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

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

Abstract.

In this study, we examine the spatial and dynamic implications of policies aimed at increasing carbon sequestration in agricultural soils. We consider incentive mechanisms designed 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 combine the dynamic microeconomic model with a carbon accounting model and a geophysical database. We assess the efficiency loss of constant per-hectare payments compared to per-ton mechanisms. The dynamic and spatial implications of these mechanisms are compared and discussed.

Keywords

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

JEL Classification : Q25, Q15

1 Introduction

Meeting the Kyoto Protocol targets may be unnecessarily costly if the efforts rely solely on the reduction of carbon dioxide emissions from fossil fuel use (see for instance Reilly et al., 1999; Hayhoe et al., 1999). Enhancing carbon sinks – and particularly in agricultural soils – has therefore drawn renewed attention as a credible and cost-effective option for greenhouse gas (GHG) mitigation policies (Smaglik, 2000; Lal and Bruce, 1999). However, although explicitly mentioned in articles 3.3 and 3.4 of the Kyoto Protocol, the inclusion of carbon sinks in international agreements remains controversial (Schlesinger, 2000).

One of the issues often raised to this respect concerns the *non-permanence* of carbon stocks in agricultural soils. On the one hand of course, carbon sequestration may help to "buy time" by providing a fast and relatively inexpensive means of reducing net GHG emissions. But on the other hand, carbon might be released back into the atmosphere as a result of a change in practices and/or land-use (Arrouays et al., 2002). In addition, soil carbon stocks are subject to *saturation* (McCarl et al., 2001). As pointed out by Feng *et al.* (2002), non-permanence[1] and – to a lesser extent – saturation of carbon stocks in soils make carbon sequestration essentially different from GHG abatements. From an economic perspective, the issue is thus to assess in a dynamic setting how the social value of carbon sequestration in agricultural soils compares with that of CO_2 abatements (Feng, 2002; McCarl et al., 2001).

The dynamics of carbon stocks in agricultural soils should therefore be explicitly taken into account in economic studies of GHG mitigation policies. In other words, the issue is not only to assess how farmers 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.

In the recent empirical literature about GHG emissions from agriculture, comprehensive abatement cost estimates have been published for France (De Cara and Jayet, 2000), the EU (De Cara and Jayet, 2001), and the US (Schneider, 2000; McCarl and Schneider, 2001). These studies include carbon sequestration as well as agricultural emissions of nitrous oxide and methane and are based on supply-side oriented, mathematical-programming models. This type of modelling approach, however, does not give an appropriate account of the dynamics of carbon sequestration, as it mostly relies on average changes in carbon stocks applied to instantaneous area changes. The same argument applies to econometric-based models of land-use estimating the opportunity costs of converting agricultural land to more carbon-sequestering cropping systems and/or practices (Newell and Stavins, 2000; Plantinga et al., 1999).

Another key-feature of carbon sequestration in agricultural soils lies in the *spatial heterogeneity* of sequestration potentials and abatement costs (Freibauer *et al*, 2004). A study by Antle et al. (2003) highlights the importance of spatial heterogeneity with respect to monitoring costs and its implications for the design of effective incentive mechanisms. In a second-best approach to this issue, these authors empirically address the trade-off between monitoring costs (per-ton contracts) and loss of efficiency (per-hectare contracts).

The main objective of the present paper is to develop methods to assess the costs and the potentials of carbon sequestration in agricultural soils, accounting for both *spatial* and *dynamic* dimensions. Two interrelated questions are thus examined in this paper: *when* and *where* does sequestration occur? Our empirical analysis focuses on carbon sequestration permitted by multi-annual energy crops in the Central Plains of Thessaly, Greece. Several elements in the policy context strengthen the interest of such an assessment in this region. Firstly, concern is growing in Greece about overproduction of annual crops such as cotton and durum wheat, because of increased pressure on the environment (overuse of inputs, water quality, etc.) and co-responsibility penalties triggered by the exceeding of the CAP maximum guaranteed quantities. Secondly, as the EU promotes alternatives for fossil fuels, bio-energy regional projects that use multi-annual crops to generate electricity are seriously considered by policymakers. Multi-annual energy crops may constitute an interesting option for both environmental and policy purposes.

The paper is organized as follows. In section 2, we present the stylized dynamic micro-economic land-use model, accounting for multi-annual crops. In section 3, we discuss the specificities of the region of the study with respect to initial policy context, land-use patterns, crop substitution possibilities, and spatial heterogeneity. We also present the carbon accounting method and discuss the assumptions we make in the application of the model derived from section 2. In section 4, we discuss the results. In particular we discuss the timing and the spatial repartition of carbon sequestration as well as the relative efficiency of per-hectare and per-ton mechanisms. Finally, we draw various conclusions in terms of policy-making from our analysis.

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

2.1 Gross margin maximization problem

We first study the problem faced by a farmer who has to plan his planting sequence on the k-th land-unit for a finite time horizon T. We consider the corresponding discrete-time, discounted gross margin maximizing program. 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).

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

where $a_{t,j,k}$ is the area in crop $j \in J$ at date $t \in \{1,\ldots,T\}$ on land-unit $k \in K$. J is the feasible set of crops and 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 by $r_{t,j}$ and $c_{t,j}$, respectively. The discount rate ρ is assumed to be constant over the time horizon and across farmers.

To compute the variations of carbon stocks in soils, we need to consider when each hectare[2] has been planted with crop j. Therefore, we rewrite $a_{t,j,k}$ as the sum

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

where $\alpha_{t,l,j,k}$ is the crop j area remaining at date t that has been 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 $a_{t,j,k} = \alpha_{t,l,j,k}$.

2.2 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 date t with 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 with crop j for the entire period of time

$\lfloor t, \ldots, t+\tau_j-1 \rfloor$. To capture the impact of multi-annual cropping systems, we thus consider the following sets of constraints:

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

As a result of equations (2), the total area planted in a specific multi-annual crop cannot decrease before the end of its useful life.[3] In addition, the program has to verify the following area-availability and non-negativity constraints:

(3) $$\sum_{j \in J} a_{t,j,k} \leq A_k \quad \forall \{t,k\} \in \{1,\ldots,T\} \times K$$

(4) $$a_{t,j,k} \geq 0 \quad \forall \{t,j,k\} \in \{1,\ldots,T\} \times J \times K$$

(5) $$\alpha_{t,l,j,k} \leq A_k \quad \forall \{t,k\} \in \{1,\ldots,T\}^2 \times J \times K$$

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

The program for land-unit k is thus the following:

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

Further, as the time horizon of the problem is finite, the terminal conditions need to be defined. The gross margin generated beyond T is not taken into account. This is particularly important in the case of multi-annual crops. We assume a zero residual value of the multi-annual crops beyond the time horizon, as we have to compare the gross margins of annual and multi-annual crops over the same time horizon. The same assumption applies for the value of the remaining carbon stocks beyond T (see section 3.4).

2.3 Carbon accounting

Carbon sequestration 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, $\Delta C_{t,k}$, is written as follows:

(6) $$\Delta C_{t,k} = f\left(\{\alpha_{t,l,j,k}\}_{t,l=1,\ldots,T,j\in J}; \phi_k\right)$$

Note that the amount of carbon sequestered on land-unit k depends on the complete history of land-use on the land-unit considered ($\{\alpha_{t,l,j,k}\}_{t,l=0,\ldots,t,j\in J}$), and not simply on the area planted at date t.[4]

2.4 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 $G_{t,k}$.

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

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

Following Antle *et al.* (2003), we consider two types of incentive mechanisms: a per-ton subsidy, $G_{t,k} = q_t.\Delta C_{t,k}$ and a per-hectare payment, $G_{t,k} = s_{t,j,k}.\alpha_{t,l,j,k}$. 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 at the current price in 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 is the case if $s_{t,j,k} = \sum_{k\in K} \Delta C_{t,k} \big/ \alpha_{t,l,j,k}$), this instrument leads to higher costs of sequestration for the same quantity of sequestered carbon.

As pointed out by Antle et al. (2003), 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 easily be overcome through the use of a first-best per-ton mechanism. 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 for achieving efficient levels of sequestration. In fact, a system whereby all farmers are offered the same per-hectare payment regardless of their abatement costs tends to overpay (resp. underpay) sequestration on the less (resp. more) efficient fields. Nevertheless, this type of contracts is likely to be less costly 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 efficiency losses 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 detailed information about the repartition of the abatement costs among farmers, as only average emission factors are required. However the latter type of contract involves incentives that lead to efficiency losses. The greater the heterogeneity among abatement costs, the higher are the efficiency losses. 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.

2.5 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.[5]

Another key-dimension in farmers' decision-making relates to the timing of planting multiannual crops. The trade-off then lies 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 a 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.

3 Application to the region of Thessaly, Central Greece

3.1 Policy context and current land-use pattern

The substitution of multi-annual crops for cotton and wheat on irrigated and on 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). Indeed, a member State exceeding its aggregate production quota foregoes a reduction in the intervention price. This mechanism, however, has failed to restrain Greek cotton production[6]. 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 into seeking alternative crops. Wheat (durum) is essentially cultivated on dry land and does not provide a credible alternative to cotton since durum wheat production is also subject to binding caps in terms of subsidies in the region.

Several proposals have been examined, such as support to the industry livestock and the cultivation of feed crops or, alternatively, the planting of energy crops in support of bio-energy regional projects to generate electricity. Energy crops 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 have become of prime importance, the European Union attempts to comply with its international commitments promoting alternative energy sources to that of 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 the grounds of environmental protection.

Carbon sequestration, along with other environmental benefits that result from bio-energy production, have been assessed in a previous study about the selection of the optimal bio-electricity projects in Thessaly (Rozakis et al., 2001). Compromise solutions were found using multi-criteria methodology, on the basis of ex post trade-offs over criteria such as budgetary burden, carbon sequestration, CO_2 abatements due to substitution for fossil fuels, production cost, employment, value added, etc. In the present paper, the crop-mix decision process includes carbon sequestration as an endogenous variable, allowing a better assessment of policies instrument specifically designed to encourage carbon sequestration.

In the present study, we focus study on the substitutions of wheat and cotton by two energy crops. Table 1 summarizes the possible substitutions for the major annual crops.

<INSERT Table 1 **ABOUT HERE>**

3.2 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 that of durum wheat. The initial wheat price is taken from European Commission (2002). This price includes the CAP durum subsidy and a relative durum-specific relative premium, both of which are kept constant for the whole planning period. The initial cotton price (74 €/t) is taken from USDA-FAS (2003). We assume that, starting from this point, the price meets the world price by 2007 and increases 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 the breakdown of 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 2.

<INSERT Table 2 **ABOUT HERE>**

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

3.3 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 that for the entire plain. The Spot

XS image used focuses on an area about 45,000 ha in size 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 units with similar soil type, slope, and current land use were gathered in the same class. 1,090 classes are considered in this case study. After obtaining this information, expert knowledge was used to estimate yields of all conventional and energy crops examined for each class (416 classes with arable crops). 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 since 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.

3.4 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 associated with land management and biomass utilization strategies to and from the atmosphere. 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 in 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. Organic matter decay in the "Dead organic matter" pool produces CO_2, which 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).

The inputs needed for running the carbon sequestration model are defined at the class level. Soil characteristics, land-use history, and yields[7], are used in the computation the carbon sequestration parameters (tCO_2) for the given time-horizon. The main results in terms of carbon sequestration parameters are summarized in Table 3. These parameters represent the per-annum increase in carbon stocks when converting land from annual crops to miscanthus or cynara. They are computed as the yearly average of the total amount of sequestered carbon over the considered crop useful lifespan (10 years).

<INSERT Table 3 **ABOUT HERE>**

4 Results

4.1 Regional supply of carbon sequestration

Using the parameters computed as described in the previous section, we are now able solve to solve the model for each class retained in the analysis.[8]

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. These models are ran for carbon payments ranging from 0 to 200 €/t CO_2. The individual results are then aggregated across classes. Figure 1 shows the total carbon supply aggregated over the ten-year horizon.

<INSERT Figure 1 **ABOUT HERE>**

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 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 100 $ktCO_2$, the marginal abatement cost remains below 20 €/tCO_2, which is the threshold set by the European Climate Change Programme (2003) in its assessment of mitigation strategies. For marginal abatement costs ranging from 30 to 130 €/tCO_2, the slope of marginal abatement costs becomes steeper and the sequestration potentials ranges from 250 $ktCO_2$ to 400 $ktCO_2$ per year. The maximum carbon value examined in this analysis corresponds to a sequestration potential of nearly 700 kt CO_2 per year.

4.2 Timing of the carbon sequestration supply

The results presented in section 4.1 are naturally dependent on the total area planted with energy crops, as these crops allow for higher rates of carbon sequestration. They also strongly depend on the timing of the plantings. 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 in Table 4 for four values of the carbon payment (0, 50, 100, 200€/tCO_2). Initially, the total area is fully planted with wheat (16,347 ha) and with cotton (6,822 ha). For a carbon payment of 50 €:t/CO_2, miscanthus replaces cotton starting on year 4. By year 6, the whole area where cotton is initially grown is converted to miscanthus.[9] 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 100 €/tCO_2, 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 a carbon payment higher than 200 €/tCO_2 that almost complete substitution occurs between cotton and miscanthus from the first year onwards. As the carbon payment increases from 100 to 200 €/tCO_2, the cynara area almost triples and totals 7,840 ha in the first year, increasing very slightly afterwards.

<INSERT Table 4 **ABOUT HERE>**

The resulting amount of carbon sequestration over time and for various values of the carbon payment is shown in Figure 2. Little sequestration is achieved in the first four years for a carbon payment ranging from 0 to 30 €/tCO_2. As the carbon value increases, the year in which carbon sequestration starts to increase significantly is driven earlier on. For carbon values around 200 €, a plateau is reached as no further substitution is possible, even starting from the first year.

<INSERT Figure 2 **ABOUT HERE>**

4.3 Spatial distribution of carbon sequestration

The next step in our analysis involves identifying where sequestration occurs for different levels of carbon price. Figure 3 shows land-units sequestering carbon by cultivating either cynara or miscanthus at $t = T$ for two values of carbon.

For a carbon value of 30 €/tCO_2, Figure 3.a shows the expansion of miscanthus on land previously used for cotton cultivation. An important part of cotton area shifts to miscanthus by the fifth year of the planning period, no further substitution between cotton and miscanthus occurs in subsequent years.

<INSERT Figure 3 **ABOUT HERE>**

It is only when carbon values reach higher levels, that cynara expands significantly, indicating higher marginal sequestration costs for this crop. As a matter of fact, for a carbon value of 60 €/tCO_2, farmers start to switch to cynara on the dry lands located the Northwestern part of the region of study, while the Southwestern part (irrigated land) is mostly planted in miscanthus starting this time by the fourth year of the planning period. A few additional farmers substitute miscanthus for cotton in the fifth year, covering most of the cotton cultivated area. The most productive, non-irrigated land-units in the central part of the region remain planted in wheat until the end of the planning period.

4.4 Spatial heterogeneity and second-best policy

As discussed in Section 2.4, economic instruments that are 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. However, depending on the magnitude of the costs of on-site measurements relative to land-use observations, simpler per-hectare payment mechanisms may be preferred by the environmental agency.

In this section, a comparison of the relative efficiency of the two types of contracts is made. We first compute per-hectare sequestration coefficients, which are derived for each crop based on simple regional average of per-hectare carbon sequestration. These coefficients, once multiplied by the carbon payment, are introduced in the individual programs as a crop-specific per hectare payment. Thus, all farmers who plant the same area in a given crop are offered the same payment whatever their actual sequestration costs. Similar to the approach exposed in section 4.1, we let the carbon value vary from

0 to 200 €/tCO_2. The total carbon supply in the case of per-hectare payment is shown in Figure 4.a and compared to the per-ton payment case. Differences between per-ton and per-hectare contracts in terms of carbon sequestration for each year and each carbon value are shown in Figure 4.b.

As expected, per-hectare mechanisms involve lower sequestration than per-ton mechanisms for the same value of the carbon payment. Interestingly, Figure 4.b shows that this difference mainly results from a difference in the timing of carbon sequestration. In the case of per-hectare mechanisms, carbon sequestration occurs later on than in the case of per-ton payments. Indeed, Figure 4.b indicates that per-ton instruments enable carbon sequestration up to 90% higher than under a per-ton contract for a given year and a given carbon value. The biggest differences occur in the early years, as per-ton contracts provide incentives to switch earlier on to multi-annual crops. In the subsequent years, the differences diminish as wheat and cotton area are replaced by miscanthus and cynara.

<INSERT Figure 4 **ABOUT HERE>**

5 Concluding remarks

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. To do so, we combined a dynamic micro-economic model, a carbon-accounting model and a GIS to assess carbon sequestration costs and potentials at a regional level. We examined the regional potentials of carbon sequestration in soils cultivated with multi-annual energy crops, as well as their spatial distribution and the timing of carbon supply over a time frame compatible with the Kyoto Protocol. Our results show that these energy crops may contribute in the effort undertaken to reduce GHG emissions, as long as carbon sequestration can be accounted for in GHG national inventories.

In this study, we emphasize the sequestration potentials permitted of two energy crops that are of particular interest in Mediterranean agriculture. A wider range of actions is actually available to encourage carbon sequestration and reduce net GHG emissions from agriculture. Further analyzes should account for changes in practices (particularly those regarding tillage) and should consider a larger set of cropping and forestry activities. Conversely, carbon sequestration is only one of the benefits associated with the cultivation of energy crops. Further research is needed to provide a more comprehensive assessment 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 the form of the support to agriculture within the CAP framework.

This article also provides an empirical comparison of the impacts of per-ton and per-hectare instruments with respect to carbon sequestration and quantified the efficiency loss associated with per-hectare payments. This efficiency loss is mainly explained by later land conversion to multi-annual cropping systems that results in lower sequestration over a given time-horizon. In terms of policy making, the ranking of per-ton and per-hectare payments clearly depends on the initial heterogeneity among farmers with respect to carbon sequestration potential, on the magnitude of monitoring costs, and on the information accessible to the environmental agency. Our results regarding the difference in marginal costs under 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 lifespan 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 the one hand, it may favour 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 potentials strongly depend on the number of years a given crop remains planted on a given hectare. This would strengthen the interest of the timing of carbon payments.

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*. **46**(2):231-250.

Antle, J. M., S. 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. INRA Editions, Paris, France.

De Cara, S. and P.-A. Jayet: 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 P.-A. Jayet: 2001. "Agriculture and Climate Change in the European Union: Greenhouse gas Emissions and Abatement costs". *Contributed paper*, AAEA Annual Meeting, Chicago.

European Climate Change Programme: 2003. *Can we meet our Kyoto targets?* Second ECCP progress report, European Commission, DG ENV, Brussels, Belgium. http://www.europa.eu.int/comm/environment/climat/eccp.htm.

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* 02-320, 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., M. D. Rounsevell, P. Smith and J. Verhagend: 2004. "Carbon sequestration in the agricultural soils of Europe". *Geoderma* (in press).

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.

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.

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". *CARD 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):211-235.

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):812-824

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*. Joanneum Research, Institute of Energy Research, Austria. 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*. PhD, Texas A& M University, College Station.

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

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

USDA-FAS: 2003. "Greece - Cotton and products annual". *GAIN Annual Report* GR3011, USDA - Foreign Agricultural Service.

Notes

[1] Indeed, the permanence issue can be addressed by distinguishing between accumulation of carbon stocks and the storage of carbon. Accumulation refers to the increase of carbon stocks in soils and is a positive flux. Arguably, accumulation provides a positive externality, as it offsets CO2 from the atmosphere and results in a reduction in atmospheric CO2 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 the maintenance of a given level of carbon stock.

[2] Indeed, at this level of generality, $\alpha_{t,l,j,k}$ can also stand f or 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 4 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.

[3] This is a rather strong assumption that 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 also seems 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 favour annual crops over multi-annual crops, as the opportunity cost associated with multi-annual cropping systems increases.

[4] 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.

[5] Another way to estimate abatement costs would be to introduce a constraint that imposes a minimum quantity of carbon sequestered (say $\overline{Q}$) for a given land-unit in the initial program. The shadow price associated with this constraint would thus reflect the

marginal variation of the discounted gross margin due to a marginal variation in 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 to the "primal" computation of abatement costs).

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

[7] In order to compute the yields at the land-class level, geo-referenced data about soil type, slope, land type are used. We thus a productivity map with several grades of fertility for each crop. In the case of conventional crops (wheat and cotton), yields statistics are available at the municipality level (Varela *et al* 2001). As for energy crops, yields data are taken from experimental plantations (about ten sites in the region). At the land-class level, yields are obtained as the product of the productivity index and the relevant yield data point.

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

[9] This result is of course also driven by the evolution of cotton relative to the miscanthus price. The assumption presented in section 3.2 of a cotton price falling until 2007 to meet the US price is also a major driver in the substitution of cotton by miscanthus.

Figures

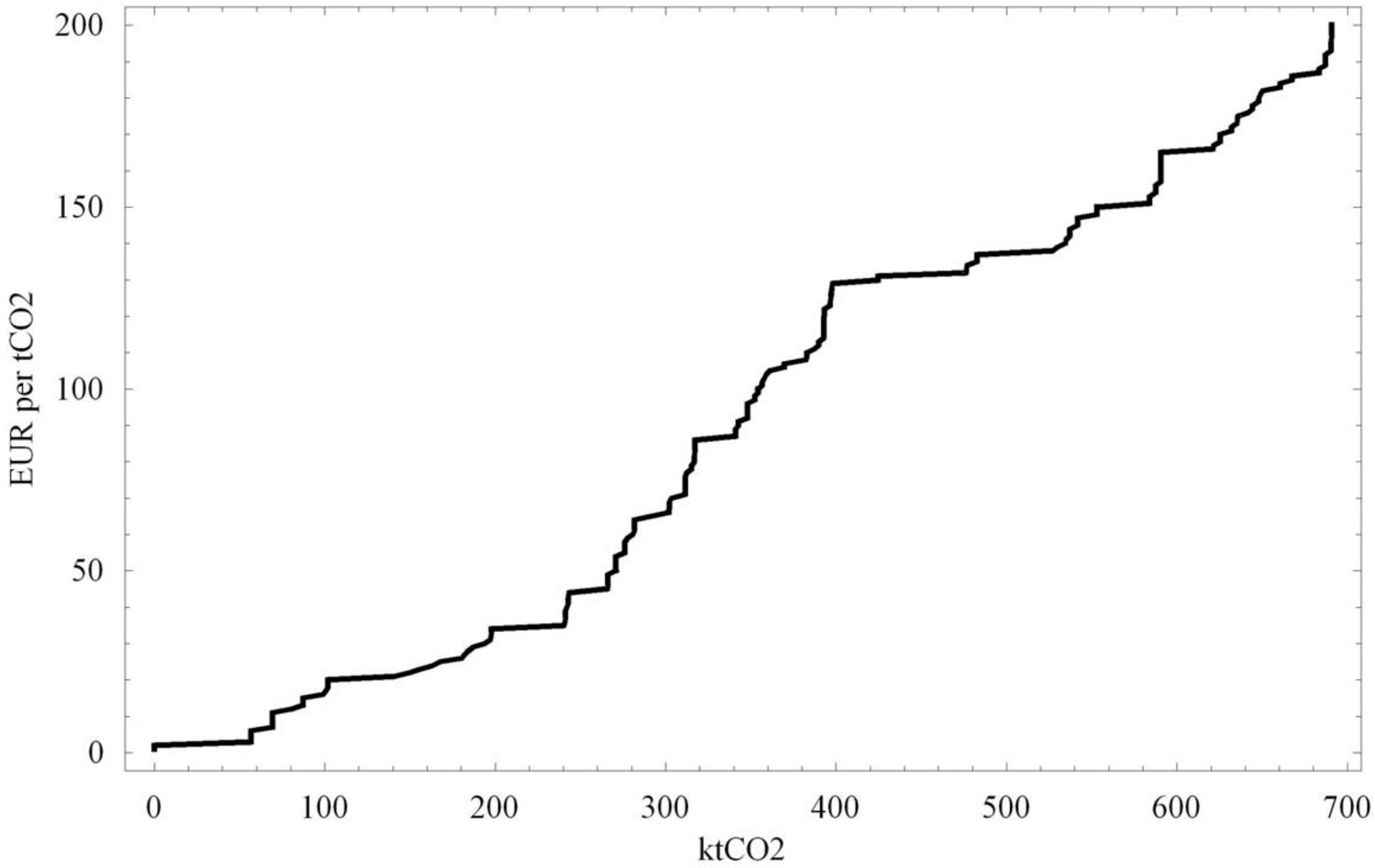


Figure 1. Ten-year regional carbon supply under a per-ton carbon payment

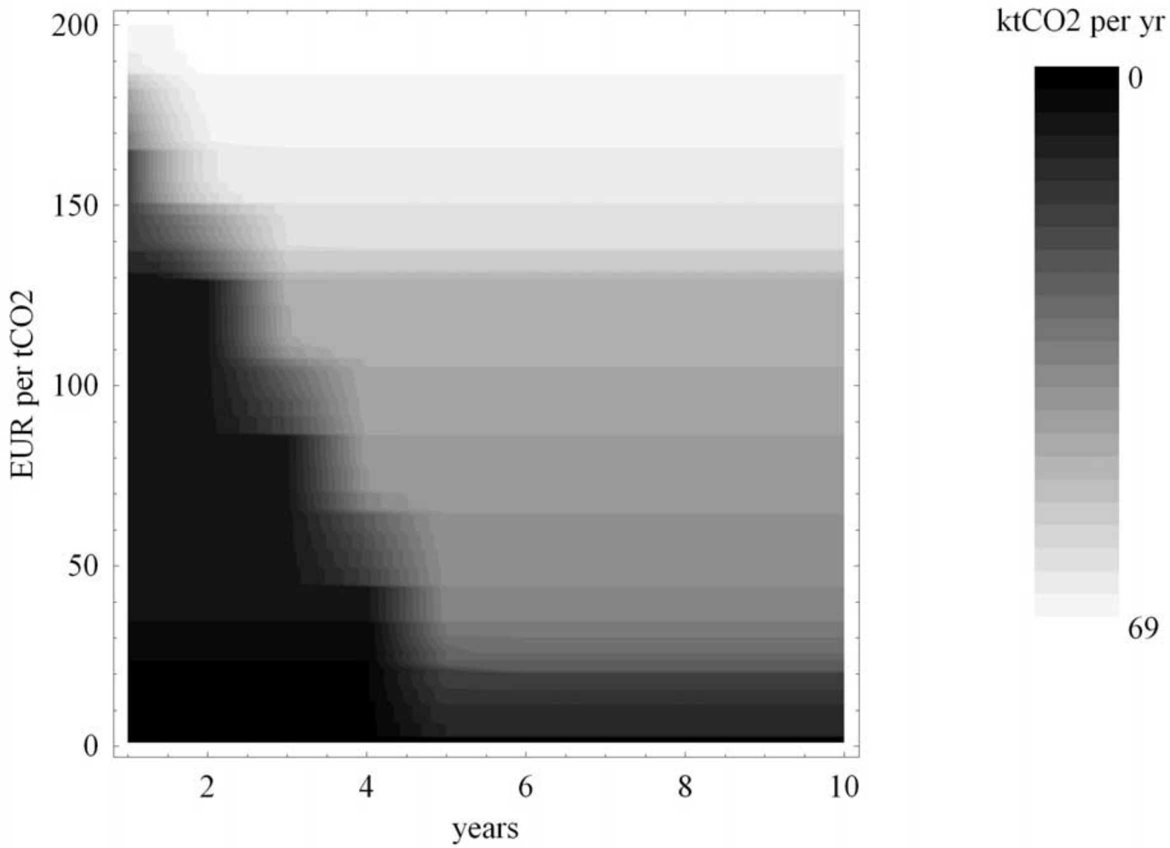
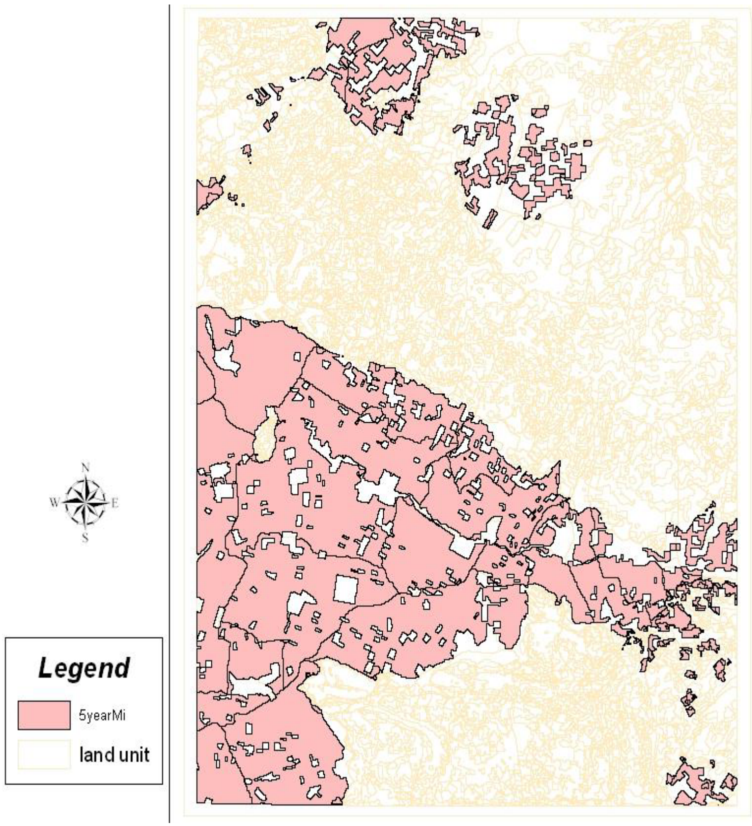
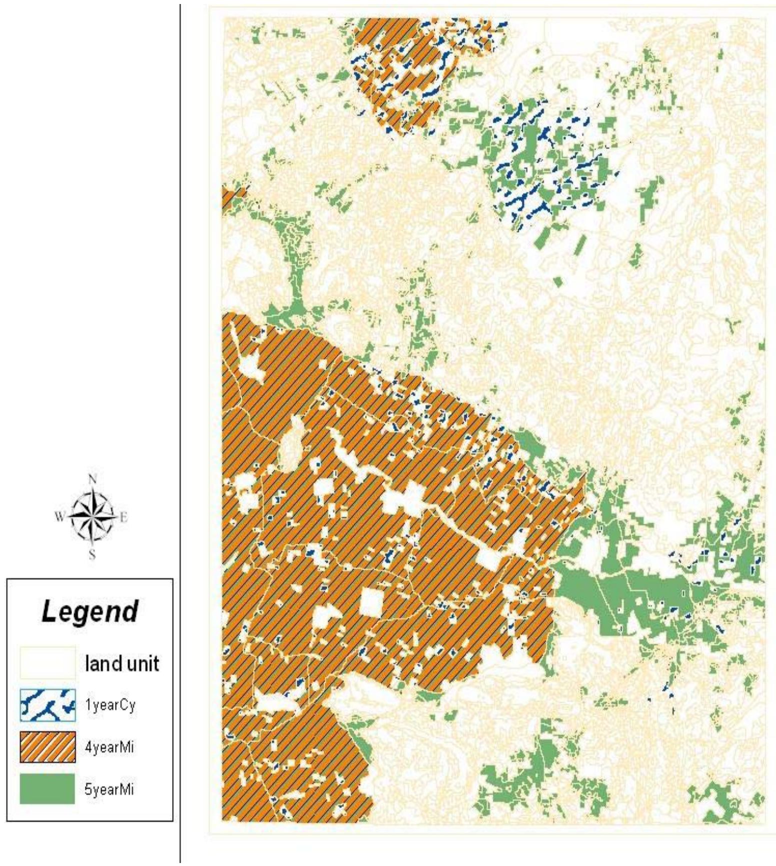


Figure 2. Evolution of per-year carbon supply under a per-ton carbon payment

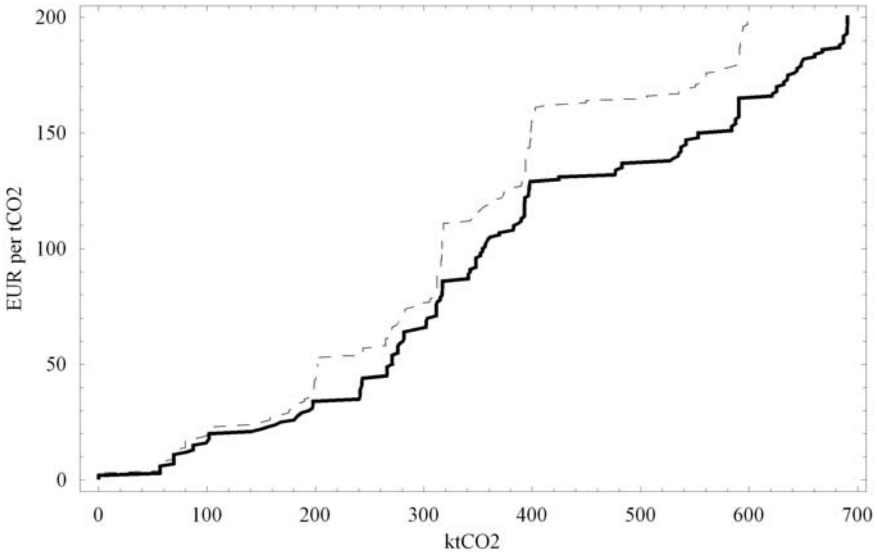


a. Carbon value: 30 €/tCO_2

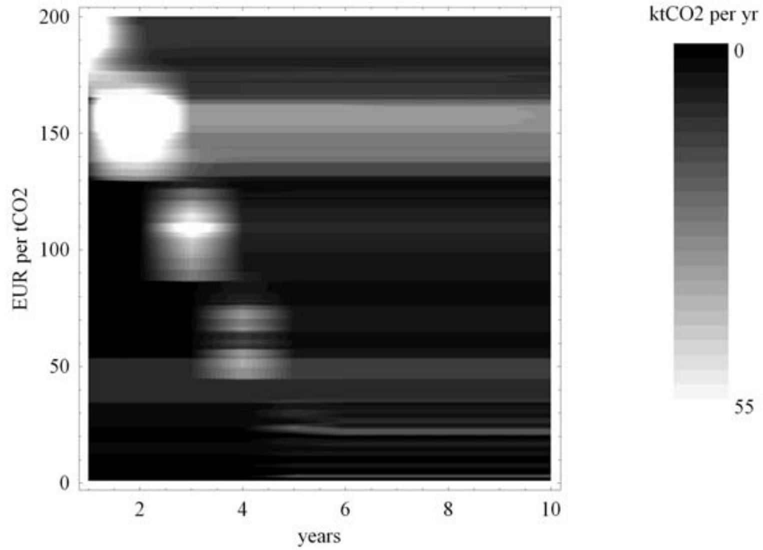


b. Carbon value: 60 €/tCO_2

Figure 3. Area allocation at date *T* for two per-ton carbon payments



a. Comparison of regional carbon supply under per-ton (fill) and per-hectare (dashed) carbon payments



b. Difference in per-year carbon supply between per-ton and per-hectare carbon payments

Figure 4. Comparison of per-ton and per-hectare carbon payments

Tables

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.	-

Table 1: Current agricultural cultivations and energy crop substitution possibilities

Crop	Yield					Area	Prices		Variable cost
	Avg.	Std. Dev.	Min	Max	Avg growth	2002	2002	2012	
	t/ha		t/ha	t/ha	%	,000 ha	€/t	€/t	€/ha
Wheat	3.52	0.68	2.10	5.00	1.1	16,347	220	207	578
Cotton	3.33	0.38	2.30	3.90	0.6	6,822	740	350	642
Cynara	22.33	4.51	10.00	30.00	- (*)	- (*)	70	70	1,752
Miscanthus	22.79	2.86	35.00	50.00	- (*)	- (*)	55	55	2,390

(*) Only experimental plantations of miscanthus and cynary currently exist in the area.

Table 2: Data and assumptions

	Unit	Average	Std Dev	Min	Max
Class Area	ha	56.52	59.01	1.01	276.83
Cotton to cynara	tCO_2/ha/yr	2.17	0.95	0.53	2.66
Wheat to cynara	tCO_2/ha/yr	1.72	0.49	0.23	2.39
Cotton to miscanthus	tCO_2/ha/yr	7.78	3.63	5.69	8.35

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

Table 3. Carbon sequestration parameters: Descriptive statitistics.

Payment	Crop	Area at time t									
		t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
(€/tCO2)		(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)
0	Cynara	0	0	0	0	0	0	0	0	0	0
	Cotton	6,822	6,822	6,822	6,822	6,822	6,822	6,822	6,822	6,822	6,822
	Miscanthus	0	0	0	0	0	0	0	0	0	0
	Wheat	16,347	16,413	16,413	16,413	16,413	16,413	16,372	16,413	16,413	16,372
50	Cynara	2,380	2,380	2,380	2,380	2,380	2,380	2,380	2,380	2,380	2,380
	Cotton	6,822	6,822	6,822	4,499	68	49	49	49	49	49
	Miscanthus	0	0	0	2,323	6,754	6,773	6,773	6,773	6,773	6,773
	Wheat	13,967	14,032	14,032	14,032	14,032	14,032	13,991	14,032	14,032	13,991
100	Cynara	2,556	2,556	2,556	2,556	2,556	2,556	2,556	2,556	2,556	2,556
	Cotton	6,822	6,822	3,775	49	1	0	0	0	0	0
	Miscanthus	0	0	3,048	6,773	6,821	6,822	6,822	6,822	6,822	6,822
	Wheat	13,791	13,857	13,857	13,857	13,857	13,857	13,816	13,857	13,857	13,816
200	Cynara	8,505	8,505	8,505	8,505	8,505	8,505	8,505	8,505	8,505	8,513
	Cotton	0,533	43	1	0	0	0	0	0	0	0
	Miscanthus	6,289	6,779	6,821	6,822	6,822	6,822	6,822	6,822	6,822	6,822
	Wheat	7,842	7,907	7,907	7,907	7,907	7,907	7,867	7,907	7,907	7,858

Table 4: Area allocation and carbon payment