta}}^{\theta} -C_\theta(q(\zeta), s(\zeta)/M) d\zeta \tag{12}$$

where the first term is the profit of the firm characterized by the lowest potential for additional carbon sequestration, and the second term accounts for the informational benefit of any firm characterized by a higher potential ($\underline{\theta} < \theta$).

The monotonicity condition holds, as the monotone inverse hazard rate property is a sufficient condition insuring separating contracts (Assumption $H1$). Again Assumptions $H5$ and $H4$ ensure that the iso-profit curves of the agricultural firms cross only once in (Λ, q), which implies that $\partial q_t/\partial\theta \geq 0$ *i.e.* the sequestration effort required from a plot of land increases with its sequestration potential θM.

With incomplete information, the regulator's problem of maximizing expected social welfare $E(W)$ is

$$\max_{y_t(\theta),q_t(\theta)} EW \Leftrightarrow \max_{y_t(\theta),q_t(\theta)} \int_{\underline{\theta}}^{\bar{\theta}} \left[\int_0^T U(y_t, M - s_t, , e_t, H_t)e^{-\rho t}dt\right] f(\theta)d\theta$$
$$+ \int_{\underline{\theta}}^{\bar{\theta}} \left[\int_0^T [\lambda p_t y_t - \lambda\pi(y_t, q_t, s_t/M) - (1+\lambda)C(y_t, q_t, s_t/M)]\, e^{-\rho t}dt\right] f(\theta)d\theta$$
$$st \begin{cases} IC1,\ IC2,\ PC \\ \dot{s}_t = -q_t \\ s_0 = A = \theta M \Leftrightarrow S_0 = 0, \mu_0 \end{cases}$$

The first-order necessary conditions become (see the proof in the Appendix 7.3):

$$p_t = C_y(y_t, q_t) - \frac{U_E e_y}{(1+\lambda)} \tag{13}$$
$$\mu_t = (1+\lambda)C_q(y_t, q_t, s_t/M) - U_E e_q - \lambda\frac{(1-F(\theta))}{f(\theta)}C_{\theta q}(q_t, s_t/M) \tag{14}$$
$$\dot{\mu}_t = \rho\mu_t - U_2(M - s_t) - \varepsilon U_H - \frac{(1+\lambda)}{M}C_s(q_t, s_t/M) + \lambda\frac{(1-F(\theta))}{f(\theta)}C_{\theta\theta}(q_t, s_t/M) \tag{15}$$

From these necessary conditions, we can observe that unlike the complete information case, new terms appear in the equations: these terms account for the marginal information costs. As a result, we get the trade-off for the regulator between efficiency in the sequestration activities and informational rents. Optimal sequestration flows $q_t^*(\theta)$ set the monetary transfers in our contract design $(\Lambda_t(\theta), q_t^*(\theta))$. Comparing these necessary conditions with the ones obtained with complete information allows us to draw the following conclusions. It is worth noticing that, in our framework, imperfect information does not change the impact of the environmental co-effects of sequestration practices.

Firstly, because of our separability assumption about the cost function (Assumption $H6$), the first order condition is unchanged for output (13). But, as $C_{yq} \geq 0$, if the process of carbon sequestration is slowed under incomplete information, the level of output can increase relative to the complete information case. This is part of the trade-off resolution: it is optimal for the regulator to slow sequestration and pay a lower subsidy to maintain the same level of profit.

Secondly, the firm with the highest potential for additional carbon sequestration produces the optimal level of agricultural commodity and sequesters carbon with respect to the optimal path (a non-distortion at the highest level). All firms, except for those with lowest potential, would get an information rent which allows them to get a higher subsidy compared to the complete information case and to sequester a lower amount of carbon. The regulator minimizes the cost of this regulation policy by allowing the lowest possible information rents: the additional profit, compared to its reservation profit, of the less efficient firm is nil ($\pi_t(\underline{\theta}) = \Pi_t(\underline{\theta})$) and the others get an extra subsidy. This leads to distortions pushing practices towards those of the less efficient firms (Baron and Myerson, 1982).[13] This part of the contract may seem rather unfair because in this model, as the lower efficiency in sequestration activities for a firm is due to its earlier adoption of sequestration practices, for a given nature of its soil and consequently for a given M. But in fact this unfairness is counterbalanced by the decreasing reservation profit: the fixed part of the subsidy is actually a kind of reward for early adopters but they obtain the lowest marginal subsidy for further sequestration. In the end, both effects play in the opposite directions and the *ex post* profit could be either decreasing or increasing with θ, depending on the convexity of the information rent and on the highest component among the reservation profit or the informational rent (see Figure 3).

$$\Lambda_t(\theta) = \pi(y_t^*(\theta), q_t^*(\theta), s_t(\theta)/M) - p_t y_t^*(\theta) + C(y_t^*(\theta), q_t^*(\theta), s_t(\theta)/M)$$

---

[13] Because the potential for additional carbon sequestration is similar to an exhaustible resource, our results are close to those obtained in the case of exploitation of such an exhaustible resource with incomplete information (Hung *et al.*, 2006).

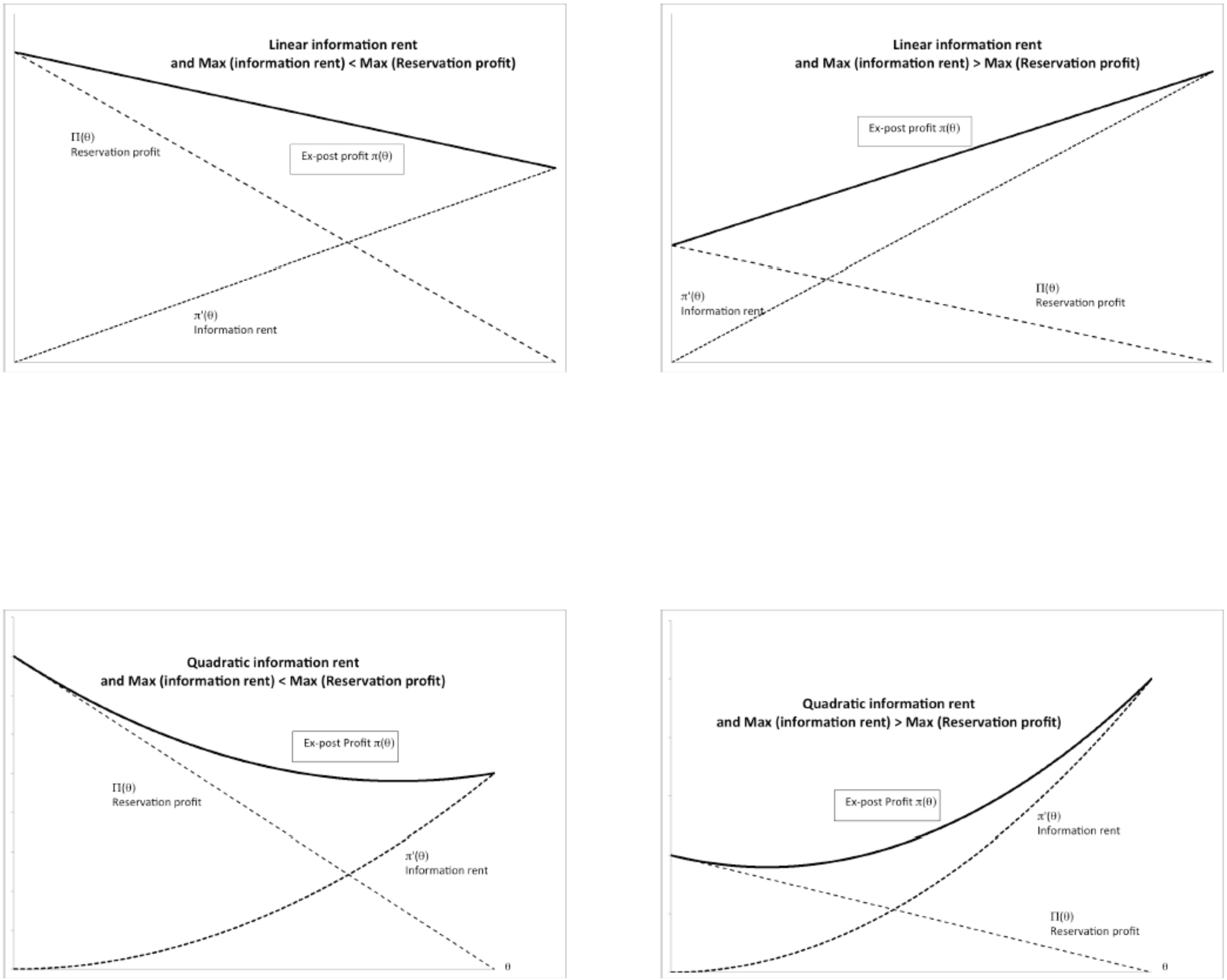

Figure 3: Information rent, reservation profit and ex-post profit

As for implementation, since $q_t^*(\theta)$ is strictly increasing, the sufficient condition for feasibility of the contract is verified and $q_t^*(\theta)$ can be inverted. Thus, the case is similar to Osmundsen (1998), which allows us to conclude that revelation of the type of the plot of land (and of its initial potential for additional carbon sequestration) and the choice of the optimal sequestration path can be implemented through a tangent hyperplane, i.e. in our case, through a combination of per-hectare subsidies and of output subsidies.

Thirdly, the Hotelling rule is changed by incomplete information about initial conditions, because the cost function exhibits a stock dependency ($H4$). It follows that incomplete information slows the sequestration process for all types except for the most efficient ones (because $C_{\theta\theta} \geq 0$ which implies that $\dot{\mu}_t$ is higher and $\dot{q}_t$ is lower than under complete information) but would not prevent obtaining the highest potential for additional carbon sequestration as soon as differentiated subsidies are provided at each period of time (equation (15)), if and only if the overall cost were not asymptotic: but with our Assumption $H4$, the maximal absolute potential cannot be reached even with complete information. $S_T(\theta)$ still increases with θ but is lower than under complete information. As a result, a lower range of plot types will exhaust the maximal economic potential for carbon sequestration $\Theta M < \underline{\theta} M$. This result is consistent with the intuition (like in Poudou and Thomas, 2000 for mining concessions): because imperfect information increases the sequestration cost for the regulator, it is optimal to reduce the information rent by lowering the amount of sequestered carbon and by allowing a larger number of farms not to exhaust their potential.

From a technical point of view, because the Inada condition is verified only for the total carbon carbon stock released in the atmosphere Σ (and not for S since $U_S(S=0) = U_S(\Sigma_0 - (1-\theta)\,M) > -\infty$) and because the reservation profit of the firm is positive except for $\overline{\theta}$, the shutdown of the less efficient firms might be desirable (Laffont and Martimort, 2002) if their reservation profit is too high compared to the social surplus obtained from their future sequestered carbon. In the following proposition, we assume that it does not happen.

This leads to the following Proposition.

Proposition 3 *With incomplete information, the potential for additional carbon sequestration is similar to an exhaustible resource and the carbon sequestration process occurs following the optimal path defined by this Hotelling rule with trade-offs as with complete information:* (*i*) *the regulator has to trade-off between the efficiency in the sequestration activities and informational rents allowed to the agricultural firms and differentiated subsidies have to be provided at each period of time;* (*ii*) *all firms, except for those with the lowest potential, would get an information rent above their reservation profit;* (*iii*) *for a given* M*, the sequestration process is slowed except for the firm with the highest potential* $\overline{\theta}$ *(i.e. the lowest sequestration effort before the contract);* (*iv*) *for a given* θ*, the growth rate of the sequestration flow increases with* M*;* (*v*) *there is a threshold* $\check{\theta} < \hat{\theta}$ *such that for* $\underline{\theta} \leq \theta \leq \check{\theta}$, $s_T(\theta) = \Theta M$ *with* $\Theta < \underline{\theta}$*, and for* $\check{\theta} < \theta < \overline{\theta}$*, the remaining unexploited potential increases with* θ *and is higher than under complete information;* (*v*) *to implement the optimal sequestration path, the regulator must commit to a dynamic contract composed of a trajectory of differentiated combinations of per-hectare and per-ton of output subsidies.*

6 Concluding Comments

The various perceptions of the potential for carbon sequestration by the agricultural sector certainly lie in the difference in the share of abatement that agriculture could hold in each region.

However, European distrust about agricultural carbon sequestration also springs from the questionable permanence of the carbon storage, the difficulties of measuring actual sequestration, the uncertainties concerning the incurred costs, and the issue of designing the appropriate incentives to induce farmers to adopt new practices.

Land management changes could only occur if there are economic incentives for carbon management, and therefore if parts of the cost are borne by a policymaker. On the one hand, one part of the subsidy has to cover the cost regarding changes in practices; on the other hand, one part of the subsidy has to create incentives to induce changes. Carbon sequestration is a strategic way to mitigate GHG concentration and climate change regarding its low cost and actual implementation, while other technologies to cope with climate change appear (in a portfolio management way) (Post *et al.*, 2004). Furthermore, practically and culturally speaking, there should be a shift from a positive externality reward associated to carbon sequestration and its co-benefits provided by agricultural firms (multifunctionality), to the Payment for Environmental Services (PES), as agricultural firms provide an environmental service through carbon sequestration. In Europe, this is currently at the core of the agenda to design the new Common Agricultural Policy (CAP) from 2014 and its implementation, with regards to the allocation of funds to agricultural firms.

In this paper, we have emphasized the crucial importance of the potential for additional carbon sequestration in agricultural soils whilst designing incentive mechanisms for firms related to land heterogeneity. The policymaker has to choose between the less expensive of these policies: *(i)* the incentive policy as she offers a rewarding contract, and she might accept the cost of asymmetric information and give higher subsidies in order to induce revelation by the agricultural firm of its private information; *(ii)* the full monitoring policy if this is technically feasible as she monitors the crops and management practices of the agricultural firm aimed at raising real sequestered carbon stocks in a perfect and continuous manner, in order to be able to allocate subsidies efficiently.

One of our contributions is to build our analysis on the standard problem of the exploitation of a natural exhaustible resource for which the available stock is unknown; we proceed in an original way in viewing carbon sequestration and incentives to agricultural firms within a dynamic setting. The proposed contract has the advantage of avoiding the inefficiencies of standard subsidies - per-hectare and per-tonne - by identifying agricultural firms and of inducing truthful revelation, and to provide a fair subsidy for each firm by both paying an information rent to the most efficient ones and by rewarding the least efficient ones which were nevertheless the earliest adopters of sequestering practices. We also show that taking into account the joint externalities of carbon sequestration may lead the regulator to slow down the sequestration process, and possibly stop it, when the induced externalities have an overall negative effect. In the opposite case, the regulator will find it optimal to accelerate the process. This result emphasizes the need to value empirically the main possible co-effects due to carbon sequestration, especially because they are also heterogenous. And since we use very general assumptions to establish our results, future empirical work would be necessary to implement this approach: instead of considering a common cost envelope for all agricultural farms, it might be necessary to estimate the cost function associated with each combination of crop and land-use management system.

Finally, we may consider a few extensions of our model and analysis. Firstly, incomplete information would also appear through moral hazard which is created by high costs of monitoring. This implies that firms might not fulfill their contractual commitment. As we have shown that taking into account the characteristics of carbon sequestration does not modify the standard argument about *ex ante* incomplete information (adverse selection), we can then accept the standard result about *ex post* incomplete information (moral hazard), without any additional economic model. With incomplete information regarding the strategy of the firm during the contract, the planner must give a greater subsidy in order to induce the requested behavior by the firm. Secondly, throughout the paper, we have assumed that the contract has been signed at the beginning of the first period with full commitment by both parties. According to the revelation principle, by accepting the contract, the firm reveals its real type. One could then argue that the regulator does not need to commit in the upcoming periods, but can use the revealed information to negotiate a new contract from period two. Nevertheless, if adverse selection disappears, moral hazard is very likely to remain over time. In any case, asymmetric information increases the cost of regulation and reduces the environmental efficiency of the policy, namely the total amount of carbon sequestered in the soil (Gulati and Vercammen, 2006).

We could also take into account the possibility for the government to contract with several agricultural firms during the same period: as in standard cases of multiple mines of different qualities. It would then be more profitable for the society to extract from the cheapest farms/firms. In our case, the regulator would choose to contract first to sequester carbon on the highest quality lands and with the highest remaining potential. For the other ones, the payment would only aim at preventing them to release the already stocked carbon. The same choice may be made in case the government budget constraint is binding.

7 Appendix

7.1 The social welfare function

The current planner's social welfare function W_t can then be defined as the sum of the consumer surplus (V_t) and the profits of the agricultural firm (Π_t), that is $W_t = V_t + \Pi_t$.

The consumer surplus maybe be written as:

$$\begin{aligned} V_t &= U(y_t, M - s_t) - p_t y_t - (1+\lambda)\Lambda_t(\theta) \\ \text{with } U_1 &\geq 0,\, U_{11} \leq 0 \text{ and } U_2 \geq 0,\, U_{22} \leq 0 \\ \text{and Inada conditions } &: U_\Sigma(\Sigma = 0) = -\infty \text{ and } \lim_{\Sigma \to 0} \Sigma U_\Sigma = 0 \\ \text{with } \Sigma &= \Sigma_0 - [(1-\theta) M + S_t] \end{aligned}$$

The profit of an agricultural firm is:

$$\pi(y_t, q_t, s_t, M) = p_t y_t - C(y_t, q_t, s_t/M) + \Lambda_t(\theta)$$

Even if the choice variable of the regulator is the level of the subsidy individualised according to the characteristics of the firm, it is much more significant to consider that, by setting a level of subsidy, the regulator actually chooses the firm's profit. By rewriting the previous equation, we can obtain the level of subsidy $\Lambda_t(\theta)$ needed to provide a given profit to the firm:

$$\Lambda_t(\theta) = \pi(y_t, q_t, s_t, M) - p_t y_t + C(y_t, q_t, s_t/M)$$

Introducing this expression in V, and then into W we obtain the following expected social welfare function that the planner seeks to maximize (equation (1)):

$$EW_t = \int_{\underline{\theta}}^{\overline{\theta}} W_t f(\theta) d\theta$$

7.2 Complete information

The current Hamiltonian value $\mathcal{H}$ for the regulator's problem with complete information is:

$$\begin{aligned} \mathcal{H} &= U(y_t, (1-\theta) M + S_t) + \lambda p_t y_t - (1+\lambda) C(y_t, q_t, \theta - S_t/M) + \mu_t q_t \\ &= U(y_t, M - s_t) + \lambda p_t y_t - (1+\lambda) C(y_t, q_t, s_t/M) + \mu_t q_t \end{aligned}$$

The first-order necessary conditions are $\partial\mathcal{H}/\partial y_t = 0$; $\partial\mathcal{H}/\partial q_t \leq 0$; $q_t \partial\mathcal{H}/\partial q_t = 0$ and $-\partial\mathcal{H}/\partial S_t = \partial\mathcal{H}/\partial s_t = \dot{\mu}_t - \rho\mu_t$ that leads to (2), (3) and (4), when carbon is actually sequestrated ($q_t > 0$).

$$\begin{aligned} p_t &= C_y(y_t, q_t) && (2) \\ \mu_t &= (1+\lambda) C_q(y_t, q_t, s_t/M) && (3) \\ \rho\mu_t &= \dot{\mu}_t + U_2(M - s_t) + \frac{(1+\lambda)}{M} C_s(q_t, s_t/M) && (4) \end{aligned}$$

7.2.1 Dynamics of the sequestration flow

By differentiating (3) and (2) and using (4), and with the additional assumption that $\dot{p}_t/p_t = \rho$, one obtains:

$$
\begin{aligned}
&\left[\underbrace{C_{qq}(y_t, q_t, s_t/M)}_{+} - \underbrace{\left(C_{yq}(y_t, q_t)\right)^2 / C_{yy}(y_t, q_t)}_{+}\right] \frac{\dot{q}_t}{q_t} \\
= \quad &\left[\underbrace{C_q(y_t, q_t, s_t/M)}_{+} - C_y(y_t, q_t)\underbrace{C_{yq}(y_t, q_t)}_{+}/\underbrace{C_{yy}(y_t, q_t)}_{+}\right] \frac{\rho}{q_t} \\
&- \frac{1}{(1+\lambda)} \frac{1}{q_t} \underbrace{U_2(M - s_t)}_{+\approx 0} - \frac{1}{M} \frac{1}{q_t} \underbrace{C_s(q_t, s_t/M)}_{-} + \frac{1}{M} \underbrace{C_{qs}(q_t, s_t/M)}_{-}
\end{aligned}
$$

The dynamics of the sequestration flow is therefore, in this general case, far from obvious. Depending on the relative values of the first and second derivatives, $\dot{q}_t/q_t$ could be either positive or negative. Under $H7$, the coefficient of $\dot{q}_t/q_t$ is négative. In the simple case where $C(y_t, q_t, s_t/M) = \alpha(q_t)c(y_t) + \beta(s_t/M)q_t$ with $\alpha(q_t) = \frac{\alpha}{2}(q_t + a)^2$, $c(y_t) = \frac{c}{2}y_t^2$, $\beta(s_t/M) = \frac{\beta}{2}\left(1 - \frac{s_t}{M}\right)^2$ since $0 < \frac{s_t}{M} < 1$, one obtains, by using (4), $C_y(y_t, q_t, s_t/M) = \frac{\alpha c}{2}(q_t + a)^2 y_t = p_t \Rightarrow y_t = \frac{2p_t}{\alpha c} \frac{1}{(q_t + a)^2} \Leftrightarrow p_t/y_t = \frac{\alpha c}{2}(q_t + a)^2$ and

$$
\dot{q}_t = \frac{\rho\alpha}{2}(q_t + a) - \frac{\beta\rho\alpha c}{12} \frac{(q_t + a)^4}{p_t^2} \left(1 - \frac{s_t}{M}\right)^2 + \frac{1}{(1+\lambda)} \frac{\alpha c}{6} \frac{(q_t + a)^4}{p_t^2} \underbrace{U_2(M - s_t)}_{+\approx 0}
$$

Even in this case, the growth rate of the sequestration flow might be positive or negative but clearly, since s_t does not increase during the contract because of the commitment of the firm to the sequestration process, this growth rate is decreasing.

Moreover, since q_t and s_t increase with θ, $\dot{q}_t$ increases with θ, according to the intuition: the highest θ (the lowest sequestration effort before the contract), and the highest the growth of the sequestration flow.

7.2.2 Remaining unexploited soil carbon capacity at the end of the contract

As $q_t(\theta)$ and $S_t(\theta)$ increase with θ, at the end of the contract the amount of stored carbon is higher on plots where the potential was at the highest at T_0. But since the potential for additional carbon sequestration at the beginning of the contract also increases with θ, theoretically $s_T(\theta)$ might decrease or increase with θ. Nevertheless, it is worth noting that, due to our thorough depiction of the different sources of heterogeneity, we can consider that, for a given observable maximal soil carbon capacity, i.e. for a given M, a plot of land characterised by $\theta > \underline{\theta}$ is nothing but the same plot of land than $\underline{\theta}$ at a previous stage of sequestration. It implies that $s_T(\theta) \geq s_T(\underline{\theta})$, denoted by ΘM. If the contract duration is sufficiently long, the unexploited potential may reach the level ΘM for any θ but if T is sufficiently low, $s_T(\theta) > \Theta M$. Between these extreme cases, there exists a threshold $\hat{\theta}$ such that for $\underline{\theta} < \theta < \hat{\theta}$, $s_T(\theta) = \Theta M$, and for $\hat{\theta} < \theta < \bar{\theta}$, the remaining unexploited potential increases with θ.

7.3 Environmental co-effects

When taking into account the other potential externalities due to the adoption of sequestering practices, the current planner's social welfare function W_t has to incorporate a modified expression of the consumer surplus (V_t) depending on the total environmental externalities, *i.e.*, the stock $H_t = \varepsilon S_t$ and the total flows $E_t = \int_{\underline{\theta}}^{\overline{\theta}} e_t f(\theta) d\theta$ at each period of time.

The consumer surplus may be written as:

$$\begin{aligned} EV_t &= \int_{\underline{\theta}}^{\overline{\theta}} U(y_t, M - s_t, , e_t, H_t) f(\theta) d\theta - \int_{\underline{\theta}}^{\overline{\theta}} p_t y_t f(\theta) d\theta - (1+\lambda) \int_{\underline{\theta}}^{\overline{\theta}} \Lambda_t(\theta) f(\theta) d\theta \\ \text{with} \quad U_1 &\geq 0,\ U_{11} \leq 0 \text{ and } U_2 \geq 0,\ U_{22} \leq 0\ ,\ U_E \leq 0 \text{ (or } U_E \geq 0),\ U_H \geq 0 \text{ (or } U_H \leq 0) \\ \text{and Inada conditions} &: U_\Sigma(\Sigma = 0) = -\infty \quad \text{and} \quad \lim_{\Sigma \to 0} \Sigma U_\Sigma = 0 \\ \text{with } \Sigma &= \Sigma_0 - \left[(1-\theta) M + S_t \right] \end{aligned}$$

The current social welfare function becomes (equation (1)):

$$\begin{aligned} EW_t = & \int_{\underline{\theta}}^{\overline{\theta}} U(y_t, M - s_t, , e_t, H_t) f(\theta) d\theta \\ & + \int_{\underline{\theta}}^{\overline{\theta}} \left[\lambda p_t y_t - \lambda \pi(y_t, q_t, \theta - S_t/M) - (1+\lambda) C(y_t, q_t, \theta - S_t/M) \right] f(\theta) d\theta \end{aligned} \tag{16}$$

The only differences caused by the introduction of the externalities concerns the consumers' utility, and they equally affect the current Hamiltonian value $\mathcal{H}$ for the regulator's problem, either with complete information or under asymmetric information.

The first-order necessary conditions are $\partial\mathcal{H}/\partial y_t = 0$; $\partial\mathcal{H}/\partial q_t \leq 0$; $q_t \partial\mathcal{H}/\partial q_t = 0$ and $-\partial\mathcal{H}/\partial S_t = \partial\mathcal{H}/\partial s_t = \dot{\mu}_t - \rho\mu_t$ that give equations (8), (9) and (10), when carbon is actually sequestered ($q_t > 0$).

The effects on the sequestration pace can be easily obtained by replacing in the expression of $\dfrac{\dot{q}_t}{q_t}$ obtained in Appendix 7.2.1 $C_y(y_t, q_t)$ with $C_y(y_t, q_t) - \frac{U_E e_y}{(1+\lambda)}$,$C_q(y_t, q_t, s_t/M)$ with $C_q(y_t, q_t, s_t/M) - \frac{U_E e_q}{(1+\lambda)}$, and $U_2(M - s_t)$ with $U_2(M - s_t) + \varepsilon U_H$.

7.4 Incomplete information

Integrating (12) by parts leads to

$$\int_{\underline{\theta}}^{\overline{\theta}} \pi(y_t, q_t, s_t/M) f(\theta) d\theta = \pi(y_t(\underline{\theta}), q_t(\underline{\theta}), s_t(\underline{\theta})/M) - \int_{\underline{\theta}}^{\overline{\theta}} C_\theta (1 - F(\theta)) d\theta \tag{A1}$$

as

$$F(\theta) = prob(A < \theta M);\; F'(\theta) = f(\theta) < 0$$

$$\begin{aligned}
& \int_{\underline{\theta}}^{\overline{\theta}} \left(\int_{\underline{\theta}}^{\theta} -C_\theta(q(\zeta), s(\zeta)/M) d\zeta \right) f(\theta) d\theta \\
= & \int_{\underline{\theta}}^{\overline{\theta}} \left(\int_{\underline{\theta}}^{\theta} C_\theta(q(\zeta), s(\zeta)/M) d\zeta \right) (-f(\theta))\, d\theta \\
= & \left[(1 - F(\theta)) \int_{\underline{\theta}}^{\theta} C_\theta(q(\zeta), s(\zeta)/M) d\zeta \right]_{\underline{\theta}}^{\overline{\theta}} - \int_{\underline{\theta}}^{\overline{\theta}} C_\theta \left(1 - F(\theta)\right) d\theta \\
= & -\int_{\underline{\theta}}^{\overline{\theta}} C_\theta \left(1 - F(\theta)\right) d\theta
\end{aligned}$$

Inserting (A1) in the expected social welfare $E(W)$, we obtain the regulator's problem:

$$\begin{aligned}
& \max_{y_t(\theta), q_t(\theta)} \int_{\underline{\theta}}^{\overline{\theta}} \left[\int_0^T U(y_t, M - s_t, , e_t, H_t) e^{-\rho t} dt \right] f(\theta) d\theta \\
& + \int_{\underline{\theta}}^{\overline{\theta}} \left[\int_0^T \lambda p_t y_t e^{-\rho t} dt \right] f(\theta) d\theta \\
& - \int_{\underline{\theta}}^{\overline{\theta}} \left[\int_0^T \left[(1 + \lambda) C(y_t(\theta), q_t(\theta), s_t/M) \right] e^{-\rho t} dt \right] f(\theta) d\theta \\
& - \int_{\underline{\theta}}^{\overline{\theta}} \int_0^T \left[\lambda \left[(C_\theta(q_t(\theta), s_t/M)) \frac{(1 - F(\theta))}{f(\theta)} \right] e^{-\rho t} dt \right] f(\theta) d\theta \\
& - \int_0^T \lambda \pi(y_t(\underline{\theta}), q_t(\underline{\theta}), s_t(\underline{\theta})/M) e^{-\rho t} dt
\end{aligned}$$

$$st \begin{cases} IC1,\, IC2,\, PC \\ \dot{s}_t = -q_t \\ s_0 = A = \theta M, \mu_0 \end{cases}$$

μ_t is the value of the costate variable at date t. S_0 and μ_0 are the initial values of the carbon stock and the costate variable. The transversality condition is $\mu_T s_T = 0$.

The current hamiltonian value $\mathcal{H}$ for the regulator's problem with asymmetric information is:

$$\begin{aligned}\mathcal{H} &= \int_{\underline{\theta}}^{\overline{\theta}} \left[U(y_t, M - s_t, , e_t, H_t) + \lambda p_t y_t\right] f(\theta) d\theta \\ &\quad - \int_{\underline{\theta}}^{\overline{\theta}} \left[(1+\lambda) C(y_t(\theta), q_t(\theta), s_t/M)\right] f(\theta) d\theta \\ &\quad - \int_{\underline{\theta}}^{\overline{\theta}} \lambda C_\theta(q_t(\theta), s_t/M) \frac{(1-F(\theta))}{f(\overline{\theta})} f(\theta) d\theta \\ &\quad - \lambda \pi(y_t(\underline{\theta}), q_t(\underline{\theta}), s_t(\underline{\theta})/M) + \mu_t \left(-q_t\right)\end{aligned}$$

Thus, the first-order necessary conditions given by equations (13), (14) and (15) are obtained.

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