Carbon sequestration through the planting of multi-annual energy crops: A dynamic and spatial assessment

Paper prepared for the 48th Annual AARES Meeting, 12-13 Feb

Stéphane De Cara (`stdecara@grignon.inra.fr`)
INRA, UMR "Économie Publique" INRA/INA PG, Centre de Grignon, BP 01, 78 850 Thiverval-Grignon, France, Tel: +33 1 30 81 53 48.

Stelios Rozakis (`stelios.rozakis@grignon.inra.fr`)
INRA, UMR "Économie Publique" INRA/INA PG and University of Crete at Rethymnon, Department of Economics

Abstract. We examine the spatial and dynamic implications of policies aimed at encouraging carbon sequestration in agricultural soils. We consider incentive mechanisms to encourage the planting of energy multi-annual crops that allow higher carbon sequestration rates for a longer period of time. By using a dynamic micro-economic model, we simulate the sequence of crop plantings over a given time horizon and investigate different payment mechanisms (per-ton or per-hectare). We discuss their implications in terms of regulation policy and efficiency. This model is then applied to the Central Plains of Thessaly, Greece, to assess the marginal costs of carbon sequestration and the optimal timing of switching to multi-annual energy crops. To do so, we couple the dynamic microeconomic model with a carbon accounting model and a geophysical database. We provide an assessment of the potential loss of efficiency related to the use of constant per-hectare payments. We also discuss the dynamic implications of these mechanisms, as well as their results in terms of spatial distribution.

Keywords: Carbon sequestration; climate change; Greece; energy crops; dynamic mathematical programming.

JEL codes: Q25; Q15.

Carbon sequestration through the planting of multi-annual energy crops: A dynamic and spatial assessment

Abstract. We examine the spatial and dynamic implications of policies aimed at encouraging carbon sequestration in agricultural soils. We consider incentive mechanisms to encourage the planting of energy multi-annual crops that allow higher carbon sequestration rates for a longer period of time. By using a dynamic micro-economic model, we simulate the sequence of crop plantings over a given time horizon and investigate different payment mechanisms (per-ton or per-hectare). We discuss their implications in terms of regulation policy and efficiency. This model is then applied to the Central Plains of Thessaly, Greece, to assess the marginal costs of carbon sequestration and the optimal timing of switching to multi-annual energy crops. To do so, we couple the dynamic microeconomic model with a carbon accounting model and a geophysical database. We provide an assessment of the potential loss of efficiency related to the use of constant per-hectare payments. We also discuss the dynamic implications of these mechanisms, as well as their results in terms of spatial distribution.

Introduction

Meeting the targets set by the Kyoto Protocol (UNFCCC, 1997) may result in high costs in a number of Annex I countries. It is this specific argument[1] that some of the initial signatory countries – among which the US, also the largest greenhouse gas (GHG) emitter in the world – have put forward advocating their withdrawal from the on-going international negotiations and from any resulting commitment. Among the remaining countries, the costs of complying with their commitment may be unnecessarily high if the efforts undertaken to reduce GHG emissions rely solely on carbon dioxide emissions from fossil fuel use (Manne and Richels, 2001; Burniaux, 2000; Reilly et al., 1999; Hayhoe et al., 1999).

Widening the scope of policy measures to include carbon sinks in agricultural soils has thus often been promoted by land-rich countries as a means of lowering the economic burden associated with emission reductions (Smaglik, 2000). Since the mid-nineties, this issue has been highly controversial in the debate over the means of achieving a global reduction in GHG emissions (IPCC, 2000; Schlesinger, 2000; Lal and Bruce, 1999).

Indeed, the inclusion of carbon sinks raises a number of issues mainly because of the short-run nature of abatements achieved by this means. On one hand, carbon sequestration may help to “buy time” (USDA, 2003) by providing a fast and relatively inexpensive means of reducing carbon dioxide concentrations within the time frame set by the Kyoto Protocol. On the other hand, reductions of this nature are not fully equivalent to emission reductions because sequestered carbon can be released quickly into the atmosphere as a result of a future change in the practices and/or land-use (Arrouays et al., 2002). Furthermore, soils are subject to saturation in the long-run and can only sequester a limited amount of carbon per hectare (McCarl et al., 2001). Consequently, the environmental gains that can be obtained thanks to carbon sequestration in agricultural soils are necessarily limited and temporary, as they correspond to the *transitional* path between two steady state levels of carbon stocks.

As pointed out by Feng et al. (2002), the non-permanent nature of carbon stocks in soils makes abatements achieved in this way essentially different from those obtained by avoiding CO_2 emissions. From an economic perspective, the issue is thus to assess how the value of one *additional* unit of carbon sequestered now in agricultural soils compares with what can

---

[1] On March 29, 2001, US President G.W. Bush stated: “We will be working with our allies to reduce greenhouse gases. But I will not accept a plan that will harm our economy and hurt American workers.”

be obtained from one unit of CO_2 avoided now (Feng, 2002; McCarl et al., 2001).[2] However, despite the necessary caveats surrounding the definition of the *environmental* value of carbon sequestration, the fact that signatory countries of the Kyoto Protocol can refer to Article 3.4 in their national inventory endows *de facto* carbon sinks with a positive – even though temporary – *economic* value.

Actually, the permanence issue can be addressed by distinguishing between *accumulation* of carbon in soil and *storage* of carbon. Accumulation consists in the increase of carbon stocks in soils and is a positive flux. Arguably, accumulation provides a positive externality, as it offsets CO_2 from the atmosphere and results in a reduction of atmospheric CO_2 concentration. Storage is slightly different as it pertains to avoided emissions (Antle et al., 2001). Up to the saturation point, farmers can provide services that take the form of both accumulation and storage of carbon. Beyond this point, no further accumulation is possible and the services provided by farmers are restricted to their maintaining of a given level of carbon stock.

In a first-best world, the dynamics of carbon stocks should thus be explicitly taken into account in the design of policies aimed at efficiently reducing GHG emissions. In other words, the issue is not only to assess how farmers will instantaneously change their practices and land allocation in response to some policy mechanisms, but also to assess the long-run effects of these measures. The timescale over which carbon sequestration is considered in the analysis is critical in this assessment (Ingram and Fernandes, 2001), particularly when dealing with multi-annual crops.

The role of agriculture in the accumulation of GHG in the atmosphere goes beyond carbon sequestration[3]. The agricultural sector is also a major emitter of methane and nitrous oxide. Several studies have estimated the costs of reducing GHG emissions from agriculture. Using a supply-side, linear-programming based model, De Cara and Jayet (2000) estimate these costs in French agriculture and extend these estimates to the European Union (2001). In addition to methane and nitrous oxide emissions from agricultural activities, the model used in this study accounts for carbon sequestration in soils and trees. The authors provide estimates of marginal and total abatement costs faced by farmers, as well as the optimal "mitigation mix" for a large

---

[2] Inventory-based studies usually rely on the use of average emissions coefficients for various cropping systems and a conversion factor ($\frac{12}{44}$) between carbon and carbon dioxide based on the carbon contents of CO_2. This is also the approach retained in the IPCC guidelines on inventory-methods for the national accounting of GHG emissions (Intergovernmental Panel on Climate Change, 1996).

[3] For a comprehensive presentation of sources of GHG emissions in the agricultural sector, see for example OECD/OCDE (2002).

range of abatement costs. A study carried out by McCarl and Schneider (2001) – based on a similar modeling approach – estimates abatement costs and potentials for US agriculture (see also Schneider (2000) for a detailed presentation of the model used). This type of modeling, however, does not give an appropriate account of the dynamics of carbon sequestration, but mostly relies on average changes in carbon stocks applied to instantaneous area changes. The same argument applies to approaches that retain econometric-based estimates of land-use elasticities to quantify the opportunity costs of converting land to more carbon-sequestering cropping systems and/or practices (Newell and Stavins, 2000; Plantinga et al., 1999).

Spatial heterogeneity with respect to carbon potentials and abatement costs[4] is also a key-dimension in this issue. Indeed, it is easily understandable that if the parameters defining carbon-sequestration potentials and abatement costs vary widely across fields in a given area, contracts that offer constant per-hectare payments to farmers are not efficient. On the other hand, first-best per-ton payments induce high monitoring costs, since actual on-site measurement are needed. Acknowledging the importance of monitoring costs and spatial heterogeneity of carbon-sequestration potentials, Antle et al. (2003) compare the relative efficiency of different contract-settings (per-hectare or per-ton). They use an econometric-process modeling approach to describe farmers' decisions in terms of land-use (Antle et al., 2001). One of the originalities of this study lies in their analysis of the trade-off between monitoring costs (per-ton contracts) and loss of efficiency (per-hectare contracts).

The purpose of the present paper is to develop methods to assess carbon-sequestration costs and potentials in agricultural soils, taking into account both spatial and dynamic dimensions. In particular, we investigate the possibility for farmers to switch to multi-annual cropping systems, which allow higher rates of carbon sequestration for a longer period of time. Beyond the assessment of carbon-sequestration costs and potentials, we examine the timing and the spatial distribution of carbon sequestration. These two dimensions (when and where does sequestration occur?) are indeed of great interest to policy makers in their assessment of what can be achieved through the implementation of mitigation policies.

In this paper, we propose an empirical assessment of the carbon sequestration potentials and abatement costs for the Central Plains of Thessaly, Greece. The coupling of a dynamic microeconomic model, a carbon module to assess carbon sequestration, and a geo-referenced

---

[4] Spatial heterogeneity with respect to emissions from agriculture has been explored at the European Union level by Freibauer (2003).

database enables us to discuss the regional supply of carbon sequestration allowed by substitution of annual crops with multi-annual energy crops.

The possibility of substitution of multi-annual crops for cotton and wheat in irrigated and in dry land, respectively, is examined. Both cotton – which has practically become a mono-culture in the area of study – and durum wheat are subject to co-responsibility payments in the context of the EU Common Agricultural Policy (CAP). As a matter of fact, a member State exceeding its aggregate production quota bears a reduction in the intervention price. This mechanism, however, has failed to restrain Greek cotton production[5]. In the recent years, the Greek cotton production boomed despite the quota, therefore triggering reductions in cotton intervention prices. This in turn has been provoking loud protests by the Greek cotton growers in recent years about shrinking farm incomes, and highlights the need for alternative crops.

Energy crops can provide such an alternative. They have been widely cultivated in Europe especially since the 1992 reform of the CAP. This reform established mandatory set aside, on which non-food crops are allowed to be grown. As environmental global issues become of prime importance, the European Union attempts to comply with its international commitments promoting substitutes to fossil fuels. Bio-energy cannot, however, become profitable for farmers without being subsidized. This is the case in France and other leading European countries, where tax exemptions are applied to bio-fuel production. The burden to the budget is justified to the taxpayers on environmental benefits grounds. Carbon sequestration has been assessed along with other environmental benefits that result from bio-energy production in Thessaly, using multi-criteria methodology (Rozakis et al., 2001). Compromise solutions pointed out in this study are based on ex post trade-offs over several criteria, including: carbon sequestration, CO_2 abatements due to substitution for fossil fuels, production costs, employment, value added, etc. In the present paper, the crop-mix decision process takes into account carbon sequestration as an endogenous variable, allowing to assess specifically carbon-oriented policy instruments.

The paper is organized as follows. In section 1, we present a stylized dynamic model that describes the inter-temporal choices of farmers in terms of land-use within a feasible set of crops that differ in their carbon-sequestration potentials. In section 2, we discuss the specificities of the region of the study – Thessaly, Greece – in terms of initial land-use patterns, crop substitution possibilities, and spatial heterogeneity. We also present briefly the carbon accounting method

---

[5] See USDA-FAS (2003) for a brief description of the European cotton policy.

and discuss the assumptions we make in the application of the model derived from Section 1. In section 3, we discuss the results. Finally, we draw from our analysis some conclusions in terms of policy-making.

1. A micro-economic, land-unit based, dynamic model of land use

1.1. GROSS MARGIN MAXIMIZATION PROBLEM

We first study the problem faced by a farmer who has to plan the sequence of planting on the k-th land-unit for a finite time horizon T. We consider the corresponding discrete-time, discounted gross margin maximizing program. When no policy is in place, the objective function of the program is written as the net discounted value of the gross margin generated on the k-th land-unit (π_k).

$$\pi_k = \sum_{t=1}^{T} \left(\frac{1}{1+\rho}\right)^{t-1} \sum_{j \in J} \left(p_{t,j}.r_{t,j,k} - c_{t,j,k}\right) a_{t,j,k}$$

where $a_{t,j,k}$ is the area in crop $j \in J$ at date $t \in \{1, \ldots, T\}$ on land-unit $k \in K$ land-unit. J is the feasible set of crops, among which farmers can choose. K is the set of land units in the region. We denote by $p_{t,j}$ the expected price of crop j at time t. The yields and per-hectare variable cost are denoted $r_{t,j,k}$ and $c_{t,j,k}$, respectively. The discount rate ρ is assumed to be constant over the time horizon and across the farmers.

To compute the variations of carbon stocks in soils, we need to consider *when* each hectare[6] was planted in crop j. Therefore we rewrite $a_{t,j,k}$ as the sum

$$a_{t,j,k} = \sum_{l=0}^{t} \alpha_{t,l,j,k} \tag{1}$$

where $\alpha_{t,l,j,k}$ is the area in crop j remaining at date t and that was planted at date l. In the case of annual crops ($j \in J_a$, J_a being the subset of J containing annual crops), we thus have $\alpha_{t,l,j,k} = 0$, $\forall l < t$ and $a_{t,j,k} = \alpha_{t,t,j,k}$.

---

[6] Indeed, at this level of generality, $\alpha_{t,l,j,k}$ can also stand for different practices, such as no- or reduced-tillage. This dimension is highly relevant to carbon sequestration issues. However, since the applied analysis carried out in Section 3 focuses on the effect of switching to multi-annual cropping systems vs the continuation of annual crops, we retain here an interpretation in terms of land-use rather than in terms of practices.

1.2. CROP ROTATION CONSTRAINTS

We assume that it is too costly to uproot multi-annual crops before the end of their useful life. As a consequence, we assume that if one hectare is planted at a date t in crop $j \in J_m$ (J_m standing for the set of multi-annual crops), for which the useful life is τ_j, the same hectare has to remain planted in crop j for the entire period of time $[t, ..., t + \tau_j - 1]$. To capture the impact of the possibility of multi-annual cropping, we thus consider the following sets of constraints:

$$\alpha_{t,t,j,k} = \alpha_{t+1,t,j,k} = \ldots = \alpha_{t+\tau_j,t,j,k} \ \ \forall \{t, j, k\} \in \{1, \ldots, T\} \times J_m \times K \tag{2}$$

As a result of equations (2), it comes that the total area planted in a specific multi-annual crop cannot decrease before the end of its useful life.[7]

In addition, the program has to verify the following area-availability and positivity constraints:

$$\begin{aligned} \sum_{j \in J} a_{t,j,k} &\leq A_k \ \ \forall \{t, k\} \in \{1, \ldots, T\} \times K &(3)\\ a_{t,j,k} &\geq 0 \ \ \forall \{t, j, k\} \in \{1, \ldots, T\} \times J \times K &(4)\\ \alpha_{t,l,j,k} &\geq 0 \ \ \forall \{t, l, j, k\} \in \{1, \ldots, T\}^2 \times J \times K &(5) \end{aligned}$$

where A_k is the total arable area available in land-unit k.

When no particular instrument is operating to encourage carbon sequestration, the program for land-unit k is thus the following:

$$(P_k^{NR}) \quad \max_{\{\alpha_{t,l,j,k}\}_{t,l=1,\ldots,T, j \in J}} \quad \pi_k \qquad \text{s.t.} \quad (1) - (5)$$

1.3. CARBON ACCOUNTING

The sequestration of carbon is assumed to depend on soil characteristics (ϕ_k) and on changes in land-use. Consequently, the additional amount of carbon sequestered on land-unit k, ΔC_k, is written as follows:

$$\Delta C_{t,k} = f(\{\alpha_{t,l,j,k}\}_{\{l \in \{0,\ldots,t\}; j \in J\}}; \phi_k) \tag{6}$$

---

[7] This assumption can be seen as rather strong and should be relaxed in further research. Nevertheless, the cost of uprooting the multi-annual crops is likely to exceed the discounted benefits that can be expected from switching land back to annual cropping systems. It seems also realistic to imagine carbon-sequestration contracts by which farmers commit themselves to keep multi-annual crops for a pre-determined period of time. This assumption tends to favor annual crops over multi-annual crops, as it increases the opportunity cost associated to multi-annual cropping systems.

Note that the amount of carbon sequestered on land-unit k depends on the whole history of land-use on the land-unit considered ($\{\alpha_{t,j,k,l}\}_{l=0,\dots,t,j\in J}$), and not simply on the area planted at date t. [8]

1.4. PER-TON CONTRACT VS. PER-HECTARE CONTRACTS AND THE VALUE OF INFORMATION

We now consider mechanisms aimed at encouraging carbon sequestration. As carbon sequestration provides a positive externality, we examine the role of payments made to farmers to switch to carbon-sequestering cropping systems. The subsidy paid to farmer k at date t is denoted by $G_{t,j,k}$.

The program that defines the sequence of plantings on land-unit k is thus modified accordingly:

$$(P_k^R) \quad \max_{\{\alpha_{t,l,j,k}\}_{t,l=1,\dots,T,j\in J}} \quad \pi_k = \sum_{t=1}^{T} \left(\frac{1}{1+\rho}\right)^{t-1} \left(\sum_{j\in J} \left(p_{t,j}.r_{t,j,k} - c_{t,j,k}\right) a_{t,j,k} + G_{t,j,k}\right)$$
$$\text{s.t.} \quad (1) - (6)$$

Following Antle et al. (2003), we consider two types of incentive mechanisms: a per-ton subsidy, $q_t.\Delta C_{t,k}$, and a per-hectare payment, $s_{t,j,k}.a_{t,j,k}$). q_t pertains directly to the social value of carbon. In a first-best world, q_t should reflect the marginal value of damage related to climate change, either obtained as the current price on a well-functioning carbon market or directly set by the regulator. $s_{t,j,k}$ should be equal to the value of per-hectare carbon sequestration (the value of a ton of carbon times a per-hectare coefficient of sequestration). To implement the first-best outcome, this instrument should thus be –unlike a per-ton subsidy– individualized to reflect the heterogeneity across land-units in terms of per-hectare sequestration potentials. If based on average sequestration factors (as it is the case if $s_{t,j,k} = \frac{1}{K}\sum_{k\in K} \Delta C_{t,k}/a_{t,j,k}$), this instrument leads to higher costs of sequestration for the same quantity of sequestered carbon.

As pointed out by Antle et al., two features make the comparison between per-ton and per-hectare contracts interesting: *(i)* the heterogeneity of sequestration costs across farmers, and *(ii)* the cost of measuring the sequestration actually achieved. Heterogeneity with respect to abatement costs would be easily overcome through the use of a per-ton mechanism, which

---

[8] In the spirit of the Kyoto commitments, $\Delta C_{t,k}$ should actually be seen as the difference with a *baseline scenario* of carbon path. Defining baseline scenarios for carbon sequestration can itself be problematic. In the subsequent analysis, the baseline scenario consists in the continuation of cultivating only annual crops. Carbon sequestration allowed by these cropping systems is thus taken as the reference.

theoretically enables the implementation of the first-best outcome. However, the implementation of per-ton contracts requires on-site monitoring and therefore involves potentially high costs. On the other hand, a constant per-hectare payment does not allow to achieve efficient levels of sequestration. In fact, by offering all the farmers the same per-hectare payment whatever their abatement costs are, such a system tends to overpay (underpay) sequestration on the less (more) efficient fields. Nevertheless, this type of contracts is likely to be cheaper in terms of monitoring costs, as monitoring relies solely on the observation of land-use. In other words, the ranking of these two instruments in terms of total welfare is not straightforward and depends on the gap between losses of efficiency and monitoring costs.

Indeed the difference between per-ton and per-hectare contracts lies in the information that can be accessed to by the regulator. In a per-ton contract, no specific ex-ante information is needed but ex-post monitoring costs may be high. By contrast, if per-hectare payments rely on a constant per-crop emission factor, the regulator does not need a detailed information on the repartition of the abatement costs among farmers, as only average emission factors are required. But the latter type of contract involves incentives that lead to efficiency losses. The greater the heterogeneity between abatement costs is, the higher efficiency losses are. Per-hectare payments may thus be a second-best if the cost of collecting ex-post on-site accurate data exceeds the loss of efficiency.

1.5. Measuring the costs of carbon sequestration

Introducing a per-ton payment enables us to estimate carbon sequestration costs both at the regional and land-unit levels. For a given level of per-ton payment, the farmers will face a trade-off between *(i)* continuing annual-cropping systems that yield higher profits, and *(ii)* converting land to multi-annual cropping systems that enable higher rates of carbon sequestration and, therefore, higher carbon subsidies. By parameterizing the per-ton subsidy in the model, we thus obtain the level of carbon sequestration supplied by farmers for each value of carbon. This supply curve of carbon sequestration also defines the marginal costs of carbon sequestration.[9]

---

[9] Another way to estimate abatement costs would be to introduce a constraint that imposes a minimum quantity of carbon sequestration (say $\bar{Q}$) for a given land-unit in the initial program P_k^{NR}. The shadow price associated with this constraint would thus reflect the marginal variation of the discounted gross margin due to a marginal variation of the required level of carbon sequestration, namely the marginal cost of carbon sequestration (see De Cara and Jayet (2000) for a detailed presentation of this method and its equivalence with the "primal" computation of abatement costs).

Another key-dimension in farmers' decision-making relates to the *timing* of planting multi-annual crops. The trade-off lies then between *(i)* switching land to multi-annual cropping systems early on to benefit from the carbon subsidy for a longer period of time and *(ii)* converting land later on to get higher profit with annual crops in the early years. This inter-temporal decision will strongly depend on the discount rate assumption and the relative price paths of the different crops.

2. Application to the region of Thessaly, Central Greece

2.1. CURRENT LAND-USE PATTERNS

In Thessaly, which is one of the most dynamic and endowed, in terms of natural resources, agricultural regions of Greece, cotton cultivation has significantly expanded in the last fifteen years to cover more than 0.4 Mha today. Price security and state investments in irrigation infrastructure resulted in private investment in irrigation and mechanization. As a consequence, traditional rotation schemes were abandoned and cotton mono-culture has come to dominate arable land farming, with all the resulting negative effects on the environment stemming from increased input use, namely fertilizers, water and pesticides. In recent years, Greek cotton production has overwhelmed the Common Agricultural Policy maximum guaranteed quantities and triggered co-responsibility penalties, resulting in lower price subsidies for cotton farmers. This fact – combined with an increased exposure to risk because of the expansion of cotton mono-culture – has raised farmers discontent and pushed them to seek alternative crops for arable land. Wheat (durum) is essentially cultivated on dry land and does not provide a credible alternative to cotton, as durum wheat production is also subject to binding caps in terms of subsidy in the region.

Several proposals have been examined, such as to support livestock and cultivate feed crops or alternatively to promote energy crops by supporting bio-energy regional projects to generate electricity. These projects are seriously discussed as they present multiple benefits are in line with EU directives on renewable energy development. We focus in the present study on the substitutions of wheat and cotton by two energy crops. Table I summarizes the possible substitutions for the major annual crops.

Table I. Substitution energy crops options (future) for current agricultural cultivations

Land-type	Energy crop potentially cultivated
Non-agricultural use	-
Winter crops (wheat, barley)	*Cynara cardunculus*
Summer crops (cotton, corn)	*Cynara cardunculus* *Miscanthus sinensis*
Pastures etc.	-

A study, that evaluated the bio-electricity production in the area, defined ranges of farm gate prices for the energy crops, taking into account available technologies, the electricity market and institutional framework of renewable energy development in Greece (Varela et al., 2001).

2.2. DATA AND ASSUMPTIONS

The price path for wheat is computed from the nominal projections provided by FAPRI (2003) for the European Union market and converted into Euros using exchange rates from the same source. Wheat production in the region is essentially composed of durum wheat. The starting point of wheat price is taken from European Commission (2002). This price includes the CAP durum subsidy and a durum-specific premium, both of which being kept constant for the whole planning period. Initial situation with regard to cotton price is taken from USDA-FAS (2003) (EUR 74 per mt). We assume that, starting from this point, the price will meet the world price by 2007 and increase accordingly to the FAPRI US farm price projection thereafter. As prices for miscanthus and cynara are essentially pre-determined by contracts, they are kept constant for the whole simulation period. As for yields, we assume the average annual growth rates computed from FAPRI projections for EU wheat and cotton. The variable costs for each crop are derived from an accounting model, that enables to breakdown the costs of multi-annual crops in order to make them comparable to those of annual cropping systems (Soldatos, 2002). These assumptions are summarized in Table II.

We assume a planning horizon of ten years. This assumption is compatible with the time frame set by the Kyoto Protocol as it pertains to the end of the commitment period (2008-12). Furthermore, we assume that the useful life of multi-annual crops is also ten years. A direct consequence of this assumption is that once miscanthus or cynara is planted on one land-unit,

Table II. Data and assumptions

Crop	Yields					Area	Prices		Var. Costs
	Avg. mt/ha	Std Dev.	Min mt/ha	Max mt/ha	Avg growth %	2002 tha	2002 EUR/mt	2012 EUR/mt	
wheat	3.52	0.681	2.10	5.00	1.1	16,347	220	207	578
cotton	3.33	0.375	2.30	3.90	0.6	6,822	740	350	642
cynara	22.33	4.511	10.00	30.00	- *	-*	70	70	1,752
miscanthus	44.79	2.855	35.00	50.00	- *	-*	55	55	2,390

* Only experimental plantations of miscanthus and cynara exist at this moment in the area.

the program is constrained to select it until the end of the simulation period on this land-unit. The assumed discount rate is 5%.

2.3. GEO-PHYSICAL DATABASE

The region of study is a flat and hilly area, a part of the Thessaly plain, located in central Greece with an average farm size larger than the average for the entire plain. The Spot XS image used focuses on an area about 45,000 ha large extended around Farsala. Based on the satellite image, additional maps (road infrastructure, electrical network, population concentration, district boundaries) were geo-referenced and digitized.

Elementary units are land-units as defined by the GIS (Geographical Information System). These land units aggregate homogeneous land pieces (pixels) that belong to the same class. Adjacent pixels of the same class form a land unit (LU, in total 12,395 land units). Through the databases created, information regarding agricultural land was processed to distinguish land classes: land unit with similar soil type, slope, and current land use were gathered in the same class. In this case study, the number of classes totaled 1,090. After obtaining this information, expert knowledge was used to estimate yields of all conventional and energy crops examined for each class. As previously mentioned, two multi-annual herbaceous crops (cynara and miscanthus), which are of specific interest in Southern Europe, were considered. Information on yields of traditional crops is very important as it determines the benefits on which the opportunity cost of land depends. Yields also determine total quantity that a land unit may supply to the plant and consequently affect the particular shape of supply curves.

2.4. DYNAMIC ACCOUNTING OF CARBON SEQUESTRATION

GORCAM (Graz/Oak Ridge Carbon Accounting Model) is a spreadsheet model that has been developed to calculate the net fluxes of carbon to and from the atmosphere associated with land management and biomass utilization strategies. The model can be applied at various levels (stand, landscape, regions, country), allows consideration of age-class dynamics and accounts for all effects along the full life cycle of wood products and bio-fuels.

The model focuses on the carbon stock change when a change in land-use occurs. The model considers changes of carbon stored in three different carbon pools: *(i)* vegetation pool: living below (woody and fine roots) and above ground (stems, branches, foliage etc.), biomass; *(ii)* dead organic matter pool: dead plant material of woody and non-wood debris as well as dead roots ; and *(iii)* soil pool: dead organic matter (humus) in the mineral soil.

The flux from the atmosphere represents the net primary production (NPP) of the crops as the net carbon uptake. Dead plant material is transferred from the “Vegetation” pool to the “Dead organic matter” pool, with woody litter production being a function of the vegetation pool size. Decay of organic matter in the “Dead organic matter” pool produces CO_2 that is directly emitted to the atmosphere, and some carbon is added to the “Soil” carbon pool, which itself also releases CO_2 (Schlamadinger et al., 2003).

This model takes soil characteristics, land-use changes, and yields as inputs. The parameters defining each class have been used to run the model and compute the carbon sequestration parameters in tCO_2 for a given time-horizon. The main results in terms of carbon sequestration parameters are summarized in Table III.

Table III. Descriptive statistics on carbon sequestration parameters

	Unit	Average	Standard Deviation	Min	Max
class area	ha	56.52	59.009	1.01	276.83
Cotton to cynara	tCO_2/ha/yr	0.80	0.946	0.00	2.66
Cotton to miscanthus	tCO_2/ha/yr	1.58	0.489	0.23	2.39
Wheat to cynara	tCO_2/ha/yr	3.14	3.633	0.00	8.35

*Source: LUC model adapted by H. Schwaiger in (*Varela et al., 2001*), ch.5*

3. Results

3.1. Regional supply of carbon sequestration

Using the parameters computed as described in the previous section, we can now solve the model for each class retained in the analysis.[10]

The first step of our analysis consists in determining the supply curve of carbon sequestration at the regional level. Each individual model (including the per-ton payment and the carbon budget relationships as computed by the carbon-accounting model) is thus solved. We make the value of carbon vary in the range 0 to EUR/tCO_2 200 by steps of EUR 1. The individual results are then aggregated across classes. Figure 1 shows the aggregate results, in terms of annual sequestration for the full range of carbon values. To obtain the annual quantities of carbon sequestration, the annual fluxes were averaged over the 10-year horizon.

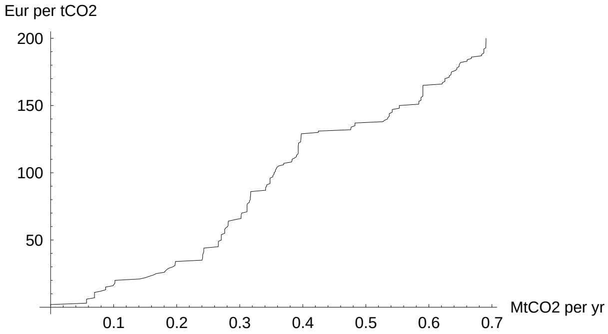


Figure 1. Regional supply of carbon sequestration and marginal costs at the regional level

The curve on Figure 1 indicates at which marginal cost a given quantity of sequestration can be achieved. The step-wise shape of the supply curve is linked to the changes in the optimal

---

[10] The model is implemented in GAMS and is available from the authors upon request.

basis for individual farmers and to the aggregation of land-unit results. The marginal costs associated with the first units of carbon sequestration are relatively low. Up to 0.1 $MtCO_2$/yr, marginal abatement costs stay below EUR/tCO_2 20. For marginal abatement costs ranging from EUR/tCO_2 30 to EUR/tCO_2 130, the slope of marginal abatement costs becomes steeper and the sequestration potential ranges from 0.2 $MtCO_2$ to 0.4 $MtCO_2$ per year. The maximum carbon value explored in this analysis corresponds to a sequestration potential of 0.7 $MtCO_2$ per year.

3.2. Timing of the carbon sequestration supply

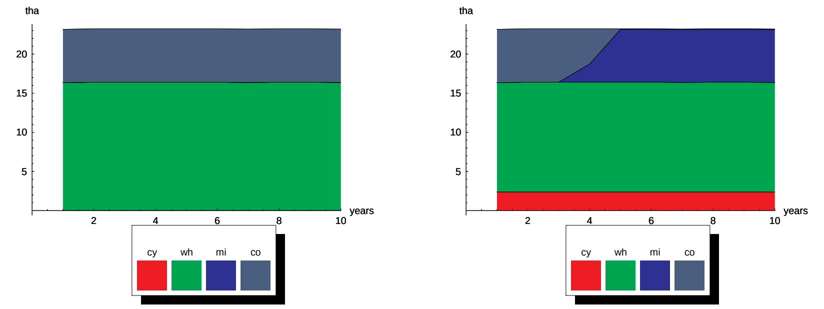
The results presented in Section 3.1 are of course dependent on the *total* area planted in energy crops, as these crops allow for higher rates of carbon sequestration. But they also strongly depend on the *timing* of planting. As the carbon value increases, the area planted in energy crops should increase, and therefore the total quantity of carbon storage. Furthermore, higher carbon values result in earlier substitution of conventional crops with multi-annual crops, as the discounted flow of carbon subsidies is more likely to exceed the present value that can be expected from annual crops.

The timing of these substitutions is presented on Figure 2 for four different carbon values (EUR/tCO_2 0, 50, 100, 200). In the initial state (Figure 2.a), the total area is fully planted in wheat (16,347 ha) and in cotton (6,822 ha). For a carbon value of EUR 50 (Figure 2.b), miscanthus area replaces cotton area starting on year 4. By year 6, the whole area where cotton was initially grown is converted to miscanthus.[11] For the same carbon value, substitution from wheat to cynara occurs earlier on and the magnitude of the change is smaller. About 14% of the initial wheat area is converted into cynara from the first year on, and this stays fairly constant over time. When carbon value nears EUR/tCO_2 100 (Figure 2.c), substitution from cotton to miscanthus occurs two years earlier and full substitution is achieved by year 4, whereas the increase in cynara area is almost unnoticeable. It is only for carbon value higher than EUR/tCO_2 200 (Figure 2.d) that almost complete substitution occurs between cotton and miscanthus from the first year on. When carbon value increase from 100 to EUR/tCO_2 200,

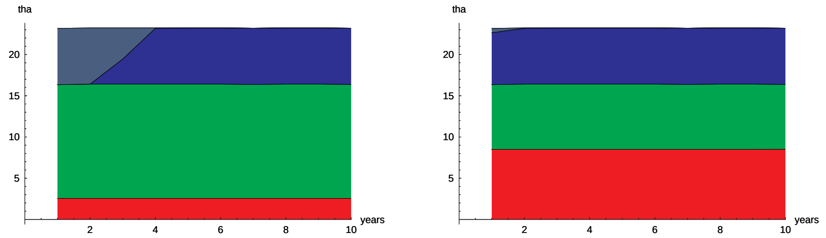
---

[11] This result is of course also driven by the evolution of cotton relatively to miscanthus price. The assumption presented in Section 2.2 of a cotton price falling until 2007 to meet the US price is also a major driver in the substitution between cotton and miscanthus.

cynara area almost triples and totals 7,840 ha in the first year, increasing very slightly afterward.



a. Carbon value: EUR/tCO_2 0 b. Carbon value: EUR/tCO_2 50



c. Carbon value: EUR/tCO_2 100 d. Carbon value: EUR/tCO_2 200

Figure 2. Area planted in annual and multi-annual crops for different levels of carbon value

The resulting carbon sequestration over time and for different carbon values are shown in Figure 3. The z-axis represents the annual increase in carbon stocks for a given value of carbon and a given year. A noteworthy result that can be drawn from Figure 3 is that little sequestration is achieved in the first four years for carbon values ranging from 0 to EUR/tCO_2 30. As the carbon value increases, the year at which carbon sequestration starts to increase significantly is driven earlier on. For carbon values around EUR 200, a plateau is reached as no further substitution is possible, even starting the first year.

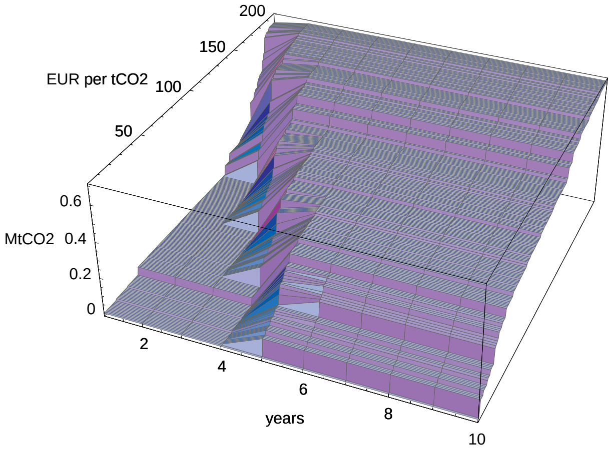


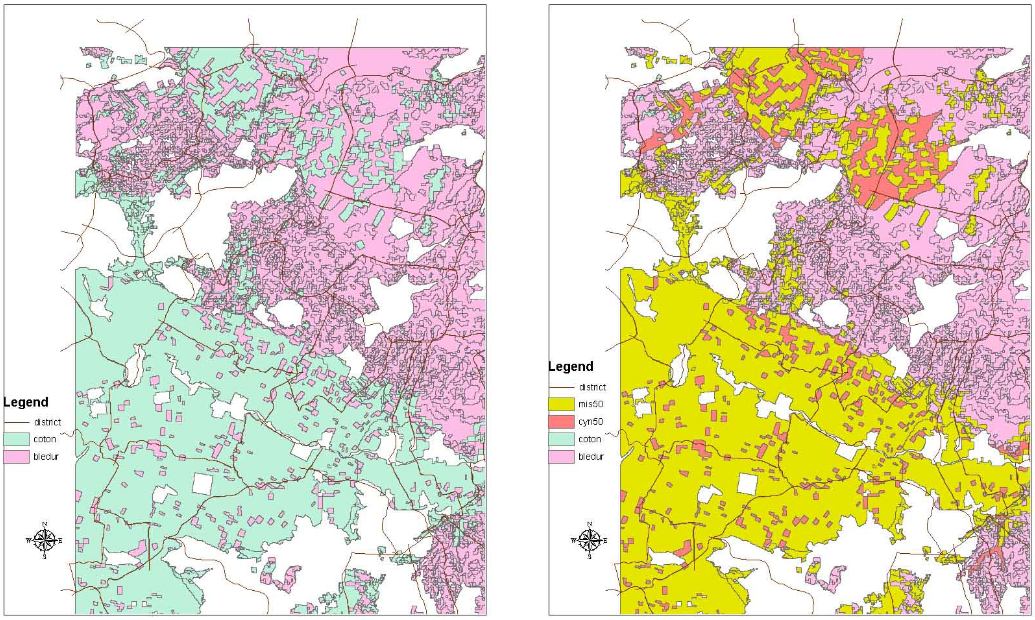
Figure 3. Marginal costs of carbon sequestration over time under a per-ton contract

3.3. Spatial distribution of carbon sequestration

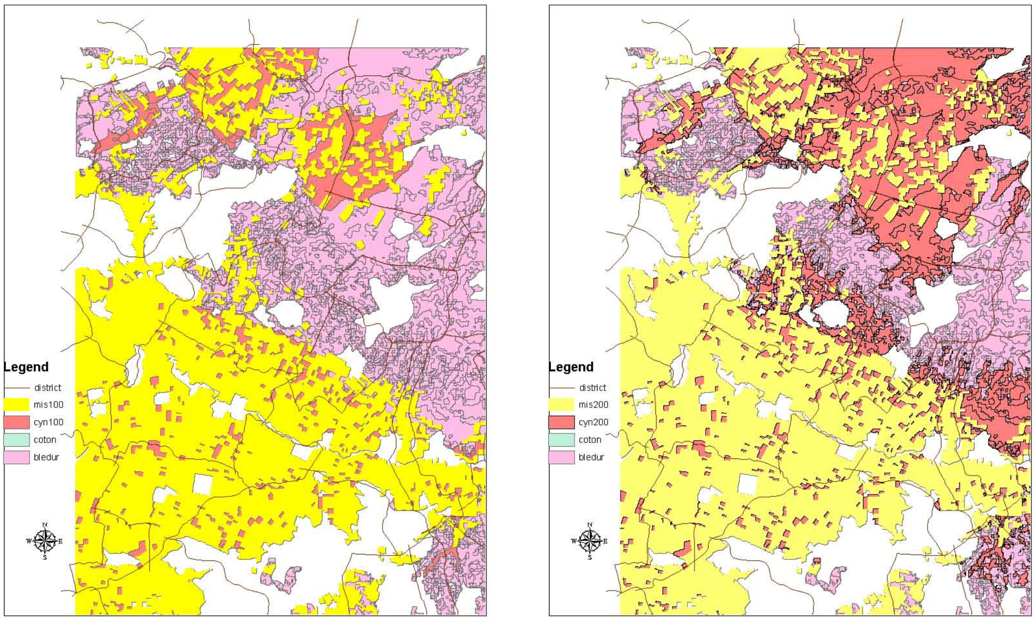
The next step in our analysis consists in identifying where sequestration occurs for different levels of carbon price. Figure 4 shows land-use at $t = T$ for four values of carbon.

For a carbon value of EUR/tCO_2 50, maps 4.a and 4.b clearly show the expansion of miscanthus on land previously used for cotton cultivation. As total cotton area shifts to miscanthus by the end of the planning period, no further substitution between cotton and miscanthus occurs when the carbon value ranges from 50 to EUR/tCO_2 200. As previously discussed, what changes in this range of carbon values is the dates at which miscanthus plantings occur (earlier plantings of multi-annual crops are indicated by a lighter shade on the map).

It is only when carbon values reach higher levels, that cynara expands significantly, indicating higher marginal sequestration costs for this crop. For the most part, cynara area appears on the dry lands located in the Northwestern part of the region of study, while the Southwestern part



a. Carbon value: EUR/tCO_2 0   b. Carbon value: EUR/tCO_2 50



c. Carbon value: EUR/tCO_2 100   d. Carbon value: EUR/tCO_2 200

Figure 4. Land use for different levels of carbon value

(irrigated land) is mostly planted in miscanthus by the end of the planning period. The most productive, irrigated land-units in the central part of the region remain planted in wheat until the end of the planning period.

3.4. Spatial heterogeneity and second-best policy

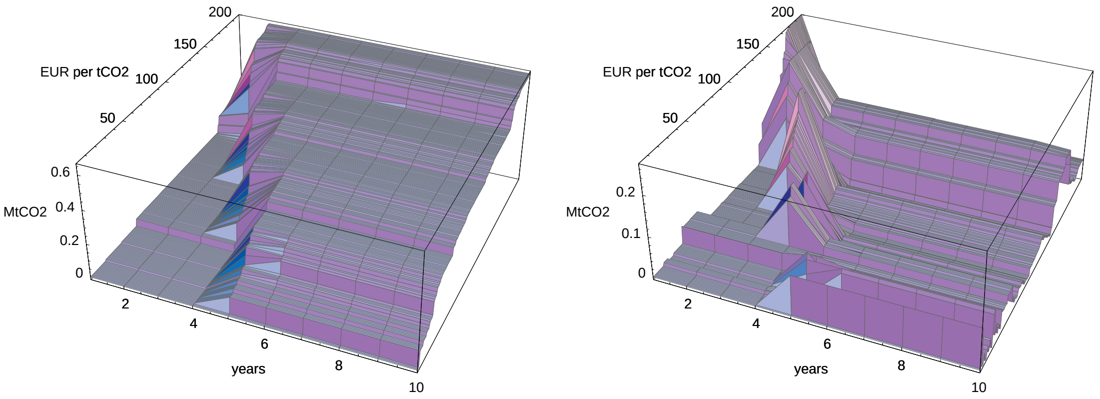
As discussed in Section 1.4, instruments directly based on the *actual* quantities of carbon sequestration are more efficient than instruments based on average sequestration coefficients. That is, the marginal cost associated with a given quantity of carbon sequestration is lower if per-ton contracts are used. If on-site measurements of actual carbon sequestration are too costly compared with the observation of land-use and individual information is not available, the environmental agency can however prefer simpler per-hectare instruments.

We propose in this section a comparison of the relative efficiency of the two types of contracts. We first compute per-hectare sequestration coefficients, which are derived for each crop based from simple regional average of per-hectare carbon sequestration[12]. These coefficients, once multiplied by the carbon value, are introduced in the individual programs as a crop-specific per-hectare payment. Thus, all farmers who plant the same number of hectares in one crop receive the same payment. Similarly to the method adopted in Section 3.1, we let the carbon value vary between 0 and EUR/tCO_2 200. Carbon abatement costs over time are shown in Figure 5.a. Differences between per-ton and per-hectare contracts in terms of carbon sequestration for each year and each carbon value are shown in Figure 5.b.

The interpretation of the shape of Figure 5.a is similar to that of Figure 3. First, as the carbon value increases, the total sequestration increases by the end of the planning period. Then, for higher carbon values, sequestration occurs earlier on. Figure 5.b indicates that per-ton instruments enable to achieve quantity of carbon sequestration up to 90% higher than what can be achieved under a per-ton contract for a given year and a given carbon value. Actually, the biggest differences appear in the early years, as per-ton contracts provide incentives to switch earlier on to multi-annual crops.

---

[12] A possible interpretation of this method may be summarized as follows: “What is the best level of carbon incentives when the environmental agency does not have access to site-specific data but only knows the average potential of each crop”.



a. Marginal costs of carbon sequestration over time under a per-hectare contract

b. Changes in carbon sequestration between per-hectare and per-ton contracts

Figure 5. Marginal cost of carbon sequestration under a per-hectare contract and comparison with per-ton contracts

Concluding remarks

By coupling a dynamic micro-economic model, a carbon-accounting model and a GIS, we provide in this paper an assessment of sequestration costs and potential at regional level. Two major dimensions were explored in this paper: *(i)* the dynamic dimension of carbon sequestration (when carbon sequestration occurs); and *(ii)* the spatial dimension of carbon sequestration (where carbon is sequestered). These two dimensions are crucial in the assessment of a policy aimed at encouraging carbon sequestration in soils.

We identified for the Central Plain of Thessaly, Greece, the regional potential of carbon sequestration in soils allowed by multi-annual energy crops, its spatial distribution, as well as the timing of carbon supply over a time frame compatible with the Kyoto Protocol. Our results show that these energy crops may contribute to the effort undertaken to reduce GHG emissions, as long as carbon sequestration can be accounted for in GHG national inventories.

In this study, we focused on the sequestration potentials permitted by two energy crops, which are of special interest to Mediterranean agriculture. A wider range of actions is actually available to encourage carbon sequestration. Further analyzes should account for changes in practices (particularly those regarding tillage) and consider a larger set of cropping and forestry activities. Conversely, carbon sequestration is only one of the benefits associated to the cultivation of energy crops. Further research is needed to provide more comprehensive assessments of land-conversion to energy crops, including CO_2 savings, lower use of inputs, better water management, etc. Another question left open to further research relates to the magnitude of the shift in public-funds between CAP-related price support to conventional crops and environmental-based subsidies. This could be a major argument in the on-going discussions about reforming support to agriculture within the CAP framework.

We also compared per-ton and per-hectare instruments with respect to their impact on carbon sequestration. To this respect, our results confirm that per-ton contracts dominate per-hectare payments. In fact, in our applied analysis, the efficiency gain is mainly driven by earlier land-conversion to multi-annual cropping systems. Thus, per-ton contracts induce higher sequestration on a longer period of time. In terms of policy making, the ranking of these instruments clearly depends on the initial heterogeneity among farmers with respect to carbon sequestration potential, on the magnitude of monitoring costs, and on the information that can be accessed to by the environmental agency. Our results regarding the difference of marginal costs between per-ton and per-hectare payments provide a benchmark value of the cost that should be exceeded in the collecting of on-site accurate data by the environmental agency.

The possibility of converting land back to annual crops (for instance by considering a planning horizon longer than the useful life of multi-annual crops and relaxing the assumption of prohibitive uprooting costs) is likely to lead to more contrasted results with respect to the evolution of land-use over time. On one hand, it may favor substitution of conventional crops by multi-annual crops, as the opportunity cost associated with multi-annual crop land would be lower. On the other hand, the annual sequestration potential strongly depends on the number of years a given crop remains planted on a given hectare. The possibility of uprooting multi-annual crops would therefore make the question of the timing of carbon payments non-trivial.

References

Antle, J., S. Capalbo, S. Mooney, E. Elliott, and K. Paustian: 2003, 'Spatial heterogeneity, contract design, and the efficiency of carbon sequestration policies for agriculture'. *Journal of Environmental Economics and Management*. In press.

Antle, J. M., S. M. Capalbo, S. Mooney, E. T. Elliott, and K. H. Paustian: 2001, 'Economic Analysis of Carbon Sequestration in Agricultural Soils: An Integrated Assessment Approach'. *Journal of Agricultural and Resource Economics* **26**(2), 344–367.

Arrouays, D., J. Balesdent, J. Germon, P. Jayet, J. Soussana, and P. Stengel (eds.): 2002, *Increasing carbon stocks in French Agricultural Soils? Synthesis of an Assessment Report by the French Institute for Agricultural Research on request of the French Ministry for Ecology and Sustainable Development*, Scientific Assessment Unit for Expertise. Paris, France: INRA. Checked May, 2nd 2003 at `www.inra.fr/actualites/rapport-carbone/synthese-anglais.pdf`.

Burniaux, J.-M.: 2000, 'A Multi-Gas Assessment of the Kyoto Protocol'. Working Paper 43, OECD/OCDE, Paris.

De Cara, S. and P.-A. Jayet: 2000, 'Emissions of Greenhouse Gases from Agriculture: the Heterogenity of Abatement Costs in France'. *European Review of Agricultural Economics* **27**(3), 281–303.

De Cara, S. and P.-A. Jayet: 2001, 'Agriculture and climate change in the European Union: Greenhouse gas Emissions and abattement costs'. Contributed paper, AAEA, Chicago, IL. Presented at the AAEA annual meeting (August).

European Commission: 2002, *The situation of agriculture in the EU*. Brussels, Belgium: European Commision.

FAPRI: 2003, *Food and Agricultural Policy Research Institute: World Agricultural Outlook 2003*. Ames, IA: Iowa State University.

Feng, H.: 2002, 'The Dynamics of Carbon Sequestration and Measures of Cost-Effectiveness'. Working Paper 02-WP 320, CARD, Iowa State University, Ames, IA.

Feng, H., J. Zhao, and C. L. Kling: 2002, 'The time path and implementation of carbon sequestration'. *American Journal of Agricultural Economics* **84**(1), 134–149.

Freibauer, A.: 2003, 'Regionalised inventory of biogenic greenhouse gas emissions from European agriculture'. *European Journal of Agronomy* **19**(2), 135–160.

Hayhoe, K., A. Jain, H. Pitcher, C. MacCracken, M. Gibbs, D. Wuebbles, R. Harvey, and D. Kruger: 1999, 'Costs of Multigreenhouse Gas Reduction Targets for the USA'. *Science* **286**, 905–906.

Ingram, J. and E. Fernandes: 2001, 'Managing carbon sequestration in soils: concepts and terminology'. *Agriculture,Ecosystems & Environment* **87**(1), 111–117.

Intergovernmental Panel on Climate Change: 1996, *IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*. Revised edition.

IPCC: 2000, *Land Use, Land-Use Change and Forestry*, Special Reports. Geneva, Switzerland: WMO/UNEP.

Lal, R. and J. P. Bruce: 1999, 'The potential of world cropland soils to sequester C and mitigate the greenhouse effect'. *Environmental Science & Policy* **2**(2), 177–185.

Manne, A. and R. Richels: 2001, 'An Alternative Approach To Establishing Trade-Offs Among Greenhouse Gases'. *Nature* **410**, 675 – 677.

McCarl, B. and U. Schneider: 2001, 'The Cost of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry'. *Science* **294**, 2481–2482.

McCarl, B. A., B. C. Murray, and U. A. Schneider: 2001, 'Influences of Permanence on the Comparative Value of Biological Sequestration versus Emissions Offsets'. Working Paper 01-WP 282, CARD, Iowa State University, Ames, IA.

Newell, R. and R. Stavins: 2000, 'Climate Change and Forest Sinks: Factors Affecting the Cost of Carbon Sequestration'. *Journal of Environmental and Resource Economics* **40**(3), 211.

OECD/OCDE: 2002, 'Agricultural Practices that Reduce Greenhouse Gas Emissions: Overview and Results of Survey Instrument'. Technical Report COM/ENV/EPOC/AGR/CA(1998)149/FINAL, Environment Directorate, Directorate for Food, Agriculture and Fisheries, Paris, France.

Plantinga, A., T. Mauldin, and D. J. Miller: 1999, 'An Econometric Analysis of the Costs of Sequestering Carbon in Forests'. *American Journal of Agricultural Economics* **81**(4), 812.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, and C. Wang: 1999, 'Multi-Gas Assessment of the Kyoto Protocol'. *Nature* **401**, 549–555.

Rozakis, S., P.G.Soldatos, L. Kalivroussis, and I.Nikolaou: 2001, 'Multiple Criteria Decision Making on bio-energy projects assisted by G.I.S.: The case of Farsala'. *Journal of Geographical Information and Decision Analysis* **5**, 49–64.

Schlamadinger, B., G. Marland, and L. Canella: 2003, 'The Model GORCAM, Graz / Oak Ridge Carbon Accounting Model'. Web site, Joanneum Research, Institute of Energy Research, Austria and Oak Ridge National Laboratory, USA. Checked on May, 2nd 2003 at `www.joanneum.ac.at/GORCAM.htm`.

Schlesinger, W. H.: 2000, 'Carbon sequestration in soils: some cautions amidst optimism'. *Agriculture, Ecosystems & Environment* **82**(1–3), 121–127.

Schneider, U. A.: 2000, 'Agricultural Sector Analysis on Greenhouse Gas Emission Mitigation in the United States'. Ph.D. thesis, Texas A& M University.

Smaglik, P.: 2000, 'United States backs soil strategy in fight against global warming'. *Nature* **406**, 549–550. (News).

Soldatos, P. G.: 2002, 'Building the annual equivalent cost of perennial energy crops'. *Options Méditéranéennes (Série A)* **48**, 159–167.

UNFCCC: 1997, 'Kyoto Protocol to the United Nation Framework Convention on Climate Change'. Official text, UNFCC (Climate Change Secretariat). Checked June, 15th 2002 at `http://unfccc.int/resource/docs/convkp/kpeng.pdf`.

USDA: 2003, 'Soil Carbon Sequestration: Frequently Asked Questions'. Web site, USDA. Checked on April, 17th 2003 at `http://www.usda.gov/oce/gcpo/sequeste.htm`.

USDA-FAS: 2003, 'Greece - Cotton and products annual'. GAIN Annual Report GR3011, USDA - Foreign Agricultural Service. Checked May, 2nd 2003 at `www.fas.usda.gov`.

Varela, M., R. Saez, E. Castellano, C. Cardiel, L. Kallivroussis, P. Soldatos, S. Rozakis, H. Schwaiger, G. Jungmeier, and I. Nikolaou: 2001, *Energy crops integration using a multiple criteria decision-making tool*. Madrid, Spain: Ciemat. 228 p.