DYNAMIC ECONOMIC ANALYSIS OF PERENNIAL ENERGY CROPS - EFFECTS OF THE CAP REFORM ON BIOMASS SUPPLY IN GREECE

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Abstract

Energy from the biomass of perennial crops can offset emissions of greenhouse gases from fossil fuel combustion and increase energy self sufficiency. This study uses a dynamic, multi-farm, mathematical programming model to analyze the impact of the Common Agricultural Policy reform in 2003 on biomass supply from the Kopais plain in central Greece. The perennial energy crops under review are *Arundo donax* L. (Giant Reed), *Miscanthus x giganteus* (Miscanthus), *Panicum virgatum* L. (Switchgrass) and *Cynara cardunculus* L. (Cardoon). Farm survey results from 40 farms are processed with the Biomass Economic Evaluation model to obtain micro-economic data for both conventional and energy crops. Policy simulations with the multi-farm model show that the 2003 policy reform with decoupled subsidies except for cotton and energy crops lowers the cost of biomass between 2 and 4 Euro per ton. Switchgrass appears to be the most attractive option, followed by Cardoon and Miscanthus. Arundo is never preferred. Relative to the previous agricultural policy setting of Agenda 2000, the biomass potential increases more for smaller farms and farms with a higher share of cotton, vegetables, or trees.

Keywords

Energy crops, Common Agricultural Policy, Climate mitigation Economics, Arundo, Miscanthus, Switchgrass, Cardoon, Mathematical programming, Dynamic cost minimization, Bioenergy potential, Biomass supply curve, Kopaida, Greece

JEL classification

Q12, Q18, Q28, Q42, Q58

1 Introduction

Limited fossil fuel resources, concerns about climate change, and technical progress in biomass processing have increased researchers' and policymakers' attention to bioenergy. While the long term role of bioenergy within the diverse suit of renewable energy sources remains uncertain, many studies suggest at least a transitional role (McCarl and Schneider, 2000). In Europe, the political belief in bioenergy is reflected by several directives and proposals to promote bioenergy issued by the European Commission over the last decade. These include:

- White Paper on Energy strategy that suggests the increase of renewable energy sources contribution to 12% of the EU gross inland primary energy consumption by the year 2010,
- Directive 2003/30 on promotion of liquid bio-fuels for transport
- Directive 2001/77 on promotion of electricity generated by renewable energy sources
- Directive 2003/87 on trading system of greenhouse gases rights etc.
- Special subsidy of 45 €/ha for energy crops (Council Regulation (EC) 1782/2003)

Despite considerable political support and technical progress in bioenergy supply chains, private market uptake has been below expectations. Possible reasons include a currently very low carbon credit price and the lack of economics in many engineering based bioenergy studies. Schneider and McCarl (2006) showed substantial differences between engineering based technical potentials and opportunity cost included economic potentials of energy crop systems. Thus, cost efficiency, is one of the most important factors for biomass in order to penetrate European energy markets.

The opportunity cost of bioenergy is affected by agricultural policies. The latest Common Agricultural Policy (CAP) reform (Council Regulation (EC) 1782/2003) decouples partly the subsidization system from conventional crop production, for the period 2006-2013. Previous research in Greece (Lychnaras and Rozakis, 2006) showed that the direct cost of biomass may decrease up to 50% when the current CAP is fully applied to perennial energy crops. Because, adoption of the decoupled subsidization system on energy crops is already decided, this work performs a dynamic analysis on energy crops production and examines the results of the current CAP medium/long-term.

The analysis of the current CAP effects on the farms of Kopaida plain of Central Greece is of great interest because of the agricultural structure of this region. The specific area is mainly cultivated with cotton, maize and other arable crops, which are now receiving much lower direct subsidy. As a result of decoupled subsidization of conventional crops, the energy crops are becoming more and more attractive as an alternative use of land for Kopaida farms.

2 Methodology

The proposed methodology adopted, in the context of the computerized model, demands the decomposition of the project into a number of *activities*[1] which sufficiently describe all required jobs for plant installment and cultivation (AAEA, 2000). Each operation is characterized by its *timing* (both duration per hectare and seasonality within each year) and its requirements for *labor*, *equipment* and *materials*.

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[1] ABC (Activity Based Costing) analysis.

Mechanical equipment may be hired if own machinery is insufficient or non existent. When hired, its cost is equal to the rent paid; otherwise its hourly cost is the sum of depreciation, interest, maintenance, insurance and fuel. Fuel consumption depends upon operation and machinery used.

Land is an essential factor of agricultural production and in most cases a major cost item. The cost of agricultural products may be significantly increased if planted on high cost land and vice versa. Therefore, land cost must be carefully estimated in all agricultural projects. If there is a fairly competitive market for land, one may assume that its rent adequately reflects its real cost. However, if there is no market, the cost of land is not easily identifiable. In such cases one needs to estimate its opportunity cost as expressed by the net economic output of current land use. For project evaluation purposes involving alternative uses of the same land, the cost of land can be excluded, since it is a common cost item in both the “with” and “without” situations. Under special circumstances, when farmers are partners in agricultural cooperatives, it is possible to contribute to the Balance Sheet with e.g. the use of their land, in which case the cost of land may be regarded as the return on their contribution to the project. In this research, instead of the land rent, the opportunity cost of land was considered. The opportunity cost of land was estimated for each parcel of every farm of the analysis in a context of a mathematical programming approach, based on the revenue from conventional crops produced in 2006 (see details above).

Labor is usually provided by the farmer and his family, but it may also be hired, especially during peak labor demand, e.g. planting or harvesting times. Hired labor in most cases has a market specified rate, which can be used in the analysis. Imputed labor cost should be principally evaluated at its opportunity cost, i.e. the amount of income forgone for shifting family labor from current activity due to the needs and requirements of the project.

Subsidies are sometimes granted in order to support current agricultural policies. These are temporary cash injections, influencing production decisions, but external to the financial mechanism and identity of production. The subsidization system is described below at the case study.

2.1 Biomass Economic Evaluation (BEE) model

BEE is a computerized model developed by the Laboratory of Agribusiness Management of the Agricultural University of Athens (Soldatos et al, 2003[2]; Soldatos and Lychnaras, 2003), which performs a full economic analysis of energy crop production (Lumby and Jones, 1999). The model is composed of two main modules: (i) cost analysis and (ii) financial. The first performs cost estimation of biomass cultivation, both by activity and by input factor of production. The second carries out financial analysis, based on calculated future balance sheets, financial results and expected cash-flows. The model can analyze annual and/or perennial energy crops. Still, it can analyze single or multiple crop systems.

The most relevant features of BEE are the following: (a) it is a standard MS Win XP application with internet support were the user may also find download database files of case studies (http://www.bee.aua.gr); (b) it performs detailed monthly monitoring of activity levels and operation needs (labor, raw materials, machinery usage etc.); (c) it carries out full economic analysis by agricultural activities and by factor of production. The estimated cost is reported by ton or hectare; (d) it performs full financial analysis in standard accounting formats. The model estimates all principal financial statements (monthly balance sheets, income and cash flows statements) for every crop; (e) it identifies all relevant cash flows of each crop in order to consolidate results of projects incorporating more than one crop; (f) it has user friendly input forms and reports.

2.2 Multi-Farm Optimization Model

To estimate biomass supply, we employ a dynamic mathematical programming model, which maximizes the present value of the net annual profits, before sales, of a system that covers a sample of representative farms and harvesting service provided by a cost-minimizing company, subject to:

- Resource endowment constraints, which restrict the cultivated and the available area of each parcel,
- Policy constraints, which enforce subsidy-related minimum cultivation areas. Under the CAP-2003 scenario, farmers have to cultivate an area equal to the area selected for subsidization, in order to receive the decoupled subsidy. Additionally, 20% of the selected area for subsidization have to be cultivated with Vetch or Alfalfa,
- Transition constraints. These constraints link activity levels between adjacent periods and are active for perennial crops, such as energy crops and alfalfa, and machines.
- Machinery-capacity constraints, which restrict the monthly usage of harvesting and baling machines and the required number of machines, considering monthly available hours and best machinery usage,
- Biomass production, storage and supply constraints, which restrict the monthly biomass production and storage, and
- Biomass demand constraints, which force the model to supply a certain minimum in each month.

The decision variables of the model are:

- The cultivated area of each crop in each parcel of every farm and year
- The number of agricultural machines
- Machinery monthly utilization
- Biomass production
- Biomass storage
- Biomass supply

The objective function of the model (profit maximization) considers i) the revenue from sales, subsidies and terminal values of perennial crops and ii) production cost, machinery cost, harvesting and baling cost, and storage cost. Because there is no rental market for harvesting and baling of multi-annual energy crops, we simulate the "private company" cost-minimizing behavior by restricting the number of machines for harvesting and baling to integer values.

The detailed description of the model is presented in the Appendix.

3 Biomass Production Conditions in Central Greece

3.1 The study region

The plain of Kopais is located in the Voiotia region of Central Greece and covers an area of about 18 thousand hectares with about 9.5 thousand farms. The main cultivations are cotton, maize, alfalfa, industrial tomato and small grains. According to the data of the National Statistical Service of Greece (NSSG), about 1/3 of the farms (3.5 thousand) are very small (less than 2 ESU – European Size Unit) and not considered in this analysis because their total contribution is small and farm commodity based profit maximization may not adequately describe the decisions of this group. The analysis here uses results from detailed questionnaires of 40 small, medium, and large sized farms with different commodity focus. A brief summary of these farms is provided in Table 1.

<insert Table 1>

The fact that the specific area is mainly cultivated with cotton, maize and other arable crops (which are now receiving much lower subsidy), explains the importance of this work under the reformed CAP. As a result of decoupled subsidization of conventional crops, energy crops are becoming more attractive and biomass supply curve shifts down.

3.2 Cost of production

The cost of production of every conventional and energy crop was separately estimated for each parcel of every farm under review. The cost analysis of each parcel was estimated i) the production cost of the conventional crop that was produced during 2006 production period, ii) the production cost of vetch, the cost of cotton produced only for the non-decoupled subsidy and the cost of set-aside and iii) the production cost of all energy crops under review.

The farmer has the opportunity to produce cotton in order to receive the total subsidy for cotton (decoupled and non-decoupled), without the obligation of collecting the product. The production of cotton in this case is characterized by the minimum required cultivating activities. In this case, the cost of production is reduced while the income is increased by 549 €/ha (as described below). The disadvantage of this case is that there is a lost income from sales. The case of cotton production only for subsidization was only considered for parcels that were utilized for cotton production during 2006. The set aside cost is consisted by the cost of ploughing, in order to keep the field at good agricultural condition.

In the case where the parcel is non-irrigated, the only energy crop analyzed was cardoon since the climatic conditions of the specific area do not allow the production of the other three crops without irrigation. The cultivation activities of energy crops considered were common for all parcels with the exception of irrigation that was based on the water needs of every case. The differentiation of energy crops cost was based on the differentiation of yields, irrigation, farm cultivation activities peculiarity (rental needs, machinery data, efficiency and fuel consumption etc.).

The recording of cost elements was performed in physical units rather than in financial terms, (for example machine-hours, man-hours, quantities of raw materials etc.), according to BEE methodology (Soldatos et al, 2003[2]).

The farm-data concern:

- General regional financial data (short/long-term borrowing rate, inflation rate, risk premium)
- General farm data
- Total occupied land and cultivated area per crop
- Total subsidy-related area per crop
- Subsidies
- Products prices
- Labor wages
- Raw materials prices

- Parcels data (location, own and rented land, land rent, irrigation system and irrigation fee)
- Current crop data (parcel, area, number of irrigations, water availability and yield)
- Own machinery (age, purchase price, economic life, annual maintenance and insurance cost, annual average operation)
- Own constructions (age, cost, annual maintenance and insurance cost, % of use per crop)
- Other overheads
- Cultivation activities per crop and parcel (machinery used, efficiency, fuel consumption, labor, raw materials quantities, rental cost if rented)

3.3 Yields

The yield was also considered for each parcel. The conventional crops yields were extracted from questionnaires while the energy crops yields (productivity under real conditions) were estimated based on the productivity of each parcel, comparing the conventional crop yield with the average yield of the sample. Vetch and set-aside have zero yields. Table 2 presents the distribution of yields derived from the sample.

<Insert Table 2>

3.4 Prices

The prices used for the analysis were extracted from questionnaires for every farm. Cotton price ranged in 2006 from 290 to 365 €/t (price of cotton delivered at the cotton ginning unit) and he average price of the sample was 310.30 €/t. Alfalfa grass price ranged from 110 to 138 €/t (average of 118 €/t). The price of industrial tomato was 45 €/t and the maize for grass production was purchased (on the field) at the price of 30.80 €/t. The average price of maize seed in 2006 was about 140 €/t (range of 130-147 €/t). Wheat selling price had a range of 140-190 €/ha, while the average was about 148.20 €/t. Finally, oat price was about 117 €/t and cereals straw price was 90 €/t.

3.5 Subsidization system of the CAP-2003

The current CAP stands in Greece for the period 2006-2013 (Council Regulation (EC) 1782/2003), while in 2009 a reform of the subsidization system is expected. Under the current system, every farmer receives a decoupled subsidy, which is independent of what the farmer produces and is a percentage of the average subsidization that was received during the period 2000-2002. Energy crop production is subsidized by an extra amount of 45 €/ha. The farmer has the obligation to cover at least 20% of the selected area for subsidization with vetch or alfalfa. Vetch is cultivated between the production periods of annual conventional crops. In this analysis, the selected area for subsidization, in regard to the production of period 2000-2002, for every farm, is derived from the questionnaires.

In some cases, for example cereal and maize subsidization, there is a 10% deduction on the decoupled subsidy that it is called “quality deduction”. In this case, the farmer receives: a) the 100% of the decoupled subsidy for the area that it is cultivated with the previous subsidized crop (e.g. maize production between 2000-2002) and b) the 90% of the decoupled subsidy, for the rest of the selected area cultivated with other eligible crops. Taking into account that decoupled subsidy (not including any deduction) is common for conventional and energy crops, it is not considered in the analysis. For this reason, this analysis was based on the difference on the subsidy that results between crops, explained in detailed below.

Cotton: Cotton receives a 65% of the total subsidy as decoupled subsidy, that is 969 €/ha and a 35% as non-decoupled subsidy, that is 549 €/ha, while, there is no “quality deduction” or co-responsibility levy. The decoupled subsidy is referred to the selected for subsidization area, while the non-decoupled subsidy is referred to the total cultivated area of cotton. Taking into account the above parameters, the subsidy of cotton considered in this analysis was 549 €/ha.

Small cereals: This is the case for the subsidization of barley and oat in this analysis. The decoupled subsidization in this case is 151.46 €/ha (average subsidy of the period 2000-2002). On this amount, there is a quality deduction of 10% (15.15 €/ha). In result, the decoupled subsidy of the selected area is:

i. 151.46 €/ha for the production of small cereals (barley and oat in our case) or
ii. 136.31 €/ha for all other selected crops and set-aside.

In this analysis, the difference of 15.15 €/ha is considered as the subsidization of barley and oat, since the rest of the decoupled subsidy is common for all crops under review.

Durum wheat: Durum wheat receives the decoupled subsidy of small cereals plus the additional subsidy of durum wheat. The addition subsidy is 285 €/ha, multiplied with the deduction coefficient of the co-responsibility payment for Voiotia region (1.0000 for the year 2000, 0.9916 for 2001 and 0.9930 for 2002). This coefficient, calculated every year for each region, was based on total produced quantity of the specific region. When the total production of the region was higher than its upper limit of the supported quantity, than the deduction coefficient resulted to be lower that 1 (100%). As a result, the average decoupled subsidy of durum wheat is 492.81 €/ha. There is also the quality deduction of 10% (49.28 €/ha) and an extra subsidy of 40.00 €/ha for using certified seed. Finally, the farmer will receive, for the selected area:

i. 532.81 €/ha for the production of durum wheat or
ii. 443.53 €/ha for the production of other crops and set-aside.

The deference of 89.28 €/ha is considered as the subsidization of wheat.

Maize: The decoupled subsidy of maize for Voiotia region (based on the subsidization of the period 2000-2002) is 545.20 €/ha. Taking into account the 10% quality deduction (54.52 €/ha) the farmer receives for the selected area:

i. 545.20 €/ha for maize production and
ii. 490.68 €/ha for other selected crops production and for set-aside.

In the analysis, the quality deduction was only considered as the subsidy of maize.

Alfalfa: Alfalfa is not subsidized.

Industrial tomato: Industrial tomato receives price subsidization that is determined every year (Regulation (EC) 175/2002, 130/2003, 177/2004, 170/2005, 210/2006). The price subsidy for industrial tomato remains steady at 34.50 €/ton from the productive period 2002/03 to 2006/07.

Energy crops: As mentioned, the reform of CAP established the subsidization of 45 €/ha for energy crops.

3.6 Subsidization system for 2002 (Agenda 2000)

According to Agenda 2000 the deficiency payments for cotton and industrial tomato were coupled to production of every farm, while small cereals and maize were subsidized based on the cultivated area.

The subsidy of cotton for the year 2002 was about 557 €/t, while the subsidy of industrial tomato was 34.5 €/t (data source: Ministry of Agriculture Development and Food of Greece, and OPEKEPE). This value, multiplied by the yield of every parcel, estimates the subsidy per hectare for this period.

Based also on data from the Ministry of Agriculture Development and Food of Greece, the main subsidy of the area for small cereals (soft wheat, barley and oat) in 2002 was 155.6 €/ha, while the additional subsidy of durum wheat was 344.50 €/ha. The deduction coefficient of the co-responsibility payment for Voiotia region (as described before) was for the same period 0.9930. As a result, the subsidy of durum wheat for 2002 for Voiotia region was calculated as follows: 155.6 + (344.5 x 0.9930) = 497.69 €/ha. Maize subsidy for 2002 was 554.20 €/ha and set-aside subsidy was 221.10 €/ha.

3.7 Harvesting

For this analysis we have made the assumption that although the production of crops is performed by individual farmers who maximize their profit using crop rotation (combination of crops), harvesting and baling of energy crops is performed by an individual enterprise. This assumption was made based on the fact that harvesting and baling mechanical equipment is specialized and expensive. The enterprise owns a fleet of equipment and provides harvesting services for the whole area.

Arundo is harvested in chips, using a silage harvester and a lorry, while the other three crops are harvested in bales. The mechanical equipment for harvesting and baling consists in silage harvester, tractor, cutter, windrower and baler.

All economic and technical data of those operations were based on the questionnaires and the "Bioenergy Chains" research project data. The machinery techno-economic data (purchase cost, economic life, annual maintenance and insurance and average annual operation), the harvesting and baling efficiency in hours per hectare, the fuel consumption of every machine in each crop and the consumables cost (cost of net for bales) were considered. The fuel cost was calculated as the cost of diesel (€ lit-1) multiplied by the efficiency of the operation (hrs ha-1), the fuel consumption (lit hr-1) and the total cultivated area of the crop for every land unit. The average diesel price for 2006 is about 0.6 €/lit (for agricultural use).

3.8 Number of machines

The private company needs to determine the optimal number of machines required for harvesting and baling. Each crop has a limited period during which it can be harvested. In order to maximize machinery usage and to minimize harvesting cost, we assume that the whole available period for each crop can be used. According to the needs (machine hours) of every month and the availability (based on climatic and social regional conditions), the model estimates the minimum number of machines required to the "optimal" crop mix.

4 Agricultural Policies and Economic Biomass Potentials in Central Greece

To estimate the economic potentials of biomass production for bioenergy in Central Greece, we integrated the microeconomic data on 40 farms in the multi-farm decision model described above. We used a time horizon of 25 years covering the period from 2006 to 2030. The resulting model had in total 559,622 variables and 374,260 equations. The number of machinery related variables over all machinery types, age classes, and years equaled 1,429 variables, which were specified either as nonnegative, continuous or nonnegative, integer variables. While a continuous specification of the machinery variable allowed us to solve the multi-farm model as linear program (LP), a mixed integer program (MIP) was required otherwise and required about 5 times more computation time. Since the results for a few selected cases did not differ much between the LP and MIP specifications, we decided to perform the full policy scenario analysis with the time saving LP specification. Therefore, if not stated differently, the simulation results presented below pertain to the LP specification.

4.1 Agricultural Policy Scenarios

To estimate the impacts of changes in agricultural policies on economic biomass potentials, we implemented and solved six alternative agricultural policy scenarios. These scenarios reflect current, past, and possible future and are specified as follows:

- *Agenda 2000*: where the CAP subsidization system of 2002 is enforced over the entire time horizon of the model.
- *CAP 2003*: where the current CAP subsidization system and policy constraints are applied over the entire time horizon of the model (*See Appendix*).
- *Transition*: where the CAP-2003 is applied for the period 2006-2009. For the next four-year period (2010-2013) a 20% decrease in subsidy levels is assumed. After 2013 (end of the current CAP), no subsidization system is considered.
- *No CAP*: Scenario where agricultural production is performed under the rules of a free market.
- *Transition plus Climate Policy*: where the transitional policy scenario is combined with a carbon emission offset premium of 20 Euro per ton of biomass. The premium level was determined by assuming a carbon emission offset of 2/3 ton CO_2 per ton of biomass and a carbon price of 30 Euro per ton of CO_2 (9 Euro per ton of C). Given the bioenergy goals of the European Union, this carbon price reflects a conservative assumption.
- *No Cap plus Climate Policy*: where the *No Cap* policy scenario is combined with the carbon emission offset premium of 20 Euro per ton of biomass.

Furthermore, each policy scenario was solved for 16 different minimum biomass demand restrictions, i.e. for demands of 0, 50, 100, 150, …, 500, 600, …, 900, and 1000 tones DM per month over the entire area of the 40 farms. The alternative minimum demand levels were enforced in each month starting from January 2009 until the end of the planning horizon.

4.2 Biomass Supply

The 40 farms, analyzed in this study comprise a total area of 1300 ha, of which 50% is assumed to be available for energy crops production. Before solving the profit maximizing model specification of the multi-farm model, we switched off the economic objective function and maximized biomass supply. The resulting technical potential of biomass supply amounts to about 13 thousand dry tons annually, or 1083 dry tons monthly. Note that the highest minimum demand restriction equals 1,000 dry biomass tons and thus, comes very close to the technically feasible potential.

Figure 1 shows the average cost of biomass supply, in Euro/t DM as function of a) assumed policy path between 2006 and 2030 and b) specified monthly minimum restriction for biomass. These costs were computed by dividing the total biomass production over the entire horizon by the total cost increase relative to the zero biomass minimum demand restriction for each policy path. Several things can be observed. The biomass supply curve shifts downwards from the previous CAP (Agenda 2000) to the current CAP. The *Transition* and *No CAP* scenarios decrease costs even further. The lowest biomass costs, however, are observed under climate policy. These results illustrate that decoupling has a considerable positive effect on biomass production potentials. A still noticeable but smaller effect is caused by the energy crop subsidy (45 €/ha), established under CAP 2003. The difference between the *CAP 2003* and *No Cap* supply curves is about twice as small as the difference between *Agenda 2000* and *CAP 2003*. Thus, the decrease in opportunity costs from decoupling is worth more than the revenue increase from the energy crop subsidy. This effect is also confirmed by examining the shadow price levels of the area restriction (see appendix). The computed average land rent is about 650 €/ha/yr under *CAP 2003* but about 1150 €/ha under *Agenda 2000*. Note that the observed land rents in 2006 for Kopaida range from 600 to 900 €/ha and thus, agrees with the results of the optimization model.

<insert Figure 1>

Figure 2 **shows** the marginal cost of biomass, i.e. the shadow price of the minimum biomass supply restriction (see appendix), for the *CAP 2003* scenario on a monthly scale. We find a strong seasonal variation in marginal costs with the maximum value being about twice as much as the minimum value. The shadow prices are lowest in harvesting period and increase thereafter. Outside the harvesting period, the marginal costs are the sum of production cost plus storage cost. A slight kink appears between December and January. This is due to the annual discounting regime. The high shadow price differences illustrate the restrictiveness of a relatively short pre-defined harvesting period. While, agronomic considerations may justify these restrictions, our results imply that some harvesting out of season would probably be economically justified.

<insert Figure 2 here>

Figure 3 shows the contribution of the four energy crops as function of biomass minimum demand. We find fairly constant proportions with Switchgrass having the highest share, followed by Cardoon, and Miscanthus. There is no Arundo production, although in most cases, this crop has lower variable production costs than Miscanthus. However, Arundo is the only energy crop that it is harvested in chips by using silage harvester, while the other three crops are harvested and baled with the same technique. The total cost of Arundo is increased because of the need of specialized mechanical equipment that cannot be used beyond a narrow 2 month window. Note that the share of the individual energy crops do not differ between policy scenarios.

<insert Figure 3>

In general, the replacement of less profitable conventional crops causes lower opportunity cost for energy crops. Our results show that industrial tomato and alfalfa are among the more profitable conventional crops, which get replaced last. On the other hand, maize, cotton, wheat, and oat turn out less profitable and are replaced first by energy crops.

The results also showed that under CAP 2003 and for low biomass demand there are cases where it is preferable not to harvest cotton, i.e. when the production and harvesting costs are higher than potential revenues. In such cases, the farmer chooses to produce cotton for subsidization only and to receive the specific cotton subsidy without any revenues from sales. Note that the "cotton for subsidization" has minimum inputs and cost of production. Additionally, the same result stands for set-aside land, where in some cases is preferable not to produce anything. This occurs because a) in some cases the profitability of conventional crops is low or negative and b) the subsidy is decoupled form crop's production.

4.3 Variation across Farms

The major reason for including 40 different farms in a common model is to examine whether the response across farm types and farm sizes is different. The two extreme cases of response include i) homogenous response and ii) sequential response. In the first case, each farm increases its energy crop share at the same rate as the entire region. In the second extreme case, the farms adopt energy crops in sequence, i.e. the lowest cost farm would adopt energy crops first and after reaching its capacity limit, the second cheapest farm would start to contribute. Which type of response occurs depends not only on the average cost differences between farms but also on the heterogeneity of biomass production costs within farms.

As expected, our results lie somewhere in between. However, the response pattern differs between policy specifications. This is summarized in Figure 4. Under Agenda 2000, farms of different size react relatively similar to increases in biomass demand, i.e. the energy crop intensity lines are almost parallel (Panel A). The relatively decoupled system of CAP 2003, however, induces a more sequential response with smaller farms contributing first and larger farms last (Panel B). Similarly, the response of different farm type is more homogeneous for Agenda 2000 (Panel C) than for CAP 2003 (Panel D). The current CAP induces energy crops faster on cotton farms than on farms, which cultivate a variety of field crops. Farms which produce not only on crops but also vegetables and fruit trees show a mixed response. Particularly, these farms adopt a certain amount of energy crops relatively fast but then slow down. When demand reaches 500 t DM / month, cotton farms have converted most of their potential acreage to energy crops, and thus, additional demand is met by the crop-vegetable-tree farms together with mixed arable crop farms.

To explain the above findings, one should note that the current CAP policy provides a yield independent energy crop subsidy (45 Euro per ha), a decoupled lump sum payment, and a coupled subsidy for cotton producers. Under CAP 2003 conditions, cotton becomes less profitable with negative profits in some cases. This happens because 65% - equivalent to 969 €/ha - of the cotton subsidy under Agenda 2000 is converted into a decoupled subsidy and as such does not constitute cotton specific revenue. Thus, under the current agricultural policy, cotton farms have lower opportunity cost for the production of energy crops. Smaller farms adopt energy crops faster because they incur higher production cost for conventional crops than do larger farms. First, smaller farms use mechanical equipment less efficient and second, these farms often have to pay rent for a number of operations because of lack of mechanical equipment. Especially for harvesting, the cost of renting the operation is at least three times higher than the cost of using own equipment. Consequently, CAP 2003 provides an opportunity for smaller farms to replace relative expensive conventional crops by energy crops without loosing the decoupled subsidy.

<insert Figure 4>

5 Conclusions

This paper analyzes the effects of the current and expected CAP reform on biomass production potentials from Greek agriculture. We use a dynamic, multi-farm profit maximization model containing data on 304 parcels from 40 representative farms in the Kopaida region of Central Greece. Our results show that the 2003 CAP reform considerably decreases the costs of biomass supply in comparison to the former CAP, i.e. Agenda 2000. The cost savings materialize as a result of reduced opportunity costs from traditional (food) agriculture and are also reflected by reduced land rents. Moreover, the decoupling of the conventional crops subsidization, established in the latest CAP reform (2003) has a much larger effect on biomass potentials than the specific subsidy of 45 Euro/ha for energy crops.

Among the four energy crops in our model, only Switchgrass, Cardoon and Miscanthus become selected for biomass production. The harvesting period for these crops ranges from July to March (9-months period) and the harvesting can be done with common equipment for these three crops. Arundo, however, is too costly because it requires special harvesting machinery for a relatively narrow harvesting period, which is currently January to February. Thus, the harvest machinery utilization is low and the harvest time does not extent the harvesting period already covered by the other energy crops.

Regarding crop choice and land competition between energy and conventional crops, we find that cotton, maize and small cereals are the crops that might be replaced first by energy crops. Furthermore, we find that under the CAP 2003 conditions a part of the area cultivated with cotton during 2006 will be replaced by cotton cultivated only for subsidization. This happens because i) the cotton subsidy is exempt from decoupling and ii) in some cases, the cotton production is not profitable. Additionally, low profitability crops, which were grown before 2006 because of subsidies, are replaced by set-aside under the decoupled subsidization system of the CAP 2003.

The specified policy also affects the degree to which different farms engage in energy production. While there are little differences under Agenda 2000, farm size and farm type matter under the 2003 CAP. Our analysis shows that farms of the small and medium economic size category are more willing to replace a part of the currently cultivated conventional crops with energy crops. Additionally, the farms that were producing a variety of agricultural products (farms with mixed production of arable crops and trees or vegetables) will adopt energy crops faster than farms with a more specialized orientation.

Several limitations and uncertainties to this research must be noted. First, the findings presented here reflect current technologies for which data were available to us. Advances in plant breeding, field operations, and biomass storage and processing may increase the bioenergy potential. Second, prices for production inputs, traditional agricultural commodities, and biomass are assumed to be constant. Large-scale increases in European or global biomass production levels, however, may considerably increase the commodity prices for traditional agriculture, increase the opportunity costs of biomass, and thus decrease the bioenergy potential. Third, the collected data pertain to individual farms. We do not have adequate information on how representative each farm is within the analyzed region. Different weights for each farm could alter the biomass supply curve. Fourth, this decision analysis is based on profit maximization. Not taken into account are other preferences concerning culture and traditions and/or the environment. These preferences could also shift the biomass supply curve in either direction. Fifth, this analysis is based on 40 farms. A larger number of farms would increase the statistical properties of the data. Finally, all simulated results are derived from the optimal solution of the mathematical program and as such constitute point estimates without probability distribution.

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References

1. AAEA, 2000. Commodity Costs and Returns Estimation Guide. Feb 1 2000, Iowa, available at http://waterhome.brc.tamus.edu/care/Aaea/.
2. Bierman, H., Smidt, S., 1993. The Capital Budgeting Decision. 8th ed. Macmillan.
3. Lumby, S., Jones, C., 1999. Investment Appraisal and Financial Decisions, 6th ed. Thomson Learning.
4. Lychnaras, V. Rozakis, S., 2006. Economic Analysis of Perennial Energy Crop Production in Greece under the light of the new CAP. *New Medit* V(3), 29-37.
5. McCarl, B. A., Schneider, U. A., 2000. US agriculture's role in a greenhouse gas emission mitigation world: An economic perspective. *Review of Agricultural Economics* 22(1), 134-159.
6. Monti, A., Fazio, S., Lychnaras, V., Soldatos, P., Venturi, G., 2007. A full economic analysis of switchgrass under different scenarios in Italy estimated by BEE model. *Biomass and Bioenergy* 31(4), 177-185.
7. Schneider, U. A., McCarl, B. A., 2006. Appraising agricultural greenhouse gas mitigation potentials: Effects of alternative assumptions. Agricultural Economics 35(3), 277-287.
8. Soldatos, P., G., Lychnaras, V., 2003[1]. Technical-economic analysis for renewable energy chains: The case of bio-energy. Proceedings of the 8th Conference on environmental science and technology, 8-10 September 2003, Lemnos island, Greece.
9. Soldatos, P., G., Lychnaras, V., Assimakis, D., 2003 [2]. BEE Methodology. Agricultural University of Athens, Laboratory of Agribusiness Management, Athens, 2003, available at http://www.bee.aua.gr.
10. Soldatos, P.G., Lychnaras, V., Asimakis, D., Christou, M., 2004. Bee - Biomass Economic Evaluation: A Model for the Economic Analysis of Biomass Cultivation. Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, 10-14 May 2004, Rome, Italy.
11. Williams, J., R., Haka, S.,F., Bettner, M., S., Meigs, R. F., 2002. Financial and Managerial Accounting. 12th ed. McGraw Hill Higher Education.

Table 1 Sample characteristics

No	Farm No	Total area (ha)	% of cultivated area with arable crops							Economic Size[1]	Farm Type[2]
			Cotton	Alfalfa	Maize seed	Maize grass	Ind. Tomato	D. Wheat	Oat		
1	F2	2.0	100	-	-	-	-	-	-	S	2
2	F4	9.5	61	39	-	-	-	-	-	S	2
3	F14	13.0	54	46	-	-	-	-	-	S	2
4	F22	7.9	92	-	-	-	8	-	-	S	2
5	F25	9.3	100	-	-	-	-	-	-	S	2
6	F26	13.7	49	44	-	7	-	-	-	S	2
7	F33	1.7	100	-	-	-	-	-	-	S	2
8	F34	4.0	100	-	-	-	-	-	-	S	2
9	F35	4.2	100	-	-	-	-	-	-	S	2
10	F10	3.4	18	71	-	-	-	12	-	S	3
11	F28	10.8	49	31	9	-	11	-	-	S	3
12	F37	7.6	74	-	-	-	26	-	-	S	3
13	F39	4.7	43	26	11	-	-	21	-	S	3
14	F18	9.0	64	19	-	-	17	-	-	S	4
15	F36	11.5	-	87	13	-	-	-	-	S	4
16	F38	6.9	75	-	25	-	-	-	-	S	4
17	F40	4.7	100	-	-	-	-	-	-	S	4
18	F5	24.0	54	33	-	-	-	13	-	M	2
19	F6	12.9	100	-	-	-	-	-	-	M	2
20	F20	22.4	74	20	-	-	-	7		M	2
21	F29	15.0	100	-	-	-	-	-	-	M	2
22	F3	22.2	24	29	47	-	-	-	-	M	3
23	F13	40.0	-	63	38	-	-	-	-	M	3
24	F15	39.8	30	55	-	15	-	-	-	M	3
25	F21	14.3	51	-	-	-	49	-	-	M	3
26	F23	21.8	65	-	-	-	23	12	-	M	3
27	F31	27.7	-	40	36	-	-	24	-	M	3
28	F11	27.5	18	55	-	9	-	9	9	M	4
29	F16	36.1	71	29	-	-	-	-	-	M	4
30	F30	41.3	9	68	-	20	-	-	4	M	4
31	F12	42.3	83	-	-	-	15	4	-	L	2
32	F17	37.7	92	-	-	-	6	3	-	L	2
33	F24	36.2	86	-	-	-	14	-	-	L	2
34	F32	38.0	79	-	-	-	-	21	-	L	2
35	F1	57.0	42	37	13	8	-	-	-	L	3
36	F7	140.0	-	73	27	-	-	-	-	L	3
37	F19	25.0	60	16	-	-	24	-	-	L	3
38	F27	257.0	-	66	0	34	-	-	-	L	3
39	F8	157.0	38	45	-	16	1	-	-	L	4
40	F9	24.6	72	-	4	-	16	8	-	L	4

(1) Economic Size: S. 2-16 ESU, M. 16-40 ESU, L. >40 ESU

*(2) Farm Type: **1**. Mainly Cereals, **2**. Mainly Cotton, **3**. Combination of arable crops, **4**.Combination of crops (trees and garden area included)*

Table 2 Yield distribution

	Records	Average	Min	Max	St dev
Cotton	126	3.57	2.00	5.00	0.48
Alfalfa*	81	13.90	10.40	18.00	1.93
Maize – seed	25	11.20	7.50	13.00	1.41
Maize – grass	22	55.91	55.00	67.50	4.79
Industrial Tomato	16	65.00	45.00	100.00	15.28
Durum Wheat - seed	20	3.40	1.25	5.50	1.47
Durum Wheat - straw	4	1.50	1.50	1.50	-
Oat – seed	1	4.00	-	-	-
Oat - straw	1	10.50	-	-	-

* *Average yield of 5-year productive life*

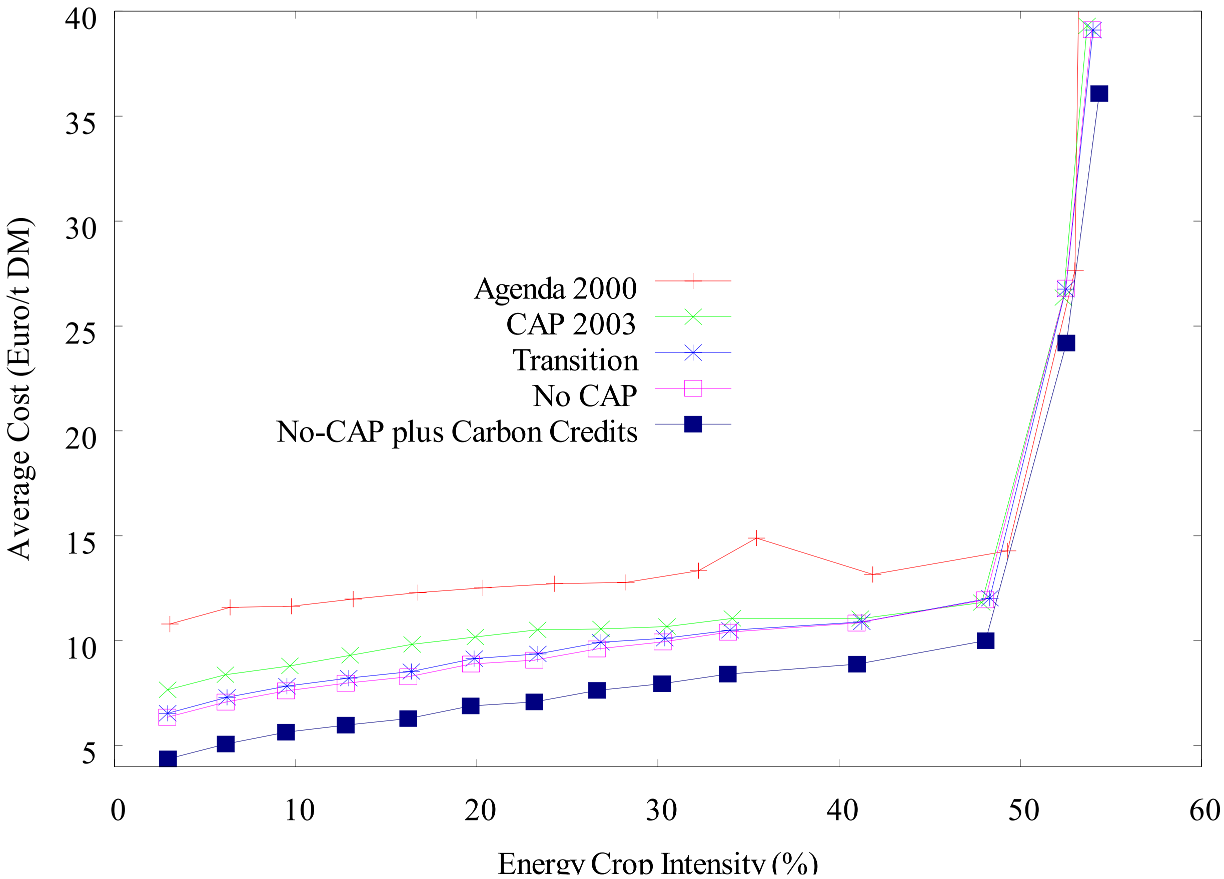

Figure 1 **Average cost of biomass as function of biomass intensity**

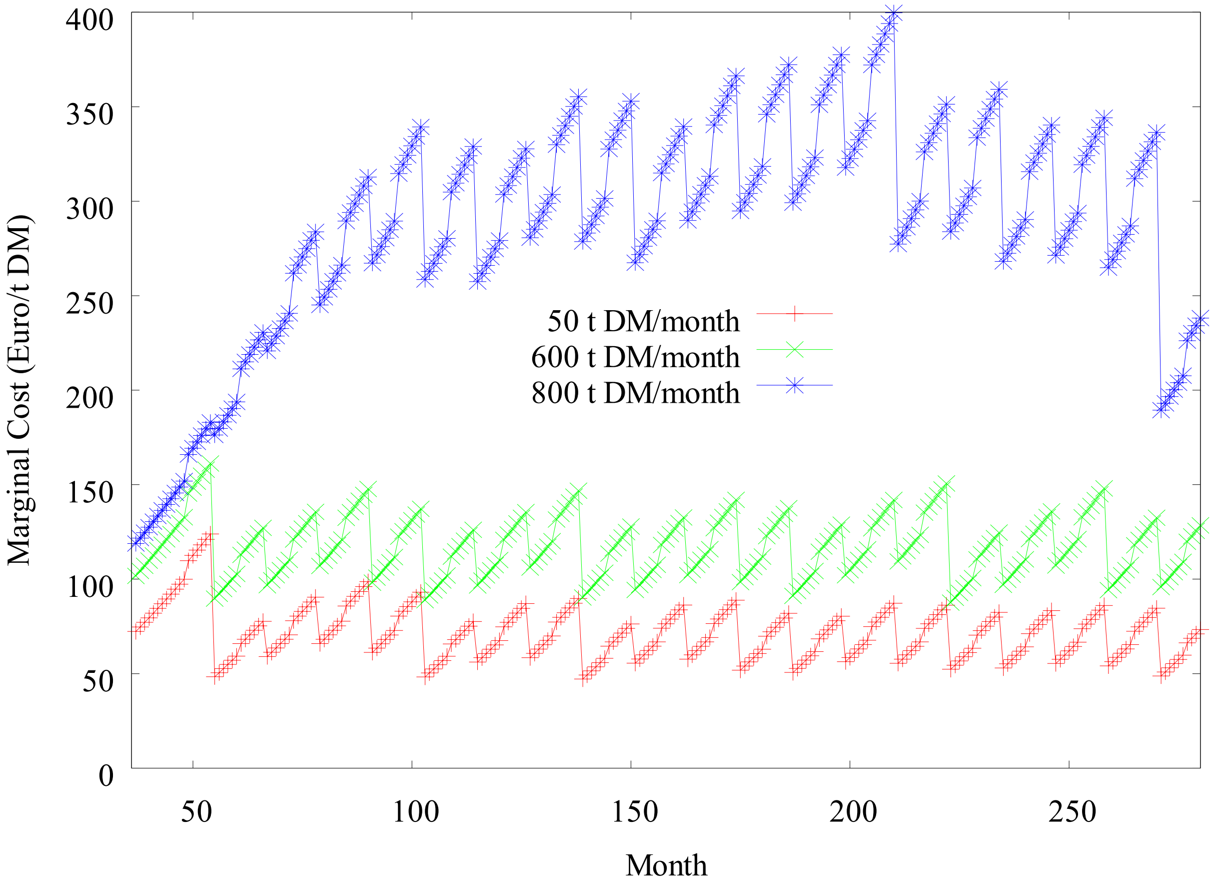

Figure 2 Marginal cost of biomass over time (CAP 2003)

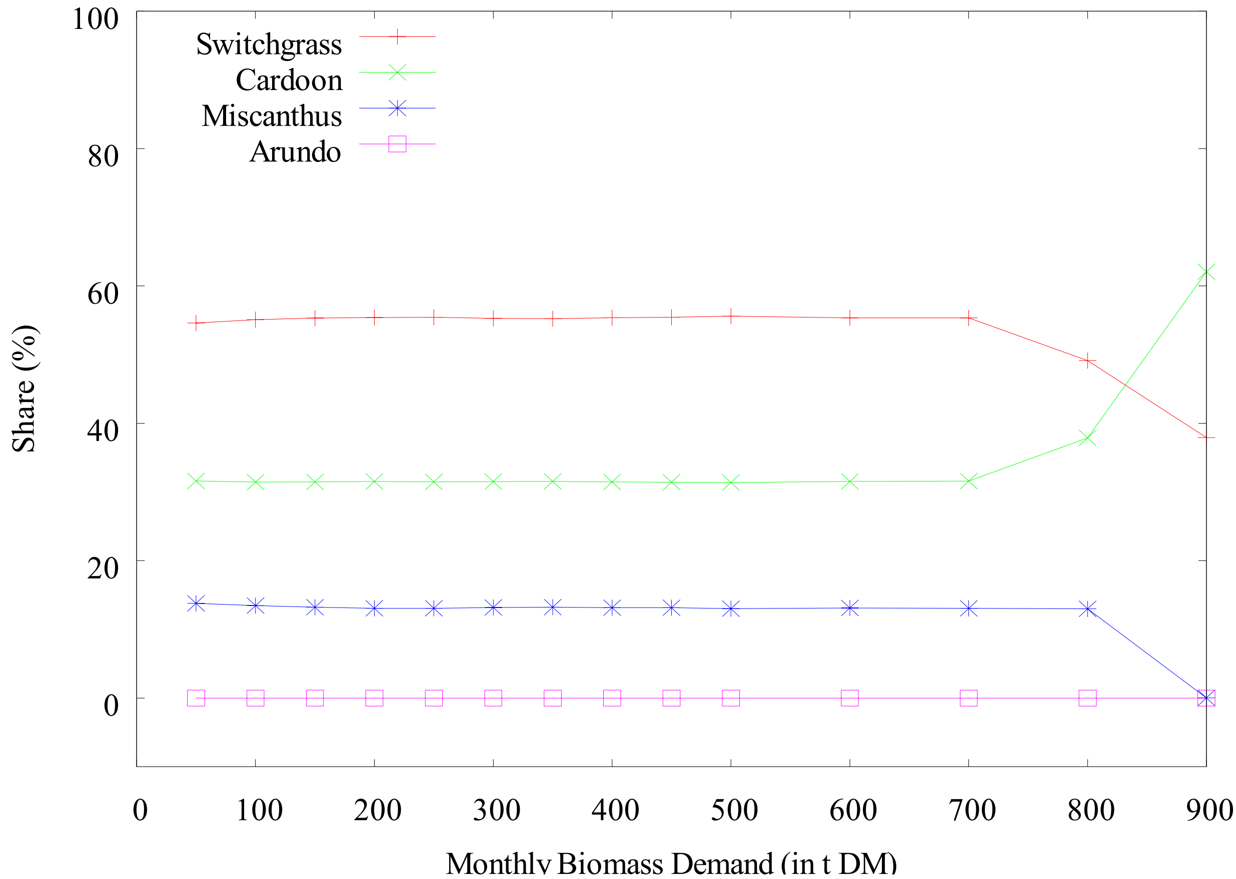

Figure 3 Cumulative area contribution (CAP 2003)

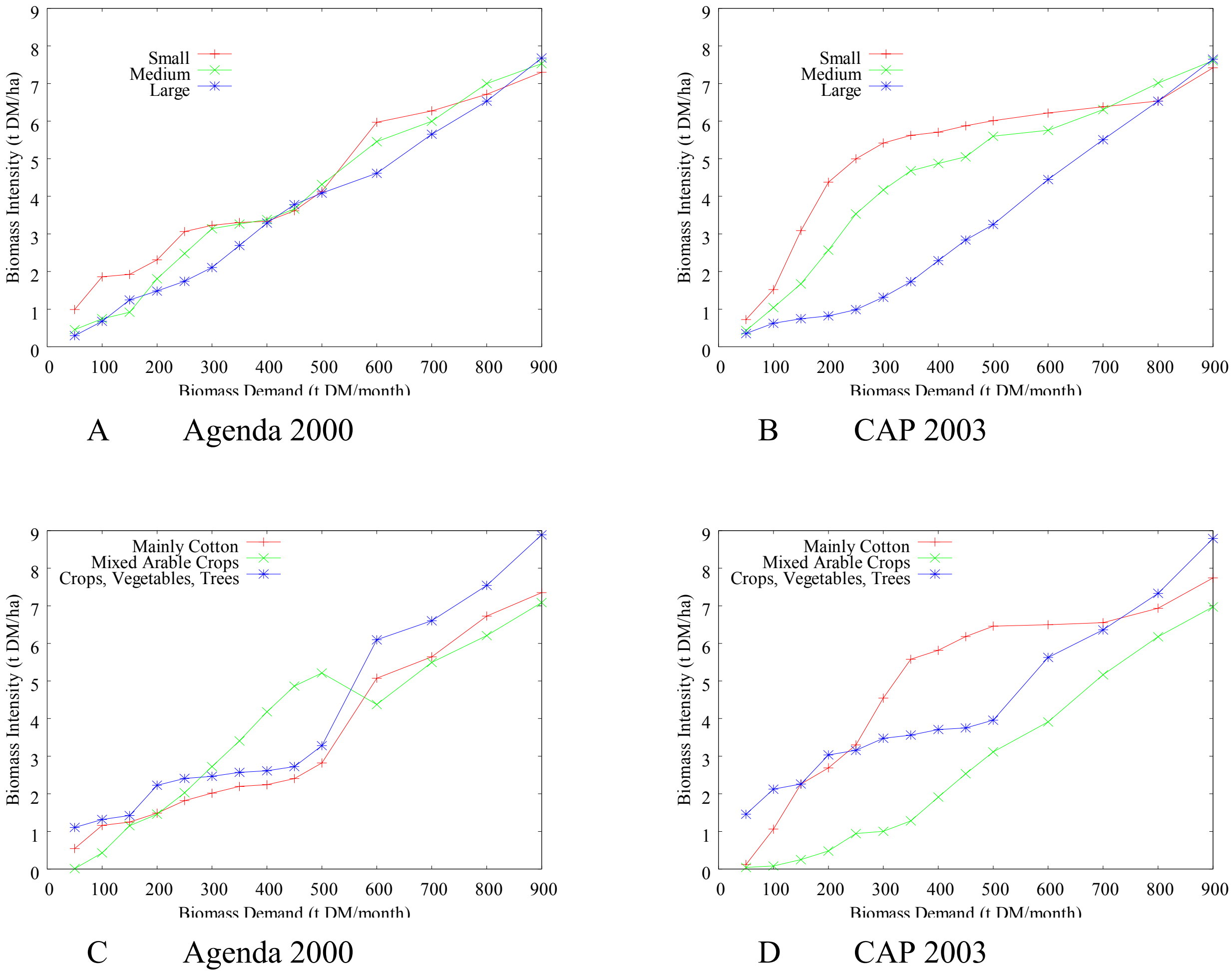

Figure 4 Policy Impacts on Biomass Potentials for Different Farms

Appendix - Dynamic Model Specification

The general formulation of this mixed integer farm level dynamic model maximises the present value of the annual profits, before biomass sales, of a system covering a number of farms and a biomass harvesting service, subject to conventional and energy crops constraints, Common Agricultural Policy constraints, harvesting storage and machinery usage constraints.

Indices

c	crops {Cotton, Alfalfa, Maize, Tomato, Wheat, Barley, Oat, Cardoon, Miscanthus, Arundo, Switchgrass, Setaside, Vetch, Subs_Cotton}
ec	energy crops {Cardoon, Miscanthus, Arundo, Switchgrass}
pc	perennial crops { Cardoon, Miscanthus, Arundo, Switchgrass, Alfalfa}
pr	products {seedcotton, grass, maizeseed, maizegrass, ind_tomato, wheatseed, barleyseed, oatseed, straw, biomass, noproduct}
bp	biomass products {biomass}
m	machinery {Sillage, Lorry10, Tractor65, Tractor90, Tractor100, Cutter, Windrower, DrumMower, Baler}
tr	tractors {Sillage, Lorry10, Tractor65, Tractor90, Tractor100}
n	months {Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec}
f	farms {farm1, …, farm10}
p	parcels {parcel1, …, parcel20}
t	period {t1, …, t25}
a	crop age {a0, …, a15}
ma	machinery age {ma1, …, ma20}
s	Common Agricultural Policy {Agenda 2000, CAP 2003, Transition, No CAP, Transition plus CP, No Cap plus CP}

Decision Variables

$A_{f,p,c,t,a}$	cultivated area (hectares)
$MO_{n,m,t}$	monthly usage of machinery (hours per month)
$St_{f,p,,bp,t,n}$	biomass storage quantity (tones)
$Q_{f,p,ec,bp,t,n}$	biomass production quantity (tones)
$SU_{f,bp,t,n}$	biomass supply (tones)

$MN_{m,t,ma}$	machinery number (integer)

Exogenous data

$Y_{f,p,c,p,a}$	yield (tones per hectare per year)
$P_{f,pr,t}$	price (euro per tone)
$PS_{f,pr,t,s}$	price subsidy (euro per tone)
$S_{f,p,c,t,s}$	area subsidy (euro per hectare)
$F_{f,p,ec,a}$	terminal value of perennial crops (euro per hectare)
PP_m	machinery purchase price (euro)
EL_m	machinery economic life (years)
MT_m	annual machinery maintenance cost (euro)
INS_m	annual machinery insurance cost (euro)
$AnnDPR_m$	annual machinery Depreciation (euro)
$HE_{m,c,a}$	machinery harvesting efficiency (euro per hectare)
$BE_{m,c,a}$	machinery balling efficiency (euro per hectare)
$HC_{m,c,a}$	machinery harvesting fuel consumption (litres per hour)
$BC_{m,c,a}$	machinery baling fuel consumption (litres per hour)
$HP_{n,c,a}$	harvesting available period (months)
BN_c	consumables (net) price for baling (euro per ton of biomass)
$PC_{f,p,c,t,a}$	production cost (euro per hectare)
$EC_{f,t}$	extraction cost of energy crops (euro per hectare)
SC_{bp}	storage cost (euro per tone)
SL_{bp}	storage losses (%)
$AV_{f,p}$	available cultivated area (hectares)
SA_f	selected subsidised area (hectares)
AHR_n	available hours per month for cultivation activities
$D_{bp,t,n}$	biomass demand (tones per month)
DP	diesel price (euro per litre)
LR	labor rate (euro per hour)
r	discount rate

Max:

$$\sum_t (1+r)^{-t} \cdot \left(\begin{pmatrix} \sum\limits_{f,p,c,pr,a} A_{f,p,c,t,a} \cdot Y_{f,p,c,p,a} \cdot \left(P_{f,pr,t} + PS_{f,pr,t,s}\right) + \sum\limits_{f,p,c,a} A_{f,p,c,t,a} \cdot S_{f,p,c,t,s} \\ + \left. \left(\sum\limits_{f,p,pc,a} A_{f,p,pc,t,a} \cdot F_{f,p,pc,a} \right) \right|_{t=T} \end{pmatrix} - \begin{pmatrix} \sum\limits_{m,ma} MN_{m,t,ma} \cdot AnnDPR_m + \sum\limits_{m,ma} MN_{m,t,ma} \left(MT_m + INS_m\right) \\ + \sum\limits_{m,f,p,c,a} DP \cdot A_{f,p,c,t,a} \cdot \left(HE_{m,c,a} \cdot HC_{m,c,a} + BE_{m,c,a} \cdot BC_{m,c,a}\right) \\ + \sum\limits_{f,p,c,pr,a} A_{f,p,c,t,a} \cdot Y_{f,p,c,p,a} \cdot BN_c \\ + \sum\limits_{tr,f,p,c,a} LR \cdot A_{f,p,c,t,a} \cdot \left(HE_{tr,c,a} + BE_{tr,c,a}\right) + \sum\limits_{f,p,c,a} A_{f,p,c,t,a} \cdot PC_{f,p,c,t,a} \\ + \sum\limits_{f,p,ec,a} EC_t \cdot \left(A_{f,p,c,t,a}\Big|_{a=K} + \left(A_{f,p,c,t-1,a-1} - A_{f,p,c,t,a}\right)\Big|_{1<a<K} \right) \\ + \sum\limits_{f,p,bp,n} SC_{bp} \cdot St_{f,p,bp,t,n} \end{pmatrix} \right), \ \forall \ s \qquad [1]$$

The objective function of the model [1] maximizes the present value of the net cash flows of a sample of representative farms and harvesting service provided by a cost-minimizing company, as the total revenue minus costs. Revenue consists of revenue from sales and subsidies. Terminal values[2] of perennial crops are also included for the last period.

Cost items account for:

a) Machines annual depreciation, including cost of capital investment (interest)[3],

b) Machines annual maintenance and insurance,

c) Machines fuel requirements, and labor wages for harvesting and baling,

---

[2]Terminal Values are estimated for every parcel as the Present Value of future profits of the rest of the productive life of the cultivation. This is equal to $PV = \sum_t \left(P_t \cdot Y_t - PC_t\right) \cdot \left(1+r\right)^{-t}$, where P_t is the price of the crop's product in period t, Y_t is the yield and PC_t is the production cost.

[3]*AnnDPR* is the annual equivalent cost of machinery purchase that takes into account the time value of money and equals to the annual depreciation plus cost of capital invested (interest). It is calculated as: $\frac{PP_m}{a(EL,r))}$, where PP_m is the purchase prise and *a(EL,r)* is the unitary annuity present value, calculated as $a(EL,r) = \frac{1-(1+r)^{-EL}}{r}$, where r is the discount rate and EL is the total economic life. The salvage value of machines at the last period is not considered, since the machinery cost in the objective function is calculated as annual cost (ordinary annuity).

d) Consumables (net) cost for biomass baling,

e) Production expenditures not related to harvesting and baling,

f) Extraction of energy crops at the end of their economic life or earlier and

g) Product storage cost

The storage cost (at the field) was estimated to 1.64 €/tone dry mater, based on the results of the European research project entitled "Bioenergy Chains"[4].

Subject to:

$$\sum_{c,a} A_{f,p,c,t,a}\Big|_{c\neq vetch} \leq AV_{f,p}\ ,\ \forall\ f,\ p,\ t\ and\ s \qquad [2]$$

$$\sum_{ec,p,a} A_{f,p,ec,t,a} \leq 0.5\cdot\sum_{p} AV_{f,p}\ ,\ \forall\ f,\ \ t\ and\ s \qquad [3]$$

$$\sum_{c,p,a} A_{f,p,c,t,a}\Big|_{c\neq vetch} \leq SA_f\ ,\ \forall\ f,\ t,\ and\ s{=}CAP\ 2003\ or\ t{\leq}8\ and\ s{=}\ \{Trans.,\ Trans\ plus\ CP\} \qquad [4]$$

$$\sum_{c,p,a} A_{f,p,c,t,a}\Big|_{c=vetch,alfalfa} \geq 0.2\cdot SA_f\quad \forall\ f,\ t,\ and\ s{=}CAP\ 2003\ or\ t{\leq}8\ and\ s{=}\ \{Tr.,\ Tr\ p\ CP\} \qquad [5]$$

The first constraint [2] is a resource restriction that restricts the cultivated area of all crops for each parcel to be less or equal than the available land. Vetch is not included in this restriction, since it is a catch crop that it is cultivated between the production periods of two annual crops. Equation number [3] restricts the maximum cultivated area of energy crops to be less than 50% of the total available area of each farm, assuming that the farmer will do in order to decrease the risk from new crops.

Restriction [4] concerns the selected area of the farm for subsidization, according to the CAP 2003 (active only for the period 2006-2013). The cultivated area of each farm has to be greater than or equal to the selected area for the farmer to receive the decoupled subsidy. Vetch is also not included. Similarly, restriction [5] depicts the obligation of the farmer to cover at least 20% of the selected area for subsidization with vetch or alfalfa (active only for 8-year period). As mentioned, vetch is cultivated between the production periods of annual conventional crops.

Vetch is a catch crop that is cultivated between two annual crops, so it can not be produced on the area that is occupied by perennial energy crops. For this reason, an equation that restricts the total area of energy crops in a farm to be less or equal of the total available land minus the 20% of the selected area for subsidization, is included. Mathematically, this restriction could be formulated as $\sum_{ec,p,a} A_{f,p,ec,t,a} \leq \sum_{p} AV_{f,p} - 0.2\cdot SA_f$. However, since equation [3] covers this restriction it is not needed explicitly.

$$A_{f,p,pc,t,a} - A_{f,p,pc,t-1,a-1} \leq 0\ ,\ \forall\ f,\ p,\ \ pc\ ,\ t{=}\{1,2,\ldots,20\},\ \ a{=}\{1,\ldots,15\}\ \ and\ s, \qquad [6]$$

$$A_{f,p,pc,t,a} = 0\ ,\ \forall\ f,\ p,\ pc,\ t{=}0,\ a{=}\{1,\ldots,15\}\ and\ s \qquad [7]$$

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[4] "Bioenergy Chains from Perennial Crops in South Europe": contract No: ENK6-CT2001-00524, http://www.cres.gr/bioenergy_chains/

Next, constraint [6] concerns perennial crops (energy crops and alfalfa) and it is the transition constraint that ensures the perenniality of those crops and restricts the existence of crops of age greater than one if the previous period there was not sufficient area of crops of age *(a-1)*, while the following restriction [7] assumes that there was no perennial crops inventory at the first period of the model.

$$MO_{n,m,t} = \sum_{ec,a}\left(\left(HE_{m,ec,a} + BE_{m,ec,a}\right)\cdot \sum_{f,p,bp}\left(HP_{n,ec,a}\cdot Q_{f,p,ec,bp,t,n}\cdot \frac{1}{Y_{f,p,c,bp,a}}\right)\right),\ \forall\ n,\ m,\ t \text{ and } s \quad [8]$$

$$\sum_{ma} AHR_n \cdot MN_{m,t,ma} \geq MO_{n,m,t},\ \forall\ n,\ m,\ t \text{ and } s \quad [9]$$

Equation [8] accounts for the monthly usage of each machine assuming that each month of the harvesting period of each crop an equal area is harvested. In this equation, the produced quantity is connected to the harvesting machines. The machinery constraint follows [9]. This equation forces the number of machines to be large enough to accommodate the needed maximum monthly operation.

$$MN_{m,t,ma} - MN_{m,t-1,ma-1} \leq 0,\ \forall\ m,\ t=\{1,2,\ldots,20\},\ ma=\{1,2,\ldots,20\} \text{ and } s, \quad [10]$$

$$MN_{m,t,ma} = 0,\ \forall\ m,\ t=\{1,2,\ldots,20\},\ ma=\{1,2,\ldots,20\} \text{ and } s \quad [11]$$

The next two restrictions [10 and 11] concern machinery also. The first equation of the this block is the transition equation for machinery life that restricts the existence of machinery of age greater than one if the previous period there was not sufficient number of machinery of age *(ma-1)*. The second of those two sets the machinery inventory at the beginning of the project to be zero.

$$\sum_{n} Q_{f,p,ec,bp,t,n} \leq \sum_{a}\left(A_{f,p,ec,t,a}\cdot Y_{f,p,ec,bp,a}\right),\ \forall\ f,\ p,\ ec,\ bp,\ t>1 \text{ and } s \quad [12]$$

$$\sum_{p}\begin{bmatrix} -\sum_{ec} Q_{f,p,ec,bp,t,n} - \left.\left(St_{f,p,bp,t,n-1}\cdot\left(1-SL_{bp}\right)\right)\right|_{n\neq Jan} \\ -\left.\left(St_{f,p,bp,t-1,n=Dec}\cdot\left(1-SL_{bp}\right)\right)\right|_{t>1,n=Jan} + St_{f,p,bp,t,n}\end{bmatrix} + \left.SU_{f,bp,t,n}\right|_{t>3} \leq 0,\ \forall\ f,\ bp,\ t>1,\ n \text{ and } s \quad [13]$$

$$\sum_{f} SU_{f,bp,t,n} \geq D_{bp,t,n},\ \forall\ bp,\ 3< t\leq 25,\ n \text{ and } s \quad [14]$$

The next three constraints concern only energy crops and biomass products and set the monthly harvested quantity of each crop and the monthly storage. The first constraint [12] of this block restricts the produced quantity of biomass products based on the yield of the energy crops. Note that the biomass production of every crop is only possible during the harvesting period of each crop. The next equation [13] connects the biomass produced quantity, stored quantity (current and previous month) and biomass supply. The stored quantity of previous month is reduced by the percentage of the losses (1% in our case). The final equation [14] of this block is the supply constraint that sets the biomass supply per month to be at least the equal to the monthly demand.

$$A_{f,c,t,a}, MO_{n,m,t}, Q_{f,ec,bp,t,n}, St_{f,bp,t,n}, SU_{f,bp,t,n} \geq 0,\ \forall\ f,\ c,\ ec,\ bp,\ t,\ n,\ a \text{ and } s$$

$$MN_{m,t,ma} \in N,\ \forall\ m,\ t,\ ma \text{ and } s$$

Finally, we have the nonnegative condition for the variables, while the variable of machinery number is integer.

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