Environmental & Resource Economics (2005) 32: 551–583
DOI 10.1007/s10640-005-0071-8

Methane and Nitrous Oxide Emissions from Agriculture in the EU: A Spatial Assessment of Sources and Abatement Costs

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Accepted 8 June 2005

Abstract. Agriculture significantly contributes to emissions of greenhouse gases in the EU. By using a farm-type, supply-side oriented, linear-programming model of the European agriculture, the baseline levels of methane and nitrous oxide emissions are assessed at the regional level in the EU-15. For a range of CO_2-equivalent prices, we assess the potential abatement, as well as the resulting optimal mix of emission sources in the total abatement. Furthermore, we show that the spatial variability of the abatement achieved at a given carbon price is large, indicating that abatement cost heterogeneity is a fundamental feature in the design of a mitigation policy. The cost savings permitted by market-based instruments relative to uniform standard are shown to be large.

Key words: agriculture, climate change, European Union, greenhouse gas emissions, marginal abatement costs, methane, nitrous oxide

JEL classifications: Q15, Q25

1. Introduction

Agriculture has been long 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 (Hayhoe et al. 1999; Reilly et al. 1999; Manne and Richels

2001). There is thus a need for the EU to find alternative abatement opportunities 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 policymakers in recent years (European Commission 1998a, b, 2002; Bates 2001).

Emissions from EU agriculture total about 405 $MtCO_2eq$ or 10% of total European emissions.[2] They are caused by crop and livestock production activities. Nitrous oxide emissions (from fertiliser application and manure management) represent approximately 210 $MtCO_2eq$, while methane emissions (from enteric fermentation, manure management, and rice cultivation) account for about 195 $MtCO_2eq$. 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 have been estimated at various scales. McCarl and Schneider (2001) provide 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). De Cara and Jayet (1999, 2000) investigate abatement costs in French agriculture. In addition to N_2O emissions from the use of synthetic fertilisers 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. Marginal abatement cost curves have been estimated on a Member-State basis by Perez et al. (2003), using the CAPRI modelling system. In addition, Perez et al. provide a regional assessment of the impacts of an EU-wide 10% reduction of total agricultural emissions. Following a similar approach, Perez and Britz (2003) and Perez et al. (2004) examine the implementation of a carbon credit system in EU agriculture, and the issue of transaction costs associated with inter-regional permit trading.

The present paper departs from the previous literature mainly through its focus on the *heterogeneity of abatement costs* within the EU. In particular, this text highlights the implications of heterogeneity for the design of a mitigation policy. Besides, the heterogeneity of abatement costs is examined both at infra-regional (farm types) and regional (FADN regions) levels. The farm-type approach is particularly useful to capture *infra-regional* variability of abatement costs. By construction, aggregate approaches, which rely on country- or regional-aggregated models, fail to encompass the variety of farming systems that exists in the EU (Perez et al. 2003, p. 7). As a direct consequence, they tend to under-estimate an important source of abatement cost heterogeneity.

The heterogeneity of abatement costs is fundamental in the choice of optimal mitigation policy instruments. Incentive-based instruments are generally viewed – at least under perfect information – as more efficient than command-and-control regulations. Incentive-based instruments tend to equate marginal abatement costs across polluting agents and consequently minimize total abatement costs. In contrast, command-and-control instruments generally result in distorted allocations of abatement efforts. 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 distortion in abatement efforts 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 permitted by 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, spatial distribution of economic and environmental impacts of a mitigation policy is of prime importance in the policy-making process. Spatial analyses that go beyond EU- or country-wide estimates of abatement costs curves are hence needed.

Three major sources of abatement cost heterogeneity can be distinguished: (i) activity-data heterogeneity; (ii) emission-factor heterogeneity; (iii) heterogeneity in the flexibility of substitutions between production activities. The first source is related to farm-size parameters such as the area allocated to each crop, animal numbers, fertiliser 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). Only the first two sources are analysed in the stylized framework developed by Newell and Stavins. The third source is often overlooked in the assessment of abatement costs and largely depends on the technical and economic possibilities of substitution between agricultural activities in the short run. In this paper, these three sources of heterogeneity are accounted for – yet to different degrees.

The objectives of this paper are threefold: (i) to assess GHG abatement costs in agriculture accounting for a wide range of sources and the diversity of farming systems in the EU; (ii) to analyse the spatial heterogeneity of abatement costs; (iii) to estimate the cost savings permitted by an IPCC-based emission tax as compared to uniform standards and highlight the link with abatement cost heterogeneity.

Following a commonly used approach in the economic literature (e.g. see McCarl and Schneider 2001 for an application to the US agriculture or Babiker et al. 2003 for a general equilibrium approach), abatement supply curves are derived through the introduction of an emission tax. The model used is a supply-side, farm-type based, linear-programming model covering the EU-15. The potential abatement and the optimal mix of emission sources resulting from an IPCC-based emission tax are assessed at the farm-type level. When aggregated at the EU level, these results indicate that a reduction of 8% of 2001 agricultural emissions (about 15% of 1990 emissions) corresponds to a marginal abatement cost slightly above 55 EUR/tCO_2eq. It is important to note, however, that the supply-side approach followed in the paper does not account for changes in prices and trade, nor does it include welfare effects beyond the impact on farmers' income. Nonetheless, the results show a large variability of the abatement actually achieved at a given carbon price, indicating that abatement cost heterogeneity is a fundamental feature. As a direct consequence, uniform standards would result in abatement costs from two to four times higher than under an IPCC-based emission tax regime.

The paper is organized as follows. In Section 2, after a brief description of the model, the various GHG sources and the IPCC methodology used in the computation of agricultural emissions are presented. The strengths and weaknesses of the IPCC methodology are discussed. Section 3 presents the results in terms of baseline emissions and optimal abatement supply for an emission tax ranging from 0 to 100 EUR/tCO_2eq. The relative weights of each source in total abatement and the relative abatement costs of each source are discussed. Spatial heterogeneity of abatement costs and implications for mitigation policies are investigated in Section 4. The variability of optimal abatement at given carbon prices is examined both at the inter- and infra-regional levels. At last, additional costs associated with uniform standards are estimated.

2. Analytical Framework

2.1. THE MODEL

The model consists of a set of independent, mixed integer and linear-programming models. Each model describes the annual supply choice of a given "farm type" (denoted by k), representative of the behaviour of ν_k "real" farmers. The farm-type representation enables to account for the wide diversity of technical constraints faced by European farmers. Each farm type k is assumed to choose the supply level and the input demand ($\mathbf{x}_k$) in order to maximize total gross margin (π^k). In its most general form, the generic model for farm type k can be written as follows:

$$\max_{\mathbf{x_k}} \quad \pi_k(\mathbf{x}_k) = \mathbf{g}_k \cdot \mathbf{x}_k \tag{1.1}$$

$$\text{s.t.} \quad \mathbf{A}_k \cdot \mathbf{x}_k \leq \mathbf{z}_k \tag{1.2}$$

$$\mathbf{x}_k \geq 0 \tag{1.3}$$

where $\mathbf{x}_k$ is the n-vector of producing activities for farm type k, and $\mathbf{g}_k$ is the n-vector of gross-margins. $\mathbf{A}_k$ is the $m \times n$-matrix of the coefficients associated with the n producing activities and defining the m constraints, and $\mathbf{z}_k$ the m-vector of the right-hand side parameters (capacities).

The components of $\mathbf{x}_k$ include the area and output for each crop (distinguishing between on-farm and marketed production), animal numbers in each animal category, milk and meat production, and the quantity of purchased animal feeding. $\mathbf{g}_k$ contains the gross margin corresponding to each producing activity: revenue (yield times price) plus – when relevant – support received, minus variable costs. As the emphasis is put on the farm-type level, each farm-type is assumed to be price-taker. All input and output prices defining the components of $\mathbf{g}_k$ are thus kept constant. Twenty-four crop producing activities are modelled. They represent most of the European agricultural land use. The set of crop producing activities includes fallow as well as the different CAP set-aside requirements. Crop production can be directly sold in the market or used for animal feeding purposes (feed grains, forage, pastures). In the latter case, the corresponding component of $\mathbf{g}_k$ only represents the variable cost of growing feed crops. Feedstuff can also be purchased. As for livestock, 31 animal categories are represented in the model (27 for cattle plus sheep, goats, swine and poultry). Total GHG emissions are endogenously computed in the model through equality constraints (see Section 2.2), and are included in $\mathbf{x}_k$. The corresponding component of $\mathbf{g}_k$ represents the emission tax (t) in euros per ton of CO_2 equivalent. In the baseline scenario, t is assumed to be zero.

The technically feasible production set is bounded by the constraints defined by $\mathbf{A}_k$ and $\mathbf{z}_k$. As the total number of non-trivial constraints is fairly large, the present description focuses on constraints that are directly relevant to GHG emissions and abatement costs. A more detailed presentation of some of the constraints is given in Appendix A.

Total crop and grassland area is constrained by the availability of land area, defined as total farm type k's land endowment (see Appendix A). In addition, crop rotation constraints are formulated as maximum area shares of individual (or groups of) crops in total area. Agricultural area is split into arable land for crops (including cultivated forage crops), grassland and meadows. Land area allocated to the various groups of producing activities is subject to upper bounds. These upper bounds summarize the dynamic nature of crop rotations in a static framework. Maximal area shares are first estimated at the regional level using the 1997 FADN observation. Initial estimates are then updated during the calibration phase (see below), assuming that the calibrated area share lies between the initial estimate and one.

Animal numbers are limited by the availability of stable places in the short-run. In order to reflect the quasi-fixed nature of livestock-related capital, animal numbers for each animal category are only allowed to vary in a limited range in the model. In all subsequent simulations, the maximum range in which animal numbers may vary is assumed to be $\pm 15\%$ of the initial animal numbers in the corresponding animal categories. The corresponding constraints are defined at the farm-type level and for each relevant animal category. Moreover, these constraints interact with other constraints, such as those related to animal feeding, demographic equilibrium and milk-quota. As a consequence, they are not necessarily binding for *all* farm types and *all* animal categories.[4] The flexibility of animal numbers is important for abatement purposes, as changes in animal diet alone are likely to provide only limited abatement if not combined with changes in livestock numbers (European Climate Change Programme 2003). In addition, cattle numbers are constrained by relationships that reflect demographic equilibrium in the distribution by age and sex classes. This approach thus corresponds to a comparative static, and is very akin to that used for crop rotation.

To feed their animals, farmers can use their own crop and forage production, or purchase concentrates and/or roughage. Four kinds of purchased concentrates and one kind of purchased roughage are considered in the model. This permits to distinguish between energy- and protein-rich concentrates, as well as between straight and compound feedstuff. Three sets of 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 cattle category is associated with a maximal quantity of ingested matter. The characteristics of feedstuff 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 category were taken from Jarrige (1998). In addition, energy and protein needs are further differentiated to account for the differences in milk and meat yields.

The last important set of constraints regards the restrictions imposed by CAP measures. Set-aside requirements, as well as milk and sugar beet quotas fall in this categories. Mandatory and voluntary set-asides are accounted for, each type of set-aside being treated as a producing activity associated with the corresponding payments. The different types of sugar beet quotas (A, B, and C) are also included. The modelling of some CAP policy instruments included in the model involves the use of binary or integer variables, whenever producers have to face mutually exclusive discrete choices. For instance, set-aside is mandatory only above a certain farm size, and involves specific payments if farmers opt in the program. Integer variables are used to reflect the binary nature of farmers' choice to this respect. This is also the case for some specific support instruments (inclusion of fodder maize in arable crop payments, extensification payments).

The computation of the parameters defining $\mathbf{A}_k$, $\mathbf{z}_k$ and $\mathbf{g}_k$, and the baseline levels of producing activities ($\mathbf{x}_k^0$) proceeds in three major steps: (i) selection, typology, and grouping of sample farms into farm types, (ii) estimation of the parameters, and (iii) calibration. The primary source of data is the Farm Accounting Data Network (FADN). The 1997 FADN provides accounting data (revenues, variable costs, prices, yields, crop area, animal numbers, support received, type of farming) for a sample of slightly less than 60,000 surveyed farmers. Approximately 50,000 sample farms are included in the model, which represent a total of more than 2.5 millions of European (full-time) farmers. Data is available at a regional[5] level (101 regions in the EU-15). Because of the annual nature of the model, sample farms defined as *Specialist horticulture* and *Specialist permanent crops* are excluded (types of farming 2 and 3 in the FADN classification). The analysis is thus restricted to the remaining population of the farmers, representing annual crop and livestock farmers. This restriction is important to keep in mind when analysing the results, as the excluded farms may represent a significant share of total agricultural area and fertiliser use in some regions.

The selected sample farms are then grouped into "farm types" (or "farm-groups") according to three main variables: (i) region (101 regions in the EU-15); (ii) average elevation (3 elevation classes: 0–300, 300–600, and above 600 m); and (iii) main type of farming (14 types of farming in the FADN classification). The typology results from the following trade-off. On one hand, the number of *sample farms* grouped in any farm type has to be large enough to comply with confidentiality restrictions (at least 15 sample farms for each farm type) and to ensure the robustness of the estimations. On the other hand, the total number of *farm types* has to be as large as possible to reduce the aggregation bias at the regional level. Each farm type thus results from aggregation of sample farms that are located in the same region, are characterized by similar type(s) of farming and belong to the same elevation class(es).[6] Following this procedure, 734 farm types are thus obtained as a combination of the 101 regions, 14 FADN types of farming, and 3 elevation classes. Each farm type is associated with a specific supply model defined by (1.1)–(1.3).

The farm-type approach is important in several respects. First, it captures the diversity of farming systems at the infra-regional level better than do models that rely on regional aggregates. Farm-type results can still be aggregated to the regional level, but the region itself is not modelled as one single "big" farm. Consequently, it is less subject to aggregation bias (e.g. see

p. 7 in Perez 2003, or p. 15 in European Commission 2002). Second, the farm-type approach better reflects the existence of a fairly diversified agriculture, as mixed farming systems are explicitly modelled.

Each individual farm in the FADN sample is associated with a weight indicating its representativity in the regional population. The individual weights of sample farms that are grouped into farm type k are aggregated (v_k) and used to extrapolate the results at the regional level.

Parameters and baseline levels of variables that are systematically estimated using FADN data include: variable costs and output prices, area and area shares for each crop, animal numbers, and support received. The estimation procedure is conducted at the farm-type level and uses the extrapolation factors provided by the FADN. As for variable costs, the model distinguishes between two categories of costs: "fertiliser use" and "other inputs" (seeds, fuel consumption, pesticides, etc.). Because of the accountancy nature of the FADN data, only total expenditure is available. Variable costs for each crop are therefore inferred from linear covariance analysis, using crops area and including a specific additive farm-type effect.

Alternative sources of information are also used whenever relevant data is lacking in FADN. An important alternative source of information is Intergovernmental Panel on Climate Change (2001b), from which emission factors are taken. Likewise, characteristics of feeding products and animal feeding requirements are obtained from technical workbooks (Jarrige 1988). At last expert knowledge is used, when no other statistical or technical source is available. This is the case for the types of fertiliser used (see Section 2.2) for each crop and each country or region and some feeding parameters.

The last step consists in the calibration of a subset of the parameters. The calibration is used to capture the variability of farm-type parameters, for which information is lacking or is insufficiently reliable. The subset of calibrating parameters includes: some of the parameters defining animal feeding requirements, life span of certain cattle categories, grassland yields, and maximal crop area shares. During the calibration phase, initial values of these parameters are re-computed in order to minimize the distance between the observation data for each farm type k, $\mathbf{x}_k^0$, and the optimal solution $\mathbf{x}_k^*$ subject to the constraint that these parameters vary in a bounded feasible range (see De Cara and Jayet 2000 for a short mathematical presentation of the calibration program). The numerical resolution of the minimization program is iterative and relies on a combination of Monte-Carlo and gradient methods.[7]

2.2. 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, fertiliser 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. Each country has to conduct quality and uncertainty assessment and to ensure time consistency of the reported inventories from 1990 on. In addition, national inventories are reviewed by a panel of international experts.[8] The common reporting framework provided by the IPCC thus emphasizes completeness and consistency, and therefore eases country-comparisons of emission inventories.

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; CH_4 emissions from rice cultivation.[9] N_2O emission from agricultural soils can be further disaggregated according to nitrogen inputs to soils: *use of synthetic fertilisers*, *manure application*, *biological nitrogen fixation*, and *crop residues*.

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 ($l=1,...,L$) sources of emissions. Let $\mathbf{f}_{k,l}=(f_{k,l,1},...,f_{k,l,n})$ be the row n-vector of emission factors for source l and farm type k. The jth entry of $\mathbf{f}_{k,l}$ is thus the emission factor associated with producing activity j. Emissions for source l and farm type k are thus defined as the inner product of $\mathbf{f}_{k,l}$ and $\mathbf{x}_k$, the column vector of producing activities. Summing emissions over emission sources ($l=1,...,L$) thus yields total emissions (e_k) for farm type k:

$$e_k = \sum_{l=1}^{L} \mathbf{f}_{k,l} \cdot \mathbf{x}_k \tag{2}$$

The interested reader is referred to Intergovernmental panel on Climate Change (2001b) for a detailed description of the components of $\mathbf{f}_{k,l}$ and of the relevant producing activities.

Each emission source is linked to the levels of the relevant endogenous variables in the model (see Table I). Country-specific emission factors are used whenever available in the 2003 national communications to the UNFCCC.[10] Otherwise, the IPCC default values are used.

A total of 11 emission sources are computed within the model and are listed in Table I. Emissions of nitrous oxide are divided into eight sub-sources: direct agricultural soil emissions (4), indirect agricultural soil emissions (2), emissions from grazing animals (1) and manure management (1). Emissions of methane are disaggregated into three sub-sources: manure

Table I. Summary of GHG emission sources accounted for in the model

Emission sources	Activity data	Linked to
N_2O agricultural soils		
Direct emissions		
Use of synthetic fertilisers	N fertiliser application	Crop area
Manure application	N excretion by animals	Animal numbers
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 numbers
Indirect emissions		
Atmospheric deposition	Total N application	Crop area and animal numbers
Leaching and run-off	Total N application	Crop area and animal numbers
N_2O manure management	Animal numbers	Animal numbers
CH_4 manure management[a]	Feed energy intake	Animal feeding and animal numbers
CH_4 enteric fermentation[a]	Feed energy intake	Animal feeding and animal numbers
CH_4 rice cultivation	Rice area	Rice area

[a]Further disaggregated into: dairy cattle, non-dairy cattle, sheep, goats, swine, and poultry.

management, enteric fermentation, and rice cultivation. The first two sub-sources are further disaggregated into six animal categories. This level of disaggregation facilitates 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 (Intergovernmental panel on Climate Change 2001a).

N_2O emissions from agricultural soils depend upon total nitrogen inputs. In the model, quantities of nitrogen applied to soils are driven by the optimal crop area mix. For each farm type k, per-hectare fertiliser expenditures for each crop are estimated from the FADN. For each crop and each country, two fertilisers are chosen among the commercial fertilisers listed in FAOSTAT and Eurostat databases. These databases cover the most commonly used fertilisers in each country. In addition, a mass ratio between the two fertiliser types is computed based on the current standard agricultural practices for each crop. Prices and nitrogen content of the two fertiliser types are taken from the FAOSTAT and Eurostat databases (year 1997). They are weighted according to the mass ratio to derive a representative composite fertiliser and to compute the per-hectare nitrogen amount applied to each crop and for each farm type. It is important to note that this approach relies on constant per-hectare nitrogen inputs for each crop and each farm type.

Nitrogen inputs and crop yields are indeed exogenous and kept constant in the subsequent simulations.[11] The implications of this assumption for abatement cost estimates are discussed in Section 3.3. Emission factors, as well as volatilization and leaching parameters are taken from each Member State's national communication to the UNFCCC. As for biological fixation and nitrogen in crop residues, the values of relevant parameters – such as nitrogen content, crop/residue ratio, and dry matter fraction – are also taken from the national communications or the IPCC defaults, depending on availability.

Methane emissions from both enteric fermentation and manure management depend on the energy content of feed intake for each animal category. In the simplest form of methane inventories, the Intergovernmental Panel on Climate Change (2001b) recommends to use average energy requirements for each animal category to derive methane emissions. In short, this implies a constant energy intake for any given animal category, and therefore constant emission factors on a per-head basis. In this case, animal numbers are the only driver of methane emissions. The approach retained in this paper is more general and more flexible. In the model, animal feeding is endogenous. The total energy intake by each animal category can thus be derived from the optimal quantity and composition of feed. Emissions are therefore computed by using the (animal-category dependent) share of total energy intake by animal category lost as methane. As a result, methane emissions are driven, not only by animal numbers, but also by the composition of animal feeding.

Manure can be either applied to crops, deposited directly on soils by grazing animals, or stored/treated using different management systems. The total production of manure-related nitrogen is computed as the product of nitrogen content of manure – defined for each animal category – and the corresponding animal numbers. Nitrogen excretion average rates for each animal category are taken from the national communications, or the IPCC defaults. Because of the lack of available data at regional or farm-type level, the shares of manure applied to crops, deposited on grassland, and handled under all management systems are also taken from the national communications, which only provide information at the country level. The country-average share is applied to each farm type.

2.3. IPCC EMISSION ACCOUNTING METHOD: DISCUSSION

The "Agriculture" category in the IPCC classification only includes emissions emitted *within* the agricultural sector. For instance, emissions caused by the production of inputs and capital goods and the transport of food and feed products are not accounted for. Nor does it include emissions related to the use of fossil fuel in agricultural production. The latter are indeed accounted for in the IPCC energy use category, and represent a relatively minor agricultural source compared to CH_4 or N_2O emissions (Bates 2001). Furthermore, 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.

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 abatement. 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 (Lal and Bruce 1999; Schlesinger 2000). In fact, accounting for carbon sequestration raises issues mainly because of the short-run and non-permanent nature of abatement 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 management 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, carbon sequestration from agricultural activities is thus not taken into account. 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 accountancy. For instance, emission estimates can be derived from biophysical models such as EPIC (McCarl and Schneider 2001) or DNDC. Alternatively, emission factors can rely on more detailed regional-specific relationships (Freibauer 2003). Arguably, these alternative accounting approaches may provide more accurate emission estimates. In fact, Freibauer (2003) questions the capability of the IPCC approach to fit specific agricultural conditions of production that prevail in a given region because of the use of 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.

Providing consistent and comparable GHG inventories methods for a large number of countries necessarily requires a simplified representation of complex biological processes. Nevertheless, 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, one can use the national communications as consistent, comprehensive and 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 the international agreements. The fact that this methodology provides the closest match to "Kyoto-compliant" emissions is the main reason motivating the choice made in the present paper.

3. Results: Marginal Abatement Costs and EU Abatement Supply

3.1. BASELINE GHG EMISSIONS FROM AGRICULTURE IN THE EU

Two preliminary scenarios are run: (i) the "Calibration year scenario" (hereafter referred to as CY-1997) corresponds to the Common Agricultural Policy as of 1997 (calibration year), and (ii) the "Reference year scenario" (RY-2001) includes changes in CAP that prevailed in 2001. RY-2001 notably includes the changes in intervention prices, per-hectare support to grains and oilseeds, as well as the changes in milk quotas and livestock subsidies that occurred between 1997 and 2001. Both scenarios are based on the same initial dataset otherwise, which is calibrated on 1997 data. In other words, the structure (number of farms, total available area, etc.) is kept constant in the two scenarios and set at 1997 values. Hence, the differences in emissions between CY-1997 and RY-2001 only arise from the aforementioned changes in the CAP parameters.

Figure 1a compares emissions reported to the UNFCCC by each of the fifteen Member States and the results of the model for the calibration year (CY-1997). Emission inventories are not available at a lower-than-country resolution in the national communications. Model results have thus been aggregated on a country-basis for comparison purposes. For each Member State, the first bar represents the emissions as reported in the 2003 communication for the year 1997. The next bar gives the country CY-1997 emission estimate.

The model covers approximately 86% of total EU-15 1997 emissions from agriculture. This partly reflects the representativity of FADN.[12] 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 74% of the remaining emissions, which represent about 17% of 1997 total emissions. Figure 1b compares observed rates of change in emissions that occurred between 1997 and 2001 with simulated rates of change (CY-1997 versus RY-2001) for all emission sources and country-aggregated emissions. The observed relative changes are well reproduced by the model (see Figure 1b).

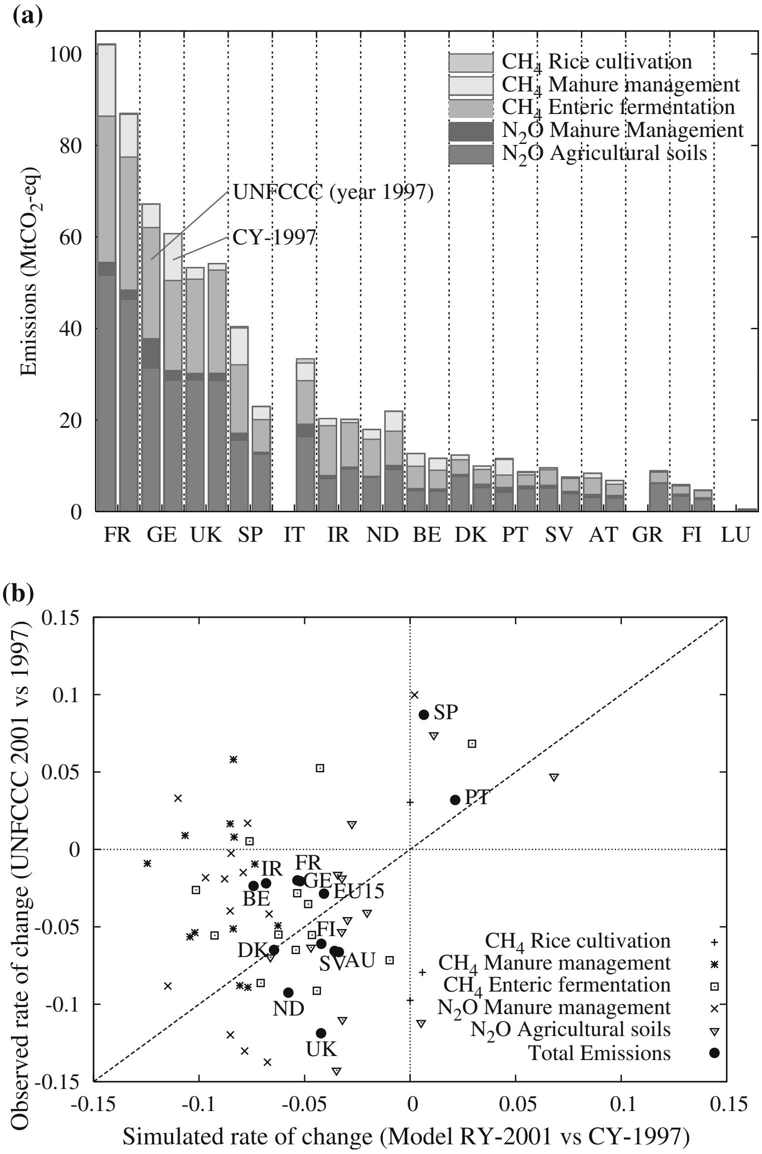

Figure 1. UNFCCC emissions versus model results.

Yet the performances of the model vary from one country to another. Generally speaking, emissions are slightly under-estimated mainly because of N_2O and CH_4 manure-related emissions. For some countries however – such as the UK or the Netherlands – baseline emissions are slightly over-estimated. These differences can be explained by differences in the representativity of FADN samples across Member States. They may also arise from different choices in the implementation of the IPCC methodology.[13]

3.2. ABATEMENT SUPPLY AND MARGINAL ABATEMENT COST CURVES

An emission tax t is then introduced in the model. It affects directly each farmer's revenue according to the total amount of CO_2-equivalent emissions. The objective function of the maximization program includes the total tax amount paid by each farmer ($t.e_k$). The simulations presented hereafter are otherwise based on RY-2001 scenario.

By construction for a given emission tax t, optimal emissions (e_k^*) 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, one thus obtains 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.

Consistently with the economic intuition, the total abatement supply is increasing with respect to the emission tax. Indeed, as a standard result of linear programming, the objective function response to an increase in any input price (here the emission tax) is piecewise linear, decreasing, and quasi-concave. Likewise, the response of each farm type's total emissions (abatement) is stepwise decreasing (increasing). In addition, the aggregate abatement supply shows a slightly concave general shape,[14] thus implying convex marginal abatement costs.

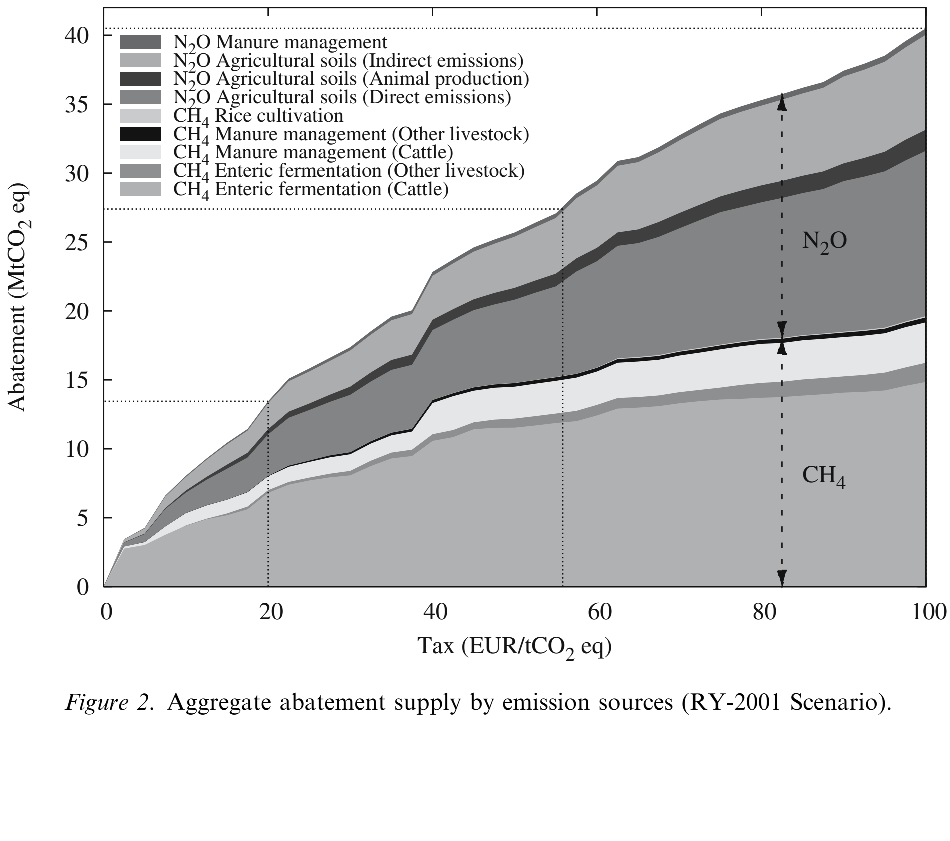

Figure 2. Aggregate abatement supply by emission sources (RY-2001 Scenario).

In its assessment of EU emission reduction potential, the European Climate Change Programme (2003) focuses on mitigation strategies that entail abatement costs not larger than 20 EUR/tCO_2eq. At this price, our results indicate that EU farmers reduce their GHG emissions by 3.9% on average compared to 2001 levels. An abatement target of 27.5 MtCO_2 implies a marginal abatement cost slightly higher than 55 EUR. This target represents 8% of RY-2001 emissions as computed by the model. The upper limit of the simulation range (100 EUR) is associated with an aggregate abatement of 40.5 MtCO_2eq (a 11.8%-reduction as compared to RY-2001 emissions).

Figure 2 also shows how the optimal "abatement mix" – i.e. the relative importance of the various emission sources in total abatement – changes with the emission tax. This gives an interesting indication of the relative abatement costs associated to each source. Remember that the tax affects *all* sources based on respective CO_2-equivalent potential. Whereas enteric fermentation is responsible for 34% of RY-2001 emissions, this source represents most of the abatement for the lower values of the emission tax. This signals lower abatement costs for enteric fermentation relatively to the other emission sources. Comparatively, N_2O emissions from agricultural soils (52% of RY-2001 emissions) are underrepresented in total abatement for the lower tax levels. Abatements of methane emissions are primarily obtained through changes in animal feeding for the lower values of t. However, as the tax increases and substitutions in animal feeding are exhausted, the share of "N_2O-agricultural soils" in total abatement tends to increase and reach 50.4% for a 100 EUR/tCO_2eq emission tax.

By the same token, abatements in manure management emissions (both N_2O and CH_4) are also found to be more costly as their share in total abatement stays below their share in total emissions for the whole explored t range. Indeed, the main means of abating emissions from this source lies in improving 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 in the model for farmers to reduce methane emissions from manure management is to reduce animal numbers, which results in higher abatement costs.[15] The relative rigidity of emissions from each source is hence a crucial feature in the magnitude of estimated abatement costs.

Figure 3 shows the evolution of agricultural emissions from 1990 through 2001 as reported in the 2003 EU communication to the UNFCCC (left axis). Two important messages are conveyed by Figure 3. First, agricultural emissions were 7.4% lower in 2001 than in 1990.[16] According to the Kyoto commitment, 2008-12 total European emissions have to be 8% lower than in 1990. Consequently, only little abatement is needed if this 8% abatement target is implemented as such in the agricultural sector. Second, Figure 3 shows that the abatement rates examined above (−3.9%, −8% and −11.8%

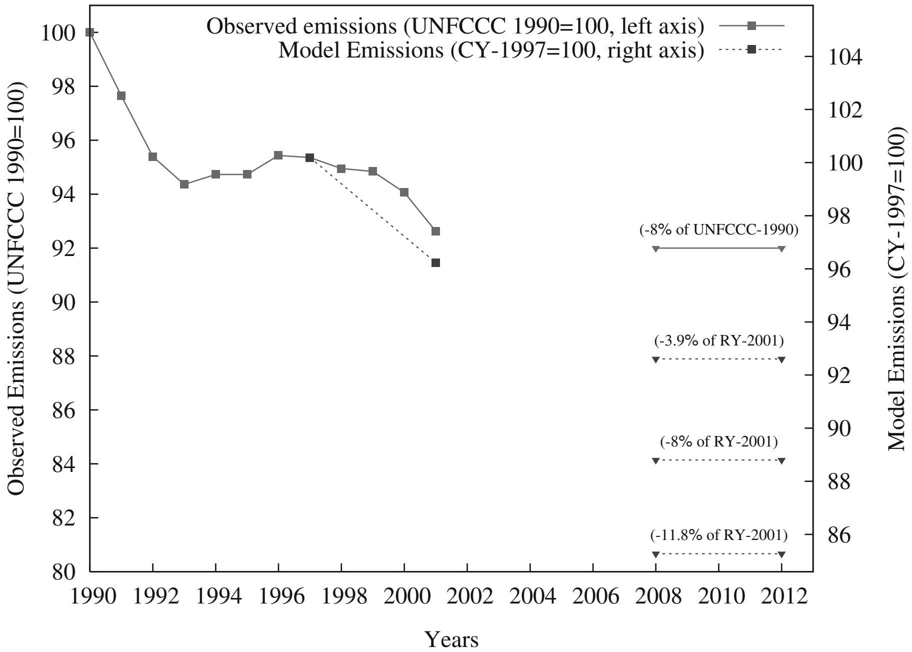

Figure 3. Evolution of agricultural emissions since 1990 and mitigation effort implied by various abatement rates.

of RY-2001 emissions) represent a significantly larger mitigation effort than what is required from the EU economy as a whole.

3.3. THE NATURE OF MARGINAL ABATEMENT COSTS: DISCUSSION

At this stage, it is important to discuss the very nature of the marginal abatement cost estimates presented in the previous section. First, results presented in Figure 2 do not include market and trade effects. As the present study focuses on the *technically feasible* changes in land allocation, animal feeding, etc., these abatement cost estimates are to be understood as supply-side response curves at the farm-type level. As such, they pertain to a given structure of agricultural prices. The price-taker assumption makes sense at the farm-type level. Yet, if an EU-wide mitigation policy were to be implemented, one may rightfully wonder what would be the impact on prices and trade, and, in turn, how abatement costs would be affected. For instance, an increase in livestock prices – resulting from declining livestock supply – would tend to increase marginal abatement costs. But, rising feed costs would play in the opposite direction. Should equilibrium prices change as a result of the implementation of a EU-mitigation policy in agriculture, the impact on marginal abatement costs would remain unclear. Besides, the simplifying assumption, whereby input and output prices are kept constant, is partially supported by the existence of CAP instruments. Intervention prices, export subsidies, set-aside and quotas tend to insulate EU agricultural markets and mitigate (at least some of) the impact on prices.

A second important feature of these abatement cost estimates lies in the assumption concerning abatement technologies. The abatements reflected in Figure 2 are *not* obtained through the adoption of new abatement technologies (such as the use of additives in animal feeding, or new investments in manure management facilities for instance). Rather they pertain to the impact of changes in the crop mix at farm-type level, in livestock numbers, and in the way animals are fed (e.g. balance between forage and concentrates). In short, examined abatements solely result from changes in the optimal production level, not from changes in the production or emission functions. Another related example is the absence of crop-yield response to nitrogen in the model (see Section 2.2). Estimated abatements stem from changes in the optimal crop mix, not from changes in nitrogen input intensity. This tends to increase the cost at which a given abatement target is achieved.

In addition, remember that the modelled set of abatement options is limited. 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. At last, the abatement cost estimates inherit the short/medium run nature from the model. Structural drivers – such as the number of farms, total land area, and CAP instruments – are kept constant here and may impact significantly abatement costs in the longer run.

These caveats have to be kept in mind when comparing these estimates of abatement costs with carbon prices published in the literature for other sectors (see for instance Viguier et al. 2003). Several of the above-mentioned assumptions appear rather conservative and tend to increase the abatement cost estimates. As an illustration, Perez and Britz (2003), using the CAPRI modelling system, find marginal abatement costs averaging 53.5 EUR/tCO_2eq for a EU-wide 10%-reduction of agricultural emissions (2009 emissions compared to 1990, regional quotas) without emission trading. In their study, Member States' marginal abatement costs range from 35 to 125 EUR/tCO_2. If marginal abatement costs are equalized (i.e. emission trading is allowed), the market-clearing carbon price is found to be approximately 43 EUR/tCO_2eq.

4. Marginal Abatement Cost Heterogeneity

4.1. REGIONAL DISTRIBUTION OF ABATEMENT COSTS

The next step consists in assessing the spatial distribution of abatement costs. For a given emission tax, marginal abatement costs are equal across farmers according to economic theory. The heterogeneity of marginal abatement cost curves implies that abatement might 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 3, this emission tax leads to a 8%-reduction in total agricultural emissions as compared to RY-2001 emissions. Abatements were then aggregated for each of the 101 FADN regions. Figure 4 shows the abatement rate (relative to RY-2001 emissions) for each FADN region in the EU-15. Regional abatement rate for region r ($\tau_r(t)$) is thus computed as follows (v_k is the number of "real" farms represented by farm type k):

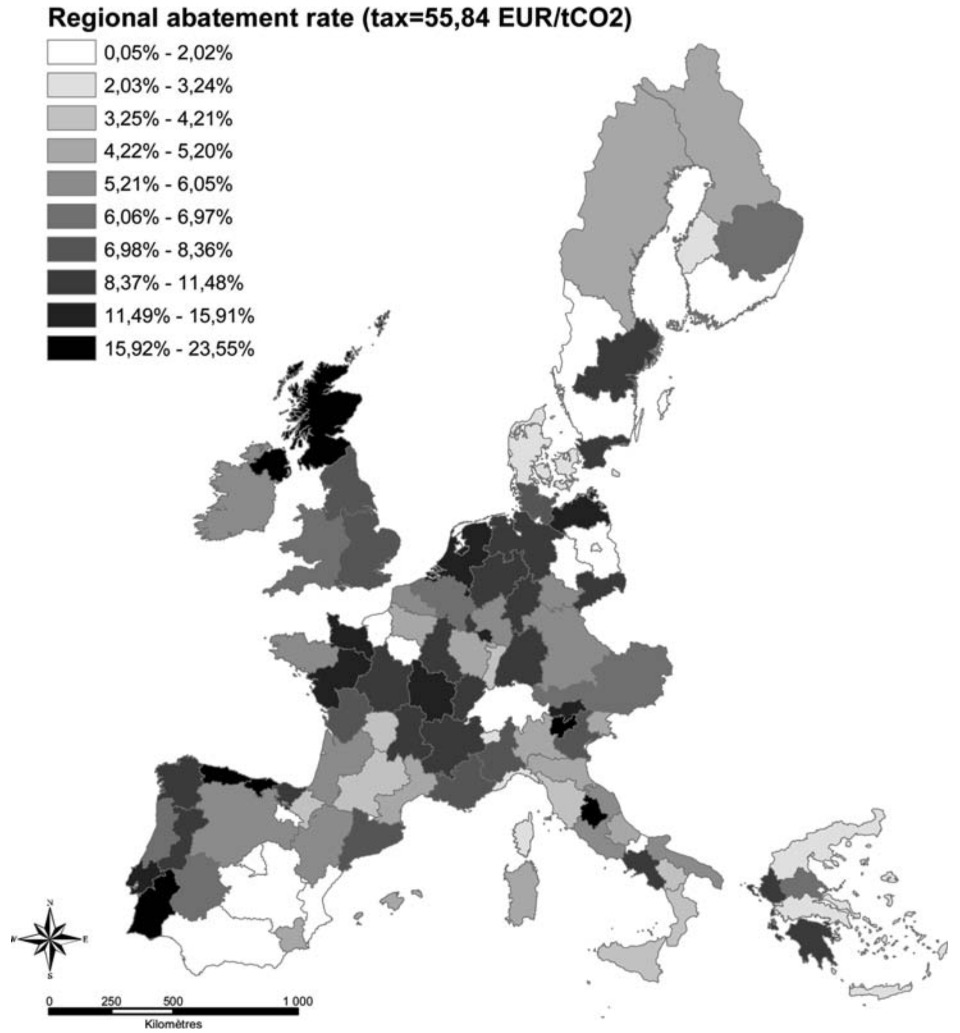

Figure 4. Spatial heterogeneity of regional abatement rates (RY-2001 scenario, $t = 55.84$ EUR/tCO_2eq, EU abatement rate is 8% compared to RY-2001). *Source of the digital map of the FADN regions: European Commission, DG AGRI.*

$$\tau_r(t) = 1 - \frac{\sum_{k \in r} v_k \cdot e_k^*(t)}{\sum_{k \in r} v_k \cdot e_k^*(0)} \quad r = 1, \ldots, 101 \tag{3}$$

The map shown in Figure 4 indicates a large variability in regional abatement rates, which range from almost 0% to 24%. Darker shades on the map signal regions where abatement rate is higher. Abatement costs in these regions are thus lower, insofar as farmers can cut baseline emissions by a higher percentage at a given marginal cost $t = 55.8$ EUR/tCO_2.[17]

Obviously, the information provided by Figure 4 is not sufficient to assess the regional distribution of *total* abatement. The distribution of baseline emissions (E_R*(0)) among regions also matters to that respect. This additional information is shown in Figure 5.

Regional abatement rates – aggregated as described in equation (3) – are sorted with respect to increasing $\tau_r(55.8)$ (x axis in Figure 5). Regions with higher abatement rates are thus located to the right of the chart. Regional abatement rates are then plotted against the cumulative baseline emissions (RY-2001) for each of the 101 FADN regions considered in the analysis.

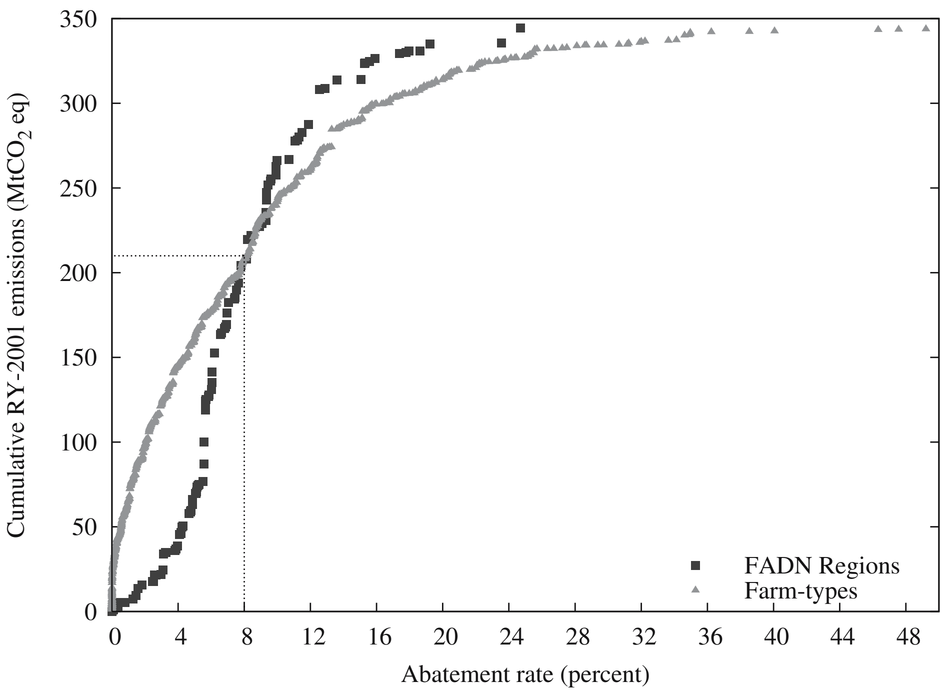

Figure 5. Distribution of regional (squares) and farm-type (triangles) abatement rates, $t = 55.84$ EUR/tCO_2eq (at this price, EU-15 abatement totals 8% of RY-2001 emissions).

Regional emissions for each abatement rate depicted in Figure 4 can therefore be derived from Figure 5 (squares). For instance, the regions with the lowest abatement rates ($\tau_r(55.8)$ ranging from 0% to 5%) represent approximately 70 $MtCO_2eq$. On the other end of the cumulative curve, another 70 $MtCO_2eq$ corresponds to abatement rates higher than 11%. Abatement rates ranging between 5% and 11% – centered around the 8% EU average reduction – concern the remaining emissions, or 205 $MtCO_2eq$.

4.2. 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.[18] The distribution of abatement rates at the farm-type level is also analysed. 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 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, infra-regional variability matters the most for the lowest abatement rates. Farm type with very low abatement rates ($< 1\%$) represents about 20% of RY-2001 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.

As the emission tax and total abatement increase, the distribution of abatement rates among the 734 farm types changes. Figure 6 shows the changes in the distribution of the individual abatement rates ($\tau_k(t)$, for $t = 20$, 55.8, and 100 EUR/tCO_2eq). These levels of emission tax correspond to EU abatement rates of approximately 3.9%, 8% and 11.8%, respectively. As expected, 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 increase in t also leads to a change in the distribution of farm types' abatement rates around the EU average reduction. For an emission tax of 20 EUR/tCO_2eq, farmers who reduce their emissions by less than the EU average abatement (3.9%) represent approximately 227 $MtCO_2eq$ in RY-2001 emissions. This number drops to 207 $MtCO_2eq$ for $t = 55.8$ EUR/tCO_2eq (8% average abatement), and to 201 $MtCO_2eq$ for $t = 100$ EUR/tCO_2eq (11.8% average abatement). This suggests a shift in the concentration of abatement efforts toward farmers with the highest baseline emissions.

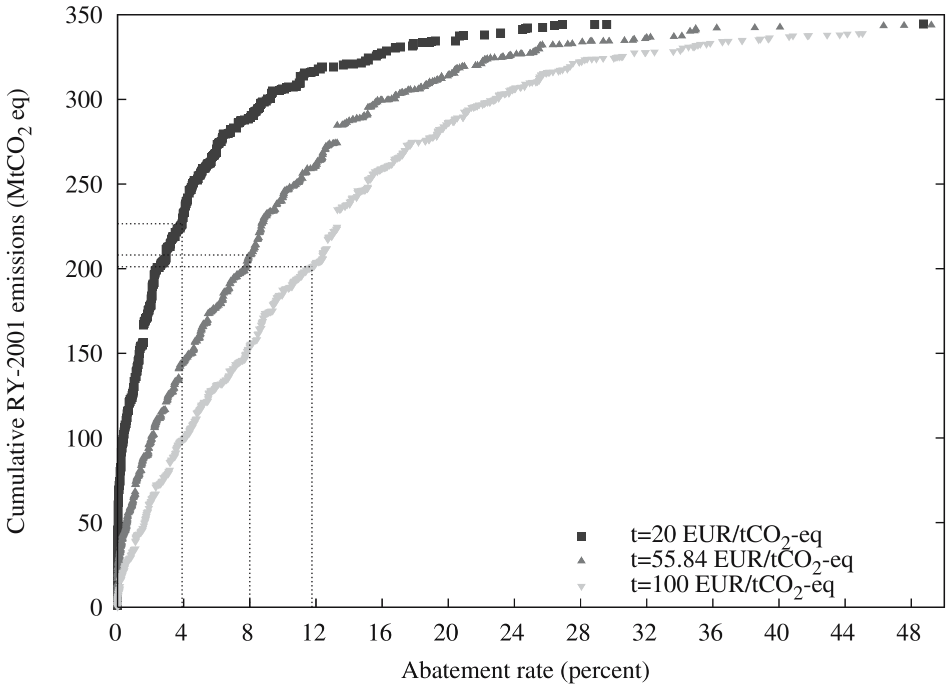

Figure 6. Distribution of farm-type abatement rates for three emission taxes (RY-2001 scenario).

4.3. ABATEMENT COST HETEROGENEITY AND THE POTENTIAL SAVINGS OF INCENTIVE-BASED INSTRUMENTS VERSUS UNIFORM STANDARDS

In the previous section, the emission tax was essentially used as a means of estimating the individual and regional marginal abatement curves. We now address the issue of implementing a mitigation policy in agriculture.

Two characteristics of the IPCC-based emission tax are important if it is foreseen to be used as a mitigation policy instrument. First, as discussed in Section 2.3, the IPCC accounting methodology does not rely on direct observation of emissions. It thus provides only an approximation of the true emission levels: IPCC emission factors are obtained as averages over a broad range of situations and do not necessarily reflect accurately emissions under specific conditions. In this sense, an IPCC-based emission tax differs from a first-best emission tax. Second, the computation of the tax paid by each farmer requires that the regulatory body can easily control the relevant activity data. Most of the needed information – such as area, animal numbers, purchased animal feeding – is already collected for CAP-support related purposes. However, some important emission-driving activities, such as on-farm consumption of animal feeding or manure application, are more costly to control.

Keeping these two caveats in mind, an IPCC-based emission tax – or, equivalently, a tradable emission permit scheme – would lead to an optimal allocation of abatement among farmers. Figures 2 and 4 would then give an appropriate picture of the impacts of an IPCC-based emission tax on the EU-15 agricultural supply.

However, as noticed by Newell and Stavins (2003), conventional standards are often preferred over market-based instruments by policymakers for various policy reasons. The European agricultural policy provides many examples of such command-and-control instruments. As an illustration, the CAP uses a flat set-aside rate as one of its major market regulation instruments. The potential savings permitted by market-based instruments relative to conventional standards are thus worth being assessed.

What happens to abatement costs if *each* farmer has to meet a given reduction target of, say, γ percent of the farm's baseline emissions? Based on textbook environmental economics, the answer is straightforward. If γ is equal among all farmers and as soon as farmers are not identical, total costs would be higher because equalization of individual marginal abatement costs cannot be achieved. The question then becomes: how much more expensive are abatements in this case? To answer this question, a new constraint is introduced in each individual farm-type model (see also De Cara and Jayet 2000 and Perez et al. 2003). In this constraint, γ is the uniform emission standard at farm-type level, and $e_k^*(0)$ is the optimal level of RY-2001 emissions for the kth farm type (2001, no emission tax):

$$e_k \leq (1-\gamma)\cdot e_k^*(0) \quad [\lambda_k(\gamma)] \tag{4}$$

Taken at the optimum, the shadow price $(\lambda_k^*(\gamma))$ associated with constraint (4) reflects the farmer's k marginal cost of cutting emissions by γ percent. In other words, $\lambda_k^*(\gamma)$ is the marginal value of the emission restriction, and can be interpreted as a quota rent. As the constraint should be binding at the optimum, $\lambda_k^*(\gamma)$ is strictly positive (Kuhn and Tucker slackness condition). As discussed in the previous section, marginal abatement cost curves have been found to vary widely at the farm-type level. A fairly large distortion in abatement costs allocation is therefore to be expected if γ is constant across farmers. Furthermore, for a given farm type k and a given value of the tax $\bar{t}$, it is always possible to compute γ_k – the subscript k is important here – such that $\lambda_k^*(\gamma_k)$ in the constrained program is equal to $\bar{t}$. In this case, it just provides another perspective on the computations presented in Section 3, as it provides the exact equivalent of farm type k's program (1.1)–(1.3), but on the dual side.

Individual marginal abatement costs are computed for three uniform abatement rates ($\gamma = 4\%$, 8%, and 12%) as the optimal shadow prices $(\lambda_k^*(\gamma))$ associated to the emission constraint (4). The average marginal abatement cost is weighted by the share of each farm type's emissions in total base emissions $E^*(0)$:

$$\bar{\lambda}(\gamma) = \frac{1}{E^*(0)} \sum_{k=1}^{734} v_k . e_k^*(0) . \lambda_k^*(\gamma) \tag{5}$$

As the imposed abatement rate γ is the same for all k and constraint (4) is binding for all k, the total EU abatement rate is also equal to γ. To meet a 4% reduction target, marginal abatement costs are on average 3.6 times higher under a uniform standard regime than under an IPCC-based emission tax regime for the same total abatement (see Table II). 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 4.2. The cost savings permitted by market-based instruments relative to uniform relative quotas can also be measured in terms of total abatement achieved at a given carbon price. Figure 2 indicates that a 73.6 EUR/tCO_2 emission tax results in a 10% abatement, more than twice as much as under a uniform standard regime.

5. 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: the *magnitude* of abatement costs in the agricultural sector and their *heterogeneity*.

On the first aspect, the range of abatements from agriculture for plausible carbon prices is found to be substantial. Despite rather conservative assumptions – such as the fixed number of farms, fixed total area, fixed crop-yield response to nitrogen, no adoption of specific abatement technology – an additional potential abatement of about 4% of 2001 agricultural emissions is obtained at a marginal cost of 20 EUR/tCO_2eq. As 2001 agricultural emissions were already 7.4% lower than in 1990, this additional abatement rep-

Table II. Comparison of marginal abatement costs under emission tax and uniform standard regimes

Abatement target γ (%)	Total abatement (MtCO_2eq)	Marginal abatement cost		Cost-saving ratio $\bar{\lambda}(\gamma)/t(\gamma)$
		Emission tax t (EUR/tCO_2)	Uniform quotas $\bar{\lambda}(\gamma)$ (EUR/tCO_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

resents a significant effort when compared to the Kyoto reference year. The downward trend observed in agricultural emissions in the last decade – possibly strengthened by the recent CAP reform – may provide efficient alternatives to emission reductions in sectors where abatement is more costly. A recent report by the European Environmental Agency (2004) projects a total EU abatement falling short by 0.8% of the Kyoto target in 2010 even in the best-case scenario of full implementation of policies and measures. This represents approximately a 34 $MtCO_2$ gap. The magnitude of abatement costs found in this paper indicates that agriculture could play a key role in bridging such a gap. The contribution of agriculture to the EU fulfilment of the Kyoto target is thus likely to be higher (in relative terms) than that of the rest of the economy. Incentives to further reductions in GHG emissions from agriculture would contribute to lower the overall costs of meeting this target. At the same time, this would fit the evolution of the CAP, whereby environmental concerns are increasingly emphasised.

As the Kyoto Protocol is now enforced, it is indeed important to consider mitigation policies that are both efficient and operational. In the design of economic instruments, one faces an important trade-off between accuracy and observability. To this respect, IPCC-based economic instruments, which are analysed in this paper, provide 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, the IPCC framework is recognized as an international reference and is based on data that is relatively easy to collect.

Abatement costs heterogeneity comes from a variety of sources. The farm-type approach captures some of these sources of heterogeneity in the results, such as those related to farms' size, crop yields and area allocation, total animal numbers, input use, and CAP support. Some are only captured at the country-level (e.g. IPCC emission factors). And, due to the lack of data, some of the sources of heterogeneity have been ignored (e.g. spatially disaggregated emission factors). Nevertheless, the results indicate a wide variability of abatement costs. This has two broad implications for policy purposes. First, the impacts of incentive-based instruments on income and environmental performances vary widely from one farmer to another. Second, the cost savings permitted by market-based instruments relatively to uniform standards are large. This means that, if mitigation policies are to make use of quantity-based instruments, substantial savings can be drawn from tradable (or at least differentiated) emission allowances. Clearly, this also means that such policies will have to go beyond uniform or region-specific standards commonly used in agricultural policies (e.g. set-aside rate or regionally differentiated reference yields). At last, this underlines the importance of the inclusion of agriculture in the European Emission Trading Scheme.

Further research is needed in order to relax some of the modelling 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 agriculture is essential for future research, as it would provide farmers with alternative ways of reducing their *net* emissions.

Acknowledgements

The authors would like to thank the participants of the 48th Australian Agricultural and Resource Economics Society Annual Conference (AARES, Melbourne, 11–13 February 2004) and two anonymous referees for very helpful comments. Thanks are also owed to Laure Bamière, Elodie Debove, Caroline Godard, Estelle Gozlan, Ariane Labat, and Uwe Schneider for their careful reading of the paper and helpful discussions.

This study was partly funded by the French Ministry of the Environment under the program *Gestion et Impacts des Changements Climatiques* (APR2001-1/01). Funding from the European Commission, DG Agriculture (AGRI/A-3/2000/003 and AGRI/G-3/2002/001) to develop the European model is also gratefully acknowledged.

Notes

1. The impacts of climate change on agriculture will not necessarily be negative for all production activities. The change in average temperatures may actually have both positive and negative impacts on yields. One has to account also 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 agriculture as reported by the EU in its 2003 communication to the UNFCCC (available at http://unfccc.int/program/mis/ghg/submis2003.html) and converted into CO_2 using the 2001 Global Warming Potentials (Intergovernmental Panel on Climate Change 2001a). Agriculture is also responsible for CO_2 emissions from fossil fuel use, but the contribution to sector total emissions is far smaller than that of methane and nitrous oxide (Bate 2001). They are thus not taken into account in the present paper. Neither are carbon offsets from agriculture (see Section 2.3).
3. The fact that the potential savings permitted by market-based instruments depend on the distribution of abatement costs makes economic sense. It is clear that in a (hypothetical) static setting whereby all agents are homogeneous with respect to abatement costs, market-based instruments (tax or tradable permits) do not perform better than uniform standards. The distortion in abatement allocation under a uniform standard increases as the heterogeneity of abatement costs increases.
4. Therefore the magnitude of the adjustment factor retained in the subsequent simulations may matter for some farm types, and not for others. Sensitivity analyses with respect to this adjustment factor indicate that, although some farm types' results might be sensitive

to a change in this value, it does not impact significantly the nature of the aggregated results presented in Section 3. Lower adjustment factors tend to shift methane abatement supply curves (see Figure 2) to the right. In the calibration phase, the adjustment factor is set to zero, that is livestock-related capital is fixed at initial endowment of farm type k.

5. The FADN regions are represented in Figure 4. The FADN region definition differs from the NUTS definition. The interested reader is referred to Figure 6 in Perez et al. for a comparison of the levels of spatial disaggregation between FADN and NUTS II. For more information on the FADN dataset, the reader is referred to http://www.europa.eu.int/agriculture/rica/.
6. Farm types may actually encompass more than one FADN type of farming and/or more than one elevation class depending on the number of sample farms and on their heterogeneity in a given region. Likewise, the grouping of sample farms may differ from one region to another: e.g. sample farms labelled in FADN as "Specialist crops" may be aggregated with "Mixed cropping systems" in one region and modelled separately in another, again depending on the number of sample farms and their heterogeneity. The number of farm types per region thus varies from 1 to 15 farm types.
7. Note that parameters estimated from FADN – such as yields and variable costs – are not changed during the calibration phase. The underlying assumption is that the corresponding information contained in the FADN dataset reflects well the economic and technical characteristics of the farm types. Discrepancies between $\mathbf{x}_k^0$ and $\mathbf{x}_k^*$ are thus assumed to be solely due to parameters for which information is lacking.
8. 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.
9. Methane emissions from rice cultivation, although a globally important source, is only a small GHG source in Europe (see Figure 1). Other sources of GHG emissions from agriculture included in the IPCC but not accounted for in the model 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 minor importance to European agriculture.
10. 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.
11. To tackle the issue of yield response to nitrogen inputs, some models retain a discrete set of fertiliser intensities, each being associated with different crop yields. This is the case for instance in ASM-GHG (McCarl and Scheider 2001), in which three levels of fertiliser intensity (low, medium, and high) are used. This is indeed more important for models that run at a regional resolution (such as ASM-GHG) than for farm-type based models: farm-type based models describe the behaviour of a larger number of farmers for the same geographic entity (e.g. region). As several farm types are modelled in each region and the fertiliser intensity differs from one farm type to another, the modelled spectrum is indeed often wider in farm-type based models when compared at the same geographic resolution.
12. Remember that some of the sample farms (permanent crops, horticulture) are excluded from the analysis.
13. 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 importance. Aggregation of these differences may lead to the magnitude of the gaps observed in Figure 1.
14. Local irregularities are due to the aggregation of stepwise-shaped changes in farm types' responses.

15. Accounting for the adoption by farmers of new manure management systems would involve additional investment and labour cost that are not considered in the model.
16. Perez et al. (2004) find that this downward trend is likely to be strengthened by the recent CAP reform.
17. Perez et al. (2003) present an assessment of the regional distribution of the impacts on the livestock sector, which, although not directly comparable with Figure 4, shows interestingly similar patterns.
18. The representativity of the FADN sample is given only at the regional level. Moreover, FADN confidentiality requirements impose to work with groups of farmers, not individual farmers.
19. Given the size of $\mathbf{A}_k$ (approximately 500 $\times$ 1000), this appendix is not intended to be comprehensive. For further information on the model, the interested reader is referred to http://www.grignon.inra.fr/economie-publique/MIRAjE/model/detail.htm and De Cara and Jayet (2000).

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Appendix A: Analytical Presentation of the Model

This appendix covers some[19] of the main features of the model. Matrices (uppercase) and vectors (lowercase) are in bold. Parameters are denoted with Greek letters, variables with Latin letters. Unless otherwise stated, all variables and parameters are positive. J is the set of crops indexed by j, and I the set of livestock activities, indexed by i. The constraints defined by $\mathbf{A}_k$, $\mathbf{z}_k$ and $\mathbf{x}_k$ are detailed through decomposing them into sub-matrices and vectors associated with the main technical modules included in the model. Activities (or variables) are presented in columns, and constraints in rows. The dimensions of sub-vectors are given in brackets. Zero values are generally omitted. $\delta_{j,j'}$ is the Kronecker symbol, equal to 1 if $j=j'$ and 0 otherwise. The vector of command variables $\mathbf{x}_k$ is broken down into eight sub-vectors: $\mathbf{y}_k$ (output quantities), $\mathbf{s}_k$ (areas), $\mathbf{a}_k$ (animal numbers), $\mathbf{b}_k$ (purchased quantities of feedstuff), $\mathbf{c}_k$ (on-farm consumption), $\mathbf{v}_k^+$ and $\mathbf{v}_k^-$ (bought and sold live animals live animals, respectively), $\mathbf{d}_k$ (dairy and other animal products). The k-index is omitted and implicit in the rest of the appendix.

Table A.1. Crop area constraints

	s						**z**
[dim]	Cereals (ha) [J_1]	Oilseeds (ha) [J_2]	Other crops (ha) [J_3]	Fodders (ha) [J_4]	Meadows (ha) [J_5]		(ha) [1]
[J_1]	$\delta_{j,j'}/\alpha_j - 1$	-1	-1	-1		$\leq$	0
[J_2]	-1	$\delta_{j,j'}/\alpha_j - 1$	-1	-1		$\leq$	0
[J_3]	-1	-1	$\delta_{j,j'}/\alpha_j - 1$	-1		$\leq$	0
[J_4]	-1	-1	-1	$\delta_{j,j'}/\alpha_j - 1$		$\leq$	0
[1]	$1/\alpha_{CER} - 1$	-1	-1	-1		$\leq$	0
[1]	-1	$1/\alpha_{OIL} - 1$	-1	-1		$\leq$	0
[1]	-1	$1/\alpha_{OCE}$				$\leq$	0
[1]				$1/\alpha_{FOD}$	-1	$\leq$	0
[1]	1	1	1	1	1	$\leq$	T

Table A.2. Crop output allocation constraints

	s			**c**	**y**			**z**
[dim]	Cereals (ha) [J_1]	Forage (ha) [J_4+J_5]	Other crops (ha) [J_2+J_3]	(t) [$J_1+J_4+J_5$]	Cereals (t) [J_1]	Other crops (t) [J_2+J_3]		(t) [1]
[J_1]	$-\delta_{j,j'}\xi_j$			$\delta_{j,j'}$	$\delta_{j,j'}$		$\leq$	0
[J_4+J_5]		$-\delta_{j,j'}\xi_j$		$\delta_{j,j'}$			$\leq$	0
[J_2+J_3]			$-\delta_{j,j'}\xi_j$			$\delta_{j,j'}$	$\leq$	0

Table A.3. Animal feeding constraints

	a	**c**	**b**	**s**		**z**
[dim]	Animals (hds) [I]	Cereals (t) [J_1]	Purchased feed (t) [5]	Fodders and meadows (ha) [J_4+J_5]		[1]
[$I\times e=\{1,2\}$]	$\delta_{i,i'}\mu_{i,e}$	$-\beta_{i,j,e}$	$-\psi_{i,q,e}$	$-\omega_{i,j,e}\ \xi_j$	$\leq$	0
[I]	$-\delta_{i,i'}\mu_{i,3}$	$\beta_{i,j,3}$	$\psi_{i,q,3}$	$\omega_{i,j,3}\ \xi_j$	$\leq$	0

Table A.4. Animal numbers demography

Cattle															Other animal			
Young (M)			Middle (M)			Old (M)	Young (F)			Middle (F)			Old (F)					
a	$\mathbf{v}^+$	$\mathbf{v}^-$	**a**	$\mathbf{v}^+$	$\mathbf{v}^-$	**a**	**a**	$\mathbf{v}^+$	$\mathbf{v}^-$	**a**	$\mathbf{v}^+$	$\mathbf{v}^-$	**a**	**d**	**a**	**d**		**z**
1													$-\rho/2$				$=0$	
-1	-1	1	$1/\epsilon$														$=0$	
			-1	-1	1	$1/\epsilon$											$=0$	
							1						$-\rho/2$				$=0$	
							-1	-1	1	$1/\epsilon$							$=0$	
										-1	-1	1	$1/(\epsilon\eta)$				$=0$	
													$-\xi$	1			≤ 0	
															$-\xi$	1	≤ 0	
1	1						1	1										
			1	1													$\leqslant (1+\phi)$	$[\mathbf{a_0}]$
					1													
													1					
															1			
1	1						1	1										
			1	1													$\geqslant (1+\phi)$	$[\mathbf{a_0}]$
					1													
													1					
															1			

Table A.5. Set-aside constraints

"Small" producers		Rotational set aside		Fixed set aside		IN	IP		$\mathbf{z}$
s_a		s_b		s_d					
$j=1$	$j>2$	$j=1$	$j>2$	$j=2$	$j>2$				
$-p_{sj}+p^r{}_j$	$-p_{sj}+p^r{}_j$	$-p_{sj}+p^r{}_j$	$-p_{sj}+p^r{}_j$	$-p_{sj}+p^r{}_j$	$-p_{sj}+p^r{}_j$				$(=\text{OBJ})$
$\xi^r{}_j$	$\xi^r{}_j$							$\leq$	ζ^s
		$-1+\theta^r$	θ^r					$\leq$	0
				$-1+\theta^f$	θ^f			$\leq$	0
1	1					$-\kappa$		$\leq$	0
		1	1	1	1		$-\kappa$	$\leq$	0
						1	1	$=$	1

A.1. CROP AREA CONSTRAINTS

Each crop is limited by its maximum area share ($\alpha_j \in [0,1]$) in total arable land. In addition, the model captures the links between total cereal area and total oilseed area on one hand, and fodder and meadows on the other hand, through area shares parameters α_{CER}, α_{OIL}, α_{OCE}, and α_{FOD}. Total land endowment is denoted by T (Table A.1).

A.2. CROP OUTPUT ALLOCATION

Crops are divided into three groups: those that can be either sold or on-farm consumed (cereals), those that can only be on-farm-consumed (forage, fodder, pastures, and grassland), and those that are only bound to be sold. The following sub-matrix describes the allocation of total crop production between marketed output and on-farm consumption. Crop yields are denoted by ξ_j (Table A.2).

A.3. ANIMAL NUMBERS, FEEDING AND DEMOGRAPHY

Energy and protein contents of purchased feed (four types of concentrates $q=1,2,3,4$, and one roughage, $q=5$) are denoted by $\psi_{i,q,e}$ ($e=1$ for energy and $e=2$ for protein). The corresponding parameters for on-farm consumption of cereals are denoted by $\beta_{i,j,e}$, and $\omega_{i,j,e}$ for fodders, forage crops, grassland, and meadows. Energy and protein requirements for animal i are denoted by $\mu_{i,e}$. Maximum quantities of ingested matter are also defined for each animal i ($\mu_{i,3}$, active for cattle, sheep and goats), as well as the matter contents of the various feedstuffs ($\beta_{i,j,3}$, $\psi_{i,q,3}$, and $\omega_{i,j,3}$) (Table A.3).

The cattle demographic module describes the relationships between different age and sex categories (M for males, F for females). The underlying assumption is that demographic equilibrium is achieved. For the sake of compactness, the presentation is limited to three age categories (young, middle, old). Likewise, the presentation does not distinguish between dairy and non-dairy livestock, although the model does. Birth rates are denoted by ρ_i, survival rates by ϵ_i, and adult life span in years by η_i. Milk (and other animal products) yields are denoted by

ξ_i. The last two blocks in the following sub-matrix correspond to the possibility for farmers to adjustment their livestock-related capital (stable places). An exponential adjustment at rate ϕ around initial endowment ($\mathbf{a}_0$) is assumed. All rates are annual rates. Animal index i is omitted and implicit in the following sub-matrix.

A.4. SET-ASIDE CONSTRAINTS

The presentation is restricted to the modelling of the different types of set aside, as it provides a good example of how threshold values and integer variables are used in the model. A double system of compensated land set-aside (fixed or rotational) is taken into account. To this regard, important CAP parameters include: reference yields for crop j (ξ_j^r), per-hectare payment (p_j^r), threshold cereal output below which farmers are considered as "small" crop producers (ζ^s), and the set-aside rate to receive compensated payments (θ^f and θ^r for fixed and rotational set aside, respectively). Distinction is thus made between "small" crop areas (s_{aj}), large crop areas associated with rotational set aside (s_{bj}), and large crop areas associated with fixed set aside (s_{cj}). Set aside activities are indexed by j ($j = 1,2$ for rotational and fixed set aside, respectively). κ is a sufficiently large number required by the solving process. p_{sj} refers to per-hectare variable cost. The values $j > 2$ denotes the rest of the crops. Two binary variables are included (IN and IP) to reflect the either/or nature of the producer choices with respect to set-aside. The constant used in the corresponding constraints is denoted by κ. The first row of the sub-matrix corresponds to the objective function (Tables A.4 and A.5).