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Greenhouse gas emissions from agriculture in the EU: A spatial assessment of sources and abatement costs

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Abstract

Agriculture contributes significantly to the emissions of greenhouse gases in the EU. By using a farm-type, linear-programming based model of the European agricultural supply, we first assess the initial levels of methane and nitrous oxide emissions at the regional level in the EU. For a range of CO_2 prices, we assess the potential abatement that can be achieved through an IPCC-based emission tax in EU agriculture, as well as the resulting optimal mix of emission sources in the total abatement. Further, we show that the spatial variability of the abatement actually achieved at a given carbon price is large, indicating that abatement cost heterogeneity is a fundamental feature in the design of a mitigation policy. We assess the efficiency loss associated with uniform standards relative to a an emission tax.

Keywords: Climate change; greenhouse gas emissions; agriculture; methane; nitrous oxide ; European Union; marginal abatement costs.

JEL Codes: Q25; Q15

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Introduction

Agriculture has long been overshadowed by energy-related issues in the policy and scientific debate surrounding climate change. In many respects though, agriculture plays a key-role in this issue: *(i)* agricultural activities contribute significantly to global emissions of greenhouse gases (GHG); *(ii)* agriculture is the major emitting sector for methane (CH_4) and nitrous oxide (N_2O) – the two main non-CO_2 GHGs included in the "Kyoto basket"; *(iii)* the impacts of climate change as predicted by climate models are expected to be stronger on agriculture[1] than on other sectors.

If mitigation policies are only focused on energy- or transport-related CO_2 emissions, the cost of achieving any given abatement is likely to be unnecessarily high (Reilly et al., 1999; Hayhoe et al., 1999; Burniaux, 2000; Manne and Richels, 2001). There is thus a need for the EU to find alternative potential abatements in other sectors to comply with its 8%-reduction Kyoto commitment. As agriculture may offer such additional reductions, this sector has drawn increasing attention from the policymakers in the recent years (Bates, 2001; European Commission, 1998a; European Commission, 1998b; European Commission, 2002).

Emissions from EU agriculture total about 405 MtCO_2eq or 10% of total European emissions[2] and involve both crop and livestock production activities. Nitrous oxide emissions represent approximately 210 MtCO_2eq, while methane accounts for about 195 MtCO_2eq. GHG emissions from agriculture result from nitrogen application to agricultural soils (N_2O), manure management (CH_4 and N_2O), enteric fermentation in livestock production (CH_4) and rice cultivation (CH_4). A key-issue in examining the role of agriculture in GHG emissions consists in assessing the abatement costs in this sector. The magnitude of abatement costs in agriculture relatively to other sectors determines both the social benefit and the effective reduction that can be expected from the implementation of a mitigation policy in this sector.

In the recent empirical literature about GHG emissions from agriculture, abatement cost curves

[1] The impacts of climate change on agriculture are not however necessarily expected to be negative for all production activities. The change in average temperatures may actually have both positive and negative impacts on yields. One has also to account for the impacts on the spatial distribution of crops as a consequence of climate change. Nevertheless, many aspects of climate change, such as the increase of extreme events occurrence and the spread of pests for instance, may affect negatively yields and farmers' revenues.

[2] Based on 2001 emissions of methane and nitrous oxide from agricultural soils, manure management, enteric fermentation, and rice cultivation, as reported by the EU in its 2003 communication to the UNFCCC (available at http://unfccc.int/program/mis/ghg/submis2003.html). Emissions of methane and nitrous oxide are converted into CO_2 by using the 2001 Global Warming Potentials (Intergovernmental Panel on Climate Change, 2001a).

have been estimated at various scales and using different modeling techniques. De Cara and Jayet (2000) have assessed the abatement costs in French agriculture. In addition to N_2O emissions from the use of synthetic fertilizers and CH_4 emissions from enteric fermentation, the authors account for the possibility of carbon sequestration in agricultural soils and explore the conversion of set-aside land into forests. Abatement costs estimates are also available in the literature at smaller (regional) scales from experimental farms (Meyer-Aurisch and Trüggelmann, 2002) or farm models (Angenendt et al., 2000). McCarl and Schneider (2001) published a comprehensive assessment of GHG abatement costs in US agriculture. Their approach includes CH_4 and N_2O emissions as well as CO_2 emissions resulting from fossil fuel use in agriculture and carbon sequestration in soils and above-ground biomass. One interesting feature of this work lies in the assessment of the impacts of alternative agricultural practices and/or production activities (e.g. reduced- or no- tillage practices, energy crops, etc...) on net emissions and abatement costs (see also Schneider and McCarl (2003)). As for the EU, marginal abatement cost curves have been estimated on a country basis by De Cara and Jayet (2001) and Perez et al. (2003).

The present paper departs from the previous literature mainly because of the focus on the *heterogeneity of abatement costs* within the EU and on the implications of this heterogeneity for the design of a mitigation policy. Abatement cost heterogeneity is indeed crucial for both economic and policy purposes. The heterogeneity of abatement costs is a fundamental determinant in the optimal choice of a mitigation policy instrument. Acknowledgedly, incentive-based instruments are generally viewed –at least under perfect information– as more efficient than command-and-control regulations and uniform standards. Incentive-based instruments tend to equalize marginal abatement costs across polluting agents and consequently minimize the total abatement cost. In contrast, uniform standards generally result in distorted allocations of the total abatement. Nevertheless, information and control costs can jeopardize the implementation of optimal instruments in practice, more particularly if spatial heterogeneity is large. There is thus a trade-off between control costs of implementing optimal instruments on the one hand, and the efficiency loss due to distorted abatement allocation on the other hand (see for instance Antle et al. (2003) for an application to the design of carbon sequestration contracts). Newell and Stavins (2003) analytically investigate the savings of incentive-based instruments relative to uniform standards. As expected, these savings are shown to increase with respect to the variance of marginal abatement costs[3]. Furthermore, in practice policymakers attach at least as much impor-

[3]The fact that the potential savings permitted by market-based instruments depend on the distribution of abatement costs makes intuitive sense. It is clear that in a (hypothetical) static setting whereby all agents are homogeneous with respect to abatement costs, market-based instruments do not do better than uniform standards. As the heterogeneity of abatement costs –approximated by the variance of abatement-cost parameters– increases, the distortions in abatement allocation under a uniform standard also increases.

tance to the spatial distribution of economic and environmental impacts of a mitigation policy as to the magnitude of these impacts. Spatial analyzes that go beyond EU- or country-wide estimates of abatement costs curves are hence needed. The interest of such a spatial approach is strengthened by the close interactions between GHG mitigation policies and other local environmental or policy concerns.

Three major sources of abatement cost heterogeneity can be distinguished: *(i)* farm-size related parameters (activity-data heterogeneity); *(ii)* per-unit of input or output emissions (emission-factor heterogeneity); *(iii)* the flexibility in the substitutions between production activities. Only the first two sources are analyzed in the stylized framework developed by Newell and Stavins. The first source is related to parameters such as the area allocated to each crop, crop production, animal numbers, fertilizer use, etc. The second arises from the variability of climate and soil characteristics, input productivity, management systems and agricultural practices (see for instance Freibauer (2003) for a spatial analysis of emission-factor heterogeneity). The third source is often overlooked in the assessment of abatement costs and depends on the possibilities of substituting emission-intensive processes with environmental-friendlier productions and/or practices in the short run (Schneider, 2002). In this paper, we account –yet to different degrees– for these three sources of heterogeneity. Our discussion of the heterogeneity of abatement costs is focused on regional rather than on farming-system dimensions, although both aspects can be examined in the light of our results.

The objectives of this paper are threefold: *(i)* assessing the abatement costs in agriculture accounting for a wide range of sources and the diversity of farming systems in the EU; *(ii)* discussing the spatial heterogeneity of abatement costs; *(iii)* estimating the efficiency loss caused by uniform standards as compared to incentive-based instruments and highlighting the link with abatement cost heterogeneity.

For a range of CO_2 prices, we assess the potential abatement resulting from an IPCC-based emission tax in EU agriculture, as well as the optimal mix of emission sources in the total abatement. Further, we show that the spatial variability of the abatement actually achieved at a given carbon price is large, indicating that abatement cost heterogeneity is a fundamental feature. As a direct consequence, uniform standards would result in abatement costs significantly higher than with an emission tax.

The paper is organized as follows. In section 1, after a brief description of the model, we present the different GHG sources and the IPCC methodology used in the computation of agricultural emissions. We also discuss in this section the interests and limits of this methodology. In section 2, we examine the results in terms of baseline emissions and optimal abatement supply for an emission tax ranging from 0 to 100 EUR/tCO_2eq. We also analyze the relative weight of each source in the total abatement. Spatial heterogeneity of abatement costs and its implications for mitigation policies are discussed in section 3. In particular, we explore the inter- and infra-regional variability of optimal abatements at given carbon prices and estimate the additional cost associated with uniform standards.

1 Analytical framework

1.1 The model

The generic model is based on mixed integer and linear programming methods. The primary source of data is the 1997 Farm Accounting Data Network (FADN). This database provides accounting data (revenues, variable costs, prices, yields, crop area, animal numbers, support received, farming system) for a sample of farmers representing more than 2.5 millions of European (full-time) farmers. Data are available at a regional level (101 regions in the EU-15). Each individual in the sample is associated with a weight indicating its representativity in the regional population. Within each of the FADN regions, the sample is divided into homogeneous farm types with respect to farming system, yields, total area, animal numbers, and average altitude.

We thus obtain 734 farm types, each being associated with a specific model. Each model describes the annual supply choices for a given farm type. The farm-type representation allows for the accounting of the wide diversity of technical constraints faced by European farmers. Each farm type is viewed as a single firm representative of the whole group behavior. Each producer (denoted by k) is assumed to choose his/her supply level and input demand (x^k) in order to maximize his/her total gross margin (π^k). Each farm-type model can be summarized as follows:

$$
(P_1^k)\left\{\begin{array}{lrcllc}
 & \max\limits_{x^k} \pi^k(x^k) \equiv g^k \cdot x^k & & & & \\
s.t. & A^k(\theta^k,\phi).x^k & \leq & z^k(\theta^k,\phi) & A^k \in \mathbb{R}^{m\times n} & \text{(C1)} \\
 & x^k & \geq & 0 & x^k \in \mathbb{R}^n & \text{(C2)}
\end{array}\right.
$$

This problem is linear with respect to x^k, the vector of the n endogenous variables. x^k includes the area in each crop, the size of the herd for each animal category, and the quantity of purchased animal feeding. The $n \times 1$-vector g^k contains the gross margin associated to each producing activity (prices plus support received minus variable costs). Thirty-two crop producing activities are allowed in the model and represent most of the European agricultural land use, including the CAP set-aside requirements. Farmers can sell their own crop production at the market price or use it for animal feeding (feed grains, forage, pastures). In the latter case, only the variable cost appears in g^k. With respect to animal feeding, farmers can also endogenously choose to purchase feedstuffs (four types of concentrates and one type of forage). As for livestock, thirty-one animal categories are represented in the model (27 for cattle plus sheep, goats, swine and poultry). The matrix A^k and the vector z^k

contain the input-output coefficients and the right-hand side of the m constraints, respectively. The vector of parameters θ^k characterizes the k-th type of producer and ϕ stands for the vector of general economic parameters not dependent on type k. The constraints can be divided into five types: *(i)* crop area allocation; *(ii)* livestock feed requirements; *(iii)* initial endowments of quasi-fixed factors (land and livestock); *(iv)* cattle livestock demography; *(v)* restrictions imposed by the CAP measures. A numerical algorithm based on Monte-Carlo and gradient methods is used to calibrate parameters in θ^k for which data is not available. This calibration procedure is based on the 1997 FADN database and relies on the minimization of the gaps between observed and simulated levels of endogenous variables (x^k) at the farm-type level.

1.2 GHG emissions from agriculture

The emission accounting method used in this paper follows the approach exposed in Intergovernmental Panel on Climate Change (2001b). This methodology combines the use of country-specific activity data –such as animal numbers, crop area, fertilizer use, manure management systems, etc.– and emission factors. All EU Member States, as signatories of the United Nations Framework Convention on Climate Change (UNFCCC), have committed themselves to report annually their GHG emissions accordingly. In addition to this commitment, countries have to conduct quality and uncertainty assessment of the data they report and to ensure time consistency of their inventories over the reported years from 1990 on.[4] The IPCC method thus provides a common reporting framework that allows for completeness and consistency. It therefore eases emission comparisons at the country level.

Agricultural activities contribute directly to GHG emissions through five main different gas-emitting processes (Intergovernmental Panel on Climate Change, 2001b): N_2O emissions from agricultural soils; N_2O emissions from manure management; CH_4 emissions from manure management; CH_4 emissions from enteric fermentation in domestic livestock; CH_4 emissions from rice cultivation.[5] Generally speaking, the IPCC computation of GHG emissions relies on linear relationships between emissions and activity data through the use of emission factors for each of the L ($l = \{1, \ldots, L\}$ sources of emissions. Total emissions are thus defined as the scalar product of the $L \times 1$-vector of the emission

[4] A certain degree of freedom is nevertheless left to countries in the choice of country-specific emission factors and/or methods. But this degree of freedom comes with the obligation to document these choices with scientifically-sound studies.

[5] Other sources of GHG emissions from agriculture are: emissions from burning of savannas and agricultural residues, N_2O emissions from sewage sludge application and from cultivation of organic soils, CO_2 and CH_4 emissions from agricultural soils. These sources are of relatively minor importance to European agriculture. In this paper, we thus focus on the five sources of emissions described above.

factors (EF) and the $1 \times L$-vector of the relevant activity data (x):

$$e = EF \cdot x = \sum_{l=1}^{L} EF_l . x_l \tag{1}$$

A detailed description of the components of EF can be found in Intergovernmental Panel on Climate Change (2001b) and is summarized in appendix A.

In the model, the emissions for each farm type are derived from the IPCC relationships as described in (1). We link each emission source to the levels of the relevant endogenous variables in the model. Equations (5)-(11) (see appendix A) describe in details the computation of the emission factors. Country-specific emission factors and other information are used whenever provided in the 2003 national communications to the UNFCCC[6]. If this information was not available at the country-level, the default IPCC values were used (Intergovernmental Panel on Climate Change, 2001b).

A total of twenty-one emission sources are computed within the model and are listed in table 2 (see appendix). Emissions of nitrous oxide are divided into eight sub-sources (four for agricultural soil direct emissions, two for indirect agricultural soil indirect emissions, one for emissions from grazing animals, and one for manure management). Emissions of methane are disaggregated into thirteen sub-sources (manure management and enteric fermentation, which are both disaggregated into six animal categories, and rice cultivation). This level of disaggregation allows a greater level of detail in the comparisons with the GHG inventories as reported in the national communications. All emission factors are converted into CO_2 equivalent by using the 2001 Global Warming Potentials (GWP, 23 for methane and 296 for nitrous oxide).

Crop-area driven emissions

With the exception of manure-related emissions, N_2O emissions from agricultural soils are linked to the area planted in each crop (endogenously computed in the model). Total fertilizer expenditures are provided by the FADN database for each farmer in the sample. The estimate of per-hectare fertilizer expenditure for each crop and each farm type is derived from simple covariance analysis. A representative composite fertilizer is assumed for each crop and each country. Fertilizer prices paid by farmers and nitrogen content were taken from the FAOSTAT and Eurostat fertilizer databases (year 1997). We thus obtain the per-hectare nitrogen amount applied to each crop for each farm type. The emission factors, and the volatilization and leaching parameters are taken from the national

[6] An overview of the methods and emission factors used in 2003 national communications can be found at http://unfccc.int/program/mis/ghg/sai2003.pdf. The detailed tables that have been used in the computation of emission factors can be obtained upon request from the authors.

communications of each Member State. As for biological fixation and nitrogen in crop residues, we use the values (nitrogen content, crop/residue ratio, dry matter fraction,...) as given in the national communications or the default IPCC values, depending on availability. Crop yields are taken from the FADN database. Our approach thus relies on constant per-hectare nitrogen inputs for each crop. Consequently, each farmer has to shift land between crops according to their nitrogen requirement in order to reduce N_2O emissions.

Animal-feeding driven emissions

Methane emissions from both enteric fermentation and manure management depend on the energy content of the feed intake for each animal category. To approximate the feed energy intake by each animal category, the method proposed in Intergovernmental Panel on Climate Change (2001b) relies basically on the fulfillment of average energy requirements for each animal category.

As we seek to capture how changes in animal feeding impact emissions, we need to make these emissions responsive to the farmers' choices in terms of animal feeding, which are endogenously computed within the model. To feed their animals, farmers can use their own crop and forage production, or purchase concentrates (4 types) or forage. Three constraints play a key-role in these decisions. Farmers have to meet the minimal digestible protein and energy needs of each animal category. In addition, each animal is associated with a maximal quantity of ingested matter. The characteristics of feedstuffs with respect to energy and protein content, dry matter fraction and digestibility, as well as the energy/protein requirements and maximal quantity of ingested matter for each animal categories have been taken from Jarrige (1988).

Animal-number driven emissions

N_2O emissions from manure management depend on the average nitrogen content of manure. Hence, they directly depend on animal numbers. The nitrogen excretion rates for each animal category have been taken from the national communications or the IPCC. Because of the lack of available data at a regional level, the average percentage of manure handled under each management system is also taken from the national communications. The country-average is applied to each farm type. In addition, some cattle categories are only allowed to vary in a limited range in the model (quasi-fixed capital assumption). In the subsequent simulations, this range represents $\pm 15\%$ of the initial animal numbers in the corresponding animal categories.

1.3 IPCC emission accounting method: Discussion

Emissions that fall under the category "Agriculture" in the IPCC classification only represent the emissions that are *directly* linked to agricultural activities. This category does not include the emissions caused by the production of inputs and capital goods and the transport of food and feed products. Nor does it include the emissions caused by the use of fossil fuel in agriculture (accounted for in the IPCC energy use category). Further, in accordance with international agreements on climate change, non-anthropogenic sources –e.g. N_2O background emissions by agricultural soils– are ignored. The emission coverage of the "Agriculture" category in the IPCC inventories, albeit very detailed for the sources accounted for, is thus rather restrictive.[7]

Another important caveat about the IPCC coverage concerns carbon sequestration. Carbon sequestration in agricultural soils and above-ground biomass is not accounted for under the "Agriculture" category but reported under "LULUCF" (Land Use, Land Use Changes and Forestry). Carbon sinks in agricultural soils and above-ground biomass have been advocated by land-rich countries as a way to provide cheap and large additional GHG abatements. Since the inclusion of carbon sinks in the Kyoto Protocol, this issue has led to a number of controversies about how to account for carbon sequestration in emission inventories (Intergovernmental Panel on Climate Change, 2000) and its actual role as a solution to tackle global warming (Schlesinger, 2000; Lal and Bruce, 1999). Actually, accounting for carbon sequestration raises issues mainly because of the short-run and non-permanent nature of abatements achieved this way (Arrouays et al., 2002; Feng et al., 2002). For instance, in-soil sequestered carbon can be released back into the atmosphere as a result of changing practices (e.g. by switching from no to conventional tillage). These features go beyond the scope of the present paper as they require a dynamic approach. In the rest of the paper, we thus do not account for carbon sequestration from agricultural activities. This aspect is nevertheless important to keep in mind when interpreting the abatement costs estimates.

The IPCC methodology summarized above is not the only available method for emissions accounting. For instance, emission estimates can be derived from biophysical models such as EPIC (McCarl and Schneider, 2001) or rely on more detailed regional-specific relationships (Freibauer, 2003). Arguably, these alternative accounting approaches may provide more accurate emission estimates. In

[7] Defining the coverage of emissions that should be taken into account within the model is not as straightforward as it seems at first glance. Let us consider for instance emissions resulting from the production of fertilizers. These emissions can relatively easily be derived from the use of fertilizers in agriculture. One may rightfully view the reporting of this information as valuable for inventory purposes. The problem arises however when assessing the abatement costs and the impacts of a mitigation policy. Including these emissions in the computation of abatement costs implies strong assumptions about the market structure and price transmission between the fertilizer industry and the farmers. In the present paper, we thus limit ourselves to the emission coverage proposed by the IPCC for agriculture.

fact, Freibauer (2003) questions the IPCC approach capability to fit specific agricultural conditions of production that prevail in a given region because of its use on emission factors averaged over a wide range of situations. Freibauer argues that IPCC emission factors are consequently associated with high magnitudes of uncertainty and hide important sources of spatial variability.

Conceivably, providing consistent and comparable GHG inventories methods for a large number of countries necessarily requires a stylized representation of complex biological processes. Notwithstanding at least three arguments support the use of the IPCC method in the present paper. First, by using country-specific emission factors as reported in the national communications, *some* of the (inter-country) variability of the emission factors is captured. Second, as countries have to report annually their emissions according to this framework, we can use the national communications as consistent, comprehensive and somewhat reliable sources in country-level comparisons. Third, from a practical point of view, IPCC figures are the reference in verifying the compliance with international commitments. So, regardless of the actual accuracy of the IPCC inventories, this method is *per se* relevant as it reflects the *actual* effort that has to be made to meet the reduction targets set by international agreements.

2 Marginal abatement costs and EU abatement supply

2.1 Initial GHG emissions from agriculture in the EU

In order to check the ability of the model to predict emission levels, we first run two preliminary scenarios. The first scenario corresponds to the Common Agricultural Policy as of 1997 ("CAP97"). It thus pertains to the base year of the FADN database. The second scenario includes changes related to the CAP that prevailed in 2001 ("Agenda 2000"). Notably, it includes the changes in intervention prices, per-hectare support to grains and oilseeds, and the changes in milk quotas and livestock subsidies that have occured between 1997 and 2001. Both scenarios are based on the same initial dataset otherwise. In other words, the structure (number of farms, total available area, etc...) is kept constant in the two scenarios. Hence, the differences in emissions between "CAP97" and "Agenda 2000" only arise from the differences in the CAP parameters.

Figure 1 compares the baseline emissions as computed by the model and the emissions reported to the UNFCCC by each of the fifteen Member States. Results have been aggregated on a country-basis as information on emissions is available only at this level of details in the national communications. For each Member State, the first two bars represent the emissions as reported in the 2003 communication for the years 1997 and 2001. The next two bars represent our emission estimates for the "CAP97" and "Agenda 2000" scenarios, respectively.

<Figure 1 about here>

The model captures approximately 85% of the total EU emissions from agriculture. This partly reflects the representativity of the FADN database. Emissions estimates are the most accurate for N_2O from agricultural soils (93%) and for CH_4 from enteric fermentation (84%). The model captures only 60-70% of the remaining emissions, which represent about 18% of the 2001 total emissions. The relative changes between the two scenarios are relatively well captured by the model.

Yet the performances of the model vary from one country to another. Generally speaking, we slightly under-estimate emissions mainly because of N_2O and CH_4 manure-related emissions. For some countries however –such as the UK or the Netherlands– initial emissions are over-estimated. These differences can be explained by differences in the FADN representativity sample across Member States. They can also arise from different choices in the implementation of the IPCC methodology.[8]

2.2 Abatement supply and marginal abatement cost curves

We then introduce in the model an emission tax t. The tax is assumed to affect directly each farmer's revenue according to the total amount of CO_2-equivalent emissions. The objective function of the maximization program (P_1^k) is modified accordingly to include the total tax amount paid by each farmer with respect to his/her emissions coming from all sources $(t.e^k)$. The simulations presented hereafter are otherwise based on the "Agenda 2000" scenario.

By construction for a given emission tax t, emissions $(e^{k*}(t))$ are such that the marginal loss of income due to an additional reduction equals t at the individual optimum for any k. By letting t vary in a given range, we depict the optimal abatement supply curve or, equivalently, the marginal abatement cost curves.Figure 2 shows the aggregate abatement supply for an emission tax varying from 0 to 100 EUR/tCO_2 by steps of 2.5 EUR.

We first focus on the aggregate results (see 2). For instance, an abatement target of 27.5 MtCO_2 implies a marginal abatement cost slightly higher than 55 EUR. This target represents 8% of the "Agenda 2000" emissions as computed by the model. As indicated in the 2003 EU communication to the UNFCCC, agricultural emissions are 7.4% lower in 2001 than in 1990 (see figure 3). If the same rate of change is applied to the computed "Agenda 2000" emissions, the 27.5 MtCO_2 target corresponds to a 14.8%-reduction in emissions compared to the 1990 levels. With respect to the Kyoto commitment –whereby the 2008/12 total emissions have to be 8% lower than in 1990–, it thus represents a significant mitigation effort for agriculture.

[8] Indeed, countries can use in their national communications simplified methods in their reporting of emissions (usually referred to as "Tier 1a methods") for sources of minor importances. Aggregation of these differences can lead to the magnitude of the gaps observed in figure 1.

<Figure 2 about here>

European Climate Change Programme (2003) has retained a carbon price of 20 EUR/tCO_2eq as the cost-effectiveness threshold in its assessment of mitigation strategies. At this price, our results indicate that GHG emissions from EU agriculture could be 4% lower than in 2001, or 11% lower than in 1990 (same assumption as above). The upper limit of the simulation range (100 EUR) is associated with an aggregate abatement of 40.5 MtCO_2 eq (nearly a 12%-reduction as compared to "Agenda 2000" emissions, and 18.3% compared to 1990 levels). Consistently with the LP nature of the model and the economic intuition, the total abatement supply is concave –implying convex marginal abatement costs.

<Figure 3 about here>

Some caveats are worth being mentioned when comparing our estimates of abatement costs with carbon prices published in the literature (see for instance Viguier et al. (2003)). Firstly, one has to remember that the modeled set of abatement options is limited in our analysis. For instance, carbon sequestration –which is not accounted for in this paper– might lower considerably the cost at which a given level of reduction in *net* emissions can be reached. Secondly, structural rigidities in the model –such as the constant number of farms, constant total land area, fixed manure management systems– tend to increase abatement costs. Altogether, our estimates can be thought as an upper limit of abatement costs that can be expected in agriculture. However and despite these caveats, our results indicate that agriculture could play a fair role in the fulfillment of with the Kyoto requirement. A recent report by the European Commission (2003) suggests that –even with the implementation of additional policies and measures– the total EU abatement is projected to fall short by 0.8% of the Kyoto target in 2010. Additional abatements from agriculture can therefore contribute to bridge such a gap.

The relative importance of the different sources in the total abatement gives an indication of the relative abatement costs associated to each source. Whereas methane emissions from enteric fermentation represents 34% of the 2001 emissions, this category represents most of the abatement for the lower values of the emission tax. This suggests lower abatement costs for this category relative to other emission sources. Abatements of methane emissions are primarily obtained through changes in animal feeding for the lower values of t. Comparatively, N_2O emissions from agricultural soils (52% of the initial emissions) are underrepresented in total abatements for the lower tax levels. However, as the tax increases and substitutions in animal feeding are exhausted, the share of "N_2O - agricultural soils" in the total abatement tends to increase and reach 50.4% for a 100 EUR/tCO_2 emission tax.

Abatements from manure management (both N_2O and CH_4) also appear to be more costly as their share in total abatements stays below their share in the total emissions for the whole t range. Indeed, the main means of abating emissions from this source lies in the changing of manure management systems. At this stage, this is not captured by the model as the fraction of manure handled under each management system is kept constant for each animal category and each farm type. As a consequence, the only way for farmers to reduce this source of emissions is to reduce animal numbers, which incurs higher abatement costs[9]. The relative rigidity of emissions from each source is hence a crucial feature in the magnitude of estimated abatement costs.

3 Marginal abatement cost heterogeneity

3.1 Regional distribution of abatement costs

Once marginal abatement costs curves are estimated, the next step in our analysis consists in assessing the spatial distribution of abatement costs. For a given emission tax, marginal abatement costs are equal across farmers. The heterogeneity of marginal abatement cost curves implies that abatements differ from one farmer to another.

Abatements for each farm type were computed for an emission tax of 55.8 EUR per ton of CO_2eq. As discussed in section 2, this emission tax leads to a 8%-reduction in total agricultural emissions as compared to initial emissions. Abatements were then aggregated for each of the 101 FADN regions. Figure 4 shows the abatement rate (relative to the "Agenda 2000" emissions) for each FADN region in the EU-15. Regional abatement rates for region R ($\tau_R(t)$) is thus computed as follows:

$$\tau_R(t) = 1 - \frac{E_R{}^*(t)}{E_R{}^*(0)} = 1 - \frac{\sum_{k \in R} e^{k^*}(t)}{\sum_{k \in R} e^{k^*}(0)} \qquad R = R_1, \ldots, R_{101} \tag{2}$$

This map indicates a large variability of the regional relative abatement rates, which range from almost 0% to 24%. Darker shades on the map signal the regions where the abatement rate relative to the initial total of regional emissions is higher. Abatement costs in these regions are thus lower, insofar as farmers can achieve higher relative abatement at a given marginal cost $t = 55.8$ EUR/tCO_2.

<Figure 4 about here>

Obviously, the information provided figure 4 is not sufficient to assess the regional distribution of the *total* abatement. The distribution of initial emissions ($E_R{}^*(0)$) among regions also matters to that respect. This additional information is shown on figure 5.

<Figure 5 about here>

[9]Accounting for the adoption by farmers of new manure management systems would incur additional investment and labor cost that are not considered in the model.

Regions are sorted with respect to increasing $\tau_R(55.8)$ (x axis on figure 5). Regions with the higher relative abatement rates are thus located to the right of the chart. Regional relative abatement rates are then plotted against the cumulative initial emissions for each of the 101 FADN regions considered in the analysis. The initial regional emissions for each abatement rate depicted on map 4 can therefore be derived from figure 5 (squares). For instance, the regions with the lowest abatement rates (ranging from 0 to 5%) represent approximately 70 $MtCO_2$eq. On the other end of the cumulative curve, another 70 $MtCO_2$eq corresponds to $\tau_R(55.8)$ higher than 11%. Abatement rates ranging between 5 and 11% –centered around the 8% EU average reduction– concern the remaining initial emissions or 205 $MtCO_2$eq.

3.2 Infra-regional heterogeneity of abatement costs

Each of the 734 farm types is known to belong to a given FADN region, although it cannot be precisely located within this region. The distribution of abatement rates at the farm-type level is also analyzed. Using the same approach as above, the 734 farm-types are sorted out with respect to increasing individual abatement rates ($\tau_k(t) = \frac{e^{k^*}(0) - e^{k^*}(t)}{e^{k^*}(0)}$). Variability at the farm-type level is by construction larger than the regional variability. The regional aggregation thus hides some of the abatement cost variability. Consequently, the farm-type cumulative curve (depicted by triangles in figure 5) is less concentrated around the EU abatement rate (8%) and the range of abatement rates is wider than at the regional level. The infra-regional distribution of abatement rates can be derived from the difference between the farm-type and the regional scatter plots. Interestingly, this infra-regional variability matters the most for the lowest abatement rates. Farm-type with very low abatement rates (<1%) represent about 20% of the initial emissions. This share drops to less than 2% when abatements are regionally aggregated. This difference tends to decrease when approaching the EU-wide average abatement rate. In terms of marginal abatement costs, this indicates a large infra-regional variance and a right-skewed distribution.

As the emission tax and the total abatement increase, the distribution of abatements among the 734 farm types changes. Figure 6 shows the changes in the distribution of the individual relative abatement rates ($\tau_k(t)$) for $t = 20$, 55.8, and 100 EUR/tCO_2. These emission taxes translate into EU abatement rates of approximately 4%, 8% and 12%, respectively. Expectedly, the higher the emission tax, the larger the abatement for all farm types. This implies a rightward shift of the cumulative curves as t increases. More interestingly, the initial emission for individual abatement rates lower than the EU average reduction is decreasing with respect to the emission tax. For an emission tax of 20 EUR/tCO_2, the farmers who reduce their emissions by less than the EU average abatement (4%) emit approximately 227 $MtCO_2$eq. This number drops to 207 $MtCO_2$eq for a 55.8 EUR/tCO_2 emission tax (8% average abatement), and to 201 $MtCO_2eq$ for a 100 EUR/tCO_2 emission tax (12% average abatement). This suggests a shift in the concentration of abatements as the emission tax increases.

<Figure 6 about here>

3.3 Abatement cost heterogeneity and the potential savings of incentive-based instruments vs uniform standards

In the previous section, we used an emission tax as a means of estimating the individual and regional marginal abatement curves. We now turn to the issue of implementing a mitigation policy of GHG emissions from agriculture. Of course, if control costs were small enough, an emission tax would be a first-best instrument and lead to an optimal allocation of abatement among farmers. If such an instrument were to be chosen, the figure 2 and figure 4 would give an appropriate picture of the impact on the total level and the regional distribution of emissions. However, as noticed by Newell and Stavins (2003), conventional standards are often preferred over first-best instruments by policymakers for various policy reasons. The potential savings permitted by first-best instruments relative to conventional standards are thus worth being assessed.

We examine the abatement costs associated with "uniform relative quotas". That is, we impose that *each* farmer has to meet a given reduction target, expressed as a percentage of his/her initial emissions. This percentage is assumed to be the same for all farmers, say α% of the farm-type initial emissions. To do so, we introduce a new constraint in each individual farm-type model:

$$e^k \leq (1-\alpha).e^{k^*}(0) \qquad (\lambda_\alpha^k) \tag{3}$$

$e^{k^*}(0)$ is the optimal level of emissions for the k-th farm type computed in the "Agenda 2000" scenario with a 0 EUR emission tax. The shadow price (λ_α^k) associated with this constraint reflects the marginal abatement cost of achieving this target for the k-th farmer. As the constraint should be binding at the optimum, $\lambda_\alpha^{k^*}$ is strictly positive. As discussed in the previous section, marginal abatement cost curves have been found to vary widely both at regional and farm-type levels. Consequently, if the imposed abatement rate is constant across farmers, marginal abatement costs are expected to differ from one farmer to another. Indeed a uniform relative quota distorts the allocation of abatement. As a result, the total abatement cost is expected to be higher under a uniform relative quota regime for the same environmental results.

This is examined on table 1. For three abatement rates (α=4%, 8%, and 12%), we compute the individual marginal abatement costs as the optimal shadow prices ($\lambda_\alpha^{k^*}$) associated to the emission constraint (3). The average of marginal abatement costs – weighted by the share of each farm type in the total initial emissions $E^*(0)$ – is computed as follows:

$$\bar{\lambda}_\alpha = \frac{1}{E^*(0)} \sum_{k=1}^{734} e^{k^*}(0).\lambda_\alpha^{k^*} \tag{4}$$

As the imposed abatement rate α is the same for all k and constraint (3) is binding for all k, the total EU abatement rate is therefore also equal to α.

The marginal cost of achieving any given reduction target can be compared for an emission tax and a uniform relative quota. To meet a 4% reduction target, the average marginal abatement costs for a uniform relative quota is 3.6 times higher than the marginal abatement costs associated with the emission tax for the same total abatement. This ratio decreases as the stringency of the quota increases: meeting a uniform 8% (12%) reduction target is 2.2 (1.7) times more expensive than with an emission tax. This decrease reflects the change in the concentration of abatement costs described in section 3.2. The efficiency loss associated with uniform relative quotas can also be measured in terms of total abatement at a given carbon price. Going back to figure 2, a 73.6 EUR/tCO_2 emission tax results in a 10% abatement, more than twice as much as under a uniform quota regime.

Abatement target	Total abatement	Marginal abatement cost		Efficiency loss
		Emission tax	Uniform quotas	
α		t	$\bar{\lambda}_\alpha$	$\bar{\lambda}_\alpha/t$
(%)	(MtCO_2eq)	(EUR t/CO_2)	(EUR t/CO_2)	
4%	13.78	20.51	73.64	3.6
8%	27.56	55.84	122.66	2.2
12%	41.35	>100.00	169.62	<1.7

Table 1: Comparison of marginal abatement costs under an emission tax and a uniform relative quota

Concluding remarks

Abatement costs are a fundamental determinant of the role that agriculture could play in meeting efficiently the EU commitment to reduce its GHG emissions. Two broad dimensions have been examined in this paper: *(i)* the *magnitude* of abatement costs in the agricultural sector and *(ii)* their *heterogeneity*.

On the first aspect, the estimated aggregate abatement supply curve indicates how much abatement would result from the implementation of an incentive-based mitigation policy. This curve can be used in assessing the impacts of either an emission-tax or a tradable-permit system, provided that is based on the IPCC emission accounting method. One important issue concerns the implementability and the efficiency of IPCC-based economic instruments, especially with regard to the trade-off between accuracy and observability. To this respect, this method provides an interesting balance. Of course, on one hand, complex emission processes are only imperfectly captured because of the use of simplified relationships between activities and emissions. On the other hand however, the IPCC framework is recognized as an international reference and is based on easily observable data[10]. This balance is of great importance in the design of operational and efficient economic instruments.

The approach retained in our analysis is somewhat pragmatical insofar as we focus on the abatement potential at given carbon prices. In many respects, several of our modeling assumptions are rather conservative (fixed number of farms, constant total area, no account for carbon sequestration, fixed manure management systems, etc.). These assumptions lead to marginal abatement costs magnitudes that lie in the upper-range of what should be expected from agriculture. Moreover, structural drivers – such as the evolution of the CAP– could also play a major role in the future evolution of GHG emissions from EU agriculture. However and despite these restrictive assumptions, our results indicate that the contribution of agriculture to the total EU abatement can be higher in relative terms than in the rest of the economy. 2001 levels of GHG emissions from agriculture are already about 7.4% lower than in 1990 (reference year for the Kyoto Protocol). Additional abatements are thus potentially available from agriculture and may provide an efficient alternative to emission reductions in sectors where abatement costs are large. Incentives to further reduce GHG emissions from agriculture would thus contribute to lower the costs of complying with the EU commitments and bridge the gap between projected total EU emissions and the Kyoto targets. At the same time, this would fit the evolution of the CAP, whereby environmental concerns are increasingly emphasized in the design of agricultural policies.

Abatement costs heterogeneity comes from a variety of sources. The regional variability –partly embedded in the FADN database– is well captured by the model for some of these sources, such as those related to farms' size, crop yields and area allocation, total animal numbers, input use, CAP support. Some are captured only at the country-level (emission factors). And, due to the lack of data, some of the sources of heterogeneity have been ignored, mostly at the infra-regional level. However, the estimated heterogeneity of abatement costs is shown to be large. This has two broad implications for policy purposes. First, the impacts of incentive-based instruments impact income and environmental performances vary widely from one farmer to another. Second, the efficiency loss associated with uniform relative quotas is substantial.

[10]Most of this information –such as area, animal numbers, purchased animal feeding– is already collected for CAP-support related purposes. Arguably however some important emission-driving activities, such as on-farm consumption of animal feeding, are more difficult to control.

If for some reason, quotas are still preferred by policymakers, it is thus worth considering differentiated ones. The optimal level at which these standards should be set –EU-wide, country-wide, regional, infra-regional, or individual– needs to be further investigated. Further research is also needed in order to relax some of our modeling assumptions. For instance, the introduction of more flexible yield responses to nitrogen inputs would contribute to lower the estimated abatement costs for N_2O emissions. So would do endogenous choices of manure management systems. Finally, the inclusion of carbon sinks in agricultural is essential for future research, as it would provide farmers with alternative ways of reducing their *net* emissions.

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Figures

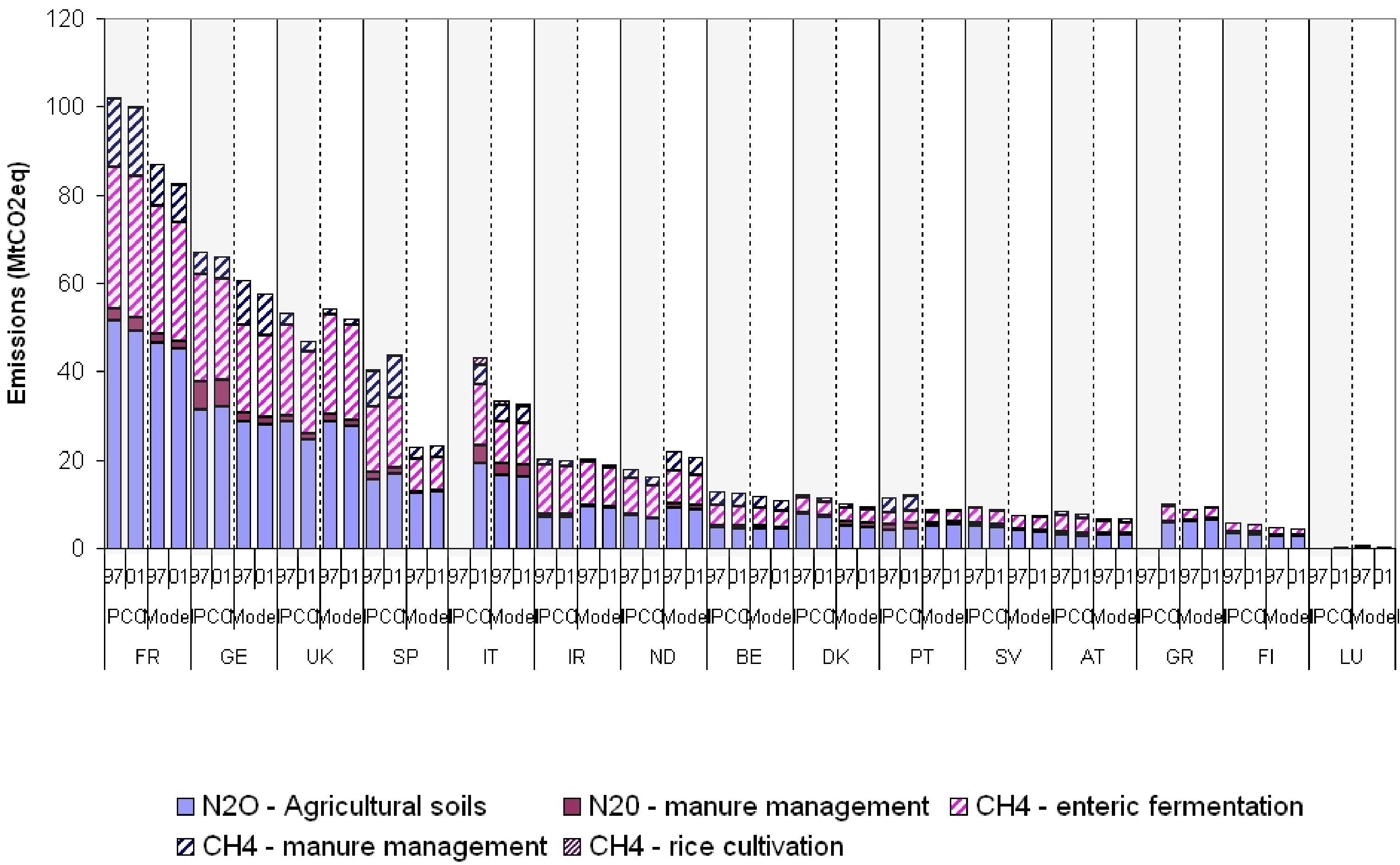

Figure 1: IPCC emissions as reported in the 2003 national communications (years 1997 and 2001) vs model computations (“CAP97” and “Agenda 2000”).

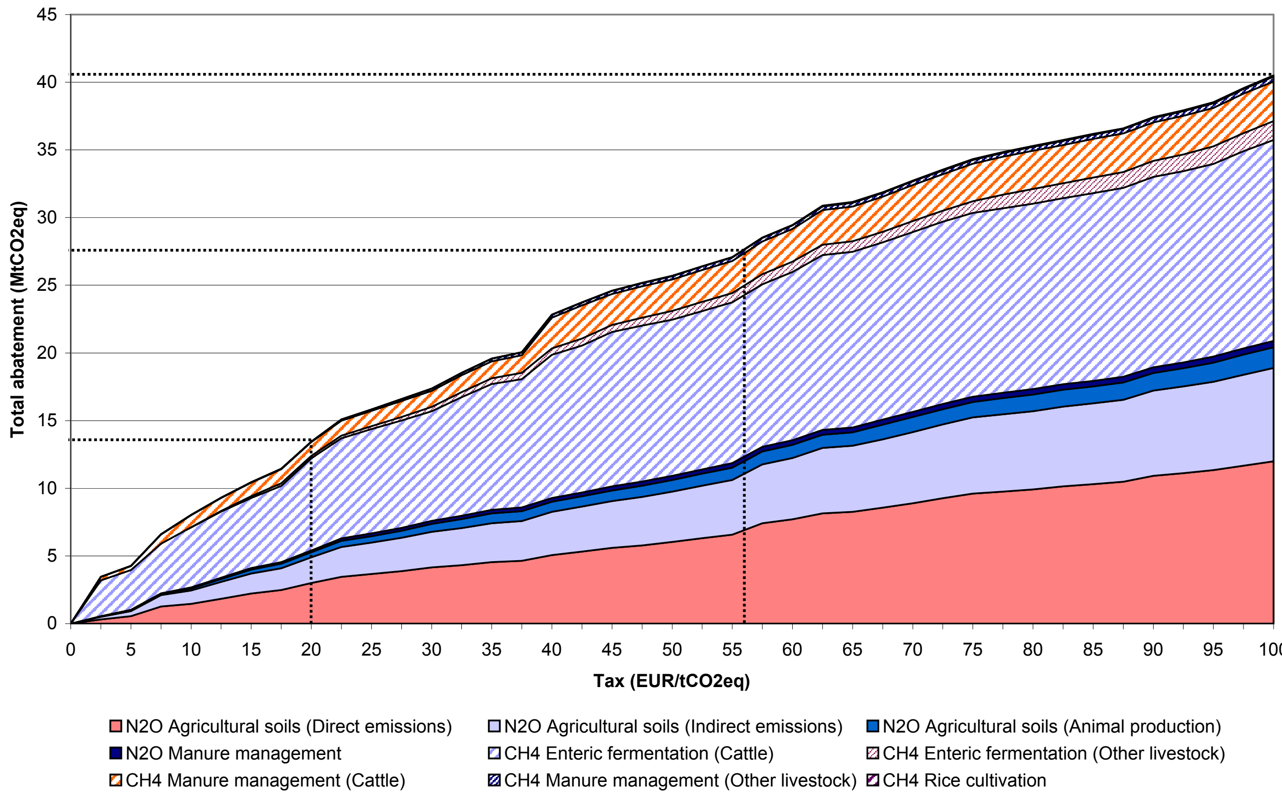

Figure 2: Abatement supply and relative shares of emission sources in the total EU abatement

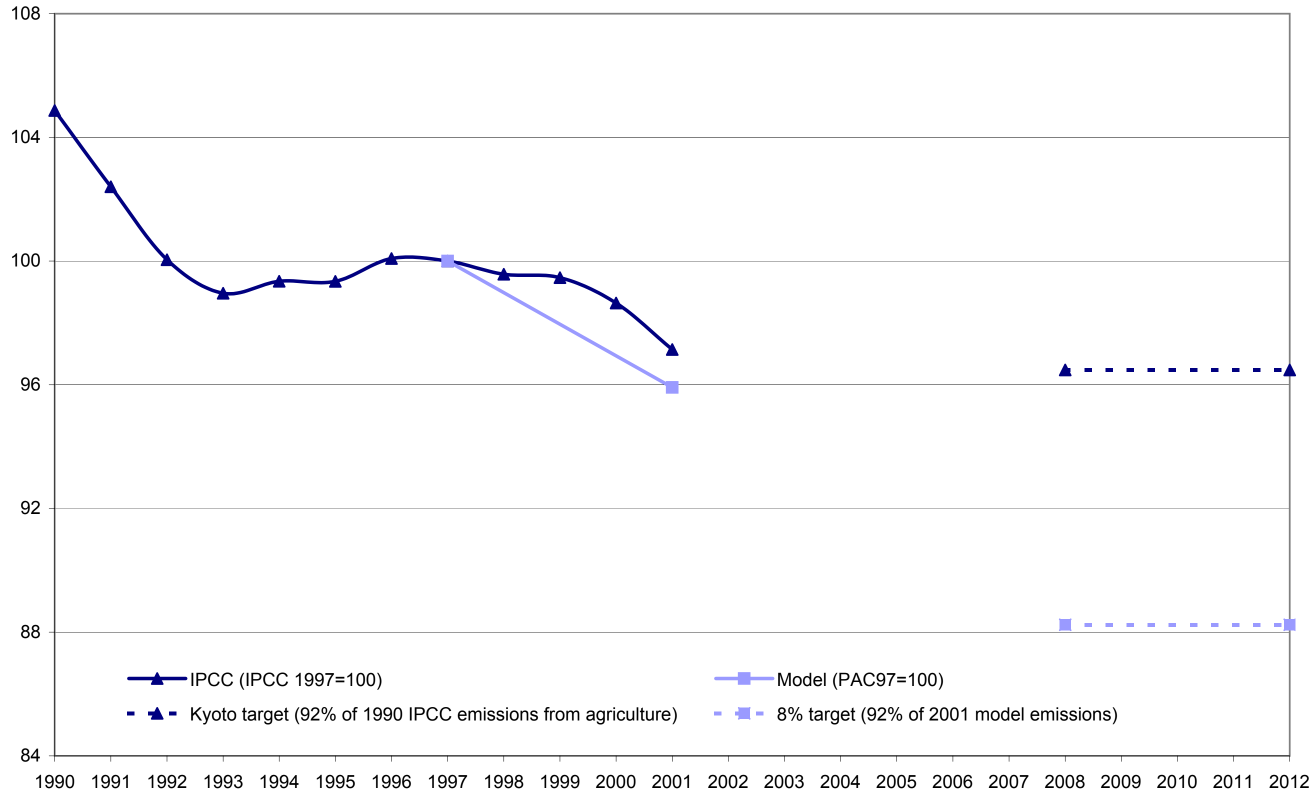

Figure 3: Comparison of the Kyoto 8%-reduction requirement for agriculture and a 8% reduction of 2001 model emissions

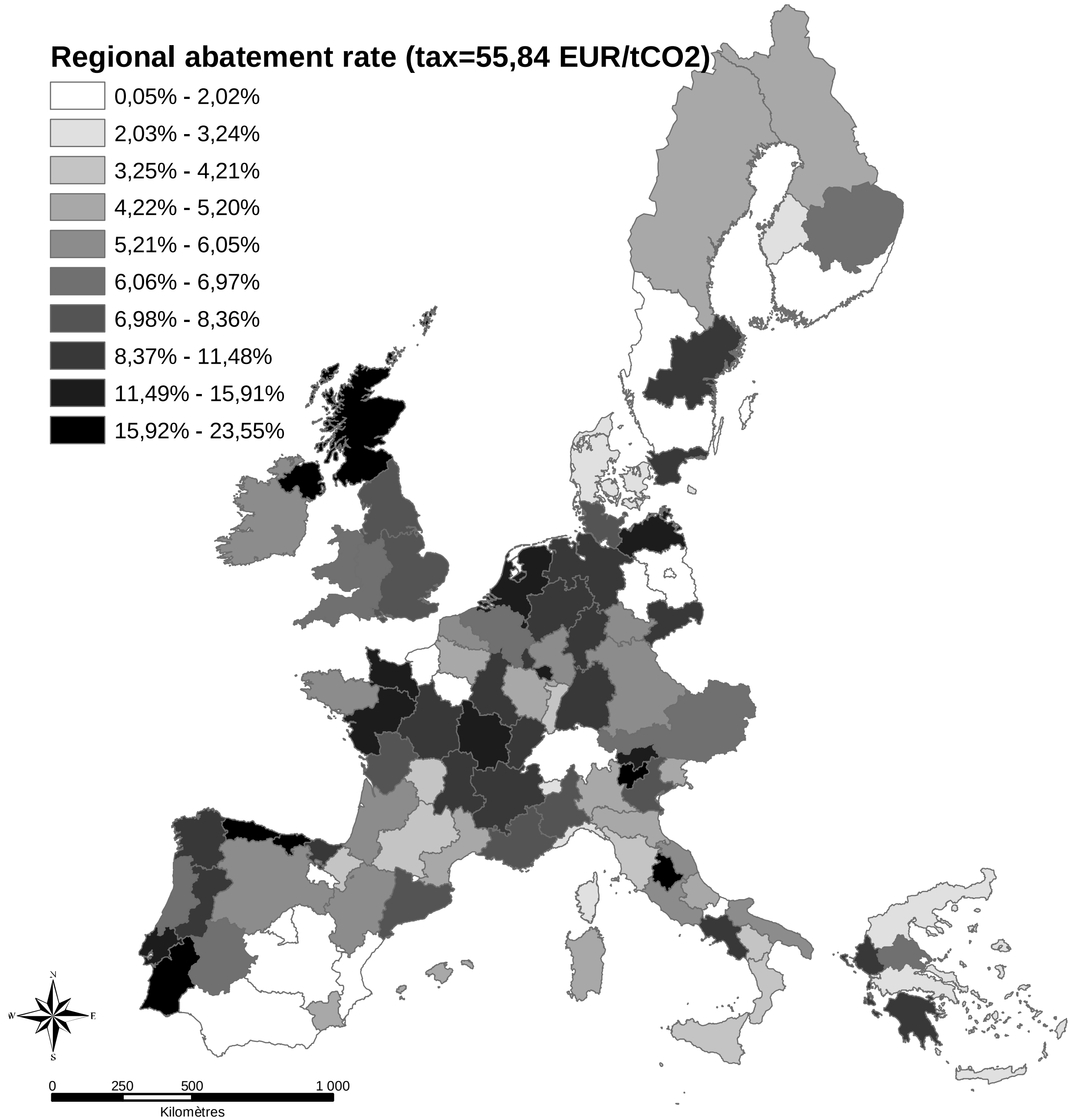

Figure 4: Spatial heterogeneity of regional abatement rates ("Agenda 2000" scenario, t=55.8 EUR/tCO_2eq, EU abatement rate is 8% compared to "Agenda 2000")

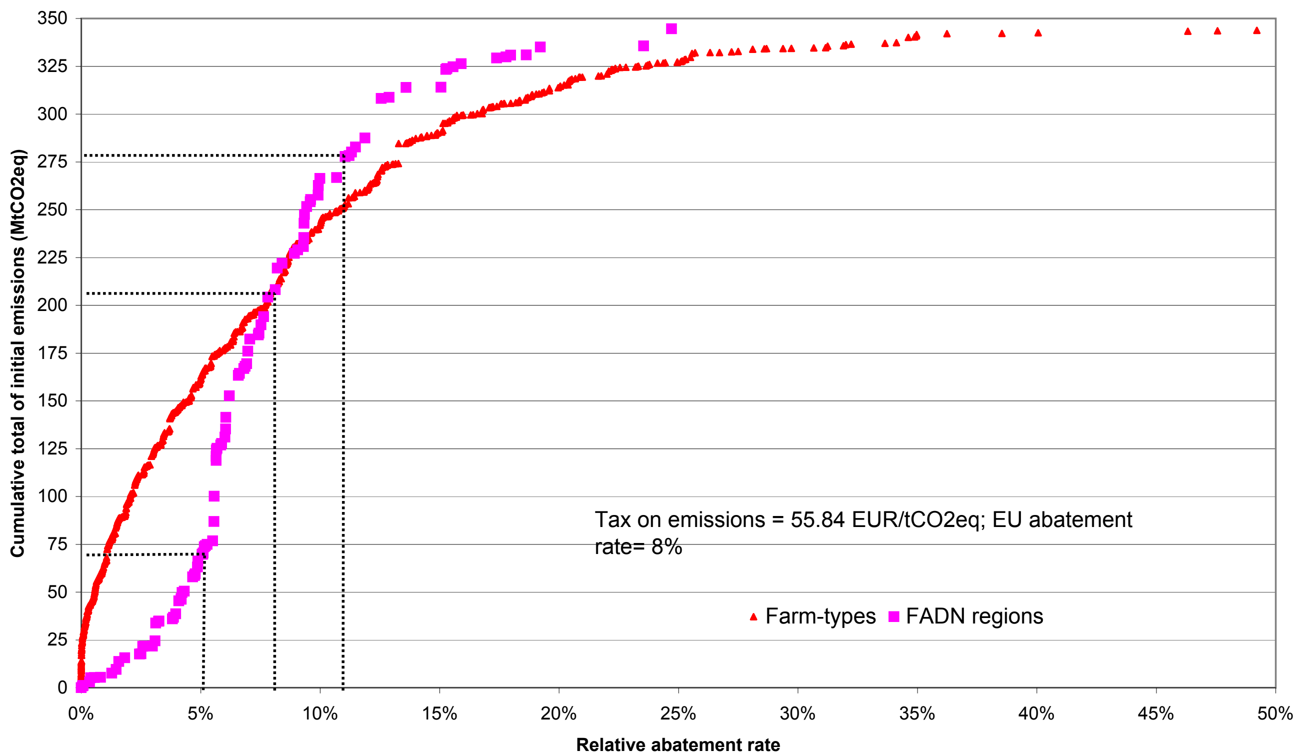

Figure 5: Regional (squares) and farm-type (triangles) relative abatement rates vs cumulative initial emissions ("Agenda 2000" scenario, t=55.8 EUR/tCO_2eq, EU abatement rate is 8% compared to "Agenda 2000")

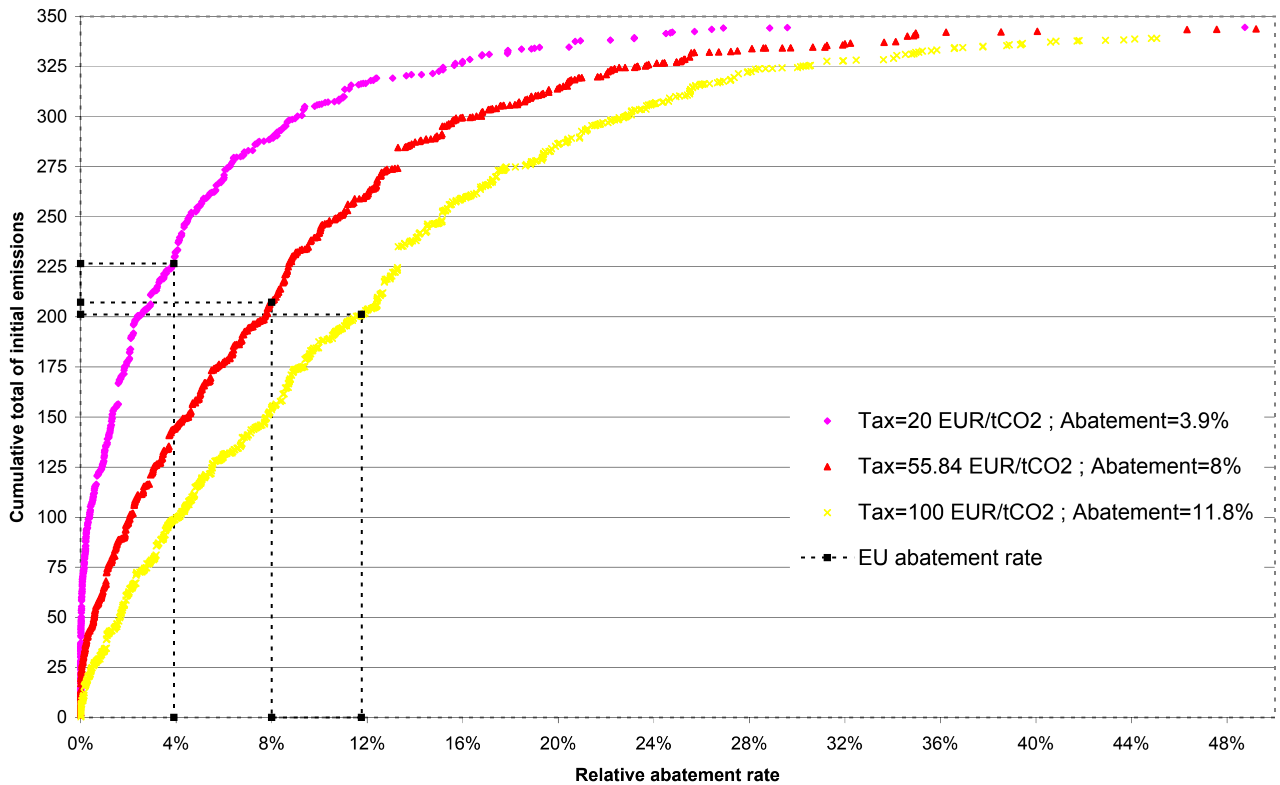

Figure 6: Scatter plots of farm-type relative abatement rates vs cumulative initial emissions for three emission taxes ("Agenda 2000" scenario)

A Appendix: Emission accounting: Description of the IPCC methodology

A.1 Nitrous oxide emissions from agricultural soils

These emissions are primarily due to the microbial process of nitrification and denitrification in the soil. Three categories of emissions are distinguished by the Intergovernmental Panel on Climate Change (2001b): direct soil emissions ($E^{AD}_{N_2O}$), indirect soil emissions ($E^{AI}_{N_2O}$), and emissions induced by grazing animals ($E^{M}_{N_2O}$).

Equations used in the calculation of N_2O direct emissions rely on a simple representation of the nitrogen cycle in agricultural soils. N_2O is a gaseous intermediate in the reaction sequence of aerobic microbial oxidation of ammonium to nitrate (nitrification) and anaerobic microbial reduction of nitrate to di-nitrogen gas (denitrification). Surveys from field experiments have shown that an increase of nitrogen availability in soils results in an increase of nitrification and denitrification rates, and consequently in higher N_2O emissions.

Generally speaking, the computation of direct N_2O emissions consists in collecting the amount of nitrogen inputs to soils (converted into N_2O equivalent[11]) and multiplying them by appropriate emission factors that reflect the percentage of the nitrogen input transformed into N_2O (denoted hereafter by EF). A detailed description of all equations used in this category can be found in Intergovernmental Panel on Climate Change (2001b, pp 4.54–4.70).

The total nitrogen input are computed for *(i)* synthetic fertilizer use ($\sum_{j\in J} N_{Sj}.S_j$, N_{Sj} being the per-hectare nitrogen input and S_j the area planted in crop j), *(ii)* animal waste applied to soils as fertilizer ($\sum_{i\in I} A_i.N_{Mi}$, where A_i is the number of animal in the ith animal category and N_{Mi} the annual per-head amount of nitrogen produced by animal i), *(iii)* nitrogen fixation by N-fixing crops (N_{Fj}, J' being the subset of N-fixing crops in the set of crops J) and *(iv)* nitrogen content of crop residues (N_{Rj}). The total amount of nitrogen input is corrected to account for the fraction of nitrogen that volatilizes as NO_x and NH_3 (γ^V_S and γ^V_M).

$$E^{AD}_{N_2O} = EF^{AD}.\left\{(1-\gamma^V_S).\sum_{j\in J} N_{Sj}.S_j + (1-\gamma^V_M).\sum_{i\in I} A_i.N_{Mi} + \sum_{j\in J'} N_{Fj}.S_j + \sum_{j\in J} N_{Rj}.S_j\right\} \quad (5)$$

Manure and synthetic fertilizer inputs also contribute to indirect N_2O emissions according to two different processes: *(i)* volatilization and subsequent atmospheric deposition of NH_3 and NO_x, and *(ii)* nitrogen leaching and run-off. The percentage of nitrogen that volatilizes as NO_x and NH_3 is taken as constant in the IPCC guidelines. So is the percentage of nitrogen lost through leaching and run-off (γ^L_S and γ^L_M). It leads to the following equation for this category:

$$E^{AI}_{N_2O} = EF^{V}.\left(\gamma^V_S.\sum_{j\in J} N_{Sj}.S_j + \gamma^V_M.\sum_{i\in I} A_i.N_{Mi}\right) + EF^{L}.\left(\gamma^L_S.\sum_{j\in J} N_{Sj}.S_j + \gamma^L_M.\sum_{i\in I} A_i.N_{Mi}\right) \quad (6)$$

[11] The conversion factor between N and N_2O is 44/28.

The last source of N_2O emissions from agricultural soils is the nitrogen content of grazing livestock excrements that are directly deposited on soils. This requires to know the percentage of manure produced by grazing livestock for each animal category ($\alpha_{i,graz}$):

$$E^M_{N_2O} = \sum_{i \in I} EF^M_{graz}.\alpha_{i,graz} A_i.N_{Mi} \tag{7}$$

A.2 Nitrous oxide emissions from manure management

N_2O emissions from manure management ($E^M_{N_2O}$) occur during the storage and treatment of manure. That is, this category covers N_2O emissions before manure is applied to land as fertilizer and excludes unmanaged manure (deposited on soils by grazing animals, see above). The IPCC method uses the average nitrogen excretion rates from each animal category (N_{Mi}), as well as the percentage of manure for each animal category handled under each manure management system ($\alpha_{i,s}$). Each management system is assigned an emission factor (EF^M_s). This computation can be described by the following equation:

$$E^M_{N_2O} = \sum_{s \in S} \sum_{i \in I} EF^M_s.\alpha_{i,s}.A_i.N_{Mi} \tag{8}$$

where S is the set of manure management systems.

A.3 Methane emissions from manure management

The decomposition of organic material contained in livestock manure in an anaerobic environment produces methane through the action of methanogenic bacteria. This occurs generally when large numbers of animals are managed in confined areas. IPCC method to compute CH_4 emissions from manure ($E^M_{CH_4}$) can be described by the following equation:

$$E^M_{CH_4} = \sum_{i \in I} \sum_{s \in S} A_i.\delta_i.VS_i.\eta_s.\alpha_{i,s} \tag{9}$$

where δ_i represents the maximum CH_4 producing capacities for animal i, VS_i represents the annual volatile excretion rate for animal i and η_s is the CH_4 conversion factor for each manure management system. VS_i depends on the energy content of feed intake and feed digestibility.

A.4 Methane emissions from enteric fermentation

Methane is also produced in large quantities during the digestive process of animals. Highest emissions occur for ruminant animals because of a significant amount of methane-producing fermentation in the rumen. Total emissions from enteric fermentation can be derived from the energy content of feed intake that is lost as methane (χ_{CH_4} is the energy content of methane). IPCC recommends to derive the amount of CH_4 emitted this way from a simple fraction (Y_i) of the gross energy intake (GE_i)

$$E^E_{CH_4} = \sum_{i \in I} A_i.Y_i.\frac{GE_i}{\chi_{CH_4}} \tag{10}$$

A.5 CH_4 emissions from rice fields

Anaerobic decomposition of organic material in flooded rice fields produces CH_4. This is a relatively minor source of CH_4 for the EU, which only concerns Mediterranean countries (Italy, Spain, Greece, France). The annual amount of CH_4 from rice cultivation ($E^R_{CH_4}$) can be derived as a constant methane flow per hectare ($EF^R_{CH_4}$), possibly differentiated according to management systems.

$$E^R_{CH_4} = EF^R_{CH_4}.S_{Rice} \tag{11}$$

Emission sources	Activity data	Linked to
N_2O Agricultural soils		
Direct Emissions		
Use of synthetic fertilizers	N fertilizer application	Crop area
Manure application	N excretion by animals	Animal number
Biological N fixation	Production of N-fixing crops	N-fixing crop area
Crop residues	Reutilization of crop residues	Crop area
Animal production	N excretion by grazing animals	Animal number
Indirect Emissions		
Atmospheric deposition	Total N application	Crop area and animal number
Leaching and run-off	Total N application	Crop area and animal number
N_2O Manure management		Animal number
CH_4 Manure management		
Dairy Cattle	Feed energy content	Animal feeding
Non-dairy cattle	Feed energy content	Animal feeding
Sheep	Feed energy content	Animal feeding
Goats	Feed energy content	Animal feeding
Swine	Feed energy content	Animal feeding
Poultry	Feed energy content	Animal feeding
CH_4 Enteric fermentation		
Dairy Cattle	Feed energy content	Animal feeding
Non-dairy cattle	Feed energy content	Animal feeding
Sheep	Feed energy content	Animal feeding
Goats	Feed energy content	Animal feeding
Swine	Feed energy content	Animal feeding
Poultry	Feed energy content	Animal feeding
CH_4 Rice cultivation	Rice area	Rice area

Table 2: Summary of GHG emission sources accounted for in the model