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Contract Design to Sequester Carbon in Agricultural Soils

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Abstract

According to several studies, agricultural carbon sequestration could be a relatively low cost opportunity to mitigate greenhouse gas (GHG) concentration and a promising means that could be institutionalised. However the potential for additional carbon quantities in agricultural soils is critical and comes from the agricultural firms behaviour with regards to land heterogeneity. In this paper, our aim is to set incentive mechanisms to enhance carbon sequestration by agricultural firms. A policymaker has to arrange incentives as agricultural firms have private information and do not spontaneously switch to the required practices. Moreover, a novelty in our paper is to show

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that the potential for additional carbon sequestration is similar to an exhaustible resource. As a result, we construct an intertemporal principal-agent model with adverse selection. Our contribution is to specify contracts in order to induce truthful revelation by the firms regarding their intrinsic characteristics towards carbon sequestration, while analytically characterizing the optimal path to sequester carbon as an exhaustible resource.

JEL classification: D60 - D62 - E62 - H23 - Q28.

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1 Introduction

Climate change is currently one of the most prominent international issue during the last years. After some difficult negotiations and a long time needed before its ratification by the requested number of countries, the Kyoto Protocol came into force in February 2005. The Annex 1 Members agreed upon diffentiated efforts of abatement of their emissions of carbon dioxide in order to stabilize the GHG concentration in the atmosphere. Carbon dioxide accounts for 80 per cent of GHG emissions from developed countries. One means for reducing CO_2 levels is carbon sequestration into forests or agricultural soils. As emphasized by Young (2003), the issue of establishing credits for forestry and agriculture as carbon sinks was hotly debated during the negotiations and, if carbon sequestration is integrated through forest sinks in the Kyoto protocol (article 3.3), additional land use activities are currently negotiated through article 3.4 of the Protocol.

Additional carbon quantities in agricultural soils are gained by the implementation of new crops or new management practices. Significant illustrations of these practices are conservation tillage, irrigation and mineral fertilization. It has been pointed out that agricultural carbon sequestration could be a relatively low cost opportunity to mitigate GHG concentration and a promising means that could be institutionalised (McCarl and Schneider, 2000; Schneider, 2002). In fact, in comparing different countries, the place given to carbon sequestration in their strategy to reduce GHG emissions has been very different. Young *et al.* (2007) compare the US and the EU choices: while the US has not ratified the Kyoto Protocol but has been encouraging the use of agricultural and forestry carbon sequestration, the EU ratified it as soon as 2002 but without using agricultural soil carbon sequestration in its strategy. A very recent study of European researchers shows indeed that Europe should consider at the contrary as a priority the development of land management policies which aim at reducing GHG emissions (Schulze *et al.*, 2009). According to Feng *et al.* (2002) (referring to Lal *et al.*, 1998), the potential for carbon sequestration of U.S. cropland through improved management could be set to 75–208 MMTC/year. A later study, by Sperow *et al.* (2003), estimated that agricultural sequestration of carbon could account for the US for 40% of the reduction of GHG emissions needed to abate american emissions at the level of 1990. In Europe, Freibauer *et al.* (2004) estimated that carbon soil sequestration could have provided 9% of the reductions required in 2005.

The various perceptions of the carbon sequestration potential 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 to measure actual sequestration, the uncertainties concerning the incurred costs, and the issue of designing the appropriate incentives to induce farmers to adopt new practices.

Scientific studies (INRA, 2002) show that the sequestration process is essentially non linear. After a move toward more sequestering management practices, carbon sequestration increases rapidly, then slows down to reach a maximum level depending on the nature of the soil, of the crops and on the practices itselves. Insights show that this 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 to sequester a finite quantity of carbon that is an absolute potential for carbon sequestration associated to these crop and practices. This is why a plot of land can be defined by its potential for additional carbon sequestration which is the gap between the maximal absolute potential for carbon sequestration in this area and the carbon stored for a given time period. The potential for additional carbon sequestration depends on land quality[1] as well as on past and upcoming crops and practices (McCarl *et al.*, 2000). In case of any move back to less sequestering pratices, carbon release is even more faster than was carbon sequestration. Taking this specific dynamics into account, Ragot and Schubert (2008) show that the only optimal policy is to encourage permanent carbon storage.

Farmers do not switch spontaneously to practices that increase social benefits and the adoption rate is likely to be lower than the socially optimal one. They indeed assess their private costs whilst ignoring the positive externality through higher sequestration that enhances social benefits. In this way, a full assessment that compares carbon sequestration costs and gains should be conducted. Schneider (2002) states these different costs as adjustment costs, opportunity costs, stickiness, market changes, and environmental and international co-effect. The great heterogeneity that can be observed again between countries regarding the use of different management practices reflect the heterogeneity of sequestration costs. For example, Weersink *et al.* (2005) state that the profitability of reduced tillage is not significantly different than the profitability of conventional practices, which is consistent with the observed common use of both tillage methods in Canada. Kurkalova (2006) observes that, switching to conservation practices does not always imply a monetary sacrifice for farmers, because even

[1] By quality we mean the environmental properties of soils.

without any subsidy, on average more than one third of U.S. acres are in conservation tillage. This is not the case in Europe where the practices which have the highest sequestration rates are also the less profitable (Pendell *et al.*, 2007). De Cara and Jayet (2000) insist on the heterogeneity of GHG abatement costs among crop-oriented and livestock farms. In many developing countries, such as in West Africa, according to Gonzalez-Estrada (2008), best management practices that generate the highest carbon sequestration rates are economically not feasible for the majority of local smallholders, unless considerable financial support is provided. As a consequence, policymakers generally have to counteract direct costs while inducing sustainable sequestering practices to increase carbon sequestration in soils. To this end, they have the opportunity to propose monetary transfers as subsidies to bring about suitable practices.

Nevertheless, the role of history and the nature of agricultural soils lead to a great spatial heterogeneity about the potentials of carbon sequestration which prevents from implementating casual regulation policies. This heterogeneity indeed involves high monitoring costs if the regulator is concerned about rewarding farmers accordingly to their results. Kurkalova *et al.* (2004) point out the difficulties incurred by a regulator willing to differentiate payments between farmers in the absence of field-scale measurement technologies. Instead of measuring the annual amount of carbon accumulated in each plot of land, one could imagine 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 satellite, but more usually with on-field inspection, the practices are not easily controlled). The same paper enlightens the related problem of the basis for incentive payments. Either the payment is based on the total amount of carbon stored 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 precocious adopters of more sequestering practices would be penalized.

Two kinds of subsidies are available for a policymaker: a per-tonne subsidy and a per-hectare or lump-sum subsidy. Pautsch *et al.* (2001) and 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. 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 per-tonne subsidies. However, on-site monitoring costs of the stored 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-ton), the preference is actually often given to 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. One could think that the implementation of carbon credits raises the same issue about monitoring costs of the effective amount of stored carbon. 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 is only around 3% of the value of carbon credit (this result 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 raising concern about climate change. Wu and Babcock (1996) develop a payment scheme that overcomes the information asymmetry between farmers and regulator 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.

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, this is a still pendant debate to assess if the positive externalities are greater than the negative ones. In fact, reduced tillage or adoption of no-tillage is shown to decrease soil erosion which in turn can reduce nutrient pollution of groundwater, but negative environmental externalities can result from increased use of pesticides (Schneider, 2002). Many studies, like Weersink *et al.* (2005), consider that reduced tillage can also 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). And 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) enlighten the fact 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 the issue of 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. For example, Krcmar *et al.* (2001) emphasize the role of uncertainty, more specifically in the case of forestry which is of great importance because forests sequester carbon at a faster rate than other terrestrial sinks. Singh and Lal (2005) or Pendell *et al.* (2007) examine all use changes and soil/crop management practices with potential for carbon sequestration in soils, *i.e.* conservation tillage methods, judicious use of fertilizers and manures, use of crop residues, diverse crop rotations, and erosion control measures. Another encompassing view of this range of issues consists in the consideration of agriculture as a provider of various ecological services (Dale and Polasky, 2007), like preservation of landscape (Goldman *et al.*, 2007), preservation from desertification (Havstad *et al.*, 2007). Antle and Diagana (2003) already mentioned the need to consider co-benefits of carbon sequestration.

In connection with these issues, the question we want to challenge in this paper is the following one: how could the regulator induce more carbon sequestration in agricultural land whilst taking into account heterogeneity in potential for additional carbon sequestration? This heterogeneity among regions, but also among plots of land in the same region (or even among plots belonging to the same farmer) cannot be observed by the regulator. This asymmetric information through private information on the farmers side depicts an adverse selection setting. Furthermore, picking sequestering practices could imply changes in the use of more fertilizers and pesticides and could generate positive or negative externalities such as variation in the groundwater pollution. This adds another source of asymmetric information and requires a more sophisticated regulation policy whilst taking into account the positive externality of sequestering carbon as well as the joint externalities.

In this paper, our aim is to set incentive mechanisms to enhance carbon sequestration as a principal-agent relationship between a regulator and agricultural firms. Asymmetric information indeed prevents a regulator from using first-best economic instruments as long as farmers get information rents. Moreover, a novelty in our paper is to show that the potential for additional carbon sequestration is similar to an exhaustible resource and its originality is that we construct a model which is built on two different streams of the theoretical literature: optimal exploitation of an exhaustible resource and mechanism design (Myerson, 1979; Baron and Myerson, 1982; Baron, 1989; Laffont and Martimort, 2002). We obtain an intertemporal principal-agent model with adverse selection. Our contribution is to specify differentiated contracts in order to induce truthful revelation by the firms regarding their intrinsic characteristics towards carbon sequestration (in a similar line than Wu and Babcock, 1996 or Canton *et al.,* 2009 except that spatial targeting of our measures would be impossible due to the monitoring costs), and we analytically characterize the optimal path to sequester carbon as an exhaustible resource. The proposed contract has the advantage to avoid the inefficiency of the per-hectare subsidy as well as the excess cost of the per-ton subsidy, and it overcomes the unfairness of the incentive mechanism mentioned by Kurkalova *et al.* (2004) by not penalizing precocious adopters of more sequestering practices.

This paper is organised as follows. In Section 2, we describe our assumptions and the model design. In Section 3, we analyse the social planner objective, and we give the menu of contracts regarding complete and incomplete information. Last, we provide a few extensions to our analysis and public policy proposals in Section 4.

2 The model

2.1 Carbon sequestration potential

Potential for additional carbon sequestration is at the core of our analysis. We describe here what is at stake. The heterogeneity depends on land quality as well as on past and upcoming crops and management practices by agricultural firms. Plots of land can be of different qualities. Even in case of equal quality, the ability of plots of land to sequester carbon can differ, according to the past crops and practices. In specific plots of land of a given quality, there is an intrinsic maximum potential for additional quantities of carbon.

The heterogeneity between two plots of land due to the dynamics of carbon sequestration is represented by the following figure (Figure 1), according to most empirical studies (INRA, 2002). To illustrate the mechanism, assume that there are four kinds of practices or crops (A, B, C, D), each of them allowing to sequester a maximum potential $S_A^* < S_B^* < S_C^* < S_D^*$. The maximal absolute potential for carbon sequestration is the same (S_D^*) 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 decided to switch from practice B to practice C and engaged on a new dynamics of sequestration from S_B^* to S_C^*. On plot 2, the decision was taken later to switch from practice A to practice B and then to sequester carbon progressivily until S_B^*. At the date of implementation of the policy (T_0), the potential for additional carbon sequestration of plot 1 ($\overline{S_1}$) is less than the potential for additional carbon sequestration of plot 2 ($\overline{S_2}$).

Given the available practices and crops, any plot of land can be entirely characterized by its potential for additional carbon sequestration, that depends on its soil nature, its location and -more specifically and unobservable- on its history of crops and practices.

2.2 The distribution of agricultural firms

By assumption, the economy is composed by a continuum of competitive agricultural firms and by a representative consumer.

On the firms side, crops and practices by an agricultural firm allow for carbon sequestration flows denoted by q_t whereas the cumulated carbon stock is set as S_t[2]. $C(y_t, q_t, e_t, s_t)$ are exploitation costs for an individual firm established by the firm output y_t, the carbon

[2] Throughout this paper the time period is denoted by the subscript t.

sequestration flow q_t, the non-point source polluting emissions due the production processes e_t, and its remaining potential for additional carbon sequestration s_t which is defined as the gap, during period t, between the potential for additional carbon sequestration in this plot of land and accumulated stocks. This gap can be formally written as $s_t = \overline{S} - S_t$, *i.e.,* this is the remaining potential for carbon sequestration. Our cost function modelling can be explained as follows. The efficiency of a particular firm in sequestering is directly linked to its potential for additional carbon sequestration denoted by $\overline{S}$. We assume that the real type of the firm is distributed according to $\overline{S}$ in a continuous manner such that $\overline{S} \in \left[\overline{S}_{\text{inf}}, \overline{S}_{\text{sup}}\right]$. $\overline{S}_{\text{inf}}$ therefore accounts for the least efficient type or the firm with the lowest additional potential for carbon sequestration while $\overline{S}_{\text{sup}}$ accounts for the most efficient type or the firm with the highest additional potential for carbon sequestration. $f(\overline{S})$ represents the probability density function on $\left[\overline{S}_{\text{inf}}, \overline{S}_{\text{sup}}\right]$ and $F(\overline{S})$ is the cumulative distribution function, which are known by the regulator. By assumption, the less the crops and the practices were previously sequestering, the less it is costly to switch to better practices (Antle *et al.*, 2002). The total cost negatively depends on the additional potential for carbon sequestration $\overline{S}$. For exhaustivity, our cost function allows for the encompassing hypothesis that exploitation costs depend on the remaining potential in carbon sequestration for each firm s_t. We may notice that this cost dependency on the accumulated stock does raise an asymptotic cost growth (Levhari and Liviatan, 1977). In the following, we will distinguish two cases: the global cost depends only on initial conditions about carbon sequestration ability, *i.e.*, on the potential for additional carbon sequestration $\overline{S}$ (assumption $A4$) or it depends on the remaining potential for additional carbon sequestration s_t (assumption $A4'$). We may underline that assumption

$A4'$ encompasses assumption $A4$.

The cost function $C(y_t, q_t, e_t, s_t)$ is defined by the following assumptions (A):

- $A1 : C_y \geq 0, C_{yy} = \partial^2 C/\partial y^2 \geq 0$, convexity in the output y_t;

- $A2 : C_q \geq 0, C_{qq} = \partial^2 C/\partial q^2 \geq 0$, convexity in the carbon sequestration flow q_t;

- $A3 : C_e \leq 0, C_{ee} = \partial^2 C/\partial e^2 \leq 0$, convexity of the abatement cost $(-C_e)$ in the polluting emissions e_t;

- $A4 : C_{\bar{S}} = \partial C/\partial \bar{S} \leq 0$, and $C_{\bar{S}\bar{S}} = \partial^2 C/\partial \bar{S}^2 \geq 0$: the lower $\bar{S}$ is, the higher the costs for sequestering practices in the future;

- $A4'$ $(alternative\ hypothesis) : C_s = \partial C/\partial s \leq 0$ $(\partial C/\partial S \geq 0)$, and $C_{ss} = \partial^2 C/\partial s^2 \geq 0$;

- $A5 : C_{yq} = \partial^2 C/\partial y \partial q \geq 0$, increasing in both arguments, $C_{ey} = \partial^2 C/\partial e \partial y \leq 0$ and $C_{eq} = \partial^2 C/\partial e \partial q \leq 0$, decreasing in both arguments, and $C_{qs} = \partial^2 C/\partial s \partial q \leq 0, C_{y\overline{S}} = \partial^2 C/\partial \overline{S} \partial y \leq 0$,

  $C_{q\overline{S}} = \partial^2 C/\partial \overline{S} \partial q \leq 0, C_{e\overline{S}} = \partial^2 C/\partial \overline{S} \partial e \geq 0$;

- $A6 : \dfrac{d}{d\overline{S}}(\dfrac{F(\overline{S})}{f(\overline{S})}) \geq 0$ or equivalently $\dfrac{d}{d\overline{S}}(\dfrac{1 - F(\overline{S})}{f(\overline{S})}) \leq 0$ respectively increasing and decreasing in $\overline{S}$ that account for monotone inverse hazard rates properties.

The remaining potential for additional carbon sequestration s_t $(s_t = \overline{S} - S_t)$ reflects asymmetric information with adverse selection through $\overline{S}$ that arises when agricultural firms do not display their real characteristics regarding their potentials for carbon sequestration.

2.3 The social planner objective

As agricultural sustainable practices elevate the quantities of carbon in soils, the accumulated carbon stock in the atmosphere decreases, which raises welfare in the economy. The consumer surplus (V) depends on the sum of the agricultural output $Y_t = \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} y_t f(\overline{S}) d\overline{S}$, on the total sequestered carbon stock $\Sigma_t = \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} S_t f(\overline{S}) d\overline{S}$ and on the total polluting emissions $E_t = \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} e_t f(\overline{S}) d\overline{S}$. The planner social welfare function can then be defined as the sum of the consumer surplus (V) and the profits of all agricultural firms $\Pi = \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \pi(y_t, q_t, s_t) d\overline{S}$, that is $W = V + \Pi$.

The consumer surplus writes:

$$\begin{aligned} V &= U(Y_t, \Sigma_t, E_t) - \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} p_t y_t f(\overline{S}) d\overline{S} - (1+\lambda) \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} T(\overline{S}) f(\overline{S}) d\overline{S} \\ \text{with} \quad U_Y &\geq 0, U_S \geq 0, U_E \leq 0 \\ \text{and Inada conditions} \quad &: \quad U_S(S=0) = +\infty \quad \text{and} \quad \lim_{S \to 0} S U_S = 0 \end{aligned}$$

where λ is the marginal cost of public funds or the opportunity cost of the regulation; $T(\overline{S})$ is the monetary transfer given to the firm to infer carbon sequestration in its plots of lands; p_t is the exogenous market price of the agricultural commodity.

The profit of an agricultural firm is:

$$\pi(y_t, q_t, e_t, s_t) = p_t y_t - C(y_t, q_t, e_t, s_t) + T(\overline{S})$$

Even if the choice variable of the regulator is the level of the subsidy individualized 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 $T(\overline{S})$ needed for allowing a given profit to the firm:

$$T(\overline{S}) = \pi(y_t, q_t, e_t, s_t) - p_y y_t + C(y_t, q_t, e_t, s_t)$$

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

$$\begin{aligned} W &= U(Y_t, \Sigma_t, E_t) \\ &\quad + \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \left[\lambda p_t y_t - \lambda\pi(y_t, q_t, e_t, s_t) - (1+\lambda)C(y_t, q_t, e_t, s_t)\right] f(\overline{S})d\overline{S} \end{aligned}$$

We assume here that all agricultural firms are committed to the policy. In fact, Wu and Babcock (1999) show that voluntary programs in agriculture 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 involved firms is large. From a technical point of view, because of the Inada condition and because the reservation profit of the firm is null under perfect competition, the shutdown of the less efficient firms is never desirable (Laffont and Martimort, 2002).

3 Information and incentives

3.1 The complete information case

With complete information, each agricultural firm potential for additional carbon sequestration denoted by $\overline{S}$ is perfectly known by the planner whose problem of maximizing social welfare is:

$$\begin{aligned}\max_{y_t,q_t,e_t} W &= \int_0^\infty U(Y_t,\Sigma_t,E_t)e^{-\rho t}dt \\ &+ \int_0^\infty \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \left[\lambda p_t y_t - \lambda\pi(y_t,q_t,e_t,s_t) - (1+\lambda)C(y_t,q_t,e_t,s_t)\right] f(\overline{S})d\overline{S}e^{-\rho t}dt\end{aligned}$$

$$st\begin{cases}\pi(y_t,q_t,e_t,s_t)\geq 0\\ s_t=\overline{S}-S_t\\ \dot{S}_t=q_t\ or\ S_t=\int_0^t q_\tau d\tau\leq\overline{S}\\ S_0=0,\mu_0\end{cases}$$

where $\pi(y_t,q_t,s_t,e_t)\geq 0$ is the participation constraint. 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 0. μ_0 is the initial value of the costate variable associated to the sequestration process. The transversality condition is given by $\lim_{t\to\infty} e^{-\rho t}\mu_t q_t = 0$.

Whilst giving a monetary transfer to the firms, the social planner increases firms' profit that is not suitable with regards to social welfare. The social planner would allow to the firms the lowest profits. The participation constraint is therefore binding for all firms, $\pi(y_t,q_t,s_t,e_t)=0$.

The current value hamiltonian $\mathcal{H}$ for the social planner's problem is then:

$$\mathcal{H} = U(Y_t, \Sigma_t, E_t) + \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \left[\lambda p_t y_t - (1+\lambda)C(y_t, q_t, e_t, s_t)\right] f(\overline{S}) d\overline{S} + \mu_t q_t$$

The first-order necessary conditions are (equation (4) with respectively Assumptions A4 and A4'):

$$\begin{aligned}
\frac{\partial \mathcal{H}}{\partial y_t} &= 0 \Leftrightarrow (U_Y + \lambda p_t) = (1+\lambda)C_y & (1)\\
\frac{\partial \mathcal{H}}{\partial q_t} &= 0 \Leftrightarrow \mu_t = (1+\lambda)C_q & (2)\\
\frac{\partial \mathcal{H}}{\partial e_t} &= 0 \Leftrightarrow U_E = (1+\lambda)C_e & (3)\\
-\frac{\partial \mathcal{H}}{\partial S_t} &= \dot{\mu}_t - \rho\mu_t \Leftrightarrow \frac{\dot{\mu}_t}{\mu_t} = \begin{cases} \rho - \dfrac{U_S}{\mu_t} & (A4) \\ \rho - \dfrac{U_S}{\mu_t} - (1+\lambda)\dfrac{C_S}{\mu_t} & (A4') \end{cases} & (4)
\end{aligned}$$

In (1), we have

$$p_t = C_y \qquad (1')$$

as the firm is price taker on the global market ($U_Y = p_t$).

The firm produces the output of perfect competition which equals the market price to its marginal cost.

The optimal amount of polluting emissions is set in (3) by the equality between the marginal damage of emissions ($U_E \leq 0$) and the marginal abatement cost raised by the marginal cost of public funds ($(1+\lambda)C_e \leq 0$). This has important consequences on the level of output and also of carbon sequestration flows. 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. Because these emissions result of the use of fertilizers in order to compensate the loss in yield, we have assumed that $C_{ey} \leq 0$ and $C_{eq} \leq 0$, which give that at the optimum, C_y and C_q are also lower than when ignoring the damage due to the emissions. As a result, the level of output and the flow of carbon sequestration are also lower.

The equation (4) can easily be interpreted when written as

$$\rho\mu_t = \begin{cases} \dot{\mu}_t + U_S & (A4) \\ \dot{\mu}_t + U_S + (1+\lambda)C_S & (A4') \end{cases} \tag{4'}$$

where U is a concave function with a decreasing marginal utility towards the accumulated carbon stock S $(U_S \geq 0, U_{SS} \leq 0)$. Because the flow of carbon sequestration is decreased by the lower optimal level of emissions, the rate of growth of the shadow price of the carbon stock is also lower than when ignoring the damage due to the emissions.

This is a Hotelling rule regarding the exploitation of the exhaustible resource which is the potential for additional carbon sequestration, s. To interpret (4), we refer to the remaining potential for additional carbon sequestration s as the state variable in connection with the accumulated carbon stock S $(s_t = \overline{S} - S_t;\ \dot{s}_t = -q_t)$.

Our cost-benefit analysis 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 discounted 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 potential for additional carbon sequestration is therefore not reduced for the future;

- U_S $(= -U_s)$ is the marginal utility of the representative consumer when the accumulated carbon stock S increases (resp. when the potential for carbon sequestration s is not reduced); this stands for the avoided damage due to carbon sequestration;

- C_S $(= -C_s)$ accounts for the marginal cost when the agricultural firm increases the accumulated carbon stock S (resp. decreases the potential for additional carbon sequestration s).

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.*

3.2 The incomplete information case

With incomplete information, the planner's objective is to derive the social optimum with an *adverse selection* setting. To this end, we lean on the revelation principle (Myerson (1979), Baron and Myerson (1982), Baron (1989)). This direct mechanism allows that the firms reveal their real types $\overline{S}$, *i.e.*, their real potential for additional carbon sequestration unknown by the planner.

The contract is a monetary transfer - sequestration flow contract $\left(T(\overline{S}), q(\overline{S})\right)$ where $T(\overline{S})$ is the subsidy depending on the potential for additional carbon sequestration $\overline{S}$.

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

$$\pi(y_t, q_t, e_t, \overline{S} - S_t, \widetilde{S}) = p_t y_t(\widetilde{S}) - C(y_t(\widetilde{S}), q_t(\widetilde{S}), e_t(\widetilde{S}), \overline{S} - S_t) + T_t(\widetilde{S}) \tag{5}$$

The Incentive Constraints $(IC1, IC2)$ and the Participation Constraint (PC) are

$$IC1 : \pi_{\overline{S}}(y_t, q_t, e_t, \overline{S} - S_t, \widetilde{S})\Big|_{\widetilde{S}=\overline{S}} = -C_{\overline{S}}(y_t(\widetilde{S}), q_t(\widetilde{S}), e_t(\widetilde{S}), \overline{S} - S_t) \geq 0 \text{ as } C_{\overline{S}} \leq 0 \tag{6}$$

The sole rational announce is then $\widetilde{S} < \overline{S}$. This announce is close to $\overline{S}_{\inf}$ in order to get the highest subsidy.

$$IC2 \ : \pi_{\overline{S}\overline{S}}(y_t, q_t, e_t, \overline{S} - S_t, \widetilde{S})\Big|_{\widetilde{S}=\overline{S}} \leq 0$$

$$PC \ : \pi(y_t, q_t, e_t, \overline{S} - S_t) \geq 0$$

Condition (6) gives the positive marginal information rent for the firm: $\pi_{\overline{S}}(y_t, q_t, e_t, \overline{S} - S_t, \widetilde{S}) \geq 0$ because $C_{\overline{S}} \leq 0$. The marginal information rent increases as $\overline{S}$ is greater.

A firm close to $\overline{S}_{\text{sup}}$ uses practices and has initial cultivations which allow one of the highest total sequestration levels. Accordingly, the higher this potential is $(\overline{S} \rightarrow \overline{S}_{\text{sup}})$, the less expensive the sequestration practices are for a high quality of agricultural soils. A firm of type $\widetilde{S}$ will announce the type of the less efficient firm (or close to the less efficient one), $\overline{S}_{\inf}$, in order to get the highest available subsidy $T_t(\widetilde{S})$. The less efficient firm is the only one that cannot understate its potential and therefore that is unable to extract the least information rent.

The information rent is then:

$$\pi(y_t, q_t, e_t, \overline{S} - S_t) = \pi(y_t, q_t, e_t, \overline{S}_{\inf} - S_t) + \int_{\overline{S}_{\inf}}^{\overline{S}} -C_{\overline{S}}(y(\tau), e(\tau), q(\tau), \tau - S_\tau) d\tau \qquad (7)$$

where $\pi(y_t, q_t, e_t, \overline{S}_{\inf} - S_t)$ is the profit of the firm characterized by the lowest potential for additional carbon sequestration, *i.e.*, the reservation profit,

and $\int_{\overline{S}_{\inf}}^{\overline{S}} -C_{\overline{S}}(y(\tau), q(\tau), e(\tau), \tau - S_\tau) d\tau$ accounts for the informational benefit of any firm characterized by a higher potential ($\overline{S}_{\inf} < \overline{S}$).

The monotonicity condition holds as the monotone inverse hazard rate property is a sufficient condition insuring separating contracts (Assumption $A6$). Another Assumption ($A7$) is necessary to set that the iso-profit curves of the agricultural firms cross only once in (T, q); this is the Spence-Mirlees condition or single-crossing property. This leads to the following lemma (See the proof in the Appendix 5.1).

Lemma 2 *The Spence-Mirrlees condition sets that the environmental effort in carbon sequestration activities is greater for the most efficient agricultural firms towards* $\overline{S}_{\sup}$, $\frac{\partial q_t(\overline{S})}{\partial \overline{S}} \geq 0$.

With incomplete information, the planner's problem of maximizing social welfare is to maximize the expected mean $E(W)$, that is

$$
\begin{aligned}
\max_{y_t(\overline{S}),q_t(\overline{S}),e_t(\overline{S})} E(W) &= \int_0^{\infty} U(Y_t,\Sigma_t,E_t)e^{-\rho t}dt \\
&+ \int_0^{\infty}\int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \begin{bmatrix} \lambda p_t y_t - \lambda\pi(y_t,q_t,e_t,s_t) \\ -(1+\lambda)C(y_t,q_t,e_t,s_t) \end{bmatrix} f(\overline{S})d\overline{S}e^{-\rho t}dt
\end{aligned}
$$

$$
st \begin{cases} IC1 \\ IC2 \\ \pi(y_t,q_t,e_t,s_t) \geq 0 \qquad (PC) \\ \dot{S}_t = q_t \ or \ S_t = \int_0^t q_\tau d\tau \leq \overline{S} \\ S_0 = 0, \mu_0 \end{cases}
$$

Integrating (7) by parts leads to (see Appendix 5.2)

$$
\int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \pi(y_t,q_t,e_t,\overline{S}-S_t)f(\overline{S})d\overline{S} = \pi(y_t,q_t,e_t,\overline{S}_{\inf}-S_t) - \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} C_{\overline{S}}(1-F(\overline{S}))d\overline{S} \qquad (8)
$$

Inserting (8) in the expected social welfare $E(W)$, we obtain

$$\begin{aligned}
\max_{y_t(\overline{S}),q_t(\overline{S}),e_t(\overline{S})} E(W) &= \int_0^{\infty} U(Y_t, \Sigma_t, E_t) e^{-\rho t} dt \\
&- \int_0^{\infty} \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \left[(1+\lambda) C(y_t(\overline{S}), q_t(\overline{S}), e_t(\overline{S}), \overline{S} - S_t)\right] f(\overline{S}) d\overline{S} e^{-\rho t} dt \\
&- \int_0^{\infty} \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \left[\lambda \left[(C_{\overline{S}}(y_t(\overline{S}), q_t(\overline{S}), e_t(\overline{S}), \overline{S} - S_t)) \frac{(1 - F(\overline{S}))}{f(\overline{S})}\right]\right] f(\overline{S}) d\overline{S} e^{-\rho t} dt \\
&- \int_0^{\infty} \lambda \pi(y_t, q_t, e_t, \overline{S}_{\inf} - \overline{S}_t) e^{-\rho t} dt
\end{aligned}$$

$$st \begin{cases} \pi(y_t, q_t, e_t, \overline{S}_{\inf} - S_t) \geq 0 \\ \dot{S}_t = q_t \ or \ S_t = \int_0^t q_\tau d\tau \leq \overline{S} \\ S_0 = 0, \mu_0 \end{cases}$$

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 $\lim_{t \to \infty} e^{-\rho t} \mu_t q_t = 0$.

By writing again the current value hamiltonian, one obtains the first-order necessary conditions:

$$p_y = C_y - \frac{\lambda}{(1+\lambda)} \left[\frac{(1 - F(\overline{S}))}{f(\overline{S})} C_{\overline{S}y}\right] \tag{9}$$

$$\mu_t = (1+\lambda) C_q - \lambda \left[\frac{(1 - F(\overline{S}))}{f(\overline{S})} C_{\overline{S}q}\right] \tag{10}$$

$$U_E = (1+\lambda) C_e - \lambda \left[\frac{(1 - F(\overline{S}))}{f(\overline{S})} C_{\overline{S}e}\right] \tag{11}$$

$$\rho \mu_t = \begin{cases} \dot{\mu}_t + U_S & (A4) \\ \dot{\mu}_t + U_S + (1+\lambda) C_S + \lambda \left[\frac{(1 - F(\overline{S}))}{f(\overline{S})} C_{\overline{S}\overline{S}}\right]_t & (A4') \end{cases} \tag{12}$$

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 $q_t(\overline{S})$ set the monetary transfers in our contract design $\left(T(\overline{S}), q(\overline{S})\right)$. Comparing these necessary conditions with the ones obtained with complete information allow us to draw the following conclusions.

Firstly, the firm with the highest potential for additional carbon sequestration produces the optimal agricultural commodity and sequesters carbon with respect to the optimal path (a no-distortion at the top result). All other firms 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 social planner minimizes the cost of this regulation policy by allowing the lowest possible information rents: the profit of the less efficient firm is nil and the others get a subsidy. This leads to distortions to the less efficient firms (Baron and Myerson, 1982)[3]. It is actually a kind of reward because in this model, the lower efficiency of a firm is due either to its sooner adoption of sequestration practices or to the inadequate nature of its soil.

Secondly, because the Hotelling rule is changed by incomplete information about initial conditions, when the cost function exhibits a stock dependency (A4), it follows that incomplete information always slows the sequestration process but does not prevent from obtaining the highest potential for additional carbon sequestration as soon as differentiated subsidies

[3]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).

are provided at each period of time (12), if and only if the global cost is not asymptotic (A4); with A4', the maximal absolute potential cannot be reached even with complete information.

This leads to the following Propositions.

Proposition 3 *With incomplete information, the regulator has to trade-off between the efficiency in the sequestration activities and informational rents allowed to the agricultural firms.*

Proposition 4 *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; differentiated subsidies have to be provided at each period of time. However, the sequestration process is slowed and this relies on the extent of the firms types.*

4 Conclusion

In this paper, we have investigated 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: the *incentive policy* as she offers a rewarding contract, and she might accept the cost of asymmetric information and gives higher subsidies in order to induce revelation by the agricultural firm of its private information; the *full monitoring policy* if this is technically feasible as she monitors the cultivations and management practices of the agricultural firm towards the real sequestered carbon stocks in a perfect and continuous manner to provide subsidies. One of the novelty of our paper is to show that our analysis is strictly similar to the standard problem of the exploitation of a natural exhaustible resource of which available stock is unknown; we proceed by an original way to view carbon sequestration and incentives to agricultural firms in a dynamic setting. The proposed contract has the advantage to avoid the inefficiencies of standard subsidies - per-hectare and per-tonne - by identifying agricultural firms and induce truthful revelation, and to provide a fair reward for each firm. We also show that taking into account the joint externalities of carbon sequestration may lead the regulator to slow down the sequestration process, but without stopping it, when the induced externalities are negative. In the opposite case, the regulator will find optimal to accelerate the process. This result emphasizes the need to accurately evaluate the possible externalities due to carbon sequestration, especially because they are also heterogenous.

Finally, we may consider a few extensions of our model and analysis. Incomplete information would also appear through *moral hazard* which is created by high costs of monitoring implying that firms do not fullfill to their contractual commitment. As we have shown that taking into account the dynamics of carbon sequestration does not modify the standard reasoning about *ex ante* incomplete information, we can then accept the standard result about *ex post* incomplete information, without any additional economic modelling. 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 behaviour by the firm. Throughout the paper, we have assumed that the contract has been signed at the beginning of the first period with full committment between both parts. 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 negociate a new contract from period two. Nevertheless, if adverse selection disappears, moral hazard is very likely to remain through time. In any case, asymmetric information increase the cost of regulation without preventing the regulator to achieve her goals.

Regarding the time length of the contract, in our framework, we could define two stages: the first stage would account for the carbon sequestration process stage while the second stage would represent the stationary carbon level stage[4]. If we suppose that it is never optimal to stop to sequester carbon, the regulator must keep on providing a subsidy to the agricultural firm even if the firm has reached its highest potential for carbon sequestration. This prevents the firm from going back to practices that sequester less carbon in the second stage. The carbon release into the atmosphere is actually quicker than during the sequestration stage[5]. The main difference between these stages is that asymmetric information is not an issue in the second stage. The absolute potential for carbon sequestration can be reached only if the production cost is not asymptotic (Levhari and Liviatan, 1977), *i.e.*, if it does not depend on the remaining potential for carbon sequestration. As we have seen that incomplete information slows the sequestration process, and this postpones the optimal date of the end of the contract.

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

[5]If the carbon value falls under the cost of sequestration, the optimal policy can be different, as 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.

5 References

Antle J., Capalbo S., Mooney S., Elliott E.T. and Paustian K.H., 2002. Sensitivity of Carbon Sequestration Costs to Soil Carbon Rates. Environmental Pollution. 116, 413-422.

Antle J., Capalbo S., Mooney S., Elliott E.T. and Paustian K.H., 2003. Spatial Heterogeneity, Contract Design, and the Efficiency of Carbon Sequestration Policies for Agriculture. Journal of Environmental Economics and Management. 46, 231-250.

Antle J. and Diagana B., 2003. Creating Incentives for the Adoption of Sustainable Agricultural Practices in Developing Countries: The Role of Soil Carbon Sequestration. American Journal of Agricultural Economics. 85(5), 1178-1184.

Baron D. P., 1989. Design of Regulatory Mechanisms and Institutions. in R. Schmalensee and R.D. Willig eds. The Handbook of Industrial Organization. Elsevier North-Holland.

Baron D. P. and Myerson R.B., 1982. Regulating a Monopolist with Unknown Costs. Econometrica. 50, 911-930.

Canton J., De Cara S. and Jayet, P., 2009. Agri-environmental Schemes: Adverse Selection, Information Structure and Delegation. Ecological Economics. 68(7), 2114-2121.

Dale V. and Polasky S., 2007. Measures of the Effects of Agricultural Practices on Ecosystem Services. Ecological Economics. 64(2), 286-296.

De Cara S. and Jayet P., 2000. Emissions of Greenhouse Gases from Agriculture: The Heterogeneity of Abatement Costs in France. European Review of Agricultural Economics. 27(3), 281-303.

De Cara S. and Rozakis S., 2004. Carbon Sequestration through the Planting of Multiannual Energy Crops: A Dynamic and Spatial Assessment. Agricultural Economics Review. 5(1), 56-72.

Feng H., Zhao J. and Kling C.L., 2002. The Time Path and Implementation of Carbon Sequestration. American Journal of Agricultural Economics. 84(1), 134-149.

R.A. Fleming and Adams R.M., 1997. The Importance of Site-Specific Information in the Design of Policies to Control Pollution. Journal of Environmental Economics and Management. 33, 347–358.

Freibauer A., Rounsevell M., Smith P. and Verhagen J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma. 122(1), Pages 1-23.

Goldman R., Thompson B. and Daily, G., 2007. Institutional Incentives for Managing the Landscape: Inducing Cooperation for the Production of Ecosystem Services. Ecological Economics. 64(2), 333-343.

Gonzalez-Estrada E., 2008. Carbon Sequestration and Farm Income in West Africa: Identifying Best Management Practices for Smallholder Agricultural Systems in Northern Ghana. Ecological Economics. 67(3), 492-502.

Gray R. and Fulton, M., 2003. Carbon Sequestration in Agriculture: The Policy Context: Discussion. American Journal of Agricultural Economics. 85(5), 1185-1186.

Havstad, K., 2007. Ecological Services to and from Rangelands of the United States. Ecological Economics. 64(2), 261-268.

Helfand G. and House B., 1995. Regulating Nonpoint Source Pollution under Heterogeneous Conditions. American Journal of Agricultural Economics. 77(4), 1024-1032.

Hung N.M., Poudou J.-C. and Thomas L., 2006. Optimal resource extraction contract with adverse selection. Resources Policy. 31, 78-85.

INRA, 2002. Stocker du carbone dans les sols agricoles en France ?, Report for the french Ministery of Ecology and Sustainable Development.

Krcmar E., van Kooten G., Stennes B. and Vertinsky I., 2001. Carbon Sequestration and Land Management under Uncertainty. European Journal of Operational Research. 135, 616-629.

Kurkalova L., Kling C. and Zhao, J., 2004. Value of Agricultural Non-point Source Pollution Measurement Technology: Assessment from a Policy Perspective. Applied Economics. 36(20), 2287-2298.

Kurkalova L., Kling C. and Zhao J., 2006. Green Subsidies in Agriculture: Estimating the Adoption Costs of Conservation Tillage from Observed Behavior. Canadian Journal of Agricultural Economics. 54(2), 247-267.

Laffont J-J. and Martimort D., 2002. The Theory of Incentives: the Principal-Agent Model. Princeton University Press.

Lal R., Kimble J.M., Follett R.F. and Cole C.V., 1998. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann Arbor MI: Sleeping Bear Press.

Levhari D. and Liviatan N., 1977. Notes on Hotelling's economics of exhaustible resources. Canadian Journal of Economics. 10, pp.177-192.

McCarl, B.A.and Schneider U.A., 2000. Agriculture's Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective. Review of Agricultural Economics. 22, pp.134–159.

Mooney S., Antle J., Capalbo S. and Paustian K., 2004. Design and Costs of a Measurement Protocol for Trades in Soil Carbon Credits. Canadian Journal of Economics. 52(3), 257-287.

Myerson R.B., 1979. Incentive Compatibility and the Bargaining Problem. Econometrica. 47, 61-74.

Pautsch G.R., Kurkalova L.A., Babcock B.A. and Kling C.L., 2001. The Efficiency of Sequestering Carbon in Agricultural Soils. Contemporary Economic Policy. 19, 2), 123-134.

Pendell D., Williams J., Boyles S., Rice C. and Nelson R., 2007. Soil Carbon Sequestration Strategies with Alternative Tillage and Nitrogen Sources under Risk. Review of Agricultural Economics. 29(2), 247-268.

Plantinga A. and Wu J., 2003. Co-benefits from Carbon Sequestration in Forests: Evaluating Reductions in Agricultural Externalities from an Afforestation Policy in Wisconsin. Land Economics. 79(1), 74-85.

Ragot L. and K. Schubert, 2008. The optimal carbon sequestration in agricultural soils: do the dynamics of the physical process matter?. Journal of Economic Dynamics and Control. 32(12), 3847-3865.

Samarawickrema A. and Belcher K., 2005. Net Greenhouse Gas Emissions and the Economics of Annual Crop Management Systems. Canadian Journal of Agricultural Economics. 53(4), 385-401.

Schneider U.A., 2002. The Cost of Agricultural Carbon Savings. Working Paper 02-WP 306, Center for Agricultural and Rural Development, Iowa State University.

Schulze E. D., Luyssaert S., Ciais P., Freibauer A., Janssens I. A. et al., 2009. Importance of Methane and Nitrous oxide for Europe's Terrestrial Greenhouse-Gas Balance. Nature

Geoscience. 686, 842-851, doi: 10.1038/ngeo686.

Singh B.R. and Lal R., 2005. The Potential of Soil Carbon Sequestration through Improved Management Practices in Norway. Environment, Development and Sustainability. 7, 161–184.

Sperow M., Eve M. and Paustian K., 2003. Potential soil C sequestration on US agricultural soils. Climatic Change. 57(3), 319–339.

Weersink A., Pannell D., Fulton M. and Meyer-Aurich A., 2005. Agriculture's Likely Role in Meeting Canada's Kyoto Commitments. Canadian Journal of Agricultural Economics. 53(4), 425-441.

Wu J. and Babcock B., 1996. Contract Design for the Purchase of Environmental Goods from Agriculture. American Journal of Agricultural Economics. 78(4), 935-945.

Wu J. and Babcock B., 1998. The Choice of Tillage, Rotation, and Soil Testing Practices: Economic and Environmental Implications. American Journal of Agricultural Economics. 80(3), 494-511.

Wu J. and Babcock B., 1999. The Relative Efficiency of Voluntary vs. Mandatory Environmental Regulations. Journal of Environmental Economics and Management. 38(2), 158-175.

Young, L., 2003. Carbon Sequestration in Agriculture: The U.S. Policy Context. American Journal of Agricultural Economics. 85(5), 1164-1170.

Young L., Weersink A., Fulton M. and Deaton, B., 2007. Carbon Sequestration in Agriculture: EU and US Perspectives. EuroChoices. 6(1), 32-37.

6 Appendix

6.1 The single-crossing property

The Spence-Mirrlees condition or single-crossing property can accordingly be derived from any firm profit function as follows:

$$\begin{aligned}
\frac{\partial}{\partial \overline{S}}\left[\frac{\partial \pi(\widetilde{S})}{\partial \widetilde{S}}\right] &= 0 \\
&\Leftrightarrow \frac{\partial \pi^2}{\partial \overline{S}^2} + \frac{\partial \pi^2}{\partial \widetilde{S} \partial \overline{S}} = 0 \text{ where } \frac{\partial \pi^2}{\partial \overline{S}^2} \leq 0 \text{ and } \frac{\partial \pi^2}{\partial \widetilde{S} \partial \overline{S}} \geq 0
\end{aligned}$$

$$\frac{\partial \pi^2}{\partial \overline{S}^2} \leq 0 \text{ from profit maximizing second-order condition}$$

and

$$\frac{\partial \pi^2}{\partial \widetilde{S} \partial \overline{S}} \geq 0 \text{ as}$$

$$\begin{aligned}
\frac{\partial \pi^2}{\partial \widetilde{S} \partial \overline{S}} &= -C_{y\overline{S}} \frac{\partial y_t}{\partial \widetilde{S}} - C_{q\overline{S}} \frac{\partial q_t}{\partial \widetilde{S}} - C_{e\overline{S}} \frac{\partial e_t}{\partial \widetilde{S}} \geq 0 \\
\text{where } C_{y\overline{S}} &\leq 0, \; C_{q\overline{S}} \leq 0 \text{ and } C_{e\overline{S}} \geq 0 \; (A5)
\end{aligned}$$

which leads

$$\begin{aligned}
-C_{y\overline{S}} \frac{\partial y_t}{\partial \widetilde{S}} &\geq C_{q\overline{S}} \frac{\partial q_t}{\partial \widetilde{S}} + C_{e\overline{S}} \frac{\partial e_t}{\partial \widetilde{S}} \\
&\Leftrightarrow \frac{\partial y_t}{\partial \widetilde{S}} \geq \frac{-C_{q\overline{S}}}{-C_{y\overline{S}}} \left|\frac{\partial q_t}{\partial \widetilde{S}}\right| + \frac{-C_{e\overline{S}}}{-C_{y\overline{S}}} \left|\frac{\partial e_t}{\partial \widetilde{S}}\right|
\end{aligned}$$

that is a sufficient condition for

$$\frac{\partial y_t}{\partial \widetilde{\overline{S}}}_{\widetilde{S}=\overline{S}} \geq 0 \text{ and } \frac{\partial q_t}{\partial \widetilde{\overline{S}}}_{\widetilde{S}=\overline{S}} \geq 0$$

6.2 Integration by parts

Integrating (7) by parts leads to

$$\int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \pi(y_t, q_t, e_t, \overline{S} - S_t) f(\overline{S}) d\overline{S} = \pi(y_t, q_t, e_t, \overline{S}_{\inf} - S_t) - \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} C_{\overline{S}}(1 - F(\overline{S})) d\overline{S} \qquad (8)$$

as

$$\begin{cases} F(\overline{S}) = prob(S < \overline{S}) \\ G(\overline{S}) = 1 - F(\overline{S}) = prob(S > \overline{S}); 1 - G(\overline{S}) = F(\overline{S}) = prob(S < \overline{S}) \\ G(\overline{S}_{\sup}) = 0, G(\overline{S}_{\inf}) = 1 \\ F'(\overline{S}) = f(\overline{S}) < 0; G'(\overline{S}) = -f(\overline{S}) > 0 \end{cases}$$

and

$$\begin{aligned} \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} \pi(y_t, q_t, e_t, \overline{S} - S_t) f(\overline{S}) d\overline{S} &= -\left[\pi(\overline{S}) G(\overline{S})\right]_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} - \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} C_{\overline{S}} G(\overline{S}) d\overline{S} \\ &= \pi(\overline{S}_{\inf}) - \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} C_{\overline{S}} G(\overline{S}) d\overline{S} \\ &= \pi(\overline{S}_{\inf}) - \int_{\overline{S}_{\inf}}^{\overline{S}_{\sup}} C_{\overline{S}}(1 - F(\overline{S})) d\overline{S} \end{aligned}$$