

Incorporating carbon sequestration into CGE¹ models: a prototype GTAP model with land uses.

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1. Introduction

1.1. *The context*

The Kyoto Protocol, agreed at the third conference of the parties to the UN Framework Convention on Climate Change, commits a group of countries to reduce their emissions of greenhouse gases (GHGs). These countries (known as “Annex 1 countries”) have agreed, but not yet ratified, emission constraints corresponding to a cut of emissions by around 5 per cent relative to their 1990 levels, to be achieved by the period 2008-12. Article 3 and Annex A of the Protocol specify its coverage in terms of different gases. In addition to carbon dioxide, the Protocol includes five gases or groups of gases: methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons,

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perfluorocarbons and sulphur hexafluoride. It also incorporates the GHG emissions generated by changes of land uses.

However, many quantified assessments of the economic costs of the Protocol have focused exclusively on carbon dioxide, ignoring the other GHGs and the carbon sinks potential. In so doing, these studies tended to overestimate the costs of meeting the Protocol targets. First, trends in emissions of non-CO₂ gases affect overall abatement needs and thereby economic costs. Second, there may be large differences of marginal abatement costs across different gases and the fact that the Protocol allows substitution among gases implies that efficiency gains can be achieved by substituting low-cost emission cuts for high-cost ones.

Unfortunately, information about the costs of reducing the non-CO₂ emissions as well as the cost of inducing carbon sinks by reducing the net-emissions from land-use changes remains much more limited and what exists is rarely in agreement. An important part of these divergences arises from the large uncertainty about the magnitude of net GHG emissions from agricultural and forestry activities. Furthermore, when information about net emissions from land-use changes exists (see, for instance, Houghton, 1999; McCarl, 1998), it is not readily available in a format that economic modelers can incorporate into Computable General Equilibrium (CGE) models.

Recognizing this information gap, the US Environmental Protection Agency (EPA) is funding a project of developing an integrated data base for assessing GHG mitigation policies with a special emphasis on the link between changes in land uses and changes in net GHGS emissions from agriculture and forestry. The coverage of this database involves all GHGs from all major sources, with a special focus on GHGs emissions related to land-use and practice changes in agriculture and forestry. This database will be integrated with the worldwide economic data set that is provided and regularly updated by the Global Trade Analysis Project (GTAP). Its aim is to make available to CGE modelers a set of standardized data that would enable them to take better account of the net GHG emissions from agricultural and forestry activities in their analysis of the strategies to stabilize the earth's climate. The project will also identify a methodological approach to integrate GHG emissions from agricultural and forestry activities into CGE models. As part of this later objective,

this paper reports the preliminary results from a prototype CGE model that incorporates carbon sequestration from land use changes.

The paper is organized as follows. After a brief review of existing studies, the second section discusses a number of methodological issues related to the treatment of non-CO₂ abatement technologies and the specification of land use changes in an CGE framework. The third section described the structure of the prototype model. This model - referred to as GTAPE-L (E for energy, L for land) – is an extension of the standard GTAP model described in Hertel, 1997. The fourth section addresses a number of specific issues related to data and calibration. The methods described in this section are rudimentary and primarily reflect the lack of data available at the time of writing this report. The next section discusses a set of preliminary results that are illustrative of the kind of analysis that could be conducted if this approach were to be developed further. The last section review options for further progresses.

1.2. *Studies including non-CO₂ gases*

For long, quantified assessments of the economic costs of achieving the Kyoto Protocol targets only considered carbon dioxide emissions from fossil fuel burning (see Weyant and Hill, 1999; OECD, 1999). Though initially scarce, the evidence on the effects of widening the gas coverage is currently mounting. Results from the GTEM model (Brown et al. , 1999) suggest that the inclusion of methane and nitrous oxide reduces the marginal costs of meeting the Kyoto targets by a third compared with a situation where the targets are reached through cuts in CO₂ emissions alone. A study by Burniaux (2000) confirms these estimates with marginal abatement cost savings ranging from 55 per cent in Eastern Europe to 6 per cent in Japan. However, this study highlights the large degree of uncertainty surrounding the inclusion of the non-CO₂ gases as well as the fact that their beneficial impact might be relatively short-lived in a longer-term perspective. More recent studies report even larger gains from considering multi-gas targets, up to a 50 per cent reduction of the marginal abatement costs (see for instance, Jensen and Thelle, 2001).

Progress in incorporating the non-CO₂ gases into CGE models has been made possible thanks to the efforts in constructing Marginal Abatement Curves (MACs) for the major GHGs such as those estimated by the US Environmental Protection Agency

(EPA, 1999) and the IEA Greenhouse Gas R&D Programme (1999). For the non-Annex 1 countries however, information about MACs remain scarce and the empirical evidence about the impact of the non-CO₂ gases uncertain and controversial³.

1.3. *Studies including carbon sinks*

Incorporating carbon sinks into CGE model remains at its infancy so far. Available studies follow an aggregate approach based on regional abatement curves for forest sinks. The results from Manne and Richels (2000) suggest that the inclusion of both non-CO₂ gases and carbon sinks would reduce the marginal cost of meeting the Kyoto targets by 48 per cent. In a similar way, Reilly et al. (1999) estimated that both together the impact of the non-CO₂ gases and sinks could reduce the cost of meeting the Kyoto agreement by 60 per cent. These cost saving potentials vary widely across Annex 1 countries, ranging from 33 per cent in Japan to 72 per cent in the Other OECD region. For the US, the combined impact of the non-CO₂ gases and forest sinks would amount to a reduction of the marginal abatement cost of achieving the Kyoto commitment by 51 per cent (Reilly et al., 2000).

These studies suggest that the cost saving for extending the gas coverage beyond the carbon dioxide from fuel combustion is substantial. Given their aggregate nature however, they make difficult to assess all the implications of carbon sequestration on land uses, agricultural prices and outputs.

2. Methodological issues

³ For instance, results from the OECD GREEN model (Burniaux, 2000) suggest that the potential for abating non-CO₂ gases in developing countries is relatively smaller than in developed countries while recent results from the MIT model point to the opposite.

In contrast with existing studies, this analyze aims at incorporating carbon sinks from land use changes explicitly into a fully disaggregated CGE model. The decision to allocate land to alternative competing uses, such as cultivating wheat or growing a forest, is treated explicitly in this model. To keep the structure of the model relatively simple at this stage, this decision is specified in a comparative static framework. Introducing dynamics is one of the ways along with this model could be further improved. In addition, the structure of this model is designed such as to distinguish the net emission changes from land use changes (i.e. from shifting a cornfield into a forest, for instance) from emission changes that are related to changes in land management practices (i.e. changing the tillage method or the rate of fallow).

Any carbon sequestration policy will imply large-scale changes of land uses. Most likely, this will induce waves of price increases affecting agricultural, urban and recreational lands. In turn, these price increases will modify the farmer decisions, affecting the output and input mix in agriculture and possibly modifying the amount of GHGs that are emitted in agriculture. For instance, higher cropland prices might induce farmers to use higher quantities of fertilizers, therefore increasing the emissions of nitrous oxide or to shift towards livestock productions that emit methane. The modeling framework proposed here aims at incorporating most of these spillover effects. In this respect, it considers all activities that compete for land in an integrated multi-input, multi-output framework. In addition to the net emissions related to land, the model also incorporates the major sources of methane and nitrous oxide emissions, especially those that are related to agricultural production.

2.1. Incorporating engineering information about alternative technologies into a CGE model

Abatement options for carbon dioxide from fossil fuel burning are restricted to substitution between fuels, production factors and products. In contrast, abatement options for the non-CO₂ gases are much more diverse and involve substitutions between alternative technologies rather than between products. In “bottom-up”

approaches, all alternative technologies are considered explicitly. However, the approach followed here is a “top-down” one where the engineering information about alternative technological options is summarized by using a reduced form function.

This is best illustrated by taking the case of methane emissions from livestock manure management. One possibility in order to reduce these emissions could be to switch towards dry manure management systems because methane production in dry, aerobic conditions is minimal. This is unfeasible however because it would imply a shift of the entire production process and a significant threat of surface and ground water pollution. The alternative option is to recover the methane before it is emitted into the air. This recovered methane is then flared or used to produce heat or electricity. Three recovery methods are available. Covered anaerobic digesters are better used in temperate or warm climates at dairy and swine farms. Complete-mix digesters are tanks into which manure and water are added and removed regularly. It is not recommended for dairy farms because of the high solids contents of dairy manure. Plug-flow digesters are better used in colder climates and almost always used at dairies where the consistency of the cow manure allows for the formation of “plugs”. This description is not intended to disgust the reader but rather to illustrate the complexity of the engineering information that needs to be collected in order to estimate the costs of reducing non-CO₂ emissions.

Studies – like those published by the US EPA (EPA, 1999) or the IEA Greenhouse Gas R&D Programme (1999) – provide detailed descriptions of the various technological options to reduce non-CO₂ emissions. They also estimate marginal abatement curves (MACs) that relate emission reductions to the corresponding value of carbon equivalent⁴. Figure 1 shows the MAC for methane

⁴ A carbon-equivalent is a common unit that allows to add-up emissions from various gases. Following the Article 5 of the Kyoto Protocol, emissions of different GHGs have to be converted into carbon equivalents (Ceq) by using their Global Warming Potentials (GWPs) – i.e. the ratio of the “radiative forcing” of the gas integrated over a given period of time to the corresponding radiative forcing of CO₂ over the same period of time. The following table shows how emissions are converted into carbon equivalents.

emissions from livestock manure in the US as estimated by the EPA (see EPA, 1999, p.5-14). MACs depend on the choice of a discount rate⁵ as well as on assumptions regarding energy prices (i.e. the electricity price for the case of manure emissions described above).

Several common features characterize most MACs available in the literature. First, the high-cost end of the MAC is often vertical, reflecting the perception of engineers that emissions cannot be reduced beyond a certain minimum level. In some countries and for some emission sources, the maximum reduction potential is often all what engineers are able to say about potential abatements. Second, most MACs imply that some reductions can be achieved at zero cost or even with a benefit (this corresponds in Figure 1 to the area between the axes origin and the intercept of the MAC with the ordinate).

Incorporating MACs into a CGE model is a matter of trade-off between the quality of the fit to the MAC and the constraints associated with the theoretical structure of the model. It involves a number of modeling choices. A first choice is whether emissions should be considered as joint-products or, alternatively, as production factors. Treating emissions as joint-products is implemented by making the emission rates responsive to the carbon price through some kind of “response function” that can be easily calibrated such as to fit the MAC provided in the literature. The problem with this approach is that it misses to take into account the additional resources (capital, inputs) that are needed to implement an alternative

	Lifetime	GWP	carbon equivalence ⁽²⁾
Carbon dioxide (CO ₂)	50-200	1	0.27
Methane (CH ₄)	12	21	5.73
Nitrous Oxide (N ₂ O)	120	310	84.55

(1) calculated over a time horizon of 100 years.

(2) the carbon equivalence expresses the amount of carbon equivalent (C-eq) corresponding to one ton of each gas. For instance, one ton of CO₂ contains 0.27 ton (12/44) of C-eq. and one ton of methane is equivalent to 5.73 (21 time 12/44) tons of C-eq.

⁵ EPA MACs are constructed assuming a discount rate of eight percent equally applied to all sources.

technology with a lower emission rate. The example about methane emissions from manure management described above suggests that implementing methane recovery is likely to be relatively capital-intensive. Therefore, it is more appropriate to treat emissions as an input in the production function. As this input is taxed, substitution towards other inputs, including capital, approximates the use of additional resources that are required to implement a cleaner technology.

The approach followed in this model uses the method developed by Hyman (2001). It treats emissions as part of the Constant Elasticity of Substitution (CES) nesting of the production function (see section 3.2 below). This concept is illustrated in Figure 2. The output of the livestock sector is a composite good formed of methane emissions and livestock output net of methane emissions. Depending on the value of the CES substitution elasticity, the rate of emissions per unit of livestock output varies in response to the price of carbon. The value of the substitution elasticity is chosen such as to fit best the MACs from the engineering literature.

This approach has two important implications. First, the MAC derived from a CES function originates at the axes origin (as can be seen from the diagrams in the Annex 1 on MACS calibration). Therefore, it rules out the possibility that some abatement can be achieved at no cost (often referred to as “no regret” options). This reflects the view widely shared among economists that if “no-regret” options really exist, there is no reason why they should not be implemented in reality (and already incorporated in the baseline scenario). Alternatively, if “no-regret” options are not implemented in reality, it is because they imply costs that are not taken into account by engineering estimates, such as those associated with risk aversion, imperfect information, liquidity constraints, lack of access to capital, ... Though excluding “no regret” options, the CES based approach still implies that substantial emission reductions can be achieved at relatively low cost, even with very low values of the CES substitution elasticity (see section 4.1 on calibration).

Second, there is no absolute ceiling below which emissions cannot be cut further with a CES-derived MAC. Though steep sloped, the high-cost part of a CES-derived

MAC is never vertical. Thus CES-derived MACs cannot accommodate maximum reduction potentials, as those assessed by engineering studies. This may not be a problem in face of the argument that technology experts only consider technologies that exist now or are foreseeable to exist in the future given that we are living in a world with little or no incentive to mitigate emissions. But, the mere fact of imposing emission reductions may trigger the development of new cleaner technologies. In that sense, the slope of the high-cost segment of the MAC reflects some kind of “induced technical progress”.

In the model described below, the CES-based method of incorporating GHGs is used for methane and nitrous oxide emissions but also for emissions from land uses. In the later case, the emission rates per unit of land decline as the carbon price increases, reflecting the shift towards land management techniques that release less carbon in the atmosphere (such as more conservative tillage method, for instance).

2.2. *land use and land management changes*

Carbon sequestration through land uses involves a portfolio of various strategies, such as reforestation, lower deforestation, development of biofuel offsets or carbon sequestration into existing agricultural soils. Incorporating these options into a CGE model requires an appropriate specification of the land market including, in particular, the landowner’s decision of whether to keep land in its status quo use or to convert it to serve another purpose. In principle, this decision is best represented in a dynamic optimization framework in which the landowner maximizes the present discounted value of the stream of expected future returns from changing the status of a given land (see, for instance, Newell and Stavins (2000) for such an approach).

Transposing this decision into a comparative static framework makes its specification much more simple. The landowner uses his land where it gets the highest possible return such as to maximize his profit. In reality, land prices differ widely even across small area. This reflects mainly the heterogeneous nature of land: land quality differs from one plot to another. Additionally, it may reflect the impact

of sector specific policies (such as subsidies for wheat or soybeans production), the costs of changing land status and/or the fact that a land plot producing high wheat yields is not necessarily appropriate for growing, let say, biomass. All of this strongly suggests that land is far from a perfectly malleable factor of production.

In the static model used here, each land type is in fixed supply and the landowner chooses the optimal land allocation mix across alternative uses such as to maximize his revenue, given a Constant Elasticity of Transformation (CET) function. For instance, there is an initial amount of crops land and the landowner decides either to keep this land in the crops sector or to change its status, for instance, into forestry land or urban land. There are many technical and economic considerations that underlie such kind of decision. These are reflected by the propensities to keep land in its current status or to change it to another status (i.e. through calibration, these propensities are equal to the shares of the CET function). These propensities are derived from the land status changes observed over a given period, as they are estimated by land transition matrices (see below section 4.2).

The approach also considers the behavior of land users. Facing a tax on deforestation, farmers are likely to use more intensively the land that is already under cultivation. As a result, the price of farmland will increase, inducing landowners to divert land from other uses, including forestry, into agriculture. This illustrates the potential spill-over effects across various sequestration options: a tax on deforestation is likely to have adverse effects on afforestation (alternatively, a subsidy on afforestation should also increase deforestation), hence the need to consider a mix of policy instruments. Demand equations for each land use are part of the CES production nesting (see section 3.3 below). Thus, in the model considered here, any type of land use is determined simultaneously by specific demand and supply function and an equilibrium price that equates demands and supplies.

3. The structure of the GTAPE-L model

The GTAPE-L model is based on the version 5 of the GTAP data base. It is a multi-regional, multi-sectoral static CGE, the structure of which is similar to that of the standard GTAP model (Hertel, 1997). Compared with the standard GTAP model, GTAPE-L has been extended in a number of ways in order to deal with carbon dioxide emissions from fossil fuel combustion, methane and nitrous oxide emissions and land uses. The rest of this section discusses these extensions. GTAPE-L has five regions/countries and 10 sectors, the content of which is detailed in Tables 1 and 2.

3.1. *Production structure and inter-fuel substitution*

As already mentioned, the only way carbon dioxide emissions can be reduced is by substitution across fuels, production factors and capital. It is important, therefore, that the production structure adequately reflects existing technologies. “Top-down” models usually represent the range of technological options in an aggregate way by using nested production functions. The nesting pattern as well as the values of the CES elasticities is critical in determining the technological response of the model.

GTAPE-L has the same production structure than GTAP-E (Burniaux and Truong, 2002). The production nesting resembles the one used in similar models, such as the OECD GREEN model (Lee et al., 1994) or the model developed by Babiker, Maskus and Rutherford (Babiker, Maskus and Rutherford, 1997). Output is made up of a number of non-energy intermediate inputs and of a composite “value-added + energy” input (see, Figure 3). In all sectors, except in the crops sector (see below section 3.2), the first level production nesting has a Leontief structure. The composite “value-added + energy” input is made up of land, a natural resource, labor and a composite “capital + energy” input. The third CES level describes the relationship between capital and a composite energy input. This specification potentially allows distinguishing a short-term technological response where capital and energy are complementary and a long-term response where they are substitutes. The fourth level allocates the aggregate demand for the composite energy input into electricity and a composite non-electric input. In turn, the composite non-electric

input is made up of coal and a composite energy input including the remaining fossil fuels (fifth level). Finally, the bottom level of the production function describes the inter-fuel substitution between crude oil, natural gas and refined petroleum products. The values of the substitution elasticities for each level are reported between brackets on Figure 3 (see also a discussion about these values in Burniaux and Truong, 2002).

3.2. *Non-CO₂ gases*

1.1.1. Methane emissions

The major sources of methane emissions include: methane generated by anaerobic decomposition of organic waste on landfills; methane from anaerobic decomposition of plant matter in rice fields; methane from livestock manure management and enteric fermentation; methane from leaks and venting in natural gas system and methane from coal mining.

In GTAPE-L, methane emissions are included as a production factor at the top of the CES nesting, as in Figure 2. Thus, for a number of sectors (rice, livestock, coal and natural gas), output is made up of methane emissions and a composite factor, the structure of which, in turn, is similar to the tree-structured nesting of Figure 3. The value of the top level elasticity is chosen such as to best fit the engineering MAC (see section 4.1 and Annex 1).

1.1.2. Nitrous oxide.

N₂O is produced naturally in soils through the microbial processes of nitrification and de-nitrification. The principal source of emissions is the addition of nitrogen to the soil principally by the application of synthetic nitrogen based fertilizers or by nitrogen deposited by grazing animals. Fertilizer application also leads to indirect emissions resulting from fertilizer volatilization and N₂O production due to surface run off and sub-surface leaching of nitrogen from soils (IEA Greenhouse Gas R&D Programme, 2000).

In GTAPE-L, we make the assumption that nitrous oxide emissions are associated with the amount of chemicals input into the crops sector⁶. As the Figure 4 shows, the aggregate demand for chemicals by the crops sector derives from the first level CES function. This demand is made up of nitrous oxide emissions and a composite chemicals input net of emissions. In turn, this composite input is made up of domestic and imported chemicals as part of the Armington specification of the bilateral trade flows. The amount of nitrous oxide emissions per unit of chemicals used is constant (the second level elasticity is equal to zero in Figure 4) reflecting the fact that the effectiveness of existing potential options still needs to be proven.

Not all non-CO2 emission sources are included in the current version of the model. In particular, methane emissions from landfills, nitrous oxide emissions from fossil fuel combustion and chemical processing, the chlorofluorocarbons, the tropospheric ozone and the other trace gases are not included.

3.3. *Land uses and net emission rates*

The structure of the land market in GTAPE-L is illustrated in Figure 5. The Figure 5 refers to the crops sector, though the production structure is the same for all the producing sectors. First, the farmer decides the total amount of land he needs (second level CES). The next level of decision is whether he will use more or less intensively the land that is already used to grow crops or whether he will expand the crops land area by diverting land from other sectors (such as livestock or forestry). The third CES level in Figure 5 represents this decision. The Figure 5 also shows the decision by the landowner to allocate land across different uses. This is specified using a Constant Elasticity of Transformation (CET) function with the value of the transformation elasticity determining the degree of land mobility. Thus the model simultaneously determines demands and supplies for each bilateral land use across sectors as well as the equilibrium prices that equalize these demands and supplies.

⁶ The version 5 of the GTAP data base does not allow to distinguish a fertilizer sector.

4. Data issues

4.1. Calibration of MACs for non-CO₂ gases

As mentioned earlier, the non-CO₂ gases are specified as parts of the CES nesting. Let the output of a given sector that emits a non-CO₂ gas be represented by $\tilde{X}$ (i.e. the output of the livestock sector including methane emissions). We assume that this output is a CES aggregate of non-CO₂ emissions and a corresponding output net of emissions (i.e. livestock output excluding methane emissions):

$$[1] \quad \tilde{X} = \left(a \cdot X^{-r} + b \cdot C^{-r} \right)^{-\frac{1}{r}}$$

where X is the sector output net of emissions and C represents the non-CO₂ emission (in tons of Ceq).

First order conditions allow to derive the amounts of output and emissions that are needed to make up the composite output including emissions:

$$[2] \quad X = a^s \cdot \left(\frac{p_X}{P} \right)^{-s} \cdot \tilde{X}$$

$$[3] \quad C = b^s \cdot \left(\frac{p_C}{P} \right)^{-s} \cdot \tilde{X}$$

where p_X is the price of the output net of emissions; p_C , the price of carbon emissions (in USD per ton of Ceq); and P , the price of the composite output including emissions. s is the value of the substitution elasticity (equal to $1/(1+\rho)$). In turn, the composite price P is a CES aggregation of p_X and p_C :

$$[4] \quad P = \left(a^s \cdot px^{1-s} + b^s \cdot pc^{1-s} \right)^{\frac{1}{1-s}}$$

As usual with CES functions, the parameters a and b are calculated through calibration on the benchmark data given normalization rules for prices. Both px (the output price net of emissions) and P (the composite output price) are assumed to be equal to unity. In the meantime, the base year level of emissions C is assumed to correspond to a very low and arbitrary carbon price (0.5 USD per ton of Ceq).

Given the normalization rules for prices, equations [2] and [3] are used to calculate the parameters a and b respectively :

$$[5] \quad a^s = \frac{px \cdot X}{P \cdot \tilde{X}}$$

$$[6] \quad b^s = \frac{pc \cdot C}{P \cdot \tilde{X}} \cdot pc^{s-1}$$

Equations [5] and [6] allow to calculate the values of α^σ and β^σ as functions of expenditure shares: i.e. the shares of output expenditures (net of carbon) – $px \cdot X$ – and carbon expenditures – $pc \cdot C$ – in total expenditures – $P \cdot \tilde{X}$ (including carbon emission valued at an arbitrary and very low carbon price pc of 0.5 USD per ton of Ceq.).

In practice, a calibration run is first completed, assuming very low carbon taxes (0.5 USD per ton of Ceq) and all CES substitution elasticities equal to zero (thus carbon is strictly complementary to all outputs or demands). This calibration run

generates a consistent data set⁷ that serves as a basis to calculate the parameters α^σ and β^σ using equations [5] and [6].

Engineering surveys provide MACs that relate the level of emissions to the price of carbon in a way that is similar to equation [3]. The level of the CES elasticity σ is then chosen such as the emission level calculated by using equation [3] best fit the engineering MACs for increasing carbon price levels.

The Table 3 reports the value of the CES substitution elasticities that are used in the current version of the model for various non-CO2 sources⁸. These elasticities are small, ranging from 0.06 to 0.2. The Annex 1 reports additional information on the sources that have been used to establish the engineering MACs and how these fit with the CES-based MACs. In the current version of the model, all substitution elasticities related to emissions from land uses are equal to zero.

4.2. Land transition matrices

The specification of the land market in GTAPE-L is based on an accounting framework that report all changes of land status over a given period of time. The Figure 6 illustrates this framework. It identifies sectors from which land originates and sectors that are using land. Therefore, for each land category – in the current version of the model, there is only one single land category – there is a sector-by-sector “land transition” matrix that reports all changes of land status over a given period. For instance, the land transition matrix reports how many hectares of crops land has been transformed into forest (afforestation) as well as the amount of forest hectares that are transformed into agricultural or urban land. The diagonal flows of the land transition matrix correspond to the land that has not changed status over the period (i.e. the land that has remained under cultivation in the crops sector or the land

⁷ The level of the GHGs emissions in this run are therefore slightly different from the observed GHGs emissions in the base year. In practice, the divergence is small and can be reduced by lowering the level of the carbon tax in the calibration run.

⁸ At this stage, the same MAC is used for all regions of the model.

that remains permanently covered by forests). The sum of the columns of the matrix gives the land allocation across sectors at the beginning of the period. The sum of the rows gives the land allocation at the end of the period.

The land transition matrices that are currently used in GTAPE-L are derived from the IMAGE2.2 model. The Integrated Model to Assess the Global Environment (IMAGE) is a dynamic integrated assessment modeling framework for global change (Alcamo J., 1994; Leemans et al., 1998). In the IMAGE2.2 version, the general equilibrium economy model, WorldScan, and the population model, PHOENIX, feed the basic information on economic and demographic developments for 17 world regions into three linked subsystems: i) the Energy-Industry System (which calculates regional energy consumption, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable energy technologies and emissions of greenhouse gases (GHG), ozone precursors and acidifying compounds); ii) the Terrestrial Environment System (land-use changes on the basis of regional consumption, production and trading of food, animal feed, fodder, grass and timber, with consideration of local climatic and terrain properties and emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of CO₂ between terrestrial ecosystems and the atmosphere); and iii) the Atmospheric Ocean System (changes in atmospheric composition using the emissions and by taking oceanic CO₂ uptake and atmospheric chemistry into consideration, changes in climatic properties by resolving the changes in radiative forcing caused by greenhouse gases, aerosols and oceanic heat transport)⁹.

Recently, the Intergovernmental Panel on Climate Change (IPCC) published a set of new scenarios in the Special Report on Emissions Scenarios (SRES) (IPCC, 2001). These scenarios are based on a thorough review of the literature, the development of narrative 'storylines' and the quantification of these storylines using six different integrated models from different countries. The IMAGE2.2 model has been used to

⁹ For a summary description of the changes introduced in the IMAGE2.2 version, see IMAGE Team, 2001).

simulate these scenarios and the results are reported on a CD-ROM (IMAGE Team, 2001).

The land transition matrices used in this version of GTAPE-L are based on the B2 SRE scenario. This scenario is characterized by moderate economic growth, emphasis on environmental protection and social equity and decentralized solutions. It is based on the assumption that governance is effective at the national and regional level, not at the global level. The land transitions are calculated on the basis of the land allocation changes reported in the B2 scenario in 1995. For the US and the European Union¹⁰, the cells of the IMAGE2.2 model of which the corresponding land status has changed in 1995 are aggregated. The result of this aggregation reports two non-zero transitions in the US and the EU: from crops to natural vegetation and from natural vegetation to timber extraction. Based on these transitions and subject to some assumptions¹¹, the land transition matrices for the US and the EU are calculated and reported on Table 4.

4.3. *Net emission rates associated with land uses and land use changes*

The land transition matrices describe the pattern of land status changes observed during a period around the benchmark year. With every land use is also associated a corresponding net emission rate (in million tons of Ceq.). Thus, the data base of GTAPE-L contains the amount of hectares of – let say - forestry land that is transformed yearly into agricultural land on average but also the amount of carbon emissions that is released into the atmosphere as a result of this change. However, changing land status disturbs net carbon fluxes to the atmosphere for several years. For instance, after cutting a forest, the respiration flux from soil remains high for a

¹⁰ This version of the paper only considers mitigation policies in the US and the EU.

¹¹ For instance, that the natural vegetation that is harvested for timber extraction and then let abandoned for re-growing is accounted for in the diagonal of the transition matrix (i.e. permanent forest land).

few years, depending on the natural vegetation and the climate circumstances. Alternatively, it takes time before a newly planted forest generates substantial net sequestration. The dynamic nature of carbon release and sequestration from land uses cannot be taken into consideration in the static framework of GTAPE-L. But, given this dynamics, it is appropriate to consider the average net emissions changes that are associated to the land transitions over a certain period of time rather than to use one-year emission rates.

The IMAGE2.2 model has been used to simulate the land transitions observed in 1995 and to calculate the associated net emission changes over a period of 10 years. Four types of net emissions are considered:

- The net emissions from agriculture and extensive grasslands that are abandoned and turn back to natural vegetation. Soil respiration of abandoned land generates carbon emissions that gradually turn into sinks as the natural vegetation re-grows. Over a period of 10 years, the average net emissions in the US and the EU are negative¹². Clearly, the time span over which net emissions are averaged is critical in estimating a representative net emission rate for the land that returns to natural vegetation.
- The net emissions associated with the change from natural vegetation to agricultural land. The sign of these net emissions is unambiguously positive. The amount of carbon that is released in the atmosphere by new agricultural land remain relatively high for several years after this land has been cleared.
- The emissions associated with the change from natural vegetation to extensive grasslands.
- The emissions associated with the change from natural vegetation to re-growth after timber extraction. In the current version of GTAPE-L, these emissions are associated with the permanent use of forest land (i.e. the diagonal of the forestry sector in the land transition matrix).

¹² Though there are regions where letting agricultural lands to turn back to natural vegetation generates positive net emissions on average over a period of 10 years, as simulated by the IMAGE2.2 model.

The net emission matrices corresponding to the land transition matrices are reported on Table 5 and the corresponding emission rates, on Table 6. According with these estimates, abandoning agricultural land to natural vegetation – which involves afforestation and reforestation – sequesters an average of 20 tons of Ceq per km² in the US and around 100 tons of Ceq per km² in the EU. At this stage, these estimates are very preliminary and subject to a different interpretation of the results from the IMAGE2.2 model. It must also be noted that the net emissions from land that remains permanently under the same status (for instance, sinks into permanent forests) are not taken into account in this version of the model (with the exception of emissions from timber extraction).

5. Preliminary results

The following results are very preliminary and must be considered as illustrative of the type of information provided by GTAPE-L rather than an assessment of the sequestration potential. In particular, the methodology to integrate information from carbon cycle models needs many improvements. These preliminary results concern the impact of a 30 per cent reduction of all GHG emissions in the US and the EU. In both regions, this targets is achieved in three different ways: i) by reducing carbon dioxide emissions only; ii) by reducing emissions of carbon dioxide, methane and nitrous oxide from all sources, excluding land use changes; and, iii) by reducing all three GHG emissions from all sources, including land use changes¹³. The total abatement (in million tons of Ceq) is the same in the three scenarios and so is the environmental benefit.

¹³ In this later scenario, net emissions from land that does not change status (i.e. emissions from timber extraction) are not involved.

5.1. *Potential cost savings and gas contribution*

5.1.1. Marginal abatement costs

The Figure 7 reports the marginal abatement costs in the US and the EU under the three alternative scenarios described above. The introduction of the two non-CO₂ gases – methane and nitrous oxide – lowers the marginal abatement costs by about 20 per cent. This is less than the cost saving reported by previous studies that have assessed the cost of the Kyoto Protocol. However, since this estimate is done in a comparative static framework, it excludes the so-called “baseline effects”¹⁴.

Taking into account the sequestration potential from land use changes further reduces the marginal abatement costs. But while this potential seems negligible in the US (-3 per cent), it is very substantial in the EU (-30 per cent). In the EU, incorporating the non-CO₂ gases and sinks all together cuts the marginal abatement cost by half, compared to only a fifth in the US. The explanations for the divergence between the US and the EU are analyzed below.

Figures 8.1 and 8.2 show the contribution of the various gases and sinks to the total abatement in the US and the EU respectively. In both regions, carbon dioxide remains the bulk of the total abatement, even when the non-CO₂ gases and sinks are taken into account. Methane and nitrous oxide emissions are reduced by small amount (20 million tons of Ceq in the US and 10 million tons of Ceq. in the EU) when only carbon dioxide emissions are cut, reflecting the complementary links among emissions, especially in the coal mining and natural gas sectors. The major difference between the two regions relates to the role of carbon sequestration through land use changes. In the US, 8.5 million tons of Ceq. only are sequestered at a

¹⁴ The targets decided at Kyoto are expressed relatively to the emission levels in 1990. Therefore, the abatement effort implied by the Kyoto Protocol depends on the growth of emissions from 1990 to the first commitment period (2008-2012) and any estimate of abatement costs will depend on how this growth is projected in the baseline scenario. Since non-CO₂ gases are often projected to grow less than CO₂ or even to decline over time, their inclusion in the target reduces its tightness, something that is often referred to as a “baseline effect”. In a static framework such like GTAPE-L, there is no such kind of baseline effect and the results from such type of model are best interpreted in a context that is different from the Kyoto Protocol.

marginal abatement cost of 85 USD per ton of Ceq. This is much below the range of the mitigation response functions estimated by Gillig, McCarl and Sands (2002) for the US where around 100 million tons of Ceq. can be sequestered at a marginal abatement cost of about 50 USD per ton of Ceq. In contrast, 56 million tons of Ceq. are sequestered in the EU at a marginal abatement cost of 144 USD per ton of Ceq.. Though, to some respect, this might also be considered as an underestimation, it is striking that such an amount suffices to cut the abatement cost in the EU by a third. Central to the magnitude of the cost saving originating from sinks is the imputed degree of land mobility. This will be developed further below.

5.1.2. Macro-economic costs.

One advantage of GE models is that they provide quantitative measurements of the macro-economic costs based on a consistent accounting of producer and consumer surplus losses. The Table 7 reports the percentage changes of the households utility per capita in the three alternative scenarios described below. Though GHG mitigation policies usually imply large energy price shifts and energy output drops, the aggregate costs at economy-wide levels look relatively modest. In the scenario that takes into account carbon sequestration, a 30 per cent reduction of emissions would reduce household utility by less than 1 per cent (0.2 per cent in the US, 0.9 per cent in the EU). The cost reductions from the inclusion of the non-CO₂ gases and carbon sequestration respectively are comparable with the marginal cost reductions reported above.

5.2. *Impact on prices and outputs*

The Table 8 reports the impact on sector outputs and prices. As expected, carbon dioxide abatement mostly hurts the energy sectors with coal mining output cuts almost by half and drops by about 30 per cent of the natural gas production and by

10 to 20 per cent of the petroleum product output¹⁵. Extending the coverage to the non-CO₂ gases (excluding emissions from land uses) shifts the burden of the mitigation effort onto agriculture: rice output falls by 20 to 30 per cent (reflecting taxes on methane emissions); crops output, by 3 to 4 per cent (as nitrous oxide emissions are taxed) and livestock output, by about 1 per cent (as methane emissions are taxed). Incorporating sinks from land use changes has a twofold impact on agriculture. On one hand, agriculture benefits from the overall reduction of the marginal abatement cost – at least in the EU – resulting from the shift towards sequestration. On the other hand, more agricultural land is diverted into reforestation or afforestation resulting into an increase of crops land prices (+ 37 per cent compared with – 2 per cent in the scenario without sequestration in the EU; - 3 per cent compared with – 7,5 per cent in the US)¹⁶. In Europe – where the impact of sequestration is higher – the first effect dominates and agricultural output falls less than in the scenario without sequestration. In the United States – where sequestration has almost no impact – the opposite outcome occurs with agricultural output falling more.

5.3. *Impact on land use allocation*

The Table 9 illustrates the magnitude of the land reallocation implied by the simulated sequestration program. One drawback of an CGE model, such like GTAPE-L, is that it considers “efficiency units” (in 1995 USD) instead of physical units (km² or hectares). This makes difficult to figure out concretely what would be the consequences of a given sequestration effort on land area. The Table 9 reports the percentage changes of the land value-added generated in the crops, livestock,

¹⁵ With a higher carbon content, the output of petroleum products should normally falls more than natural gas. This is more than offset by the existence of higher taxes on petroleum products – especially in Europe – than for natural gas. Since a carbon tax is an excise tax, its impact on consumer prices is reduced the higher the level of the existing taxation.

¹⁶ Agricultural land price increases result from the increased demand for agricultural land for reforestation/afforestation as well as the capitalization into the agricultural land rent of the subsidies associated with the corresponding sequestration.

forestry and other (urban, residential and recreative) sectors. In the US, the land value-added in forestry would increase by 16 per cent and the land value-added in the crops sector would be reduced by 1 per cent following a carbon tax of 85 USD per ton of Ceq. The corresponding changes in Europe are much more dramatic: an increase of the land value-added in forestry by 39 per cent together with a 7 per cent reduction in the crops sector. Though these results – as the others - are mostly illustrative, they seem to indicate that any sequestration program, if it has to be influential in cutting marginal abatement costs, will have dramatic implications on land reallocation and rural landscape.

5.4. *Sensitivity analysis*

5.4.1. Land transitions and emission rates

Most striking in the above results is the unbalanced impact of sequestration in the US and the EU. Part of the explanation relates to the fact that, according with the IMAGE2.2 data, the proportion of agricultural land that is abandoned each year to natural vegetation is higher in Europe (3.8 per cent) than in the US (2.4 per cent). Another factor may be the larger net sequestration rate in the EU (104 tons of Ceq. per km² and per year) than in the US (21 tons of Ceq. per km² and per year). The results in Figure 9 unambiguously show that the later factor explains most of the divergence between the impact of sequestration in the US and the EU. The Figure 9 compares the cost saving of sequestration in the US under alternative assumptions. The first assumption is to apply the same proportion of agricultural land diverted to reforestation/afforestation in the US than in the EU. This results into a small increase of the net sequestration rate per efficiency unit (from 0.058 tons of Ceq per 1997 USD to 0.06 tons of Ceq per 1997 USD) and a corresponding marginal increase of the cost saving potential (from 3.2 per cent to 4.8 per cent reduction of the marginal abatement cost). Assuming next that both the proportion of agricultural land diverted to reforestation/afforestation and the sequestration rate are the same in the US than in Europe raises the rate of sequestration in the US to 0.3 tons of Ceq. per 1997 USD. This is three times higher than in Europe, the explanation being that the implicit land

price in the forestry sector – as derived from the IO tables – is much lower in the US than in the EU. Accordingly, the potential cost saving from sequestration in the US under this second assumption is quite substantial, reaching almost 45 per cent of the marginal abatement cost without sequestration, compared with 30 per cent in the EU.

This illustrates that any assessment of the cost saving associated with carbon sequestration by using this methodology will depend critically on i) the land transitions; ii) the net emission rates associated to the transitions; and, iii) the implicit land prices in the various sectors. Improvements in collecting this information will be central in order to obtain credible estimates of the carbon sequestration potential.

5.4.2. The degree of land mobility and the issue of land heterogeneity

Central to the net emissions from land uses is the decision to change land status, for instance from crops to forest or the reverse. In GTAPE-L, this decision is represented by a CET function (see section 3.3). In the central scenario described above, the value of the transformation elasticity is equal to one. The results reported on Table 10 relate to the US; they highlight how sensitive the sequestration potential is to the imputed value of the transformation elasticity. For, instance, assuming full land mobility across various uses yields a very substantial cost saving potential (with the marginal abatement cost falling by 73 per cent compared with 3 per cent only in the central scenario) and large amounts of carbon sequestration (287 million tons of Ceq. compared with only 8 million tons of Ceq. in the central scenario). Though land is by nature an heterogeneous factor and assuming perfect land mobility most likely unrealistic, it remains that the cost saving from sinks varies from a few to 70 per cent as land mobility increases.

Such a high sensitivity to one single parameter may be considered as a drawback of the methodological approach followed in GTAPE-L. There are at least two ways to overcome this problem. First, studies using more disaggregated sector models of agriculture and forestry may provide estimates of the total amount of sequestration corresponding to a given marginal abatement cost and it is then possible to choose a value of the transformation elasticity that yields results compatible with these

estimates. For instance, in the Table 9, a value of the CET elasticity equal to 5 yields sequestration of the range estimated by Gillig, McCarl and Sands (2002) (i.e. 129 million tons of Ceq. at a marginal abatement cost of 53 USD per ton of Ceq). Sequestration of this range contributes substantially in reducing the marginal cost of GHG abatement (by 39 per cent, see Table 9). The second way to reduce the influence of the land mobility elasticity on the results is to consider several land categories corresponding to different climatic and ecological zones. A specific transition matrix would describe the land transitions within each zone while land mobility between zones would be prohibited¹⁷ (see more on this issue on section 6 below).

5.4.3. Alternative transition patterns and policy design

This final section examines the sensitivity of the results to alternative policy design. According with the data from IMAGE2.2, there is no deforestation in the US and the EU during the base year 1995. Therefore, emission abatement in the central scenario can only be achieved by growing forest on previously agricultural lands. Alternatively, one might allow for some deforestation and see if this affect the marginal abatement cost. Incorporating net emissions from land that does not change status in addition to emissions from land use changes is another policy alternative¹⁸.

The Table 11 reports results from two alternative scenarios including deforestation and sinks into permanent, full-grown forests. The results show little divergence compared with the central scenario. As expected, allowing for deforestation and including the carbon sinks into permanent forests contribute to lower the marginal abatement costs. Rather than the type of policy instrument that is used to reduce emissions from and increase sinks into land, it is the magnitude of the net emission rates that matters.

¹⁷ Considering only one single land category – as in the current version of GTAPE-L – implies quite unrealistically that a field in Mississippi can be changed into a pine forest in New England.

¹⁸ Note that the Kyoto Protocol only considers emissions resulting from changes in land uses.

6. Concluding remarks

Though preliminary at this stage, the above results support some tentative statements:

- The methodological approach followed in this model takes consistent account of the main inter-sectoral spill-over effects from carbon sequestration, in particular those arising from land use reallocation. However, at this stage, this approach has a number of drawbacks. In particular, it does not allow to make any assessment of the magnitude of the cost-saving from sequestration since the results are very sensitive to the values of a number of key-parameters, such as the net emission rates and the degree of land mobility. Considerable progress in data collection has yet to be achieved in order to narrow the degree of uncertainty surrounding the values of these parameters.
- The above results suggest that, depending on the values of these key-parameters, the cost saving from carbon sequestration is potentially quite substantial and higher compared with the cost-saving obtained from incorporating the non-CO₂ emission sources.
- A higher cost saving from sequestration is associated with large amount of land reallocation and price shifts.

The current version of GTAPE-L can be considered as nothing but a preliminary step of a sustained effort over the longer term. It aims merely at illustrating the potential merits of the approach while helping to identify the data that will be needed. Further improvements will require both considerable progresses in the data collection and changes of the model structure. Ultimately, these improvements should lead to building an integrated GTAP database to be made available to the worldwide community of researchers working on economic assessments of the policies to mitigate climate change.

Progress on data collection should focus on:

- Improving the calculation of the land transition matrices. In that respect, whether the new FARM data base developed by Roy Darwin and his colleagues at the Economic Research Service (ERS) of the US Department of Agriculture (USDA) could be integrated and generate better estimates of land transitions is critical. This

database is disaggregated by countries and therefore readily compatible with the version 5 of the GTAP database. It would allow distinguishing several land categories, insofar reducing the sensitivity of the results to the imputed degree of land mobility.

- Collecting non-CO₂ emission rates for the major GHG sources and the associated MACs.

- Improving the estimates of the net emission rates from land uses and land use changes either by using the information from the FARM data base or by relying on carbon-cycle models.

- Establishing MACs that incorporate the response of the land management practices to increasing carbon prices.

Further extension of the model could possibly involve:

- Reviewing the literature in order to collect information about the structure of the production function in agriculture and the values of the key substitution elasticities ¹⁹. An appropriate representation of the farmer behavior is critical in assessing the impact of the non-CO₂ abatements and the response to large-scale carbon sequestration programs.

- Distinguishing a bio-fuel sector.

- Introducing emission changes from adaptation of land management practices explicitly: i.e. by disaggregating the net emission rates associated with diagonal land uses (land that does not change status) into sinks and emissions that can be reduced by adopting alternative land management practices.

- Introducing dynamics of land stocks and carbon sequestration.

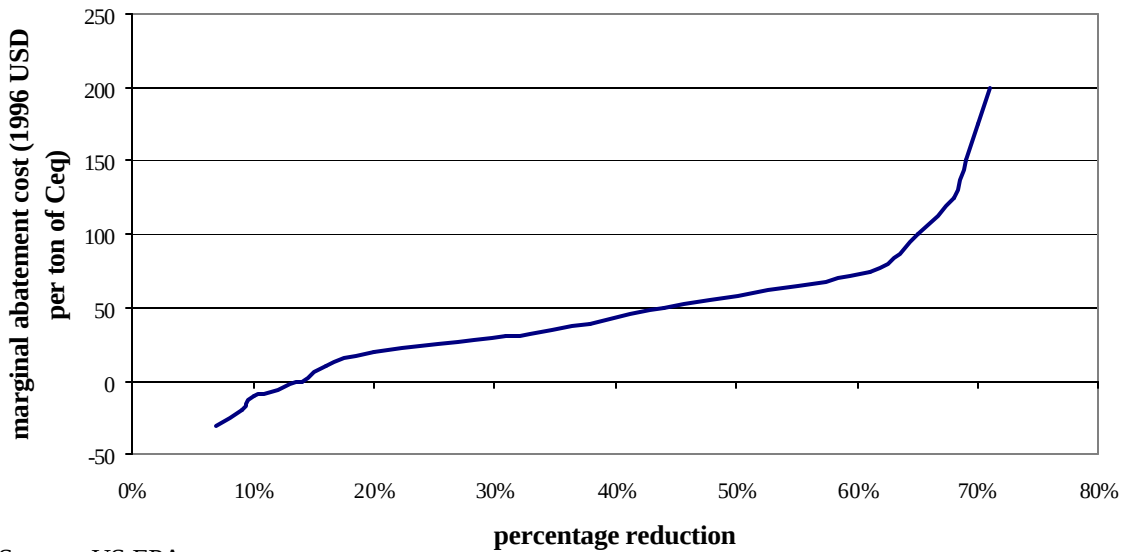
¹⁹ See Burniaux and Truong, 2000 for a similar approach.

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Figure 1 : Marginal abatement curve for methane emissions from manure management in the US



Source : US EPA

Figure 2 : Incorporating GHGs into the production function.

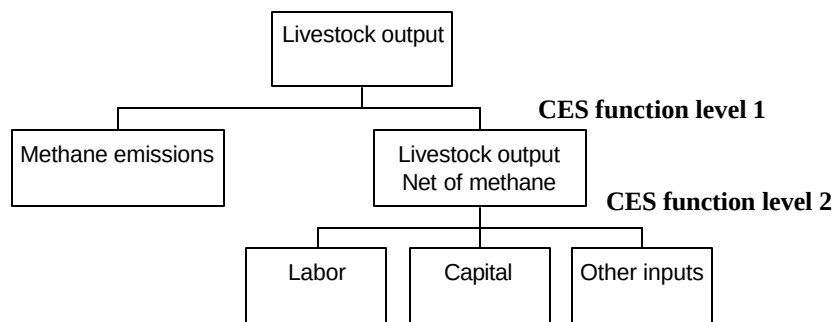


Table 1 : Sectoral aggregation of GTAPE-L.

GTAPE-L sectors			GTAP version 5 sectors		
No.		Description	No.	Code	Description
1	Rice	Rice	1	pdr	paddy rice
2	Crops	Primary agriculture and fishing	2	wht	wheat
			3	gro	cereal grains nec
			4	v_f	vegetables, fruit, nuts
			5	osd	oil seeds
			6	c_b	sugar cane, sugar beet
			7	pfb	plant-based fibers
			8	ocr	crops nec
			14	fsh	fishing
3	Livestock	Livestock products	9	ctl	bovine cattle, sheep and goats
			10	oap	animal products nec
			11	rmk	raw milk
			12	wol	wool, silk-worm cocoons
4	Forestry	Forestry	13	for	forestry
5	Coal	Coal Mining	15	col	coal
6	Oil	Crude oil	16	oil	oil
7	Gas	Natural gas extraction	17	gas	gas
			44	gdt	gas manufacture, distribution
8	Oil_Pcts	Refined oil products	32	p_c	petroleum, coal products
9	Electricity	Electricity	43	ely	electricity
10	Oth_ind_ser	Other industries and services	18	omn	minerals nec
			19	cmt	bovine cattle, sheep and goat
			20	omt	meat products
			21	vol	vegetable oils and fats
			22	mil	dairy products
			23	pcr	processed rice
			24	sgf	sugar
			25	ofd	food products nec
			26	b_t	beverages and tobacco products
			27	tex	textiles
			28	wap	wearing apparel
			29	lea	leather products
			30	lum	wood products
			31	ppp	paper products, publishing
			33	crp	chemical, rubber, plastic prod
			34	nmn	mineral products nec
			35	i_s	ferrous metals
			36	nfm	metals nec
			37	fmp	metal products
			38	mvh	motor vehicles and parts
			39	otn	transport equipment nec
			40	ele	electronic equipment
			41	ome	machinery and equipment nec
			42	omf	manufactures nec
			45	wtr	water
			46	cns	construction
			47	trd	trade
			48	otp	transport nec
			49	wtp	water transport
			50	atp	air transport
			51	cmn	communication
			52	ofi	financial services nec
			53	isr	insurance
			54	obs	business services nec
			55	ros	recreational and other service
			56	osg	public admin. and defence, edu
			57	dwe	ownership of dwellings

Table 2 : regional aggregation of GTAPE-L

GTAPE-L sectors			GTAP version 5 sectors		
No.		Description	No.	Code	Description
1	USA	United States	19	USA	United States
2	EU	European Union	31	AUT	Austria
			32	BEL	Belgium
			33	DNK	Denmark
			34	FIN	Finland
			35	FRA	France
			36	DEU	Germany
			37	GBR	United Kingdom
			38	GRC	Greece
			39	IRL	Ireland
			40	ITA	Italy
			41	LUX	Luxembourg
			42	NLD	Netherlands
			43	PRT	Portugal
			44	ESP	Spain
			45	SWE	Sweden
3	RoA1	Oth. Annex 1 countries	1	AUS	Australia
			2	NZL	New Zealand
			5	JPN	Japan
			18	CAN	Canada
			46	CHE	Switzerland
			47	XEF	rest of EFTA
			48	HUN	Hungary
			49	POL	Poland
			50	XCE	rest of Central European Assoc
			51	XSU	former Soviet Union
4	CHIND	China and India	3	CHN	China
			15	IND	India
5	RoW	Rest of the World	4	HKG	Hong Kong
			6	KOR	Korea, Republic of
			7	TWN	Taiwan
			8	IDN	Indonesia
			9	MYS	Malaysia
			10	PHL	Philippines
			11	SGP	Singapore
			12	THA	Thailand
			13	VNM	Viet Nam
			14	BGD	Bangladesh
			16	LKA	Sri Lanka
			17	XSA	rest of South Asia
			20	MEX	Mexico
			21	XCM	Central America and Caribbean
			22	COL	Colombia
			23	PER	Peru
			24	VEN	Venezuela
			25	XAP	rest of Andean Pact
			26	ARG	Argentina
			27	BRA	Brazil
			28	CHL	Chile
			29	URY	Uruguay
			30	XSM	rest of South America
			52	TUR	Turkey
			53	XME	rest of Middle East
			54	MAR	Morocco
			55	XNF	rest of North Africa
			56	BWA	Botswana
			57	XSC	rest of SACU
			58	MWI	Malawi
			59	MOZ	Mozambique
			60	TZA	Tanzania, United Republic of
			61	ZMB	Zambia
			62	ZWE	Zimbabwe
			63	XSF	rest of southern Africa
			64	UGA	Uganda
			65	XSS	rest of sub-Saharan Africa
			66	XRW	rest of world

Figure 3 : Tree-structured production function in GTAPE-L

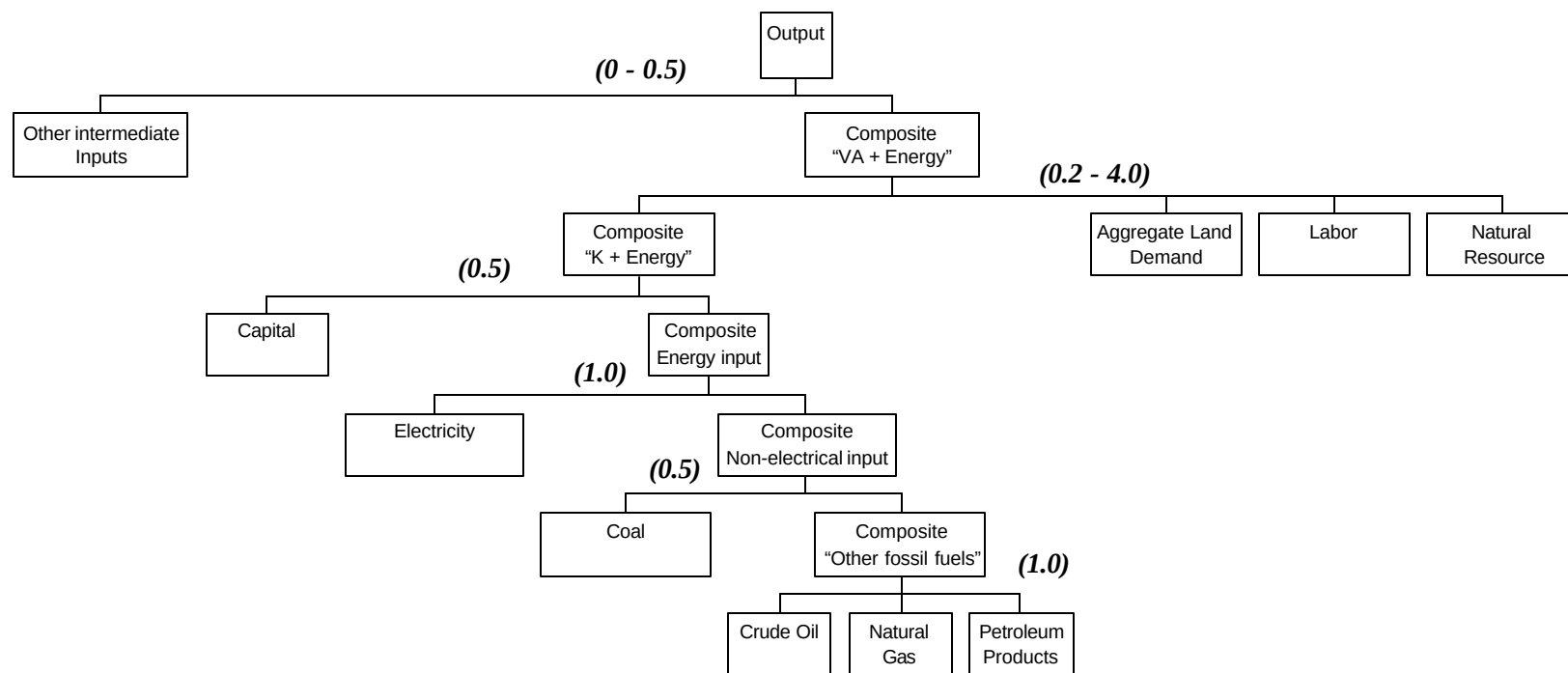


Figure 4 : nesting of nitrous oxide emissions in GTAPE-L.

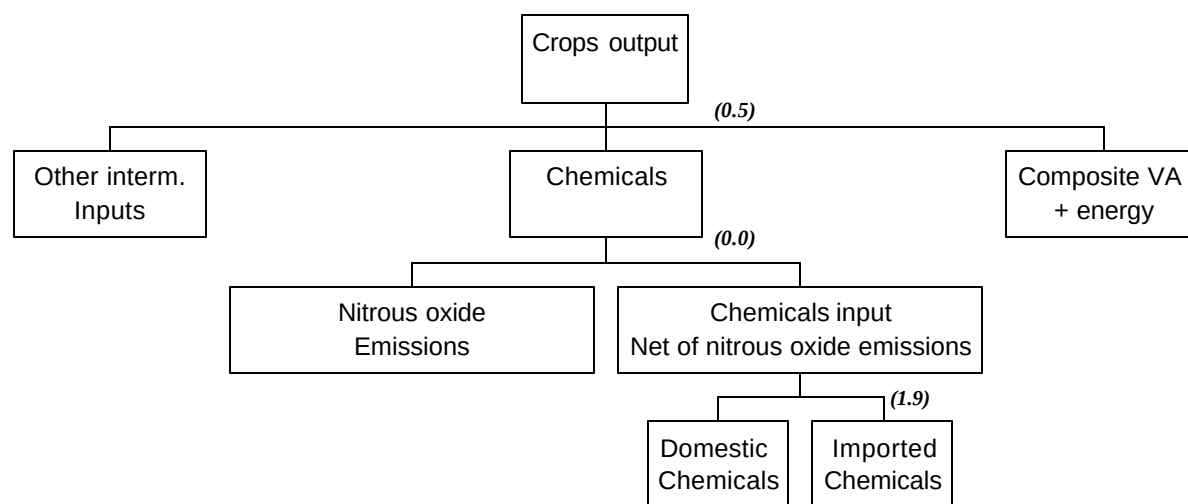


Figure 5 : Structure of the land market in GTAPE-L.

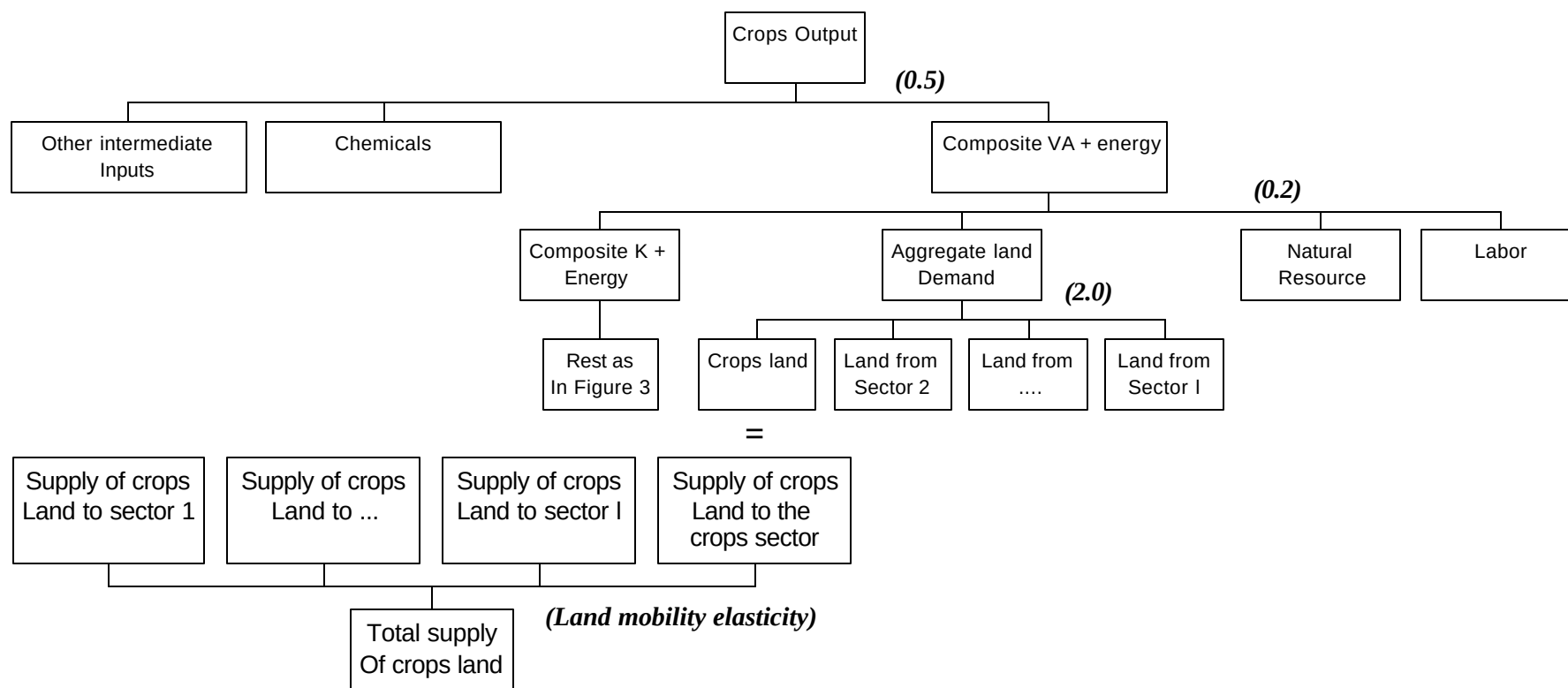


Table 3 : Values of the substitution elasticities for various non-CO2 emission sources

Sources	Values of the CES substitution elasticities
methane emissions from livestock production	0.062
methane emissions from rice cultivation	0.08
methane emissions from coal mining	0.2
methane emissions from natural gas systems	0.12
nitrous oxide emissions from crops	0

Notes : the same elasticity values are used in all regions of the model.
all substitution elasticities related to land uses are equal to zero.

Figure 6 : a land transition matrix

		Sectors that are using land					initial land allocation
		sector 1	...	sector j	...	sector n	
Sectors from which land originates	sector 1	$lnd_{1,1}$	...	$lnd_{1,j}$	...	$lnd_{1,n}$	$\sum_j lnd_{1,j}$
	...	...		...			...
	sector i	$lnd_{i,1}$	...	$lnd_{i,j}$	...	$lnd_{i,n}$	$\sum_j lnd_{i,j}$
	...	...		...			...
	sector n	$lnd_{n,1}$	...	$lnd_{n,j}$	...	$lnd_{n,n}$	$\sum_j lnd_{n,j}$
final land allocation		$\sum_i lnd_{i,1}$	...	$\sum_i lnd_{i,j}$	...	$\sum_i lnd_{i,n}$	$\sum_i \sum_j lnd_{i,j}$

Table 4 : land transitions in 1995 (km² per year)

Table 4.1 : United States

	Crops	Livestock	Forestry	Others	Total
Crops	3797322		91446	2431	3888768
Livestock		285817			285817
Forestry			2554746		2554746
Others				2372221	2372221
Total	3797322	285817	2646192	2374652	

Table 4.2 : European Union

	Crops	Livestock	Forestry	Others	Total
Crops	1267324		50222	342	1317546
Livestock		165669			165669
Forestry			1770616		1770616
Others				345626	345626
Total	1267324	165669	1820838	345968	

Table 5 : emissions from land uses in 1995 (million tons of Ceq per year)

Table 5.1 : United States

	Crops	Livestock	Forestry	Others	Total
Crops				-1.9	-1.9
Livestock					0.0
Forestry			4.4		4.4
Others					0.0
Total	0.0	0.0	2.5	0.0	2.5

Table 5.2 : European Union

	Crops	Livestock	Forestry	Others	Total
Crops				-5.2	-5.2
Livestock					0.0
Forestry			3.9		3.9
Others					0.0
Total	0.0	0.0	-1.3	0.0	-1.3

Table 6 : emission rates in 1995 (tons of Ceq per km²,year)

Table 6.1 : United States

	Crops	Livestock	Forestry	Others
Crops	0.0	0.0	-20.8	0.0
Livestock	0.0	0.0	0.0	0.0
Forestry	0.0	0.0	1.7	0.0
Others	0.0	0.0	0.0	0.0

Table 6.2 : European Union

	Crops	Livestock	Forestry	Others
Crops	0.0	0.0	-103.5	0.0
Livestock	0.0	0.0	0.0	0.0
Forestry	0.0	0.0	2.2	0.0
Others	0.0	0.0	0.0	0.0

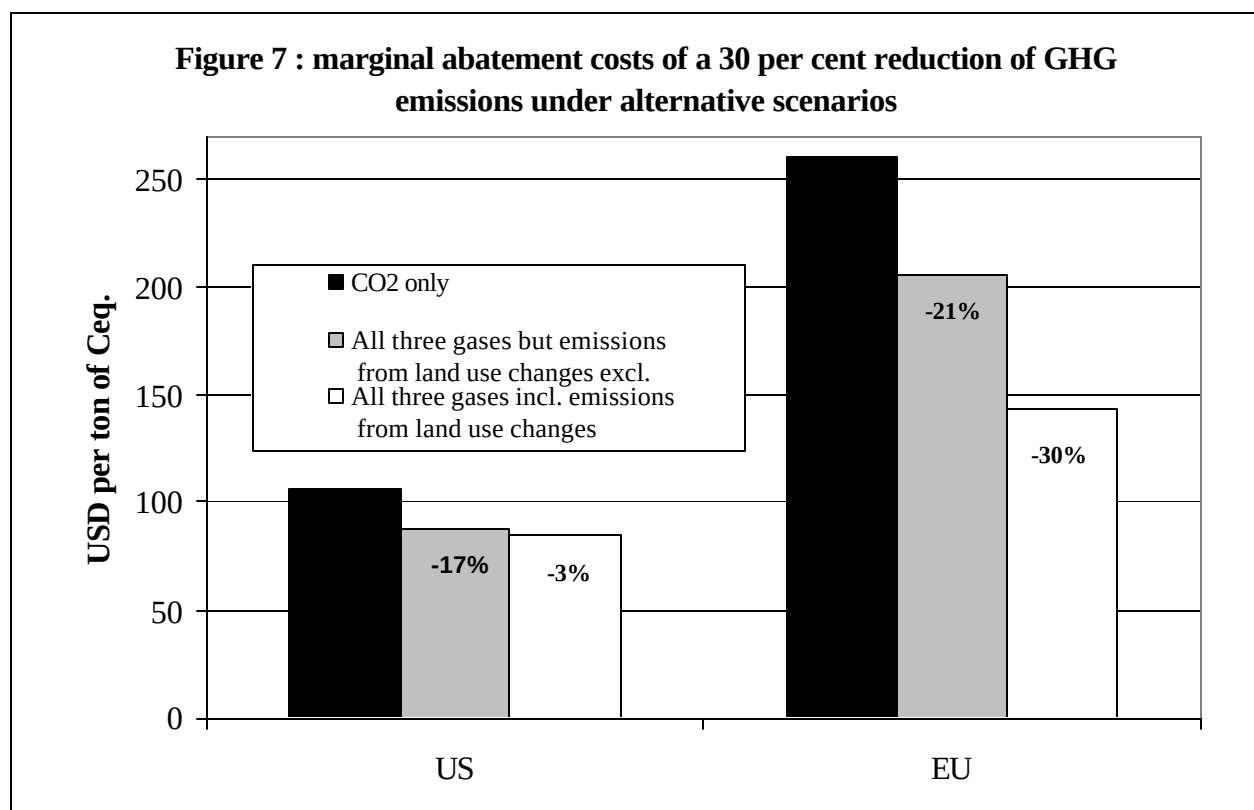
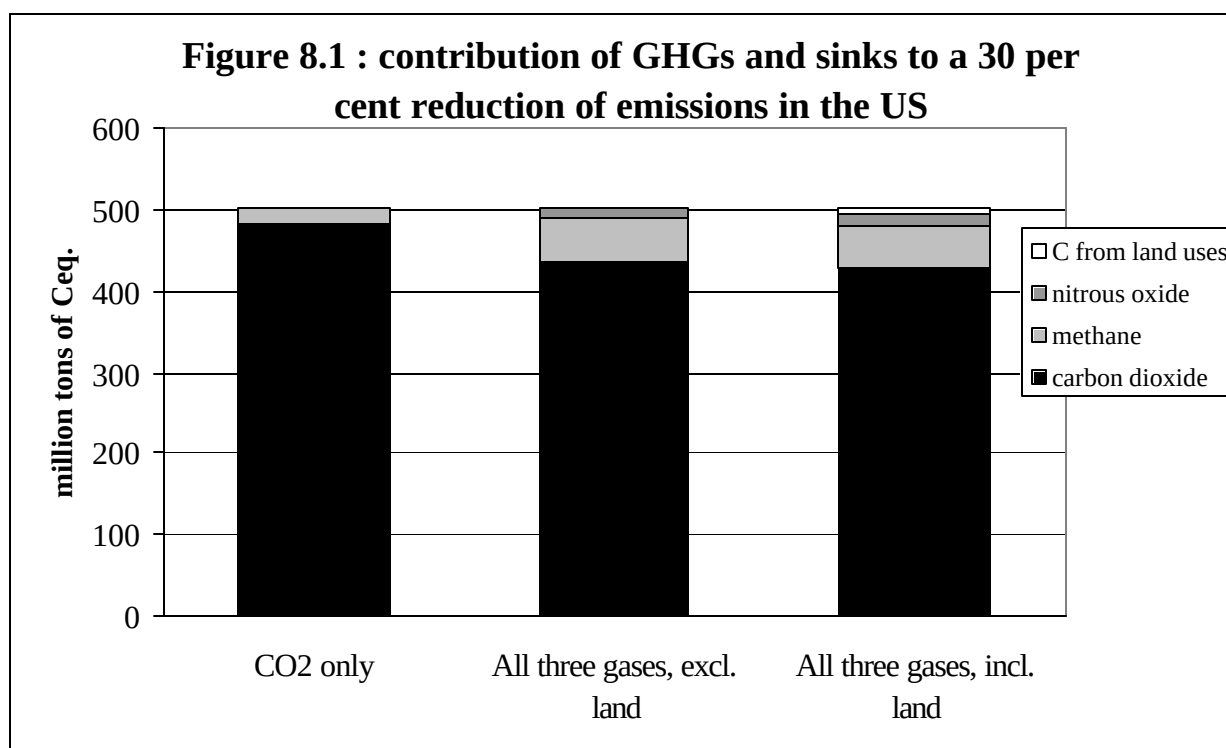


Table 7 : Macro-economic costs of a 30 per cent reduction of all GHG emissions under various alternative scenarios (percentage changes of households utility per capita)

	US	EU
CO ₂ only	-0.30	-1.61
All three gases but emissions from land use changes excl.	-0.24	-1.31
Cost reduction (%)	-20%	-19%
All three gases incl. Emissions from land use changes	-0.24	-0.89
Cost reduction (%)	-4%	-32%



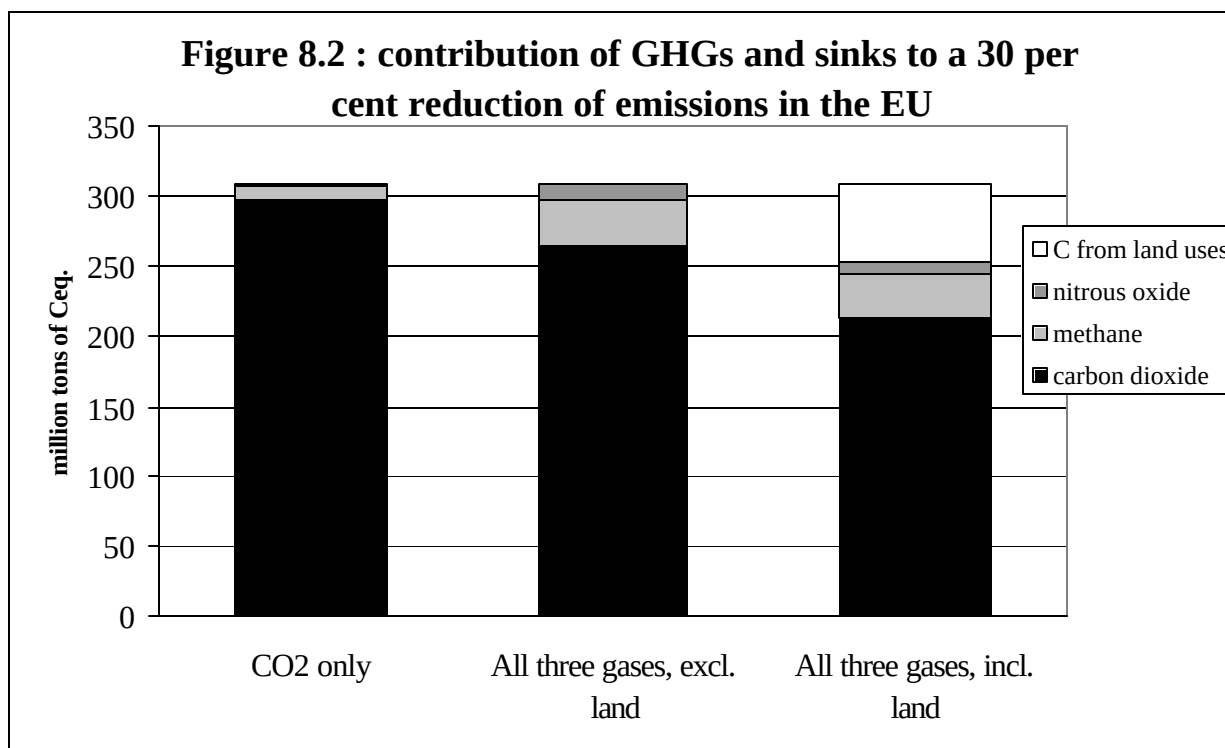


Table 8 : Output and price changes under various scenarios of a 30 per cent abatement of total emissions in the US and the EU (in percentage).

	CO ₂ only		All three gases, excl. land emissions		All three gases, incl. land emissions	
	US	EU	US	EU	US	EU
Output changes						
Rice	-5.5	-4.5	-23.3	-33.3	-22.6	-19.7
Crops	-2.1	-0.7	-4.1	-3.1	-4.4	-3.0
Livestock	-0.8	-0.6	-1.3	-1.2	-1.3	-0.8
Forestry	-0.7	-0.3	-0.4	0.0	1.3	2.5
Coal	-42.1	-55.1	-39.5	-55.7	-38.6	-48.7
Oil	-6.8	-5.1	-5.6	-4.2	-5.0	-3.8
Gas	-29.2	-34.9	-28.1	-35.9	-27.4	-28.1
Oil_Pcts	-21.7	-13.3	-18.7	-10.7	-18.3	-7.3
Electricity	-6.6	-11.4	-5.9	-10.1	-5.8	-8.1
Chemicals	-2.8	-3.7	-2.8	-3.6	-2.9	-2.4
Oth_ind_ser	-0.3	-0.6	-0.3	-0.5	-0.2	-0.3
Price changes⁽¹⁾						
crops land	-6.8	-1.4	-7.5	-2.0	-2.9	37.1
crops output	2.8	1.5	6.2	6.1	6.4	5.9
forestry output	1.0	0.0	1.0	0.0	-1.6	-4.0

(1) equilibrium market prices, excluding carbon taxes/subsidies.

Table 9 : land value-added reallocation in the scenario implying carbon sequestration (percentage changes)

	US	EU
Crops	-1.2%	-6.5%
Livestock	0.0%	0.0%
Forestry	15.7%	38.7%
Others	0.0%	0.0%

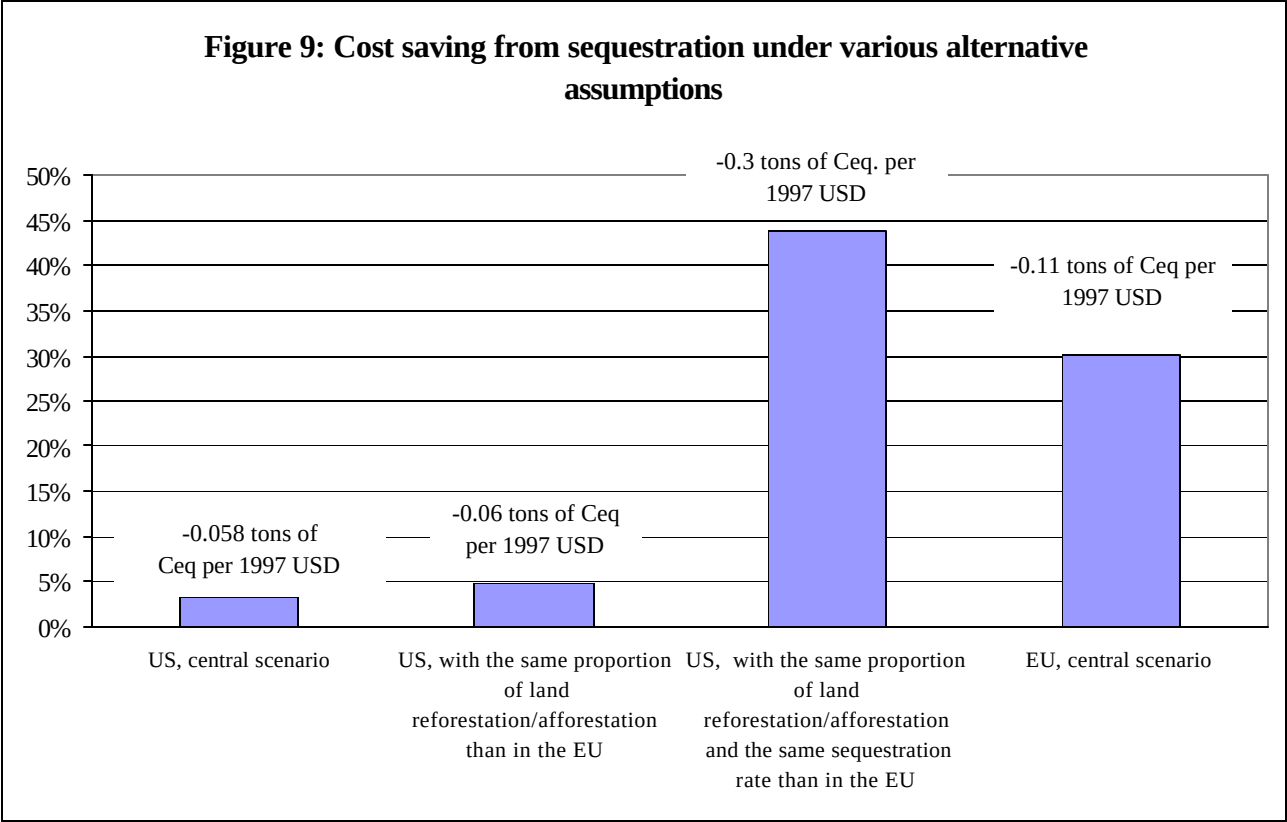


Table 10 : carbon sequestration and land mobility in the context of a 30 percent reduction of GHG emissions in the US

Scenario	value of the CET elasticity for land	marginal abatement cost (USD per ton of Ceq.)	net sinks (million tons of Ceq)
All three gases, excl. emissions from land uses	1	88	1
All three gases, incl. emissions from land uses; low land mobility	0.2	87	1
All three gases, incl. emissions from land uses; medium land mobility	1	85	8
All three gases, incl. emissions from land uses; land mobility calibrated on Gillig and al.	5	53	129
All three gases, incl. emissions from land uses; land fully mobile	infinite	24	287

Table 11 : Cost saving from sequestration under alternative transition patterns and policies (percentage changes of marginal abatement costs resulting from the inclusion of land emissions).

	US	EU
Central scenario; including only land use changes	-3.2%	-30.1%
Assuming deforestation ⁽¹⁾ ; including only land use changes	-3.4%	-34.8%
Assuming deforestation; all land uses including land that does not change status ⁽²⁾	-3.5%	-34.8%

(1) with a positive emission rate twice as high as the sequestration rate of reforestation/afforestation

(2) assuming that full grown forests (land that remains permanently covered with forest) are sinks.

Figure 1 : Marginal abatement curve for methane emissions from manure management in the US

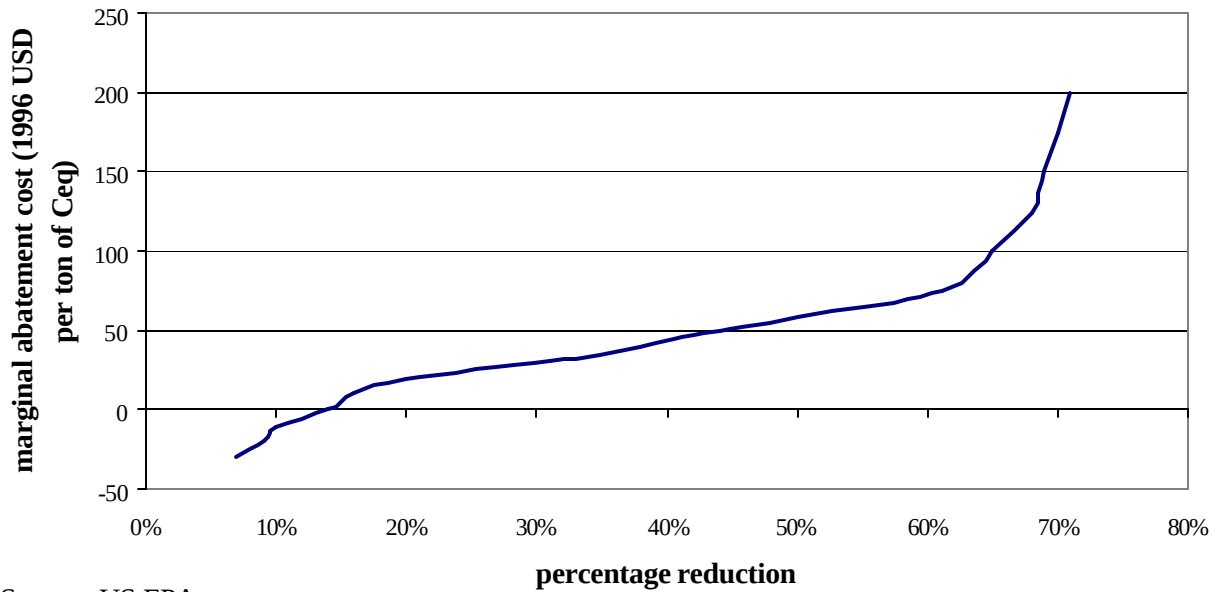


Figure 2 : Incorporating GHGs into the production function.

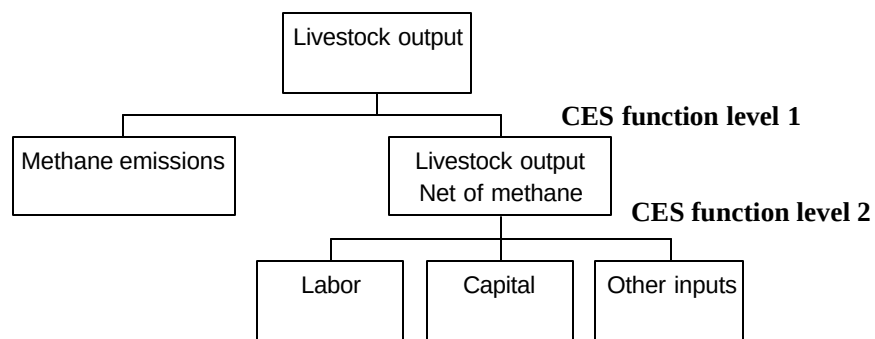


Table 1 : Sectoral aggregation of GTAPE-L.

GTAPE-L sectors			GTAP version 5 sectors		
No.		Description	No.	Code	Description
1	Rice	Rice	1	pdr	paddy rice
2	Crops	Primary agriculture and fishing	2	wht	wheat
			3	gro	cereal grains nec
			4	v_f	vegetables, fruit, nuts
			5	osd	oil seeds
			6	c_b	sugar cane, sugar beet
			7	pfb	plant-based fibers
			8	ocr	crops nec
			14	fsh	fishing
3	Livestock	Livestock products	9	ctl	bovine cattle, sheep and goats
			10	oap	animal products nec
			11	rmk	raw milk
			12	wol	wool, silk-worm cocoons
4	Forestry	Forestry	13	for	forestry
5	Coal	Coal Mining	15	col	coal
6	Oil	Crude oil	16	oil	oil
7	Gas	Natural gas extraction	17	gas	gas
			44	gdt	gas manufacture, distribution
8	Oil_Pcts	Refined oil products	32	p_c	petroleum, coal products
9	Electricity	Electricity	43	ely	electricity
10	Oth_ind_ser	Other industries and services	18	omn	minerals nec
			19	cmt	bovine cattle, sheep and goat
			20	omt	meat products
			21	vol	vegetable oils and fats
			22	mil	dairy products
			23	pcr	processed rice
			24	sgr	sugar
			25	ofd	food products nec
			26	b_t	beverages and tobacco products
			27	tex	textiles
			28	wap	wearing apparel
			29	lea	leather products
			30	lum	wood products
			31	ppp	paper products, publishing
			33	crp	chemical, rubber, plastic prod
			34	nmn	mineral products nec
			35	i_s	ferrous metals
			36	nfm	metals nec
			37	fmp	metal products
			38	mvh	motor vehicles and parts
			39	otn	transport equipment nec
			40	ele	electronic equipment
			41	ome	machinery and equipment nec
			42	omf	manufactures nec
			45	wtr	water
			46	cns	construction
			47	trd	trade
			48	otp	transport nec
			49	wtp	water transport
			50	atp	air transport
			51	cmn	communication
			52	ofi	financial services nec
			53	isr	insurance
			54	obs	business services nec
			55	ros	recreational and other service
			56	osg	public admin. and defence, edu
			57	dwe	ownership of dwellings

Table 2 : regional aggregation of GTAPE-L

GTAPE-L sectors			GTAP version 5 sectors		
No.		Description	No.	Code	Description
1	USA	United States	19	USA	United States
2	EU	European Union	31	AUT	Austria
			32	BEL	Belgium
			33	DNK	Denmark
			34	FIN	Finland
			35	FRA	France
			36	DEU	Germany
			37	GBR	United Kingdom
			38	GRC	Greece
			39	IRL	Ireland
			40	ITA	Italy
			41	LUX	Luxembourg
			42	NLD	Netherlands
			43	PRT	Portugal
			44	ESP	Spain
			45	SWE	Sweden
3	RoA1	Oth. Annex 1 countries	1	AUS	Australia
			2	NZL	New Zealand
			5	JPN	Japan
			18	CAN	Canada
			46	CHE	Switzerland
			47	XEF	rest of EFTA
			48	HUN	Hungary
			49	POL	Poland
			50	XCE	rest of Central European Assoc
			51	XSU	former Soviet Union
4	CHIND	China and India	3	CHN	China
			15	IND	India
5	RoW	Rest of the World	4	HKG	Hong Kong
			6	KOR	Korea, Republic of
			7	TWN	Taiwan
			8	IDN	Indonesia
			9	MYS	Malaysia
			10	PHL	Philippines
			11	SGP	Singapore
			12	THA	Thailand
			13	VNM	Viet Nam
			14	BGD	Bangladesh
			16	LKA	Sri Lanka
			17	XSA	rest of South Asia
			20	MEX	Mexico
			21	XCM	Central America and Caribbean
			22	COL	Colombia
			23	PER	Peru
			24	VEN	Venezuela
			25	XAP	rest of Andean Pact
			26	ARG	Argentina
			27	BRA	Brazil
			28	CHL	Chile
			29	URY	Uruguay
			30	XSM	rest of South America
			52	TUR	Turkey
			53	XME	rest of Middle East
			54	MAR	Morocco
			55	XNF	rest of North Africa
			56	BWA	Botswana
			57	XSC	rest of SACU
			58	MWI	Malawi
			59	MOZ	Mozambique
			60	TZA	Tanzania, United Republic of
			61	ZMB	Zambia
			62	ZWE	Zimbabwe
			63	XSF	rest of southern Africa
			64	UGA	Uganda
			65	XSS	rest of sub-Saharan Africa
			66	XRW	rest of world

Figure 3 : Tree-structured production function in GTAPE-L

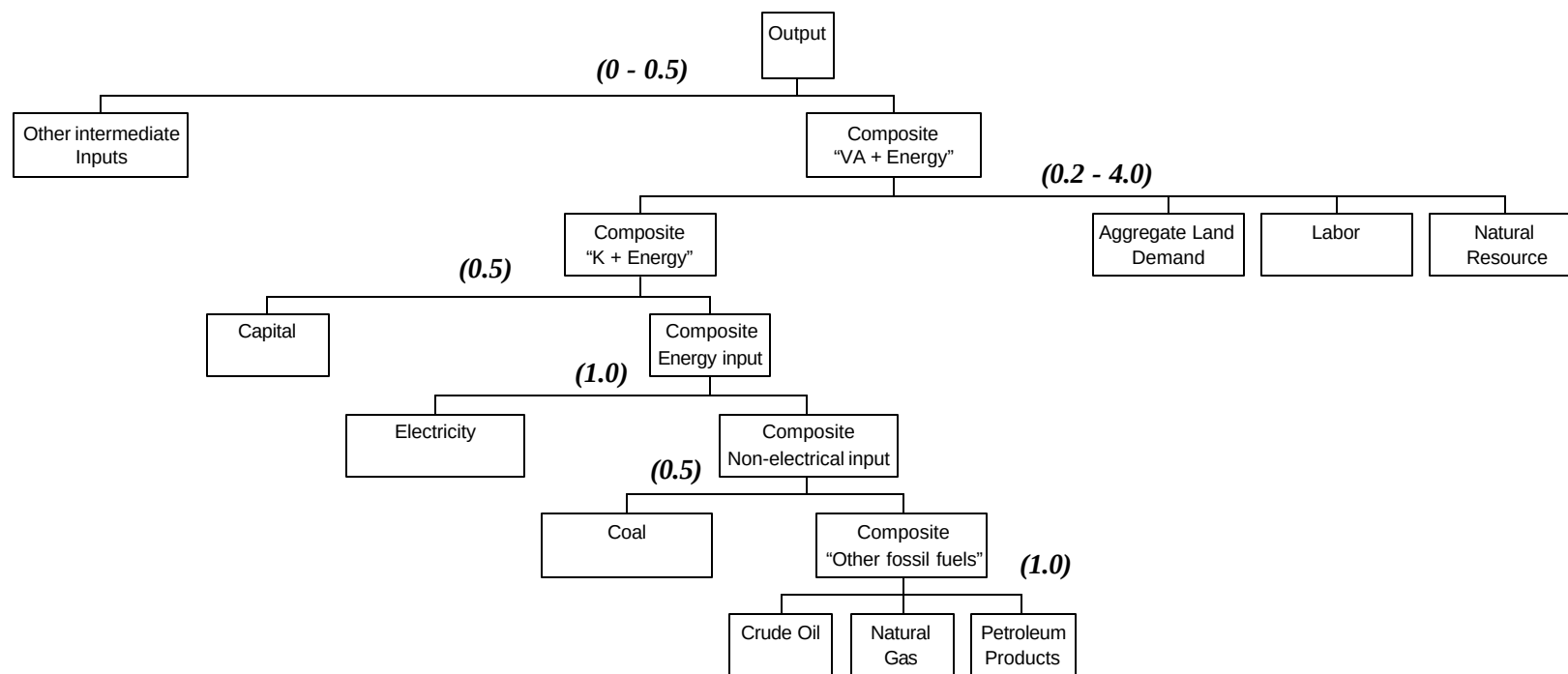


Figure 4 : nesting of nitrous oxide emissions in GTAPE-L.

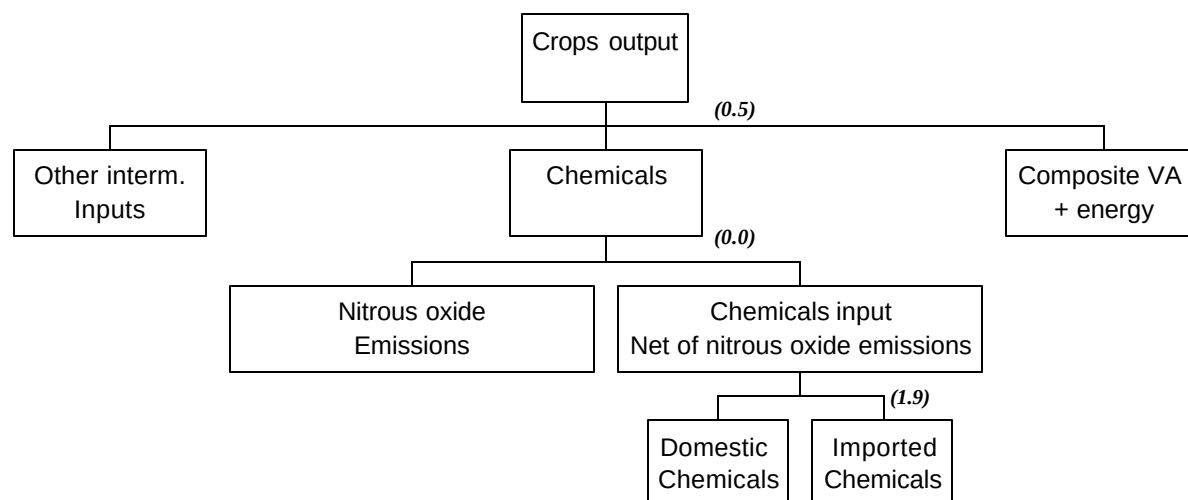


Figure 5 : Structure of the land market in GTAPE-L.

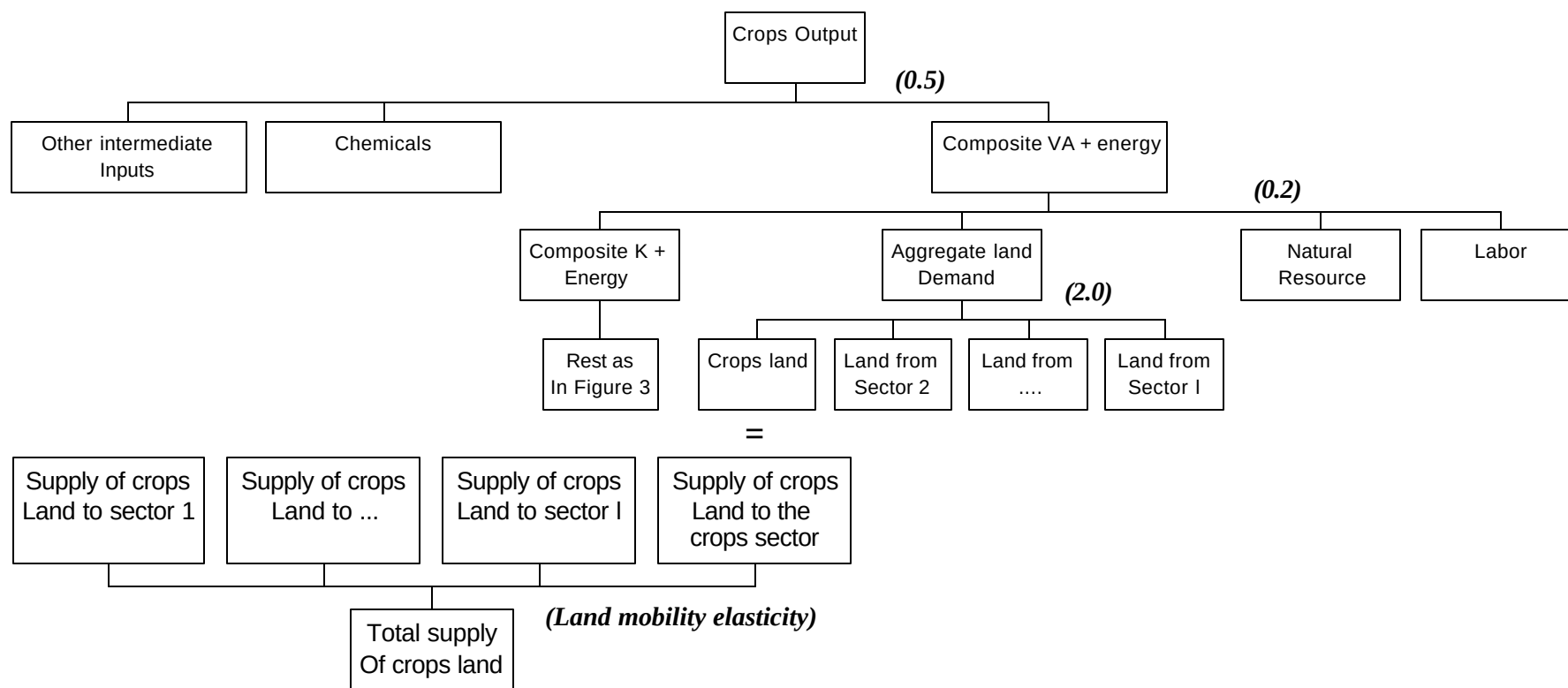


Table 3 : Values of the substitution elasticities for various non-CO2 emission sources

Sources	Values of the CES substitution elasticities
methane emissions from livestock production	0.062
methane emissions from rice cultivation	0.08
methane emissions from coal mining	0.2
methane emissions from natural gas systems	0.12
nitrous oxide emissions from crops	0

Notes : the same elasticity values are used in all regions of the model.
all substitution elasticities related to land uses are equal to zero.

Figure 6 : a land transition matrix

		Sectors that are using land					initial land allocation
		sector 1	...	sector j	...	sector n	
Sectors from which land originates	sector 1	$lnd_{1,1}$	...	$lnd_{1,j}$	...	$lnd_{1,n}$	$\sum_j lnd_{1,j}$
	...	...		...			...
	sector i	$lnd_{i,1}$	...	$lnd_{i,j}$	...	$lnd_{i,n}$	$\sum_j lnd_{i,j}$
	...	...		...			...
	sector n	$lnd_{n,1}$	...	$lnd_{n,j}$	...	$lnd_{n,n}$	$\sum_j lnd_{n,j}$
	final land allocation	$\sum_i lnd_{i,1}$	...	$\sum_i lnd_{i,j}$	...	$\sum_i lnd_{i,n}$	$\sum_i \sum_j lnd_{i,j}$

Table 4 : land transitions in 1995 (km² per year)

Table 4.1 : United States

	Crops	Livestock	Forestry	Others	Total
Crops	3797322		91446	2431	3888768
Livestock		285817			285817
Forestry			2554746		2554746
Others				2372221	2372221
Total	3797322	285817	2646192	2374652	

Table 4.2 : European Union

	Crops	Livestock	Forestry	Others	Total
Crops	1267324		50222	342	1317546
Livestock		165669			165669
Forestry			1770616		1770616
Others				345626	345626
Total	1267324	165669	1820838	345968	

Table 5 : emissions from land uses in 1995 (million tons of Ceq per year)

Table 5.1 : United States

	Crops	Livestock	Forestry	Others	Total
Crops				-1.9	-1.9
Livestock					0.0
Forestry			4.4		4.4
Others					0.0
Total	0.0	0.0	2.5	0.0	2.5

Table 5.2 : European Union

	Crops	Livestock	Forestry	Others	Total
Crops				-5.2	-5.2
Livestock					0.0
Forestry			3.9		3.9
Others					0.0
Total	0.0	0.0	-1.3	0.0	-1.3

Table 6 : emission rates in 1995 (tons of Ceq per km²,year)

Table 6.1 : United States

	Crops	Livestock	Forestry	Others
Crops	0.0	0.0	-20.8	0.0
Livestock	0.0	0.0	0.0	0.0
Forestry	0.0	0.0	1.7	0.0
Others	0.0	0.0	0.0	0.0

Table 6.2 : European Union

	Crops	Livestock	Forestry	Others
Crops	0.0	0.0	-103.5	0.0
Livestock	0.0	0.0	0.0	0.0
Forestry	0.0	0.0	2.2	0.0
Others	0.0	0.0	0.0	0.0

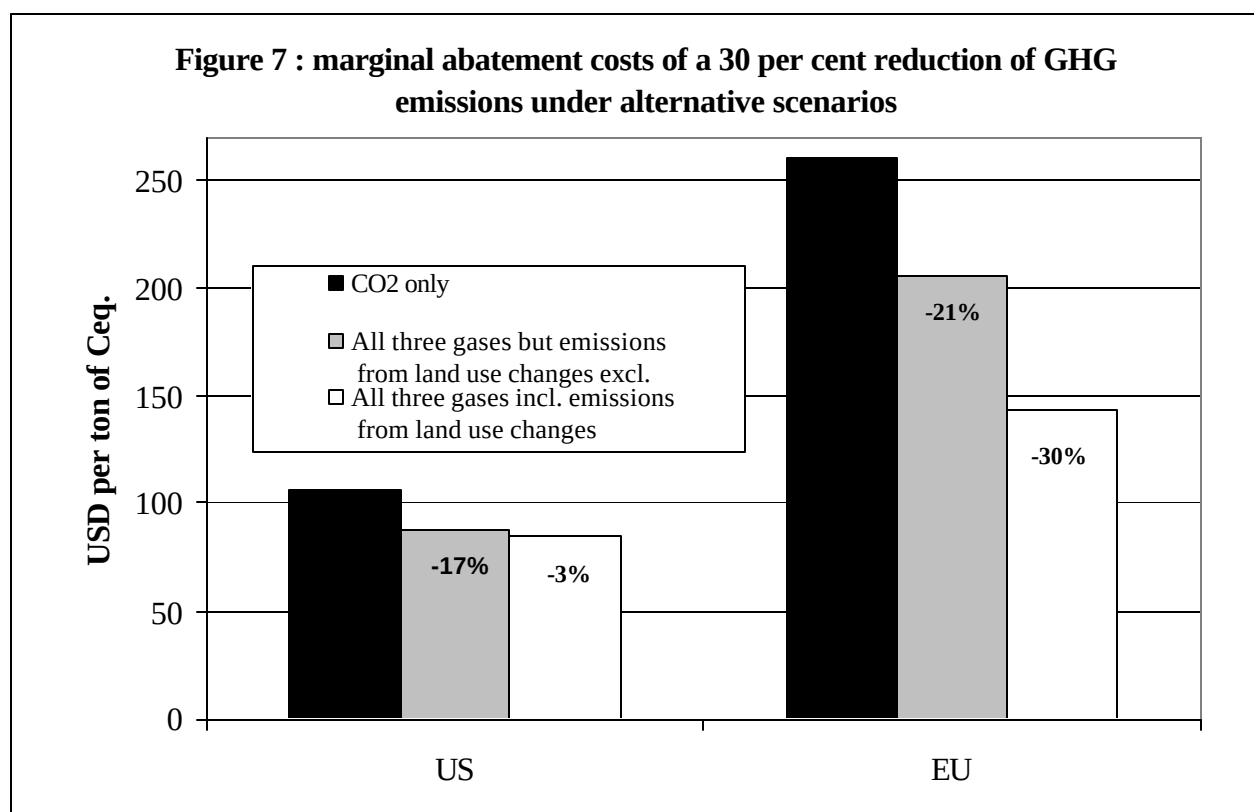
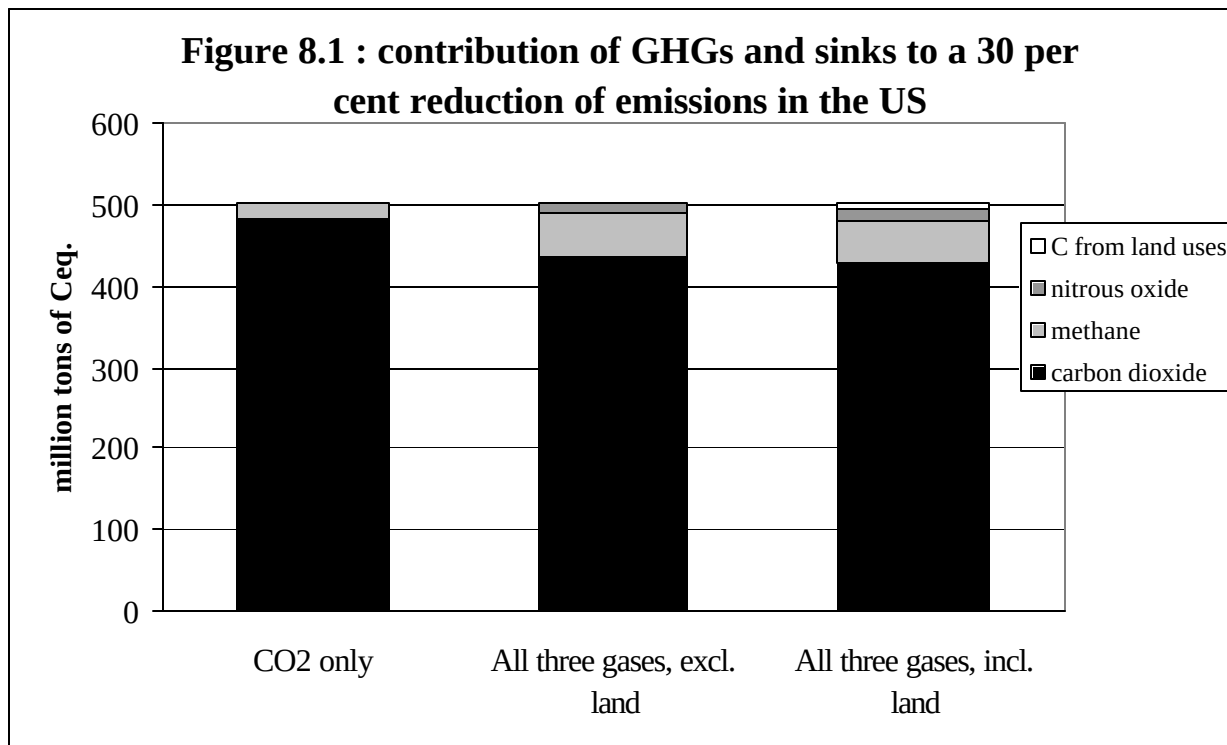


Table 7 : Macro-economic costs of a 30 per cent reduction of all GHG emissions under various alternative scenarios (percentage changes of households utility per capita)

	US	EU
CO ₂ only	-0.30	-1.61
All three gases but emissions from land use changes excl.	-0.24	-1.31
Cost reduction (%)	-20%	-19%
All three gases incl. Emissions from land use changes	-0.24	-0.89
Cost reduction (%)	-4%	-32%



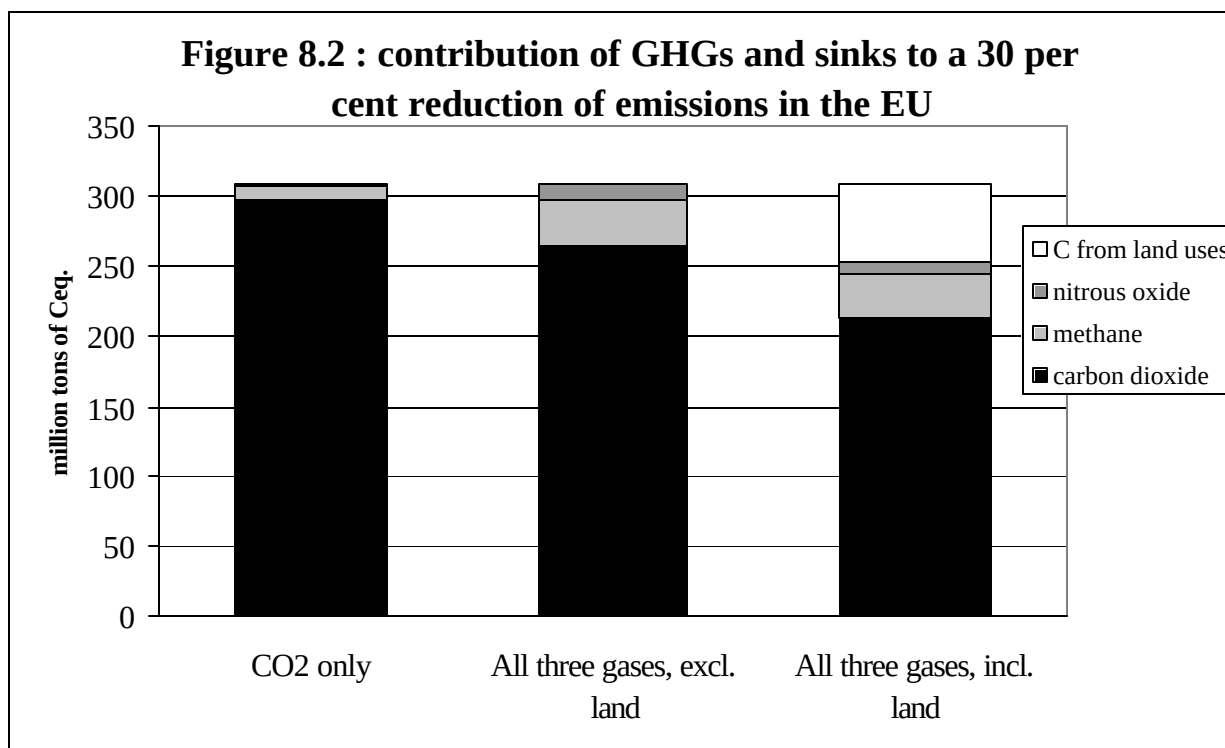


Table 8 : Output and price changes under various scenarios of a 30 per cent abatement of total emissions in the US and the EU (in percentage).

	CO ₂ only		All three gases, excl. land emissions		All three gases, incl. land emissions	
	US	EU	US	EU	US	EU
Output changes						
Rice	-5.5	-4.5	-23.3	-33.3	-22.6	-19.7
Crops	-2.1	-0.7	-4.1	-3.1	-4.4	-3.0
Livestock	-0.8	-0.6	-1.3	-1.2	-1.3	-0.8
Forestry	-0.7	-0.3	-0.4	0.0	1.3	2.5
Coal	-42.1	-55.1	-39.5	-55.7	-38.6	-48.7
Oil	-6.8	-5.1	-5.6	-4.2	-5.0	-3.8
Gas	-29.2	-34.9	-28.1	-35.9	-27.4	-28.1
Oil_Pcts	-21.7	-13.3	-18.7	-10.7	-18.3	-7.3
Electricity	-6.6	-11.4	-5.9	-10.1	-5.8	-8.1
Chemicals	-2.8	-3.7	-2.8	-3.6	-2.9	-2.4
Oth_ind_ser	-0.3	-0.6	-0.3	-0.5	-0.2	-0.3
Price changes⁽¹⁾						
crops land	-6.8	-1.4	-7.5	-2.0	-2.9	37.1
crops output	2.8	1.5	6.2	6.1	6.4	5.9
forestry output	1.0	0.0	1.0	0.0	-1.6	-4.0

(1) equilibrium market prices, excluding carbon taxes/subsidies.

Table 9 : land value-added reallocation in the scenario implying carbon sequestration (percentage changes)

	US	EU
Crops	-1.2%	-6.5%
Livestock	0.0%	0.0%
Forestry	15.7%	38.7%
Others	0.0%	0.0%

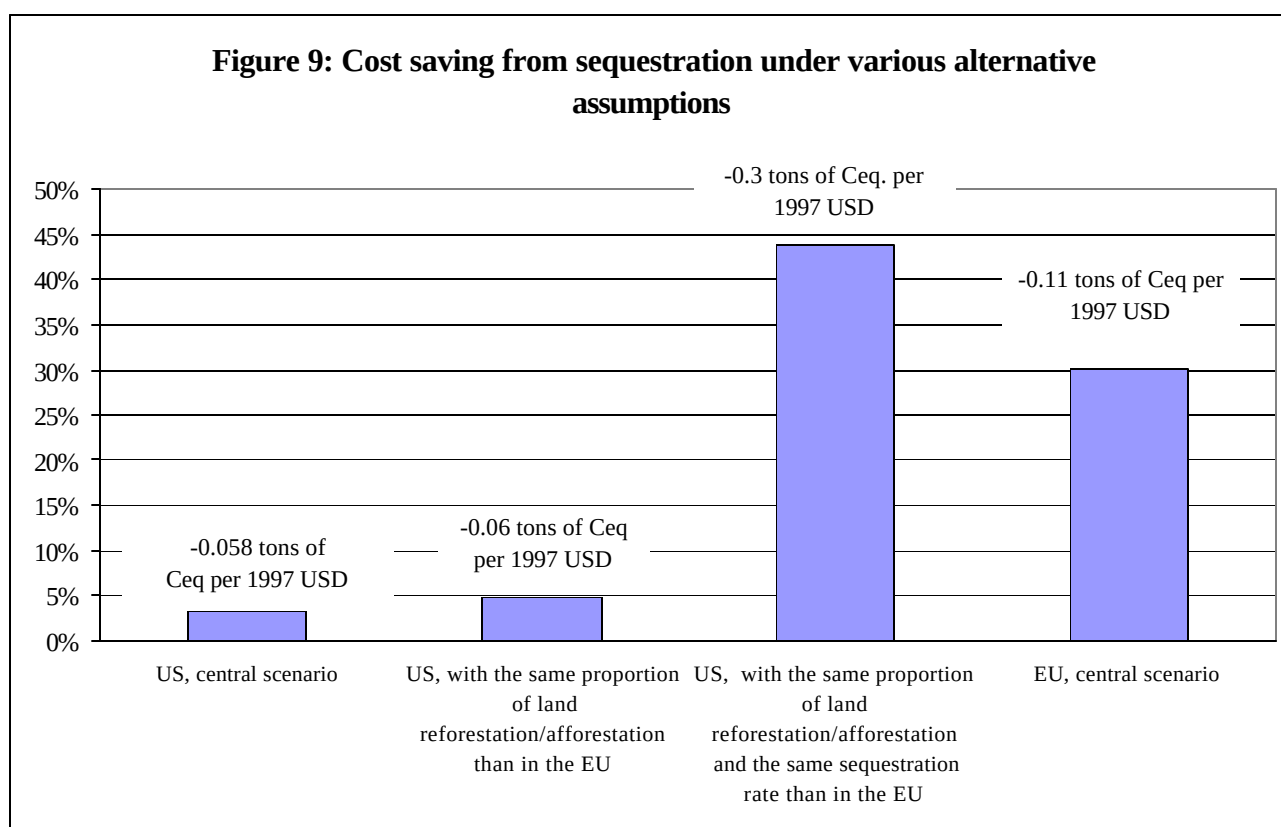


Table 10 : carbon sequestration and land mobility in the context of a 30 percent reduction of GHG emissions in the US

Scenario	value of the CET elasticity for land	marginal abatement cost (USD per ton of Ceq.)	net sinks (million tons of Ceq)
All three gases, excl. emissions from land uses	1	88	1
All three gases, incl. emissions from land uses; low land mobility	0.2	87	1
All three gases, incl. emissions from land uses; medium land mobility	1	85	8
All three gases, incl. emissions from land uses; land mobility calibrated on Gillig and al.	5	53	129
All three gases, incl. emissions from land uses; land fully mobile	infinite	24	287

Table 11 : Cost saving from sequestration under alternative transition patterns and policies (percentage changes of marginal abatement costs resulting from the inclusion of land emissions).

	US	EU
Central scenario; including only land use changes	-3.2%	-30.1%
Assuming deforestation ⁽¹⁾ ; including only land use changes	-3.4%	-34.8%
Assuming deforestation; all land uses including land that does not change status ⁽²⁾	-3.5%	-34.8%

(1) with a positive emission rate twice as high as the sequestration rate of reforestation/afforestation

(2) assuming that full grown forests (land that remains permanently covered with forest) are sinks.

7. Annex 1 : MACs calibration

7.1. *Methane emissions from livestock production*

7.1.1. Methane emissions from enteric fermentation:

Methane emissions from enteric fermentation can be reduced mainly by increasing the animal productivity (sound nutritive and veterinary practices, improved grazing management – such as intensive grazing - , artificial insemination, use of production enhancing agents). Trade and pricing policy reforms, to the extent that they increase productivity, may also contribute to lower methane emissions.

The reduction potential for dairy methane emissions is calculated assuming that the combined effect of milk productivity growth (300 pounds of milk per cow per year), a high rate of adoption of recombinant bST (bovine Somatotropin : a production enhancing agent) and multiple-component pricing (a pricing system of milk in which not only the butterfat content but also other components, such as protein, are reflected in the price) reduces emissions in 2020 from 9.91 million tons of Ceq. to 8.48 million tons of Ceq (EPA, 1999, p.6.8, exhibit 6-5). The reduction potential for methane emissions from beef cattle corresponds to the EPA medium emissions scenario assuming that, by 2015, the calving rate (the proportion of calves born from the total number of mature cows) has increased up to 85 per cent while the two year old heifer calving rate has increased to 75 percent. The growth-to-slaughter phase in the medium emissions baseline scenario is 20 per cent weanling/80 per cent yearling. This ratio is assumed to change to 50/50 per cent by 2010. The resulting emission reduction in 2020 is from 27.3 million tons of Ceq. down to 25 million tons of Ce. (EPA, 1999, p.6-1, exhibit 6-7). All together, the reduction potential for methane from enteric fermentation does not exceed

10 percent. The corresponding MAC is obtained by exponential extrapolation to this maximum reduction potential²⁰.

7.1.2. Methane emissions from manure management

The only feasible way to reduce methane emissions from liquid-based manure systems is to recover the methane before it is emitted in the air. This recovered methane can be flared or used to produce heat or electricity at the farm level. There are three recovery technologies available : covered anaerobic digesters, complete-mix digesters and plug-flow digesters. The EPA evaluated for the US a MAC (EPA, 1999, p. 5-14, exhibit 5-11) taking into account the recovery and utilization option chose and a range of energy prices. Additional information on the EPA methodology can be found in EPA, 1999, p.5-8 - p.5-16.

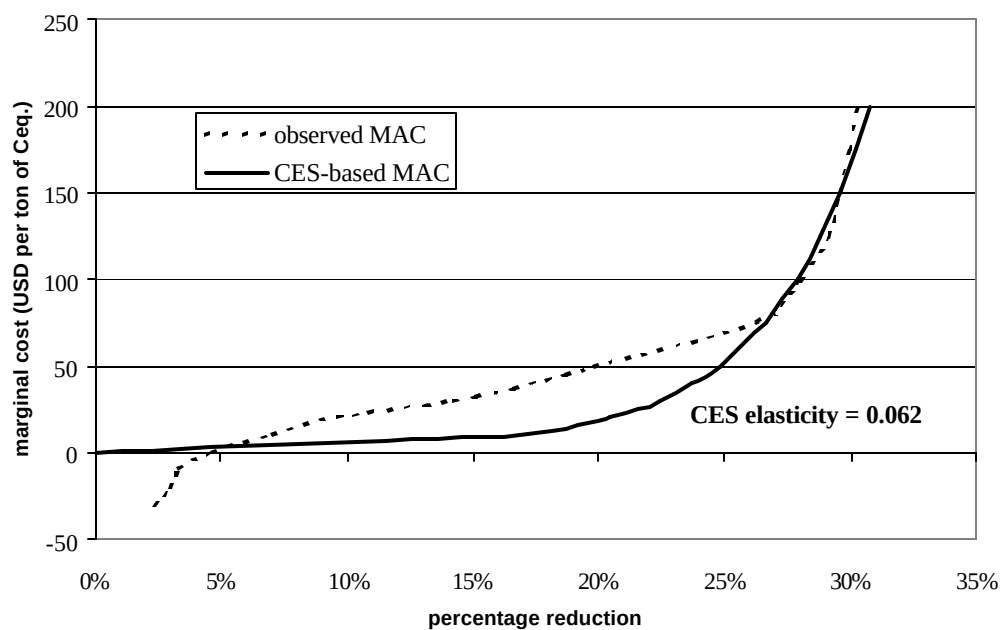
The Figure A1-1 shows the aggregate MAC for the livestock sector and the corresponding best fit for the CES-based MAC (with a CES elasticity equal to .062). For marginal abatement costs below 80 USD per ton of Ceq., the model is likely to overestimate the amount of abatement. The bias is most important for relatively low marginal costs (around 10 USD per ton of Ceq.). For marginal costs above 80 USD per ton of Ceq., the CES-based response fits the EPA MAC very well.

²⁰ Assuming that the “response function” that calculates the emission reduction achieved at a given marginal cost has the following specification (see Burniaux, 2000, p.41):

$$E = E_{MIN} + \left(\tilde{E} - E_{MIN} \right)^{-e.MC}$$

where E is the current level of emissions; E_{MIN} , the minimum emission level under which emissions cannot be reduced further (as given by the maximum reduction potential); $\tilde{E}$, the benchmark emission level (i.e. the level with no restriction); MC, the marginal abatement cost; and e an elasticity the value of which is arbitrary.

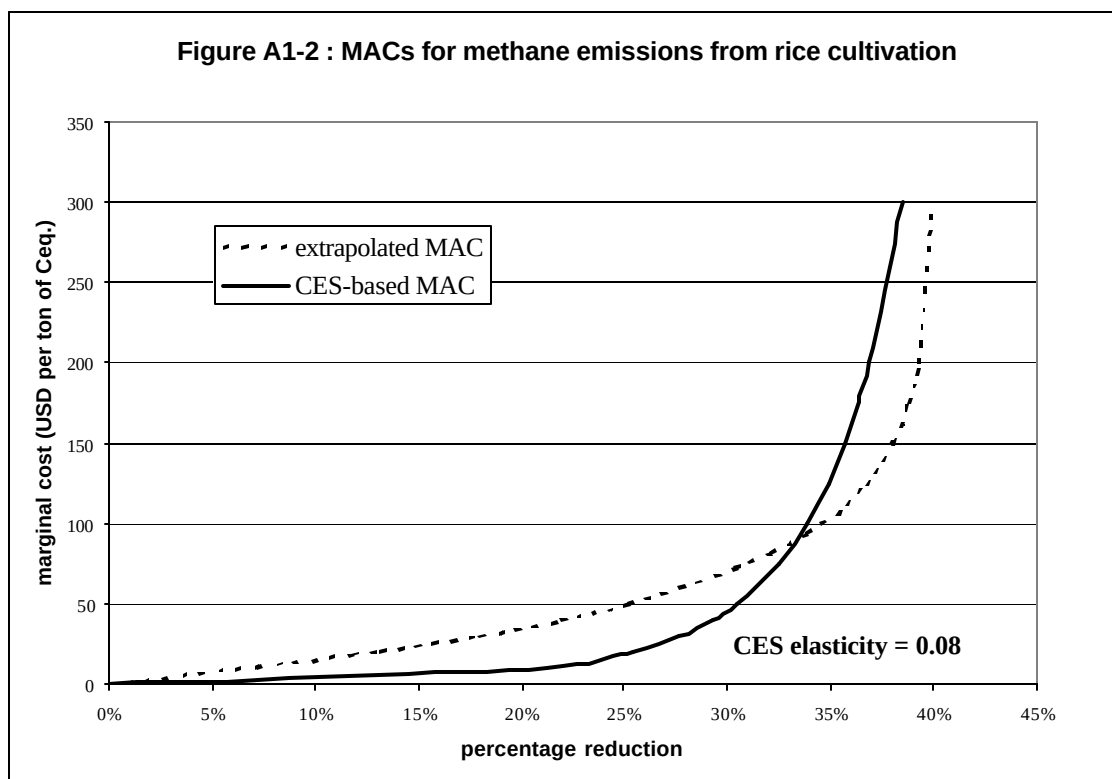
Figure A1-1 : MACs for methane emissions from livestock



7.2. *Methane emissions from rice cultivation*

Methane is generated in flooded paddy fields by the anaerobic decomposition of organic matter in the soil. It reaches the atmosphere mainly through the rice plants vascular system, though some does escape directly into the atmosphere. One possible approach to reduce emissions from rice cultivation is to alter cultivation practices, for instance by shifting to dry rice production. But the dramatic yield drop that would result from such a shift makes this option unacceptable. Alternatively, a careful selection of cultivars to be grown is likely to be the easiest mitigation option. Substituting inorganic fertilizers for the organic fertilizers that are often used could also reduce emissions, though this is likely to induce additional emissions of nitrous oxide. Finally, changes in water management practices could be effective, for instance the period during which fields are flooded. Since in many case it will involve a radical change in agricultural practices, this technique seems difficult to implement.

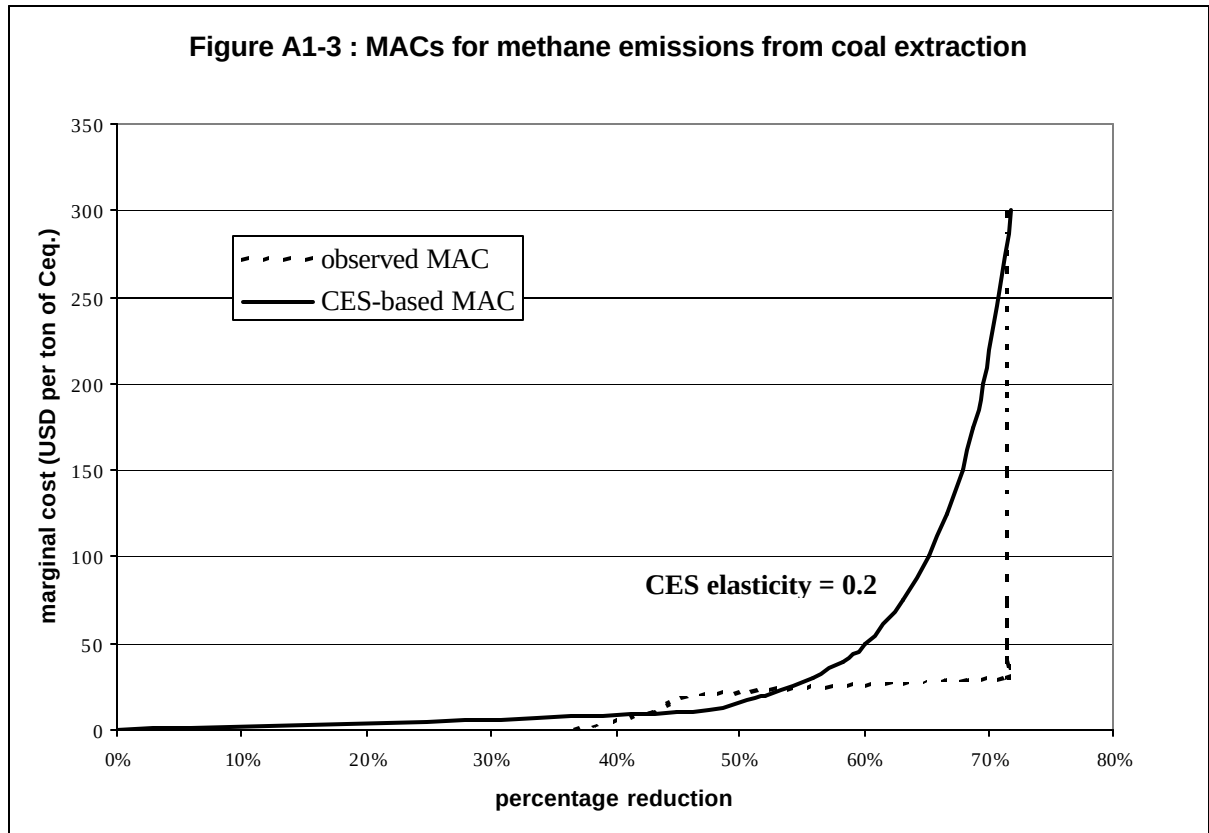
Since the rice production in the US is negligible, the US EPA provides little information on the marginal costs of abating rice fields emissions. A study by the IEA Greenhouse Gas R&D Programme estimates that the reduction potential of all available options amounts to 40 per cent (IEA Greenhouse Gas R&D Programme, 1999, P.38). The following Figure A1-2 compares the MAC that is obtained by exponential extrapolation to this maximum potential (see footnote 1) with the corresponding CES-based MAC with the value of the substitution elasticity equal to 0.08. As for methane emissions from livestock, the CES-based MAC tends to overestimate the magnitude of the abatement for relatively moderate marginal cost ranges.



7.3. Methane emissions from coal mining.

Methane and coal are formed together during a process – called coalification – that transforms plant biomass into coal. The methane that is generated during this process is stored within coal seams and the surrounding strata and is liberated into the atmosphere when the pressure above and surrounding the coalbed is reduced as a result of natural erosion or underground and surface mining. Thus underground mines, surfaces mines and abandoned mines emit methane. Methane emissions from coal mines can be reduced through the implementation of methane recovery. In the US, for instance, the major degasification methods involve vertical wells, longhole and shorthole horizontal boreholes and gob wells. Even where degasification systems are used, mines still emit significant quantities of methane vial ventilation systems. Methane recovered from coalmines can be purchased by natural gas companies or used to generate electricity. The analysis made by the US EPA shows that 37 per cent of the methane emitted by coalmines can be reduced at no cost. The total reduction potential in 2010 would amount to more than 70 per cent (EPA, 1999, p.4-11, exhibit 4-8).

The following Figure A1-3 shows the EPA MAC for methane emissions from coalmines together with the CES demand function for methane emissions that corresponds to a value of the substitution elasticity equal to 0.2.

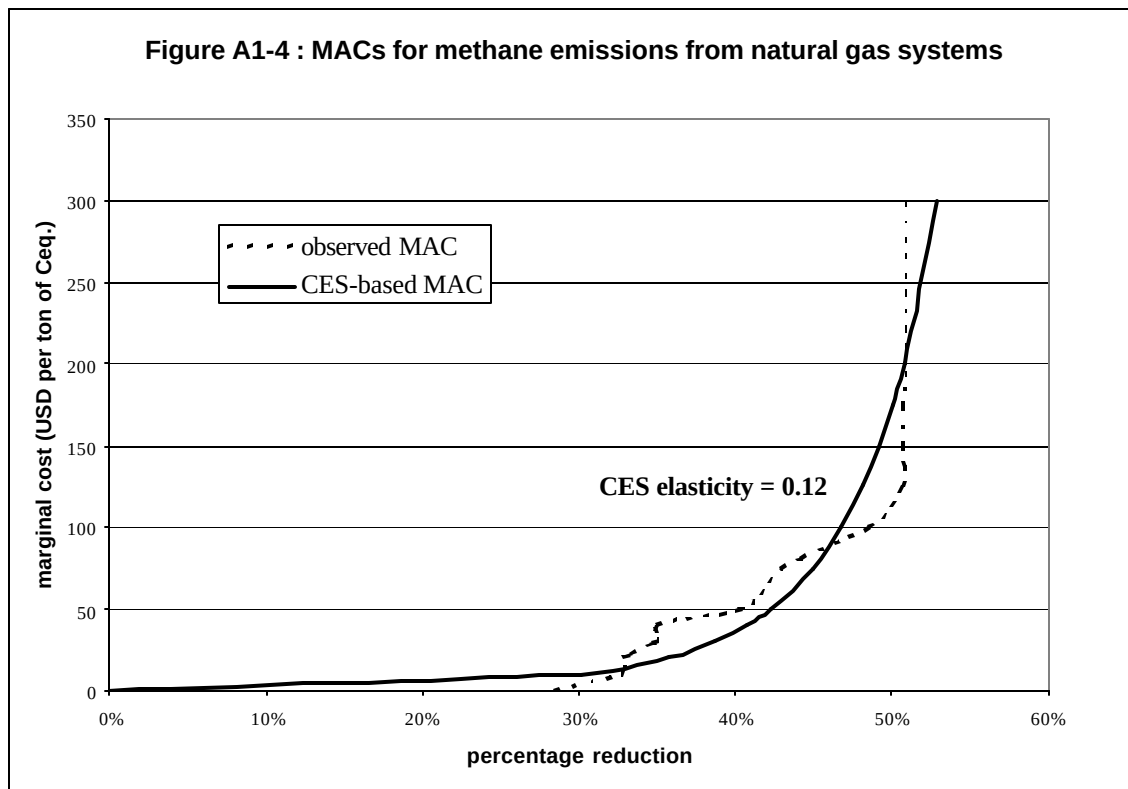


7.4. Methane emissions from gas natural systems

Methane emissions occur during production, processing, transmission and distribution of natural gas. From wellhead to end user, the gas moves through a multitude of valves, processing mechanisms, compressors, pipes and other equipments that let escape small amounts of methane into the atmosphere. In many instances, gas is vented into the atmosphere as part of normal operations. The US EPA and the natural gas

industry have identified several Best Management Practices (BMPs) that are cost-effective in reducing methane emissions. Based on these BMPs, the EPA has established a MAC that implies a maximum reduction potential equal up to 50 per cent (EPA, 1999, p.3-9, exhibit 3-9).

The following Figure A1-4 compares the EPA MAC with a CES emission response corresponding to a value of the substitution elasticity equal to 0.12.



7.5. Nitrous oxide emissions from fertilizer uses

N₂O is produced naturally in soils through the microbial processes of nitrification and de-nitrification. The principal source of emissions is the addition of nitrogen to the soil principally by the application of synthetic nitrogen based fertilizers or by nitrogen deposited by grazing animals. Fertilizer application also leads to indirect emissions

resulting from fertilizer volatilization and N_2O production due to surface run off and sub-surface leaching of nitrogen from soils. The IEA Greenhouse Gas R&D Programme, 2000, has calculated an abatement cost curve for nitrous oxide emissions. The study concludes that “the package of agricultural measures would reduce anthropogenic N_2O emissions by only 0.2 per cent cumulatively by 2020, with a small fraction ($<0.1\%$) of this reduction achieved at a net saving, because so many of the possible techniques are as yet unproven” (IEA Greenhouse Gas R&D Programme, 2000). Therefore, in the current version of the model, we assume that the value of the CES substitution elasticity is equal to zero.