Evaluating socio-economic and environmental sustainability of the sheep farming activity in Greece: A whole farm mathematical programming approach

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Abstract: *Ruminant livestock farming is an important agricultural activity that is mainly located in less favoured areas. On the other hand ruminants have been identified as a significant source of greenhouse gas emissions. In this study, a whole-farm optimization model is used to assess the socio-economic and environmental performance of the dairy sheep farming activity in Greece. The analysis is undertaken in two sheep farms that represent the extensive and the semi-intensive farming systems. Gross margin and labour inputs are regarded as socio-economic indicators and GHG emissions as environmental indicators. The issue of the marginal abatement cost is also addressed. The results indicate that the semi-intensive system yields a higher gross margin/ewe (179 €) than the extensive system (117 €) and requires less labour. The extensive system causes higher emissions/ewe than the semi-intensive system (1.35 t and 0.98 t of CO_2-equivelants, respectively). In the case of the semi-intensive farm, abatement is achieved by reduction of CH_4 from sheep. This is achieved by limiting the flock size and reducing emissions/ewe. The marginal abatement cost of the semi-intensive farm is higher than the marginal abatement cost of the extensive farm. Furthermore, abatement in the extensive farm is accompanied by a change in production orientation from sheep to crop activities.*

Keywords: *Dairy sheep farming, linear programming, GHG emissions, socio-economic performance, environmental performance, abatement cost*

Introduction

Ruminant livestock farming and especially sheep farming is an important agricultural activity in Greece, since it is mainly located in less favored areas of the country and utilizes less fertile and abundant pastureland. The activity yields income for thousands (128.000) of farms mainly located in marginal areas, where few alternative economic activities can develop (N.S.S.G[1]., 2005). These farms are dairy farms, since they aim primarily at the production of sheep milk that is responsible for over 60% of their gross revenue and secondarily at the production of meat (Kitsopanidis, 2006). It is estimated that almost 40% of the total milk produced in Greece is sheep milk (N.S.S.G., 2006). Furthermore the activity contributes highly in regional development and helps maintain the population in the depressed areas, where it is located. Therefore the preservation of the activity and the income it yields is important not only for farmers but also for policy makers.

The prevailing sheep farming system in the country is the extensive system, in which the feed requirements of the flock are met mainly through grazing. Extensive breeding farms are characterized by low invested capital with low productivity flocks, consisting mainly of native races (H.M.R.D.F.[2], 2007). More modern and intensive farms that are also present, have a higher invested capital and aim to increase their productivity through supplementary feeding, mainly from on produced cereals and forage. These two main production systems identified in the Greek sheep farming activity have different characteristics and therefore different economic and environmental performance.

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The matter of Greenhouse Gas (GHG) emissions has recently received extra attention in light of the Kyoto protocol and Europe's commitment to reduce emissions by 20% by the year 2020. Agriculture has been identified as a significant source of GHGs and farmers are urged to adopt not only economically viable but also environmentally sound farming practices. GHG emissions are particularly high in the case of ruminant livestock farming because of methane production through enteric fermentation (Pitesky et al., 2009). The issue of GHG emissions in livestock farms has been addressed in a number of studies that focus mainly in dairy cow and cattle farms (Weiske et al., 2006; Olesen et al., 2006; Veysset et al., 2010). On the other hand, studies that focus on the emission of GHGs from sheep farms refer mainly to meat and wool production farms, that have different technicoeconomic characteristics than dairy sheep farms (Benoit and Laignel, 2008; Petersen et al., 2009).

This study aims primarily at the evaluation of the socio-economic and environmental performance of the dairy sheep farming activity in Greece, through the use of a whole-farm optimization model. In this model environmental performance is measured through the estimation of the net GHG emissions of the sheep farms. The issue of the GHG abatement cost is also addressed, since mitigation leads to loss of income. The analysis is undertaken in two farms representing the extensive and the semi-intensive farming systems that are commonly found in the country. In the next section the mathematical model used in the analysis is described in more detail. The characteristics of the extensive and the semi-intensive farms are also presented. The third section contains the results of the analysis and the final section includes some concluding remarks.

Data and Methods

Linear programming (LP) models are commonly used in agricultural studies (e.g. Alford et al., 2004; Veysset et al., 2005; Crosson et al., 2006). They yield the optimal amongst all feasible farm plans, taking into account technical and agronomic constraints of the farms. In the case of livestock and crop livestock farms the complexity of the farm operation and the substitution possibilities between alternative activities require the use of a model that can capture all the interrelationships of these activities. The multiple sources of GHGs in crop-livestock farms present another reason for an LP model to be used (De Cara and Jayet, 2000). Thus, a number of studies have utilized LP models to assess GHGs from various sources and identify cost-effective mitigation strategies (e.g. Smith and Upadhyay, 2005; Schils et al., 2007b; Breen and Donnellan, 2009; Petersen et al., 2009).

Therefore, a whole-farm, linear programming model is considered an appropriate tool for the estimation of the socio-economic and environmental performance of livestock farms. The model used in this analysis is a mathematical model that incorporates all livestock and crop activities of sheep farms. The characteristics of the farm model are described in more detail in the following paragraphs. The data used in the analysis is also presented in this section.

The first step of our methodology is to use this mathematical model to obtain the optimal farm plan of each of the sheep farms. This optimal farm plan is derived through gross margin maximization that is assumed to be the objective of the farmers and is used to measure the economic performance of the farms. Labour inputs in this optimal farm plan are considered as an indicator of the social performance of the farm and net GHG emissions are regarded as an environmental performance indicator. The second step of our methodology is to estimate the optimal farm plan across increasing levels of abatement, and assess impact on gross margin and labour. Following a number of studies (e.g. De Cara and Jayet, 2000; Smith and Upadhyay, 2005), this is achieved by inserting an additional constraint in the model. Specifically, if a is the level of abatement (a<1), then a new constraint is inserted in the model not allowing the net farm emissions to be more than (1-a) of the original net emissions. The shadow price of net emissions is also estimated because it indicates the GHG marginal abatement cost for each farm (De Cara and Jayet, 2000; Smith and Upadhyay, 2005).

Model specification

The crop-livestock model used in this analysis maximizes total gross margin under the technicoeconomic constraints of the sheep farms and yields the optimal farm plan. For this purpose, it utilizes detailed farm level data on all crop and livestock activities of the farms. The decision variables and the constraints of the model are presented in the next paragraphs. The GHG emission sources that have been taken into account in this analysis are also presented in detail in this section as indicators of the environmental performance of the sheep farms.

Crop and livestock activities

Crop activities of the sheep farms involve mainly forage and cereal production for livestock feeding. In the model, farmers can produce cereals and forage either for consumption in the farm or for sale, according to what maximizes their gross margin. The two farms used in this analysis produce only alfalfa and maize, which are the main crop activities of the sheep farms of the area where the analysis is undertaken.

Two livestock activities are incorporated in the model, according to the time of sale of the lambs. In the first one, lambs are sold after weaning (approximately 42 days after lambing) and the ewes are then milked. The second activity involves the rearing of the lambs for three months prior to their sale. In this second alternative the live-weight of the lambs sold is higher but the price per kilogram is smaller. Also the milk yield is much smaller, since lambs are allowed to wean for a longer period of time. The produced forage is used for the feeding of the livestock. In the model there is also a set of variables to approximate monthly distribution of the produced forage. Additionally, monthly consumption of purchased maize and alfalfa present another set of the model variables. Also, the model includes decision variables that reflect the use of pastureland and the monthly consumption of grass. The final set of variables incorporated in the model involves the monthly labour inputs (family and hired labour inputs in crop and livestock activities).

Feed requirements

The main component of the model ensures that the monthly feed requirements of the flock are balanced. Minimum intake of dry matter, net energy of lactation, digestible nitrogen and fibrous matter is ensured through monthly constraints. The feed requirements of the flock are estimated according to Zervas et al. (2000). For the productive ewes these feed requirements include requirements for maintenance, pregnancy, weaning and lactation. For the rams the requirements refer to their maintenance, while for the replacement animals the feed requirements are estimated every month taking into account the live-weight increase. The weight increase is also taken into account in the case of the lambs, for which feed requirements are estimated for the period that they remain in the farm minus the feed requirements that are satisfied from weaning. On produced feed crops, external feed inputs and available pastureland are used for the balance of the feed requirements of the flock. The nutritional value per kilogram of maize, alfalfa and grass are taken from Kalaisakis (1965) and Zervas et al. (2000).

Labour and land constraints

A second component of the model ensures that monthly labour requirements of all production activities are balanced mainly with the family labour inputs. Additional hired labour can be used if necessary in both livestock and crop activities. Labour requirements differ between farms according to the specific crop and livestock activities, management practices, type of machinery used and specific land characteristics. Land availability constraints are also incorporated in the model. They refer to the availability of irrigated land, used for alfalfa and maize production, availability of pastureland and total farm land.

GHG emissions

In this analysis an extra component has been added in this model that refers to the GHG emissions. The main GHG emissions, from livestock farms are methane (CH_4) from enteric fermentation and excreta and nitrous oxide (N_2O) from excreta. In addition, in a crop-livestock farm nitrous oxide (N_2O) emissions from fertilizer use should also be accounted for (see for example Schils et al., 2007a; Petersen et al., 2009; Veysset et al., 2010). Carbon dioxide (CO_2) emissions from energy consumption are an additional source of GHGs. In our analysis, all the potential sources of GHGs have been taken into account and added to estimate total emissions[3].

Methane production from enteric fermentation is the most important source of GHGs in livestock farms and it is associated with the feeding practices of each farm. Farmers choose to feed their flock with on produced feed and purchased feed taking into account the cost and the nutritional value of each feedstuff and the feed requirements of the flock. The ration used in this analysis is not fixed, but it is optimized (see also Petersen et al., 2009). Following the work of De Cara and Jayet (2000), methane emissions from sheep are predicted for each feedstuff according to the following equation:

$$E\text{-}CH_4/EB = -1.73 + 13.91\ dE \qquad (1)$$

Where $E\text{-}CH_4/EB$ is the percentage share of gross energy of each feedstuff loss in methane and dE is a digestibility index. The digestibility index for each feedstuff is taken from Kalaisakis (1965).

Methane produced from livestock excreta is considered negligible, since no anaerobic conditions exist during the management of manure or grazing of sheep (IPCC, 2006, Petersen et al., 2009). On the other hand when aerobic conditions exist, N_2O is produced and therefore direct and indirect N_2O emissions from livestock excreta during manure management and grazing are included in the analysis[4]. Direct and indirect emitted N_2O from manure management and pastureland are estimated according to the Tier 1 methodology proposed by the IPCC (2006). Emissions from leaching occurring in pastureland have also been taking into account but were considered negligible for manure management.

In our analysis we have included direct and indirect N_2O emissions from the use of nitrogenous fertilizers. First the total amount of nitrogen applied in fields has been calculated using the amount and the type of fertilizer (De Cara and Jayet, 2000; Petersen et al., 2009). Then direct, indirect and leaching emissions from the applied N have been estimated according to the Tier 1 methodology and the emission factors proposed by the IPCC (2006). Pre-chain emissions have also been estimated and included in the analysis, following the work of Olesen et al. (2006). As mentioned above farmers choose whether to feed their flock with on or off farm produced crops. Therefore, emissions from the nitrogenous fertilizers used for the off farm production of feedstuffs have also been estimated and incorporated in the model. Specifically, N_2O emissions from purchased alfalfa and maize have been estimated using data gathered from 85 and 73 farmers of the area, respectively.

CO_2 from energy use is another source of GHG emissions in crop-livestock farms. The main sources of energy in these farms are fuel (mainly diesel) and electricity (see also Olesen et al., 2006). To estimate the emissions from energy use, fuel or electricity requirements for every operation and type of machinery is estimated and multiplied by emission factors (Petersen et al., 2009). As in the case of N_2O, CO_2 emissions from energy requirements of purchased feed are also estimated, according to the data gathered from the farmers of the area. Other inputs like fertilizers and pesticides used in both produced and purchased crops have also caused GHG emissions when they were manufactured. These emissions have been taken into account as well, using farm level data to estimate the amount of inputs used and related literature to estimate the emissions caused by the manufacture of this

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[3] CH_4 and N_2O have been converted to CO_2-equivalents using the following conversion factors: 1kgr of CH_4 = 25 and 1kgr of N_2O=298 (IPCC, 2006).

[4] It is not possible to estimate the exact amount of N_2O emitted when manure is managed and while grazing. For this reason we have developed and incorporated in the model an index to account for livestock excreta emissions per animal. This index is estimated according to the sheep farming practices in Greece, where sheep are allowed to graze nine months of the year and therefore manure is directly applied in pastureland. Consequently, manure managed in piles comes from the three months of the winter when sheep are limited indoors.

inputs. CO_2 emissions from the manufacture of fertilizers are taken from Wood and Cowie (2004) and emissions from the manufacture of pesticides are taken from Audsley et al. (2009).

Sheep farming also has a positive impact as far as GHG emissions are concerned, since crops and pastureland are responsible for carbon sequestration. We have assumed a carbon sequestration of 110 kg of CO_2-equivelants per stremma[5] for crops (0.3 t C/ha), and 60kg of CO_2-equivelants per stremma for pastureland (0.16 t C/ha) (see also Pretty and Ball, 2001). The carbon sequestration of pasture is assumed limited because of the poor production of grass from Mediterranean pastureland. These sequestration estimations are subtracted from the total emitted GHGs estimated above so that net emissions can be assessed.

Data

The analysis is undertaken in two sheep farms that represent the extensive and the semi-intensive farming systems and are located in lowland areas of the Prefecture of Etoloakarnania, in Western Greece. More specifically the semi-intensive farm has a flock size of 315 ewes with an annual production of milk about 190 kg/ewe. The live-weight of the ewe is 60 kg and the birth rate is 1.5 lambs/ewe. The semi-intensive farm maintains 70 strm of alfalfa and 30 strm of maize for feeding of the flock and utilizes 500 strm of pastureland. The milking period is prolonged (from November to July) since there are two lambing periods, in late September and February.

The extensive farm has a flock size of 160 ewes and an annual production of milk of about 100 kg/ewe. The live-weight of the ewes and the birth rate are also smaller in the extensive farm (50 kg/ewe and 1.3 lambs/ewe, respectively). In the farm, 20 strm of alfalfa and 18 strm of maize are cultivated, but the feeding requirements are mainly met through grazing (800 strm of pastureland). Labour inputs are offered mainly by the farmer and the milking period is smaller than in the case of the semi-intensive farm (January to May). Detailed data from the two farms is used to derive all technical and economic coefficients of the model.

Application and results

The mathematical programming model is used to simulate the operation of the two farms and the optimal farm plan is obtained. This optimal farm plan is used to evaluate the performance of the farms, which is discussed in detail in the following paragraphs[6]. The constraint on net emissions is then inserted and the optimal farm plan is again obtained for various levels of abatement, through parametric optimization. This way is the best abatement strategy for each farm can be identified. Finally, the marginal abatement cost for each of the farms is estimated and the marginal abatement cost curve is built and presented in the last paragraph of this section.

Socio-economic performance

Table 1 contains the optimal farm plan for the semi-intensive farm. The total gross margin and the gross margin per ewe are 56,775 € and 179 € respectively. According to Kitsopanides (2006), semi-intensive farms are considered profitable and have an annual net return of 29.4 €/ewe. Although the model used in this analysis maximizes gross margin, fixed cost is known and can be used to evaluate net return, at 45.2 €/ewe, indicating that the economic performance of the semi-intensive farm is very satisfying. As far as the employment level is concerned, the farm offers full time employment to the two owners, since family labour is 3,463 hours, and extra hired labour is also required (87 hours). On the other hand, the extensive farm has a lower gross margin per productive ewe (117 €) (Table 2). According to Kitsopanides (2006), extensive farms have a negative net return (-5.6 €/ewe). In this

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[5] 1 stremma (strm) = 0.1 hectare

[6] It should be noted that the performance of the mathematical model is satisfactory, since the optimal farm plan is very close to the observed one, especially in the case of the semi-intensive farm.

analysis, the net return of the extensive farm is small but positive (6.4 €/ewe), indicating that the activity is viable. Labour inputs per ewe are higher compared to the semi-intensive farm because of the extra labour required for grazing and limited invested capital (eg. absence of milking machine).

The environmental performance of the two farms is discussed in detail in the next paragraph. Tables 1 and 2, though contain the optimal farm plan for the farms under the hypothesis of various levels of abatement, or in other words the optimal abatement strategy for the farms. A 10% abatement for the semi-intensive farm leads to a 5% reduction of the gross margin and a 4% reduction of labour (Table 1). At a 20% abatement level the total reduction in gross margin and labour is 11% and 7%, respectively and full time employment is offered to only one of the owners. The overall reduction is 6,262 € and the average abatement cost is 20 €/ewe, which can be used as an indication of the compensation/ewe the farmer should receive for abating.

Table 1. Optimal Solution of the Semi-intensive Farm for Different Abatement Levels.

Abatement (a)	0		0.10		0.15		0.2	
	Total	/ewe	Total	/ewe	Total	/ewe	Total	/ewe
Gross Margin (€)	**56,775**	**179**	**53,702**	**175**	**52,117**	**174**	**50,513**	**172**
Tota labour (hr)	**3,550**	**11**	**3,424**	**11**	**3,350**	**11**	**3,288**	**11**
Productive ewes	318	-	306	-	299	-	293	-
Produced maize for consumption (kg)	47,060	148	45,775	150	44,737	150	44,728	153
Purchased maize (kg)	16,638	52	17,944	59	18,796	63	19,253	66
Produced alfalfa for consumption (kg)	90,356	284	92,588	303	93,030	311	93,749	320
Purchased alfalfa (kg)	0	0	0	0	0	0	0	0
Grass consumed (kg)	250,000	786	202,069	660	179,140	599	154,913	529
Produced maize for sale (kg)	0	-	0	-	0	-	0	-
Produced alfalfa for sale (kg)	820	-	194	-	1,048	-	341	-

Table 2. Optimal Solution of the Extensive Farm for Different Abatement Levels.

Abatement (a)	0		0.10		0.15		0.2	
	Total	/ewe	Total	/ewe	Total	/ewe	Total	/ewe
Gross Margin (€)	**19,952**	**117**	**19,285**	**135**	**18,651**	**137**	**18,009**	**140**
Tota labour (hr)	**2,510**	**15**	**2,135**	**15**	**2,037**	**15**	**1,943**	**15**
Productive ewes	171	-	143	-	136	-	129	-
Produced maize for consumption (kg)	20,538	120	11,998	84	11,413	84	10,828	84
Purchased maize (kg)	0	-	0	-	0	-	0	-
Produced alfalfa for consumption (kg)	14,753	86	15,923	111	15,144	111	14,364	111
Purchased alfalfa (kg)	44,54	26	0	0	0	0	0	0
Grass consumed (kg)	320,000	1,871	306,588	2,144	291,562	2,144	276,536	2,144
Produced maize for sale (kg)	0	-	0	-	0	-	0	-
Produced alfalfa for sale (kg)	8,298	-	17,293	-	18,769	-	20,245	-

In the case of the extensive farm 10% abatement causes a significantly smaller reduction of the gross margin compared to the intensive farm (Table 2). Specifically, the reduction of the gross margin is 3.3% and it is due to the reduction of the number of ewes. On the other hand the gross margin per ewe is higher than in the case of no abatement. This is because, in the case of the extensive farm, abatement is achieved through substitution of the sheep farming activity with the crop production activity (alfalfa production for sale). This is not the case with the semi-intensive farm, where abatement was accomplished partly through the substitution of feed in the ration rather than the substitution of the sheep farming activity. Table 2 also indicates that 20% abatement causes a 9.7% reduction on the gross margin of the farm. Again the gross margin per ewe is higher than in the case of no abatement and the alfalfa production for sale is significantly increased. On the other hand, abatement has a significant impact on the employment level of the extensive farm, since sheep farming, which has high labour requirements is gradually abandoned. Specifically, 10% and 20% abatement cause 15% and 22% reduction in labour, respectively.

Environmental performance

The environmental performance of the semi-intensive and the extensive farm, and specifically their GHG emissions are presented in Tables 3 and 4. Specifically, Tables 3 and 4 contain the overall emissions of the farms and the distribution of emissions by main sources. The net emissions (total emissions minus carbon sequestration) are also presented. The main source of GHGs in sheep farms is enteric fermentation, since it is responsible for 83% of the total emitted GHGs in the semi-intensive farm and 91% in the total emitted GHGs of the extensive farm. Similar findings on the contribution of CH_4 emissions in ruminant livestock farms have been reported in previous studies (e.g. Smith and Upadhyay, 2005; Petersen et al., 2009). 13% of the emissions of the semi-intensive farm are N_2O emissions and the remaining 4% is CO_2 emissions (Table 3). As far as the extensive farm is concerned N_2O is responsible for 8% of the total emitted GHGs and CO_2 accounts for only 1% of the total emitted GHGs (Table 4). Emissions from enteric fermentation per ewe are higher in the case of the extensive farm because of the high participation of primarily grass and secondarily alfalfa in livestock feeding.

Net emissions of the semi-intensive farm are over 310 t or 0.98 t/ewe. For the extensive farm net emissions/ewe are even higher, reaching 1.35 t/ewe (net emissions are over 230 t)[7]. Tables 3 and 4 also contain emissions by source at various levels of abatement. As can be observed in Table 3, abatement in semi-intensive farms is achieved mainly by reducing CH_4 emissions from enteric fermentation.

Table 3. GHG Emissions in Kg of CO_2-equivalents of the Semi-intensive Sheep Farm for Different Abatement Levels.

Abatement (a)	0		0.10		0.15		0.2	
	Total	/ewe	Total	/ewe	Total	/ewe	Total	/ewe
Net emissions	310,530	977	279,477	913	263,950	883	248,424	848
Total GHGs	328,880	1,034	297,827	973	282,300	944	266,774	910
CH_4 emissions	272,157	856	242,288	792	227,459	761	212,511	725
N_2O excreta	37,285	117	35,878	117	35,057	117	34,354	117
N_2O fertilizer	4,129	13	4,057	13	3,999	13	3,998	14
CO_2 energy	10,714	34	10,648	35	10,595	35	10,594	36
N_2O fertilizer - purchased feed	1,806	6	1,947	6	2,040	7	2,089	7
CO_2 energy - purchased feed	2,789	9	3,008	10	3,151	11	3,227	11

Specifically, in order to achieve a 10% abatement of net emissions in the semi-intensive farm, CH_4 emissions are reduced by 11%. This reduction is achieved by the reduction of the number of ewes by 12 but also through substitution of feed. Grass is substituted by alfalfa and maize, which leads to the decrease of CH_4 per ewe and to the increase of emissions from purchased feed. Similarly, a 20% reduction of net emissions leads to a higher reduction of CH_4 (22%) (see also De Cara and Jayet, 2000) and a 16% increase of emissions from purchased feed (CO_2 and N_2O). Abatement is again achieved partly through the reduction of the number of ewes and partly through the reduction of CH_4 emissions per ewe.

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[7] The emissions are particularly high because total emissions of the flock are estimated (productive and non-productive ewes, rams, lambs and replacement animals) which are then divided by the number of productive ewes. Also emissions from all sources have been included. Finally, dairy farming has higher feed requirements than meat or wool farming and therefore higher emissions.

In the case of the extensive farm, abatement is achieved through change in production orientation from sheep to crop, as mentioned in a previous paragraph. Specifically, in the case of the extensive farm, CH_4 emissions from enteric fermentation are reduced by 8% and 17% in order to achieve 10% and 20% abatement, respectively (Table 4). This substitution of the sheep farming activity with crop activities has also been pointed out in the study of Petersen et al. (2009) on GHG abatement in extensive grazing systems of south-western Australia. In our analysis it is explained by the low gross margin of sheep farming in the extensive farm and the high yield of alfalfa. In the case of the extensive farm the overall reduction of CH_4 emissions is achieved only by reducing the flock size and not by the substitution of grass from alfalfa and maize. On the contrary the consumption of alfalfa per ewe remains almost the same through various abetment levels, while the consumption of grass per ewe is increasing, meaning that the CH_4 emissions per ewe are increasing. Unlike the case of the semi-intensive farm, under the hypothesis of 20% abatement, emissions from all sources in the extensive farm are reduced. The above findings denote the heterogeneity of the abatement strategies sheep farms in Greece are likely to follow.

Table 4. GHG Emissions in Kg of CO_2-equivalents of the Extensive Sheep Farm for Different Abatement Levels.

Abatement (a)	0		0.10		0.15		0.2	
	Total	/ewe	Total	/ewe	Total	/ewe	Total	/ewe
Net emissions	**231,481**	**1,354**	**208,333**	**1,457**	**196,758**	**1,447**	**185,184**	**1,436**
Total GHGs	260,841	1,525	237,693	1,662	226,118	1,663	214,544	1,663
CH_4 emissions	237,740	1,390	219,503	1,535	208,749	1,535	197,994	1,535
N_2O excreta	16,711	98	13,975	98	13,291	98	12,607	98
N_2O fertilizer	3,187	19	2,097	15	2,023	15	1,948	15
CO_2 energy	3,004	18	2,117	15	2,056	15	1,995	15
N_2O fertilizer - purchased feed	94	1	0	0	0	0	0	0
CO_2 energy - purchased feed	104	1	0	0	0	0	0	0

Abatement cost

Fig. 1 presents the abatement cost curve for the semi-intensive farm. As can be seen in this figure, the curve is convex indicating an increasing marginal abatement cost. The average abatement cost for a 20% abatement is 101 €/t. The marginal abatement cost is 88 €/t until 10% abatement is achieved. Then the abatement cost increases to reach 94 €/t and 118 €/t, until 15% and 50% abatement, respectively. At 55% abatement the marginal abatement cost increases rapidly, reaching 322 €/kg, indicating that an abatement higher than 55% is practically impossible.

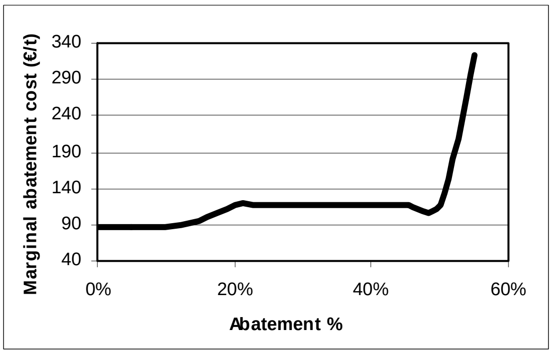

Figure 1. Marginal Abatement Cost of the Semi-intensive Farm for Different Abatement Levels

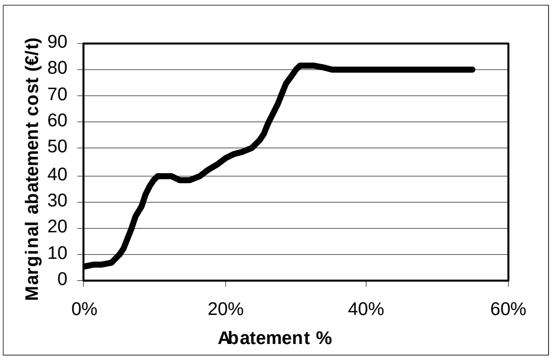

Figure 2. Marginal Abatement Cost of the Extensive Farm for Different Abatement Levels

The abatement cost curve of the extensive farm is presented in Fig. 2. As in the case of the semi-intensive farm, the marginal abatement cost of the extensive farm is also increasing, with an average of 42 €/t until a 20% abatement is reached. The shadow price of net emissions is very small at current emission levels (6 €/t) and very gradually increases to 38 €/t at 10% abatement, 46 €/t at 20% abatement, 53 €/t at 25% abatement and 80 €/t for further abatement. Breen and Donnellan (2009) estimate a marginal abatement cost of 110 to 230 €/t for dairy farms in Ireland, while De Cara and Jayet (2000) estimate the marginal cost that varies significantly among farm types from 30 €/t to 300 €/t. The low abatement cost of the extensive farm is explained by the substitution of sheep farming with crop activities. These results support the heterogeneity of the marginal abatement cost within the sheep farming activity in Greece. The heterogeneity of the GHG abatement cost has been pointed out in a number of studies (e.g. De Cara *et al*., 2005).

Assessing the marginal abatement cost is useful to policy makers who wish to develop well targeted and designed abatement policy measures. One potential policy measure is the implementation of a tax per tone of emitted CO_2-equivalents (Neufeldt and Schäfer, 2008; Petersen et al., 2009). The analysis can assist in the determination of the level of this tax according to the abatement cost of the farms (see also De Cara and Jayet, 2000). If a tax smaller than the marginal abatement cost of a farm is implemented, then the farmer will choose to pay the implemented tax instead of abating and thus the policy measure will be ineffective. Specifically, according to our analysis a tax of 80 €/t of CO_2-equivalents, will have no effect on semi-intensive farm, but will succeed to reduce emissions of the extensive farm. Furthermore, this tax will also have an impact on the sustainability of the extensive farming system since it can lead to its abandonment.

Concluding remarks

In this study a mathematical programming model was used to derive the optimal farm plan of sheep farms and estimate their socio-economic and environmental (in terms of GHG emissions) performance. The abatement strategy and the marginal abatement cost of sheep farms are also estimated. The analysis is undertaken in two sheep farms that represent the semi-intensive and the extensive production systems and includes pre-chain emissions as well as all potential emission sources in the farm. The model maximizes gross margin that is used as an economic sustainability indicator. Labour inputs are used as a social performance indicator and GHG emissions as an environmental sustainability indicator.

The results of the analysis indicate that both production systems are economically viable, though the semi-intensive farm has a higher gross margin than the extensive one. The main source of GHG emissions in dairy sheep farms is enteric fermentation. Emissions are particularly high in extensive farms, because of the excessive use of grass and alfalfa for feed. Across various abatement levels, the optimal solution indicates that abatement in semi-intensive farms is achieved mainly by decrease of CH_4 (limiting flock size and turning to concentrate feedstuff). In the case of the extensive farm abatement is achieved through partial substitution of sheep activities from crop production for sale. As far as the marginal abatement cost is concerned, it is increasing across various levels of abatement and it is significantly higher in the case of the semi-intensive farm. The results reveal a high dependency of semi-intensive farms to sheep farming, which limits abatement. The abatement cost of extensive farms is smaller, because of the smaller milk yield and therefore the smaller gross margin/ewe.

The results of the analysis of the two farms are an indication of the heterogeneity of the abatement cost amongst sheep farms with different characteristics. Utilizing a farm typology can reflect this heterogeneity more accurately and can be used to estimate the total cost of abating for the country. However the results of the analysis have highlighted some aspects of the sustainability of the sheep farming activity and can be used as a guide for the development of effective mitigation policy measures.

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