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Modeling Greenhouse Gas Emissions on Diversified Farms: The Case of Dairy Sheep Farming in Greece

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Abstract: Agricultural activity has been identified as a considerable source of Greenhouse Gas (GHG) emissions. Emissions from ruminant livestock farms are produced particularly due to CH_4 emissions from enteric fermentation. Dairy sheep farming is the most important livestock production activity in Greece, characterized by a high degree of farm diversification. This paper addresses the issue of the evaluation of GHG emissions of Greek dairy sheep farms, through the use of a whole farm mathematical programming model that uses farm level data and optimizes total gross margin. Mathematical programming models are an appropriate tool, when addressing complex issues, such as GHG emissions. The analysis is undertaken on different farm types, instead of a representative farm, to account for the heterogeneity of the sheep farming activity. Thus, marginal abatement cost and appropriate mitigation strategies for diversified farms are determined. The results indicate that intensive farms cause few emissions per produced milk (2.7kg of CO_2 eq). Also, the marginal abatement cost ranges among 51-64€/t for all types of sheep farms (at 20% abatement level). The model used in this analysis and the results it yields are useful to researchers and policy makers, who aim to design efficient mitigation measures.

Keywords: Dairy sheep farming, linear programming, GHG emissions, abatement cost

1. Introduction.

Agriculture has been identified as a significant source of Greenhouse Gas (GHG) emissions and therefore 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 (Olesen et al 2006; Weiske et al 2006; Veysset et al 2009). On the other hand, studies that focus on the emission of GHGs from sheep farms refer mainly to sheep bred for meat and wool and not for milk (Benoit & Laignel 2008; Petersen et al 2009).

Ruminant livestock farming and especially dairy 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 number of sheep bred in Greece is approximately 9.000.000 held in about 128.000 farms (N.S.S.G[1]. 2000). 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 rather depressed areas, where it is located. Therefore, the preservation of the dairy sheep farming activity and the income it yields is important not only for farmers but also for policy makers.

Furthermore, Greek sheep farms are characterized by a high degree of diversification in terms of invested capital, production orientation, breeding system, herd size, milk yield and other technicoeconomic characteristics indicating heterogeneity in economic performance and GHG emissions. Specifically, in extensive breeding systems feed requirements are met mainly through grazing, while supplementary feed is used only a few months of the year. Extensive breeding farms are characterized by low invested capital and low productivity (H.M.R.D.F.[2] 2007). More modern and intensive farms are also present in the Greek sheep farming activity. These farms have a higher invested capital and aim to increase their productivity through supplementary feeding, mainly from on produced forage.

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This study aims at the evaluation of GHG emissions of the dairy sheep farming activity in Greece, through the use of a whole farm optimization model. The model utilizes detailed farm level data and maximizes gross margin under technicoeconomic constraints of the farm, while it incorporates all potential GHG emission sources. The issue of the GHG abatement cost is also addressed, since any attempt to restrict GHG emissions should take farmers' loss of income under consideration, especially since safeguarding the income is important for the preservation of the activity and the population of depressed areas. The analysis is undertaken in four farms representing different farm types, identified through cluster analysis.

In the next section the mathematical model is described in more detail. The farm types identified are presented in section three. Section four contains the results of the analysis and the final section includes some concluding remarks.

2. Methodology

Linear programming 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 all 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 and can represent the system accurately. The multiple sources of GHGs in crop-livestock farms present another reason for a linear programming model to be used when issues of GHG emissions are addressed (De Cara & Jayet 2000, Smith & Upadhyay, 2005; Breen & Donnellan, 2009; Petersen et al 2009).

The first step of our methodology is to use this mathematical model to obtain the optimal farm plan for the sheep farms used in the analysis. This optimal farm plan is obtained through total gross margin maximization that is assumed to be the objective of the farmer. The second step of our methodology is to estimate the optimal farm plan when emissions are reduced to various levels. Following a number of studies (e.g. De Cara & Jayet 2000; Smith & Upadhyay 2005), this is achieved through parametric optimization after inserting one more constraint in the model. Specifically, if **Error! Bookmark not defined.** a is the abatement level (**Error! Bookmark not**

defined. a <1), then a new constraint is inserted in the model not allowing the net farm emissions to be more than 1-a. The gross margin is optimized again and the optimal farm plan for various levels of a is obtained. The shadow price of net emissions is also estimated because it indicates the GHG marginal abatement cost for each farm (De Cara & Jayet 2000; Smith & Upadhyay 2005).

2.1. Model specification

The crop-livestock model used in this analysis maximizes total gross margin under the technicoeconomic constraints of the sheep farms. For this purpose, it utilizes detailed farm level data on all crop and livestock activities of the farms. The decision variables, the constraints of the model and the GHG emission sources are presented in this section.

Crop and livestock activities

Crop activities of the sheep farms involve forage production for livestock feeding. In the model, farmers can produce forage either for consumption in the farm or for sale, according to what maximizes their gross margin. The economic coefficient of a crop activity for sale is the per stremma[3] gross margin and the economic coefficient for a crop activity for consumption in the farm is the variable cost. Livestock activities incorporated in the model refer to sheep production and also to goat production. The economic coefficients of livestock related decision variables are the gross margin per productive ewe or goat.

Feeding variables

The produced forage is used for the feeding of the livestock. A set of variables is used to approximate monthly distribution of the produced forage. Additionally, monthly consumption of purchased feedstuff presents another set of the model variables. The economic coefficient of this last set of variables is the price per kilogram of purchased feed. Finally, the model includes decision variables that reflect the use of pastureland and the monthly consumption of grass.

Labour variables

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[3] 1 stremma = 0.1 hectares

The final set of variables incorporated in the model involves the monthly labour inputs. The model distincts between monthly family and hired labour and also between monthly family and hired labour in crop and livestock activities. The economic coefficient of hired labour is the per hour wage.

Feed requirements

The main component of the model used in this analysis reflects the satisfaction of the monthly feed requirements of the flock. Minimum intake of dry matter, net energy of lactation, digestible nitrogen and fiber matter is ensured through monthly constraints. The feed requirements of the flock are estimated according to Zervas et al (2000). For the productive ewes (and goats) these feed requirements include requirements for preservation, pregnancy, weaning and lactation. For the rams (and male goats) the requirements refer to their preservation and extra requirements during the reproduction period. 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, since these requirements are estimated for the productive ewes. It should be noted that lambing usually occurs in late autumn or early spring, or in both periods.

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), Jarrige (1980) and Zervas et al (2000). Additional monthly constraints are incorporated in the model to ensure that concentrate feed and fodder are used in an appropriate and realistic ratio, estimated according to the feeding practices of the individual farm.

Additional constraints

Another 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 constraints are also incorporated in the model to ensure that the total area utilized by the various crop activities and pastureland are smaller than the available land of the farm. Moreover, land constraints refer to the total utilized land but also to the irrigated land where maize and alfalfa can be cultivated.

GHG emissions

The main GHG emissions, from livestock farms are methane (CH_4) from enteric fermentation and manure and nitrous oxide (N_2O) from excreta. In addition, in a crop-livestock farm nitrous oxide (N_2O) from fertilizer use should also be accounted for (see for example Schils et al 2007; Veysset et al 2009; Petersen et al 2009). Carbon dioxide (CO_2) emissions from the use of machinery is an additional source of GHGs. In our analysis, all the potential sources of GHGs have been taken into account. It should be noted that CH_4 and N_2O have been converted to CO_2-equivalents using the conversion factors proposed by the IPCC (2006). The method used to estimate emissions from various sources in the sheep farms is described in more detail in the following paragraphs. Emissions from all sources estimated as CO_2-equivalents are added together to estimate total GHG emissions of the sheep farms. Carbon sequestration has also been taken under consideration. Specifically, we have assumed a carbon sequestration of 0.3 t C/ha for irrigated crops, 0.2 t C/ha for non irrigated crops and 0.1 t C/ha for pastureland (see also Pretty & Ball 2001).

CH_4 from enteric fermentation

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. Mathematical models select the optimal combination of feedstuff and suggest the least cost ration. For this reason the ration used in this analysis is not fixed and methane emissions are predicted from intake, taking into account the requirements of the flock and the nutritional value of feedstuff (see also Petersen et al 2009). Following the work of De Cara & Jayet (2000), methane emissions from sheep are estimated for each feedstuff according to the following equations, for simple and compound feedstuff respectively:

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

$$E\text{-}CH_4/EB = 5.62+4.54\ dE \qquad (2)$$

Where E-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).

N_2O from manure

Methane produced from livestock excreta is considered negligible, since no anaerobic conditions exist during the management of manure or grazing of livestock (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. It is not possible to estimate the exact amount of N_2O emitted when manure is managed and when 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 of the farm. 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 taken into account but were considered negligible for manure management.

N_2O from fertilizer use

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 & 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).

CO_2 from energy use

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).

In our study 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-produced crops. Therefore, emissions from the nitrogenous fertilizers and CO_2 emissions from energy requirements used for the off-farm production of feedstuff have also been estimated and incorporated in the model. Specifically, emissions for purchased alfalfa, maize, barley, oat, wheat and other fodders produced in Greece have been estimated using data from the 150 farmers. For soya, which is not produced in Greece emissions are assumed 0.166 kg of CO_2 eq/kg (see Casey & Holden 2006). Other inputs like fertilizers and pesticides 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 inputs. CO_2 emissions from the manufacture of fertilizers are assumed 1.2 kg of CO_2 eq/kg of fertilizer (see also Wood & Cowie 2004). Energy requirements for the manufacture of herbicides are assumed 287MJ/kg, for insecticides 263MJ/kg and for fungicides 195MJ/kg (see also Helsel 2006). Emissions are then calculated by multiplying the total energy requirements with 0.069 kg of CO_2.

3. Farm typology

The purpose of this study is to model GHG emissions in diversified sheep farms in Greece and identify the appropriate mitigation strategies for these farms. For this reason the heterogeneity of the sheep farming activity has to be captured and examined. Therefore the analysis is undertaken in different farm types identified using multivariate analysis techniques. Originally, a stratified random sample of 150 sheep farms located in two areas of continental Greece was selected and farm level data from these farms was collected. The areas under study were chosen to represent the heterogeneity of the sheep farming activity. The first area is the Prefecture of Etoloakarnania, located in Western Greece, where sheep farming is a traditional and well established activity. Pluriactivity is common practice in the area and sheep farming is often combined with other crop activities. The second area is in Central Macedonia and specifically the Prefectures of Serres and Drama, where larger flocks are bred. The 150 farms were then used to identify different farm types using cluster analysis.

To perform the cluster analysis, three dimensions were taken under consideration, size, intensity and production orientation (see also Andersen et al 2006). Size was measured using the total gross margin of the farms and the sheep livestock units (LU). Intensity has been measured in terms of output (total milk and meat produced/LU) and input (capital/LU, forage/LU and on produced forage/LU). The production orientation was measured in terms of the origin of the farm's gross margin (gross margin from sheep/total gross margin, gross margin from crop activities/ total gross margin). For livestock farms the sheep LU/total LU variable was also used to identify production orientation. Hierarchical clustering was first performed using Ward's method. The analysis indicated three potential solutions (6 clusters, 5 clusters and 4 clusters). K-means analysis and Discriminant analysis were then performed for each one of these potential solutions (Hair et al 1998). The results indicated that the 5-cluster solution yields better results and was adopted in this analysis.

The first cluster consists of only 3 farms that have the common characteristic of a very small flock size (2.8 LU). In these farms, sheep are bred mainly for the purpose of domestic consumption. The first cluster was not included in the analysis because of the small flock size and the small proportion of farms it represents (2%). The second cluster consists of 73 farms. The sheep farms in this cluster have an average flock size of 125 sheep and an average milk yield of 110 kg/ewe/year. The average gross margin of these farms is 9,390. This cluster represents the majority of sheep farms in Greece, which are traditional farms with low invested capital and productivity.

The third cluster consists of 49 farms which are mainly characterized by the fact that a significant part of the gross margin comes from crop activities (pluriactivity). The flock size of these farms is smaller. These are crop-livestock farms with average milk yield and intensity. The fourth cluster includes 14 farms that focus on livestock activities, one of which is sheep farming. The existence of both sheep and goat farming activities in the same farm is a common practice in Greece. The majority of these farms have little crop activities and livestock is bred extensively, using pastureland for the feeding of the flock. In these mix livestock farms, milk yield and invested capital are small and the flock size is bigger. The final cluster consists of 11 intensive breeding farms with high milk yield (186 kg/ewe/year). The invested capital in these farms is high and the feed requirements of the flock are met primarily through supplementary feeding (fodder and concentrates). After identifying the different farm types, the farms that are closest to each cluster center is selected for the analysis.

4. Results

The linear programming model is used to simulate the operation of the four farms representing the four main farm types and the optimal farm plan for each of the farms is obtained at various levels of abatement. The results for each of the farm types are presented below in more detail.

Traditional sheep farm

Table 1 presents the optimal farm plan for the traditional sheep farm. The total gross margin of this farm is 7,039€. The gross margin per ewe is small (70€), mainly due to the low milk yield. The feed requirements are met primarily from on produced crops while sheep farming is the only source of income of this farm.

Table 1 also contains GHG emissions from all sources and net GHG emissions (Total emissions – carbon sequestration from pasture). The basic GHG emission source is CH_4 from enteric fermentation which is responsible for 76% of the total emissions. N_2O emissions (mainly from animal excreta) are also high and represent 20% of the total emissions. The remaining 4% comes from CO_2 emissions from the produced and purchased feed. The net emissions of the farm are 62t CO_2 eq, (about 0.6t/ewe). This level of GHG emissions is considered low and it is due to the limited contribution of grass in the feeding of the flock and the high contribution of concentrates.

The optimal farm plan for the various levels of abatement is also presented in Table 1. A 20% reduction of the emissions leads to 11% reduction of the total gross margin. The reduction of the net emissions is achieved mainly by the reduction of the total CH_4 emissions, but the CH_4 emissions/ewe are increased. This is because the farm uses limited pastureland and therefore has limited possibilities to reduce CH_4 emissions through the substitution of grass with feedstuff; thus, CH_4 reduction is achieved through the reduction of flock size. The decrease of the flock size is responsible for the decrease of N_2O emissions by 24%. The reduction of the gross margin from sheep activities is only slightly compensated by the switch in the production orientation of the farm towards alfalfa production for sale. Figure 1 presents the marginal abatement cost for the traditional farm type. The marginal abatement cost is 63.5€/t until 20% abatement is achieved and then slightly increases to 69€/t.

Mix crop-livestock farm

Table 2 presents the results of the crop-livestock farm. The optimal farm plan for this farm indicates a gross margin of 35,170€. Although the flock size of this farm is not very different compared to the previous farm, the gross margin is much higher because of the higher milk yield and because of the fact that this farm also produces alfalfa for sale. Almost one third of the farm’s gross margin comes from alfalfa production. Furthermore, this farm uses primarily pastureland (grass) for the feeding of the flock and therefore the cost of feeding is smaller (Table 2). But because of the grass used for the feeding of the flock and the extra feeding requirements from the increased milk production, CH_4 emissions are more than three times higher than in the previous case. The net emissions of this farm are 225t of CO_2 eq and consist mainly of CH_4 emissions (90%).

In the case of the crop livestock farm the 20% abatement is achieved again through the reduction of CH_4 emissions. But in this case, the emissions per ewe are also decreased. In order to achieve abatement, the farmer reduces the number of sheep but also switches to concentrates and fodder and reduces the grazing of the flock. This indicates that in order to achieve fewer emissions, flocks are bred more intensively, which is coherent with the results obtained by the examination of the previous farm type. The total gross margin reduction caused by 20% abatement is smaller (7%), because of the crop production that exists in the farm.

The marginal abatement cost of this farm is smaller compared to the previous farm (60.4€/t) until a 20% abatement is achieved (Figure 2). This is due to the mixed crop-livestock production orientation, which reflects a smaller dependency on the sheep farming activity.

Mix livestock farm

In the case of the mix livestock farm the gross margin per head is 90€, while the total gross margin of the farm is 11,111€ (Table 3). The livestock consists mainly of goats fed primarily with grass. This is the reason for the high total and per head CH_4

emissions. Specifically, the per head emissions for goats and sheep are 2,335 and 1,853 kg of CO_2 eq respectively. It should be noted that emissions are higher in the case of goats because sheep are more productive and are fed greater amounts of concentrates and fodder which, as mentioned previously reduces the produced CH_4. In other words the production system of goats is more extensive than the production system of sheep, and therefore causes more emissions. For this farm type CH_4 emissions account for 92% of the total emitted GHGs.

Table 3 also indicates that 20% reduction of emissions leads to 10% reduction of the gross margin. In the case of the mix livestock farm, reduction is achieved solely, through the reduction of the number of goats, since the sheep and crop activities remain the same. The purchased feed is reduced, but this is only the result of the reduced number of goats. The grass consumption is also reduced as a result of the restriction of the goat flock. In other words the goat production is the only production activity affected by the abatement.

As we can see in Figure 3 the marginal abatement cost of this farm is 57€/t until 20% reduction is achieved and increases to 92€/t when the reduction is 50%. The level of the marginal abatement cost is the same as in the previous cases. The fact that the number of ewes remains the same is indicating that farms of this type are likely to change their production orientation, abandon the goat production activity and turn to sheep production in order to restrict emissions. It should also be noted that although the number of sheep has not changed in various levels of abatement, this is probably the result of the fact that the farm produces very limited amounts of concentrates, which do not allow the expansion of the sheep activity. If the farm had the ability to on produce larger amounts of forage, then the sheep production activity would probably expand.

Intensive sheep farm

The final farm type examined in this analysis is the intensive sheep farm. The results of the analysis for this farm are presented in Table 4. This farm type aims only at sheep production and has a high milk yield. Therefore the gross margin per ewe and the total gross margin of the farm are very high (202€ and 45,238€, respectively). The CH_4

emissions of this farm type account for 81% of the total emissions, the N_2O emissions account for 14% and the CO_2 emissions account for the remaining 4%. As in the case of the first farm, that utilized limited pastureland, CH_4 emissions per head are very small. The per milk emissions of this farm are estimated at 2.7 kg of CO2 eq/ kg of milk and are slightly higher than the emissions of cow milk (see Weiske et al 2006). These results indicate that in terms of GHG emissions this is the most environmentally friendly dairy sheep production system in Greece. It should be noted that the high gross margin per ewe also indicates that this production system is not only environmentally but also economically sustainable.

Abatement, in the case of this farm type has a very significant effect on gross margin. Specifically, 20% abatement leads to 15% reduction of the gross margin, and a significant reduction of the flock size (20%). This farm type specializes in sheep production and therefore limited alternatives can emerge to compensate for the income loss (Table 4 indicates a slight increase of the production of alfalfa for sale).

The marginal abatement cost of this farm is presented in Figure 4. This Figure indicates that in the case of this farm type, an abatement over 35% is very difficult to be achieved, since the marginal abatement cost increases sharply (over 300€/t). The marginal abatement cost for a 20% reduction is 61.3€/t.

The results of the analysis indicate that the high specialization in sheep production and the intensive breeding of animals cause significant reductions of the gross margin, when abating. But on the other hand these production systems cause fewer emissions per kg of produced milk and are therefore efficient, not only in economic but also in environmental terms. It should also be noted that all of the marginal cost curves are convex, indicating that the marginal cost increases as abatement proceeds. Finally, it should be noted that the estimation of the marginal abatement cost can be used by policy makers to plan the appropriate mitigation strategies. For example the level of an emission tax implemented to sheep farms, can be assessed according to the marginal abatement cost. If the marginal abatement cost of the sheep farms is higher than the tax, then farmers will prefer to pay the tax rather than abating and thus the policy measure will not be effective. The total loss of income/ewe can also be used to estimate the level of compensation sheep farmers can receive for abating, if policy makers aim to safeguard their income.

5. Conclusions

In this study GHG emissions from the dairy sheep farming activity in Greece are modeled using a mathematical programming, farm level model. The model used reflects the operation of the sheep farms and includes all main sources of GHG emissions (CH_4, N_2O and CO_2). To account for the heterogeneity of the sheep farming activity in Greece, data from 150 sheep farms were collected and multivariate analysis techniques were performed to identify basic farm types.

The results indicate that the main source of GHG emissions in all farm types is CH_4 from enteric fermentation. Emissions per ewe are particularly high in the two farms where sheep is extensively bred and where grass is mainly used to meet the feed requirements of the flock (Mix crop-livestock and Mix livestock farms). N_2O emissions are the second main source of GHGs mainly because of animal excreta. Furthermore, the analysis indicates that the farm type that is more environmentally friendly, in terms of GHG emissions is the intensive one, since emissions per kg of produced milk are very small (2.7kg of CO2 eq).

The analysis also indicates the appropriate abatement strategy for each farm type. Farms that depend more on livestock activities suffer a bigger gross margin reduction when emissions are restricted (11%, 10% and 15% reduction of gross margin at 20% abatement level for the Traditional sheep farm, the Mix livestock farm and Intensive farm, respectively), while the Crop-livestock farm has a smaller gross margin reduction. The analysis also indicates that goat farming causes higher emissions than sheep farming (see Mix livestock farm) and therefore the activity is abandoned when emissions are restricted. Farms that specialize on sheep farming, suffer a high reduction of gross margin when abating (see Intensive farm), but cause fewer emissions than the extensive farms.

The marginal abatement cost is similar amongst the various farm types and is estimated at 51.2-63.5€/t and 51.2-376€/t until 20% and 50% abatement, respectively.

The marginal abatement cost is higher in the case of the two farm types that specialize on sheep farming (Traditional sheep farm and Intensive sheep farm), due to the limited production alternatives when emissions are restricted. In the case of the Intensive farm, the marginal abatement cost increases significantly after 35% abatement (over 300€/t). It should be noted that the results of these analysis can be useful to policy makers who which to identify and plan appropriate and effective mitigation policy measures.

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Appendix

Table 1. Results for the Traditional farm at various levels of abatement

	Abatement (a)									
	0		0.05		0.10		0.15		0.2	
	Total	Per head	Total	Per head	Total	Per head	Total	Per head	Total	Per head
Gross Margin (€)	**7,039**	**70**	**6,842**	**72**	**6,645**	**75**	**6,448**	**78**	**6,251**	**81**
Productive ewes	101		95		89		83		77	
Produced maize (kg)	15,281	151	13,741	145	12,201	137	10,661	128	9,120	118
Produced fodder (kg)	32,952	326	30,935	326	28,919	325	26,902	324	24,885	323
Purchased fodder (kg)	0	0	0	0	0	0	0	0	0	0
Purchased concentates (kg)	7,768	77	7,900	83	8,031	90	8,163	98	8,294	108
Grass consumed (kg)	12,000	119	11,825	124	11,650	131	11,475	138	11,300	147
Alfalfa for sale (str)	0		3		6		9		12	
Maize for sale (str)	0		0		0		0		0	
Net emissions (Kg-CO_2 Eq)	**61,698**	**611**	**58,613**	**617**	**55,528**	**624**	**52,444**	**632**	**49,359**	**641**
Total emissions (Kg-CO_2 Eq)	63,166	625	60,081	632	56,996	640	53,912	650	50,827	660
CH_4 (Kg-CO_2 Eq)	47,649	472	45,075	474	42,501	478	39,927	481	37,353	485
N_2O excreta (Kg-CO_2 Eq)	9,306	92	8,753	92	8,200	92	7,647	92	7,095	92
Emissions from crop cultivation (Kg-CO_2 Eq)	5,545	55	5,575	59	5,606	63	5,636	68	5,667	74
Purchased feed (Kg-CO_2 Eq)	667	7	678	7	689	8	700	8	712	9

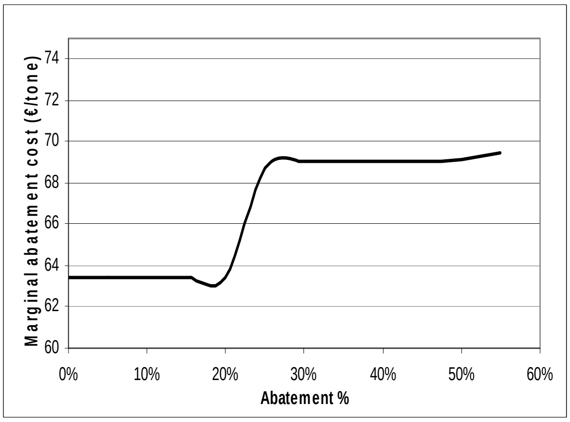

Figure 1. Marginal abatement cost of the traditional farm.

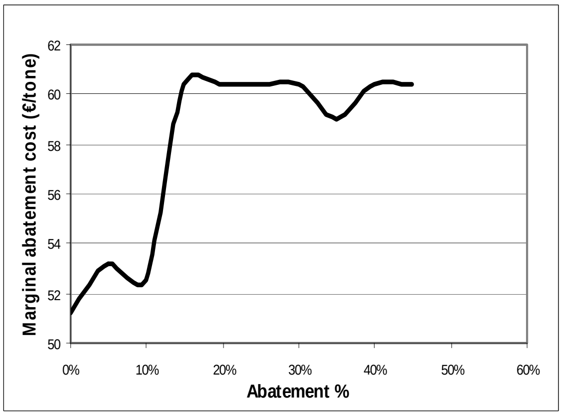

Figure 2. Marginal abatement cost of the crop-livestock farm.

Table 2. Results for the Crop-livestock farm at various levels of abatement.

	Abatement (a)									
	0		0.05		0.10		0.15		0.2	
	Total	Per head	Total	Per head	Total	Per head	Total	Per head	Total	Per head
Gross Margin (€)	**35,170**	**314**	**34,552**	**320**	**33,932**	**323**	**33,313**	**327**	**32,686**	**334**
Productive ewes	112	1	108	1	105	1	102	1	98	1
Produced maize (kg)	0	0	0	0	0	0	0	0	0	0
Produced fodder (kg)	186	2	0	0	0	0	0	0	0	0
Purchased fodder (kg)	33,900	303	33,557	311	33,833	322	34,110	334	33,580	343
Purchased maize (kg)	20,451	183	20,134	186	20,300	193	20,466	201	20,148	206
Grass consumed (kg)	252,000	2,250	237,683	2,201	221,761	2,112	205,839	2,018	191,535	1,954
Alfalfa for sale (str)	100		100		100		100		100	
Maize for sale (str)	0		0		0		0		0	
Net emissions (Kg-CO_2 Eq)	**224,751**	**2,007**	**213,513**	**1,977**	**202,276**	**1,926**	**191,038**	**1,873**	**179,800**	**1,835**
Total emissions (Kg-CO_2 Eq)	240,165	2,144	228,927	2,120	217,690	2,073	206,452	2,024	195,214	1,992
CH_4 (Kg-CO_2 Eq)	215,415	1,923	204,727	1,896	193,800	1,846	182,873	1,793	172,198	1,757
N2O excreta Kg-CO_2 Eq)	13,292	119	12,817	119	12,461	119	12,105	119	11,630	119
Emissions from crop cultivation (Kg-CO_2 Eq)	5,842	52	5,842	54	5,842	56	5,842	57	5,842	60
Purchased feed (Kg-CO_2 Eq)	5,616	50	5,541	51	5,586	53	5,632	55	5,544	57

Table 3. Results for the Mix livestock farm at various levels of abatement

	Abatement (a)									
	0		0.05		0.10		0.15		0.2	
	Total	Per head	Total	Per head	Total	Per head	Total	Per head	Total	Per head
Gross Margin (€)	**11,111**	**90**	**10,767**	**92**	**10,537**	**93**	**10,136**	**96**	**9,964**	**97**
Tota labour (hr)	1,313	11	1,252	11	1,212	11	1,141	11	1,110	11
Productive ewes	43		43		43		43		43	
Productive goats	80		74		70		63		60	
Produced oat (kg)	8,000	65	8,000	68	8,000	71	8,000	75	8,000	78
Purchased fodder (kg)	20,444	166	19,310	165	18,555	164	17,232	163	16,666	162
Purchased maize (kg)	10,071	82	9,315	80	8,811	78	7,930	75	7,552	73
Grass consumed (kg)	339,847	2,763	324,565	2,774	309,922	2,743	289,547	2,732	279,997	2,718
Net emissions (Kg-CO_2 Eq)	**269,389**	**2,190**	**255,920**	**2,187**	**243,797**	**2,157**	**226,287**	**2,135**	**218,205**	**2,118**
Total emissions (Kg-CO_2 Eq)	291,409	2,369	277,940	2,376	265,817	2,352	248,307	2,343	240,225	2,332
CH_4 sheep (Kg-CO_2 Eq)	79,687	1,853	79,687	1,853	79,687	1,853	79,687	1,853	79,687	1,853
CH_4 goats (Kg-CO_2 Eq)	186,776	2,335	174,677	2,360	163,467	2,335	147,555	2,342	140,158	2,336
N_2O excreta sheep (Kg-CO_2 Eq)	6,129	143	6,129	143	6,129	143	6,129	143	6,129	143
N_2O excreta goats (Kg-CO_2 Eq)	15,603	195	14,433	195	13,653	195	12,288	195	11,703	195
Emissions from crop cultivation (Kg-CO_2 Eq)	198	2	198	2	198	2	198	2	198	2
Purchased feed (Kg-CO_2 Eq)	3,015	25	2,816	24	2,683	24	2,450	23	2,350	23

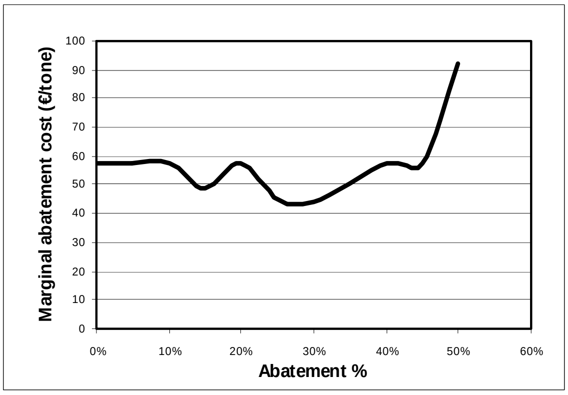

Figure 3. Mix livestock farm

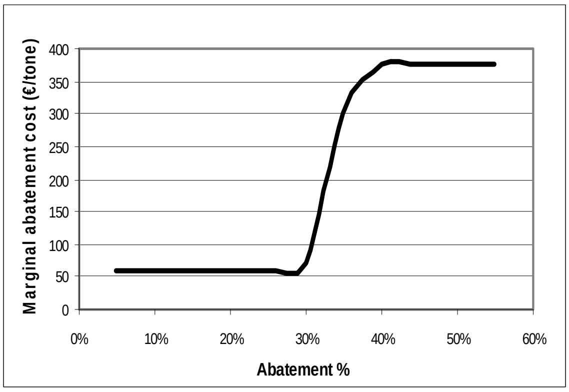

Figure 4. Intensive sheep farm

Table 4. Results for the Intensive sheep farm at various levels of abatement

	Abatement (a)									
	0		0.05		0.10		0.15		0.2	
	Total	Per head	Total	Per head	Total	Per head	Total	Per head	Total	Per head
Gross Margin (€)	**45,238**	**202**	**43,541**	**204**	**41,845**	**207**	**40,425**	**209**	**38,451**	**214**
Tota labour (hr)	1,469	7	1,402	7	1,336	7	1,281	7	1,202	7
Productive ewes	224	1	213	1	202	1	193	1	180	1
Produced maize (kg)	55,000	246	54,793	257	54,586	270	54,178	281	54,172	301
Produced fodder (kg)	0	0	0	0	0	0	0	0	0	0
Purchased fodder (kg)	76,382	341	72,631	341	68,881	341	65,812	341	61,379	341
Purchased concentates (kg)	21,382	95	17,838	84	14,294	71	11,633	60	7,207	40
Alfalfa for sale (str)	0		0		0		1		1	
Maize for sale (str)	0		0		0		0		0	
Net emissions (Kg-CO_2 Eq)	**138,750**	**619**	**131,812**	**619**	**124,875**	**618**	**119,325**	**618**	**111,000**	**617**
Total emissions (Kg-CO_2 Eq)	138,750	619	131,812	619	124,875	618	119,325	618	111,000	617
CH_4 sheep (Kg-CO_2 Eq)	112,943	504	107,397	504	101,851	504	97,313	504	90,758	504
N_2O excreta sheep (Kg-CO_2 Eq)	12,930	58	12,295	58	11,660	58	11,141	58	10,391	58
Emissions from crop cultivation (Kg-CO_2 Eq)	4,277	19	4,353	20	4,428	22	4,577	24	4,579	25
Purchased feed (Kg-CO_2 Eq)	8,599	38	7,767	36	6,935	34	6,294	33	5,272	29