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Projections of multi-gas emissions and carbon sinks, and marginal abatement cost functions modelling for land-use related sources

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Abstract

This report presents estimates of the costs of abatement of greenhouse gas emissions associated with landfills as a source of methane (CH_4), sewage as a source of methane and nitrous oxide (CH_4 and N_2O, respectively) and carbon (C) sequestration in forest plantations. This is done in the form of so-called Marginal Abatement Cost (MAC) curves. The potential for emission abatement is based on the GECS baseline scenario for the period 1995-2030 for agriculture, and land use developed with the IMAGE 2.2 model framework. The cost categories distinguished for the different emission reduction measures (ERM) include investment costs, and operation and maintenance costs, and possible revenues. These costs and revenues vary on the basis of regional estimates of costs for investments and labour, and savings and revenues. In the GECS baseline scenario the CH_4 emissions from landfills and sewage strongly increase in most world regions between 1995 and 2030 as a result of fast population growth and urbanization. As a consequence, the potential emission reduction also increases. For the estimation of the implementation degree of ERMs, assumptions are used on the basis of literature data. Costs of C plantations include those for land, forest establishment, land preparation, plant material, planting, and operation and maintenance of the plantation. The costs of C sequestration are obtained by combining the annuitized costs per hectare for each region with the per hectare average annual C sequestration rate; These costs are calculated as the mean during a 50-year period. The former Soviet Union has by far the highest potential for C sequestration at relatively low costs. Results for full implementation indicate the C sequestration potential, while results for lower implementation degrees illustrate the effect of socio-economic and other barriers that prevent realization of carbon plantations. The MAC curves developed cannot be directly used in combination with other than the GECS scenario, since both the potential emission abatement and the degree of implementation of ERMs need to be adjusted to the different scenario context. The MAC curves developed in this study and in other bottom-up costing studies are discontinuous, because ERMs are assumed to be implemented one-by-one on the basis of their cost-effectiveness.

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Contents

Samenvatting

Het doel van de studie die in dit rapport wordt gepresenteerd is het schatten van de kosten voor de bestrijding van broeikasgasemissies. Dit gebeurt met behulp van zogenaamde marginale kostencurves van de emissiereductie maatregelen van:

- Afvalstortplaatsen als bron van methaan (CH_4)
- Afvalwater als bron van CH_4 en lachgas (N_2O)
- Koolstofvastlegging door bosaanplant

Het potentieel van de emissie reductie is gebaseerd op het GECS basisscenario voor landbouw en landgebruik zoals het is geïmplementeerd in het IMAGE 2.2 model voor de scenario periode 1995-2030[1]. In algemene termen worden de ontwikkelingen in het GECS basisscenario gestuurd door een snel groeiende wereldbevolking en een hoge economische groei. Dit leidt tot sterke veranderingen in het landgebruik en hoge mate van technologische ontwikkeling. Voor de emissiebronnen en -maatregelen die in dit rapport worden beschouwd zijn de hoge graad van urbanisatie, de toenemende hoeveelheden afval die worden geproduceerd en met name de concentratie ervan in dichtbevolkte gebieden belangrijk; tevens is het potentieel voor het aanplanten van bos belangrijk.

De kostensoorten van de verschillende maatregelen voor emissiereductie zijn investeringskosten, kosten voor onderhoud en andere operationele kosten en ook eventuele opbrengsten. Deze kosten en opbrengsten variëren op basis van regionale schattingen van kosten van investeringen en arbeid, en besparingen en opbrengsten.

Voor vuilstortplaatsen zijn de emissie reductie maatregelen te categoriseren als:

- Reductie van het volume afval dat daadwerkelijk wordt gestort in een afvalstortplaats
- Reductie van CH_4 vorming en emissie uit afvalstortplaatsen

In het GECS baseline scenario stijgen de CH_4 emissies uit stortplaatsen sterk in bijna alle wereldregio's tussen 2010 en 2030 als gevolg van snelle bevolkingsgroei en urbanisatie. Door de toenemende emissie stijgt ook het potentieel voor reductie van de emissies. Voor het schatten van de graad van implementatie van maatregelen voor emissiereductie hebben we aannames gemaakt op basis van, waar mogelijk, gegevens uit de literatuur.

Er is aangenomen dat de graad van implementatie van de verschillende maatregelen voor emissiereductie hoger is in 2030 dan in 2010 omdat er dan immers meer tijd beschikbaar is geweest voor hun implementatie. Dit geldt in het bijzonder voor maatregelen die hoge investeringen vereisen in technologisch hoogwaardige apparatuur. Voorts veronderstelden we een toenemende aandacht en zorg voor een goede milieukwaliteit en klimaatverandering in de loop van de tijd, in samenhang met inkomensgroei.

Voor sommige maatregelen kan het potentieel aan emissiereductie stijgen in de loop van de tijd tengevolge van technologische vooruitgang. Echter, naarmate de reducties het reductiepotentieel benaderen wordt het steeds moeilijker en kostbaarder om nog meer reducties te realiseren.

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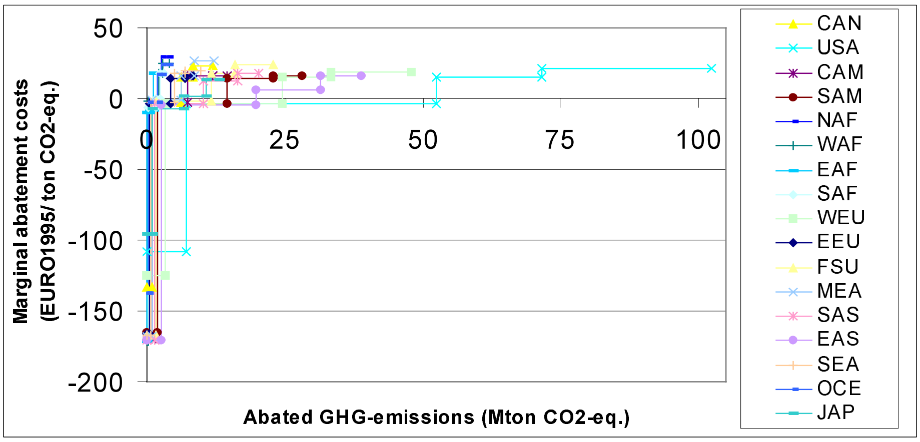
[1] De IMAGE 2.2 implementatie van de SRES scenario's is beschikbaar op CD-ROM (informatie hierover is te vinden op www.rivm.nl/ieweb). Het IMAGE-GECS baseline scenario kan worden aangevraagd (image-info@rivm.nl).

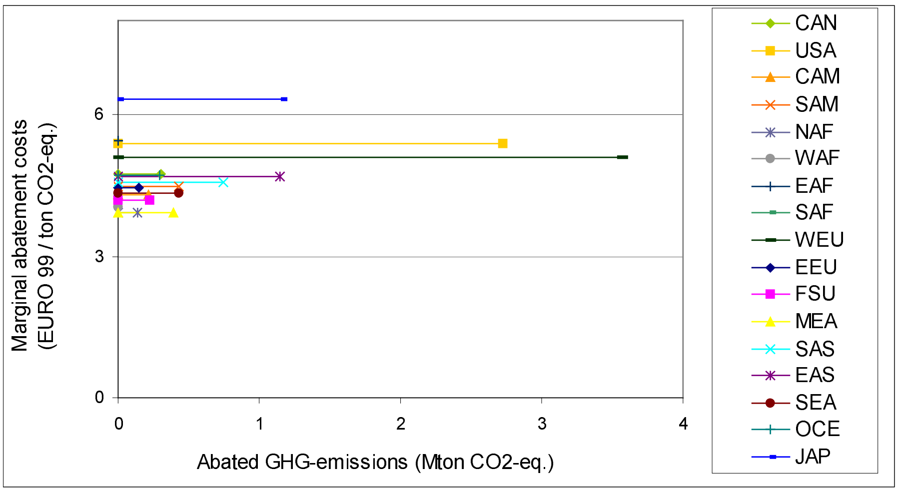


Figuur 0.1. Geaggregeerde kostencurves voor de reductie van CH_4 emissies uit afvalstortplaatsen in 2010 voor de 17 IMAGE regio's (Zie Appendix E).

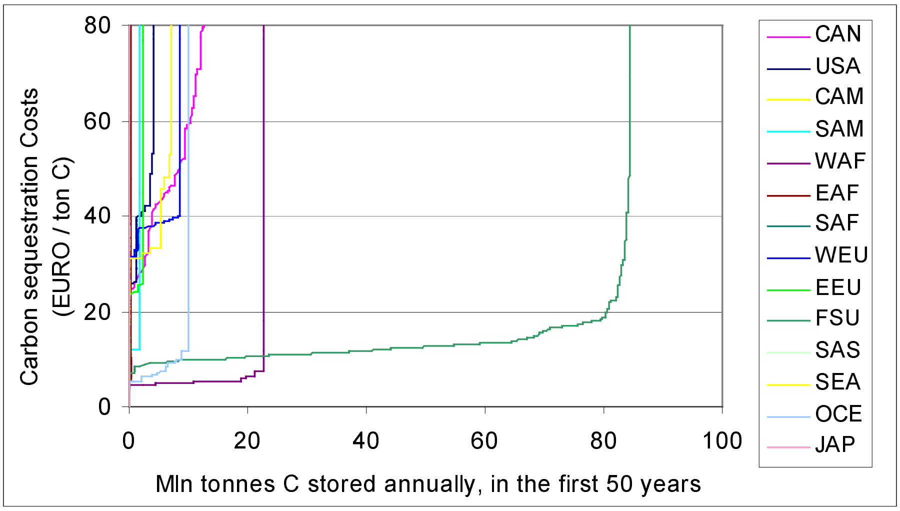
Voor sommige maatregelen is een geringe verbetering van de effectiviteit over de tijd verondersteld, voor andere maatregelen zijn geen veranderingen aangenomen. De marginale kostencurves voor de 17 IMAGE regio's voor 2010 zijn weergegeven in figuur 0.1.

Voor afvalwater zijn de beschouwde emissiereductiemaatregelen:

- Aërobe afvalwaterbehandeling
- Het opwaarderen van bestaande overbelaste afvalwaterzuiveringsinstallaties dan wel installaties met sub-optimale beluchting
- Anaërobe afvalwaterbehandeling ter stimulering van de CH_4 productie, die dan kan worden opgevangen, verzameld en na zuivering en behandeling gebruikt als brandstof. Een bijkomend voordeel komt voort uit vervanging van fossiele brandstof.



Figuur 0.2. Geaggregeerde kostencurves voor CH_4 emissiereductie bij afvalwaterbehandeling in 2010 voor de 17 IMAGE regio's (zie Appendix E).



Figuur 0.3. Geaggregeerde kostencurves voor koolstofvastlegging in bosaanplant op verlaten landbouwgebieden voor 2010 uitgaande van een hoge graad van implementatie voor de 17 IMAGE regio's (zie Appendix E).

De CH_4 emissies uit afvalwater zullen sterk stijgen in de meeste van de wereld regio's tussen 1990 en 2030 in het GECS basisscenario. Daarmee zal het reductiepotentieel in deze regio's tevens een sterke stijging laten zien. Afhankelijk van de veronderstelde graad van implementatie, zal dit leiden tot een sterke stijging van emissiereductie tussen 1995 en 2030. De geaggregeerde kostencurven voor afvalwater behandeling voor 2010 zijn weergegeven in Figuur 0.2. De kosten van reductie van N_2O uit afvalwater zijn te verwaarlozen.

Voor koolstofvastlegging is in deze studie aangenomen dat het aanplanten van bossen plaats vindt in verlaten landbouwgebieden die, te beginnen in enig jaar tussen 1995 en 2030 (de GECS scenarioperiode), gedurende een periode van 50 jaar geen ander gebruik hebben. De koolstofvastlegging is berekend als de netto ecosysteem productiviteit van de plantage, gemeten in tonnen koolstof per oppervlakte eenheid, verminderd met die van de vegetatie in het basisscenario met een voor het GECS project ontwikkelde module.

De kostensoorten van deze plantages zijn de kosten voor land, het kweken van de bomen, grondbewerking, kosten voor het planten, en onderhouds- en operationele (management) kosten van de plantage. Door het combineren van de berekende jaarkosten per hectare voor elke regio met de gemiddelde jaarlijkse koolstofvastlegging per hectare worden de kosten van de koolstofvastlegging verkregen. De jaarlijks vastgelegde hoeveelheden zijn berekend als de gemiddelde opslag over een periode van 50 jaar.

Zowel koolstofvastlegging in het potentiële areaal als vastlegging bij een graad van implementatie van 10% in 2010 en 30% in 2030 zijn berekend. De resultaten bij veronderstelling van 100% implementatie in 2010 zijn weergegeven in figuur 0.3. Het is duidelijk dat de voormalige Sovjet Unie met afstand het grootste areaal heeft tegen ook nog lage kosten. Resultaten voor de lagere implementatie graad geven aan wat het effect zou kunnen zijn van sociaal-economische en andere barrières die realisatie van bosaanplant voor koolstofvastlegging verhinderen.

Summary

The purpose of the study presented in this report is to estimate the costs of abatement of greenhouse gas emissions in the form of so-called Marginal Abatement Cost (MAC) curves of emissions associated with:

– Landfills as a source of methane (CH_4)
– Sewage as a source of methane and nitrous oxide (CH_4 and N_2O, respectively)
– Carbon (C) sequestration in forest plantations.

The potential for emission abatement is based on the baseline scenario for agriculture and land use implemented with the IMAGE 2.2 model for the scenario period 1995-2030[2]. In general terms the developments in the GECS baseline scenario are driven by fast population and economic growth leading to fast changes in land use and fast technological development. For the sources and abatement options considered in this report the fast urbanization and the increasing amounts of waste produced and its concentration in population centers are important, as well as the potential available for forest plantations.

Costs of different emission reduction measures include investment costs, and operation and maintenance costs, and possible revenues. These costs and revenues vary on the basis of regional estimates of costs for investments and labour, and savings and revenues.

For landfills the emission abatement options considered include:

– Reduction of the volume of waste landfilling
– Reduction of CH_4 generation from landfills

In the GECS baseline scenario the CH_4 emissions from landfills strongly increase in most world regions between 2010 and 2030 as a result of fast population growth and urbanization. As a result, the potential emission reduction also increases. For the estimation of the implementation degree of emission reduction measures (ERMs) assumptions are used based on - where possible – literature data.

We assumed that in 2030 there has been more time to implement ERMs so that the implementation degree of the various ERMs is higher than in 2010, particularly for ERMs requiring investments in high-tech installations. Furthermore, we assumed an increasing public concern for environmental quality and climate change, coinciding with rising incomes.

For certain ERMs the potential emission reduction may increase over time as technologies improve. However, with increasing realization of the reduction potential it may become increasingly difficult and expensive to achieve further reductions. For some ERMs we assumed a slight improvement in effectiveness over time and for other ERMs no change. The MAC curves for the 17 IMAGE regions for 2010 are presented in Figure 0.1.

[2] The IMAGE 2.2 implementation of the IPCC SRES scenarios is available on CD-ROM (for information see www.rivm.nl/ieweb). The GECS baseline scenario will be made available on request (image-info@rivm.nl).

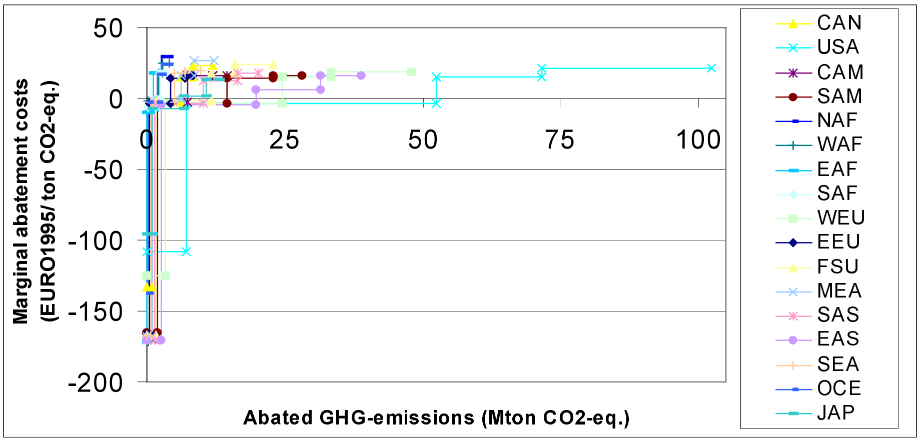


Figure 0.1. Aggregated Cost curves for abatement of CH_4 emissions from landfills for 2010 for the 17 IMAGE regions (see Appendix E).

For sewage the emission abatement options considered include:

- Aerobic wastewater treatment.
- Upgrading of existing overloaded wastewater treatment plants or plants with sub-optimal aeration
- Anaerobic treatment to stimulate CH_4 generation, which can be collected and re-used as fuel. An additional benefit is the substitution of fossil fuels.

The CH_4 emissions from sewage strongly increase in most world regions between 1990 and 2030 in the GECS baseline scenario. Therefore, the potential emission reduction also strongly increases in these regions. Depending on the assumed implementation degree this leads to a strong increase in the emission reduction between 1995 and 2030. The aggregated cost curves for sewage treatment for 2010 are presented in Figure 0.2. Costs of reduction of N_2O from sewage are negligible.

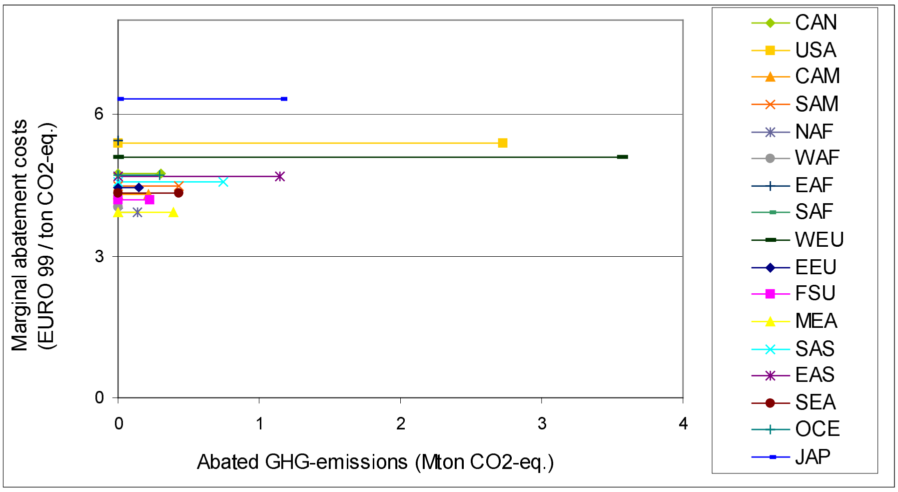


Figure 0.2. Costs of ERMs to reduce CH_4-emission from sewage in 2010 for the 17 IMAGE regions (see Appendix E).

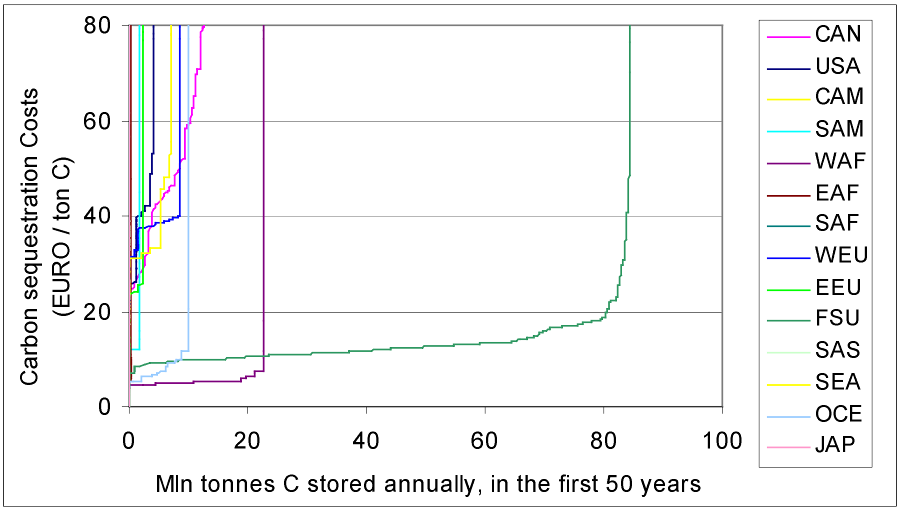


Figure 0.3. Aggregated cost curves for carbon plantations on abandoned agricultural land for 2010 using a high degree of implementation for the 17 IMAGE regions (see Appendix E).

Plantation of forests aiming at C sequestration are assumed to take place exclusively in abandoned agricultural areas, which have no other use during a 50-year period starting in any year in the period 1995-2030 (i.e., the GECS scenario period). The C sequestration is calculated as the net ecosystem productivity of the carbon plantation minus that of the original land cover type in the baseline scenario with a module that was developed for the GECS project.

Costs of C plantations include land costs, forest establishment costs, including costs for land clearing, land preparation, plant material, planting, and operation and maintenance costs of the plantation, including management. By combining the annuitized costs per hectare for each region with the per hectare average annual carbon sequestration, the costs of carbon sequestration are obtained. Annual sequestration rates are calculated as the mean sequestration rate during a 50-year period.

We consider the potential carbon plantation area as well as results for an implementation degree of 10% in 2010 and 30% in 2030. The results for full implementation are presented in Figure 0.3. It is clear that the former Soviet Union by far has the highest potential at relatively low costs. Results for lower implementation degrees illustrate the effect of socio-economic and other barriers that prevent realization of carbon plantations.

1. Introduction

1.1 Background

The goal of the Greenhouse gas Emission Control Strategies (GECS) project is to develop global scenarios in order to analyse the impacts of Post-Kyoto policies under flexibility mechanisms for emission reduction, including options to reduce greenhouse gas (GHG) emissions resulting from land use change and for strengthening carbon (C) sinks. An important aspect is the identification of emission reduction strategies that may fit in a perspective of sustainable development at European and world level, i.e. that correspond to criteria of international and intergenerational equity. Using international energy and economy models, the consequences of different patterns of international commitments, agreements and rules for the control of greenhouse gas emissions to the 2030 horizon will be analysed.

An important part of the project (work package 2) involves the development of modules to estimate the emission projection and Marginal Abatement Costs curves for GHGs other than energy related carbon dioxide (CO_2), particularly as concerns land-use and agricultural activities. One of the models to be used to this purpose is the IMAGE 2.2 model (Integrated Model to Assess the Global Environment) of RIVM, which deals explicitly with changes in land use/land cover and the associated emissions. In this way, multi-gas flexibility can be introduced in the economic trade-offs to be considered in climate change policies.

In combination with the economic and energy scenarios to be developed (work package 1), the GECS project will provide European decision-makers and negotiators with analytical and quantified information on the sectoral and economy-wide impacts of alternative schemes of emission entitlements, flexibility systems and policy instruments. It may thus help to define a European strategy in the international negotiations, while at the same time taking into account the preoccupation of sustainable development at world level.

Within the GECS project, the research on GHG emissions is organized in two sub-programs. The first sub-program focuses on emissions in the energy and industry sectors (WP2a) managed in parallel by CNRS – Institut d'Économie et de Politique de l'Énergie (CNRS-IEPE, Grenoble, France, project co-ordination), and Institute of Communication and Computer Sciences of National Technical University of Athens (ICCS-NTUA, Athens, Greece), while the second one concentrates on emissions related to land use change and agricultural activities (WP2b, see Appendix A), managed by RIVM and Centre de Cooperation International en Recherche Agronomique pour le Développement (CIRAD, Paris). CIRAD and RIVM have agreed upon a division of tasks as indicated in Appendix B.

1.2 Purpose of the study

The purpose of this study is to estimate the costs of abatement of greenhouse-gas emissions associated with waste handling (landfilling and sewage) and of C sequestration in forest plantations. This is done in the form of so-called Marginal Abatement Cost of MAC-curves (Criqui, 1999; Van Harmelen, 2001).

Any estimate of future emission reduction or abatement has to start from certain baseline (or reference) developments. A baseline scenario for agriculture and land use consists of assumptions on economic and population growth, dietary patterns, consumer preferences, agricultural practices and biofuel use, amongst others (De Vries et al., 2000). The choice of such a baseline scenario is important, because it will largely determine the estimations of emission reduction and related costs for the MAC-curves (Van Vuuren and De Vries, 2001). The baseline scenario, including projections of economic and population growth for 1995-2030, is provided by Bureau Fédéral de Plan (BFP, Brussels, Belgium) and CNRS-IEPE, two partners in the GECS project. The storyline behind the GECS baseline scenario, as well as the population and economic scenarios, are similar to the A1 scenario of the SRES-scenarios (IPCC, 2000).

We have identified the list of relevant emission-producing activities in agriculture to construct the MAC-curves from the set of baseline scenario data. Next, we have collected estimates of actual emissions, emission coefficients – i.e. emissions per unit of activity – and emission abatement costs. This has been attempted for all 17 regions in the IMAGE 2.2 model (see Appendix E) and on the basis of the available literature. This inventory is used to make preliminary estimates of aggregate emission abatement cost curves for those agricultural activities and emissions which are distinguished explicitly in the IMAGE 2.2 model (Alcamo, 1994; Alcamo et al., 1998; IMAGE-team, 2001).

This report concentrates on estimating the costs of abatement of GHG-emissions from landfills, sewage and those for C sequestration in forest plantations for 17 world regions (see division of tasks indicated in Appendix B). Since a number of similar studies have been made for European countries, the OECD Europe region is taken as a basis for the estimates for the potential mitigation options and associated costs in the other world regions. In addition, this report describes the methodology for constructing MAC curves and the problems associated with uncertainties in future agricultural production systems in general.

1.3 General aspects of MAC curves

It is generally hypothesized that the cost of reducing emissions from some well-defined activity can be described in terms of a continuous, smoothly increasing function representing marginal costs versus the absolute or relative reduction. We define a MAC curve as the constructed relationship between the fraction by which a certain well-defined (activity, year, technology) emission is reduced and the additional cost to reduce the emission with one more unit. The curve thus describes a series of Emission Reduction Measures (ERM) and its shape is usually continuously increasing. This is because the more cost-effective ERMs are implemented first. However, our calculations will result in a rectangular shape with constant cost to scale within each single ERM. Therefore, these rectangular curves need to be re-shaped into a continuous curve.

A consistent treatment of emission abatement policies and the economic gains from multi-gas flexibility should start with a conceptualization of the form:

$$E_{ijt} = f(S_{ijt}, CV_t) \qquad (1.1)$$

with:
E_{it} = emission of greenhousegas i, GHG_i from activity j at time t
S_{ijt} = value of scenario-dependent variable determining emission of GHG i from activity j at time t
CV_t= carbon value i.e. the value attached to carbon emissions in €/tC at time t.

For each given set of scenario-dependent variables S_{ijt} the MAC curve establishes the relationship between E_{it} and the carbon value *CV*. The value of *CV* is time-dependent in most scenarios. This approach should start from baseline projections generated by energy/economy models such as POLES/GEM-E3 and TIMER/WorldScan. It allows for the calculation of cost-effective abatement options at the regional and international level, either in a ‘static-comparative’ approach or in a dynamic system of endogenized permit prices.

The use of a relationship as given in equation (1.1) implies a number of explicit or implicit assumptions, including:

- The *separateness hypothesis*: it is possible to identify a set of ERMs which apply to the specific emitting activity. This may often be difficult as many ERMs are interrelated, in which case it is more realistic to think of ERM-packages.
- The *sequence hypothesis*: it is assumed that the economically rational actor will apply ERMs in order of ascending average costs, hence following the rising marginal cost curve. In reality, lack of information on the actor, interactions between various ERMs etc. may make this assumption unrealistic.
- The *add-on hypothesis*: it is possible to separate the emitting activity and the set of ERMs. This is not always possible because the ERMs are often interrelated with the activity itself. For example, when considering reduction of N_2O emissions from fertilizer application the abatement option is the improvement of the efficiency of nutrient uptake by plants, which is inherently related to fertilizer use.
- The *cost identification hypothesis*: it is generally assumed that the costs of an ERM can be correctly identified in terms of additional investments and operation and maintenance costs. In practice this depends on real-world characteristics such as activity size distribution, local availability and costs of production factors (capital, labour) and others. Moreover, many costs are not private but public costs – in particular, the infrastructural costs in the form of information and education campaigns and facilities, transport infrastructure, etc.

In general and related to the previous point, two categories of costs should be distinguished with regard to ERMs: private costs and non-private or external costs. *Private costs* are defined here as those costs (in the form of interest and depreciation on investments and operational and maintenance) which are borne directly by those responsible for the activity (Appendix C). *Non-private (or social or external) costs* are those costs which are either directly borne by other actors, like infrastructure, or indirectly by others in the form of externalities (i.e., outside market transactions).

In this study we focus on the direct, private costs (Appendix C). Private cost estimates are available in most studies dealing with cost-curves. External costs are less commonly dealt with in such studies and more difficult to estimate than private costs.

For cost calculations in all further chapters we use 1999 EUROs, represented as €99. €99 equals US$ of 1995, represented as $95. The Euro to ECU rate is 1.0. For other years the appropriate (industrial producer) price index is used to obtain €99.

1.4 Characteristics of the agricultural sector

The characteristics of land use, land use changes and agricultural production systems differ from those in the energy and industry sectors in various ways:

- *More uncertain.* The emission estimates for the different land-use related sources are much more uncertain than those for energy and industry-related emissions. This uncertainty is related to the varying reliability of statistical information on agriculture and land use, and the complete lack of information on some land-use related processes such as agricultural waste and large-scale biomass burning.
- *Less add-on.* Abatement of emissions in agricultural production systems can generally be achieved by improving efficiencies. The costs of such changes are more difficult to estimate than end-of-pipe technologies used in some energy and industry systems.
- *Indirect effects.* Modification of agricultural production through efficiency improvement may have several indirect or secondary effects. For example, improving efficiency in livestock production through increasing the portion of food crops in the ration may influence the volume of crop production, the area used for crops, and hence deforestation rates. Therefore, in many cases it is necessary to ignore such side-effects in cost estimations. Another example is fertilization of managed forests to stimulate C uptake, but may also lead to increased emissions of nitrous oxide (N_2O) and reduced methane (CH_4) sink activity. Or, restoring wetlands may lead to lower N_2O emission but higher CH_4 emission.
- *Non-private costs.* Many abatement options involve only external costs, for example strategies to decrease biomass burning through extension programmes in rural areas. Such costs are not considered, and therefore such emission reductions would have a zero cost.

1.5 Outline of this report

This report presents the methodology and results from the RIVM tasks in work package 2b as agreed upon by RIVM and CIRAD. The results of the RIVM team include the development of the GECS baseline scenario in general and for agriculture, land use and associated greenhouse gas emissions in particular (chapter 2), general aspects of marginal abatement cost curves for abatement of greenhouse-gas emissions (chapter 3), and of marginal abatement cost curves for landfills (chapter 4), sewage (chapter 5) and for CO_2 sequestration in forest plantations (chapter 6). Chapter 7 discusses other activities employed by RIVM in this project, including collection of emission estimates for non CO_2 gases from industrial and energy-related activities, and collection of country data on agricultural production and land use. The contribution of CIRAD on emission reduction in agricultural production will be described in a separate report.

2. Scenario development for agriculture, land use and greenhouse gas emissions

The results of the RIVM team include the development of the GECS baseline scenario in general and for agriculture, land use and associated greenhouse gas emissions in particular. In this chapter we will present the background of the relevant components of the IMAGE 2.2 model (section 2.1), the computation of land-use related GHG emissions (2.2), scenario assumptions for land use and agricultural production and trade (2.3), and the baseline scenario projections for land use and associated emissions (2.4).

2.1 Description of relevant IMAGE 2.2 submodels

2.1.1 Structure of IMAGE 2.2 model

The objective of the IMAGE-2.2 model is to explore the long-term dynamics of global environmental change. IMAGE 2.2 has been extensively documented (Alcamo, 1994; Alcamo et al., 1998; IMAGE-team, 2001). The main new elements of IMAGE 2.2 that differ from IMAGE 2.1 (Alcamo et al., 1998) can be found in Image-team (2001).

The model is an integration of many disciplinary models (Figure 2.1). Throughout the model interactions and several feedbacks are modelled explicitly. Routinely, in the IMAGE 2.2 framework the general equilibrium economy model, WorldScan (CPB, 1999), and the population model, PHOENIX (Hilderink, 2000), supply the basic information on economic and demographic developments for 17 socio-economic regions (see Appendix E for the definition of regions). In the GECS project, the population and economic scenarios are provided by the project partners FPB and CNRS-IEPE. These scenarios are used by the following linked models:

- The TIMER model calculates regional energy consumption, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable energy technologies. TIMER also calculates demand for both traditional and modern biofuels, which provides a link to the land-use model. On the basis of energy production and energy use and industrial production, emissions of GHGs, ozone precursors and sulphur are computed using emission factors from the EDGAR database (Olivier et al., 1996) and (Olivier et al., 2001).
- The ecosystem, crop and land-use models dynamically compute land use on the basis of regional consumption, production and trade of food, animal feed, fodder, grass and timber, and local climatic and terrain soil properties, as well as GHG emissions from land-use change, natural ecosystems and agricultural production systems and the exchange of CO_2 between terrestrial ecosystems and the atmosphere (Leemans et al., 2002).
- The atmospheric and ocean models calculate changes in atmospheric composition on the basis of the above GHG emissions and by accounting for oceanic CO_2 uptake and atmospheric chemistry. Subsequently, climate changes are computed by resolving the changes in radiative forcing caused by GHGs, aerosols and oceanic heat transport.

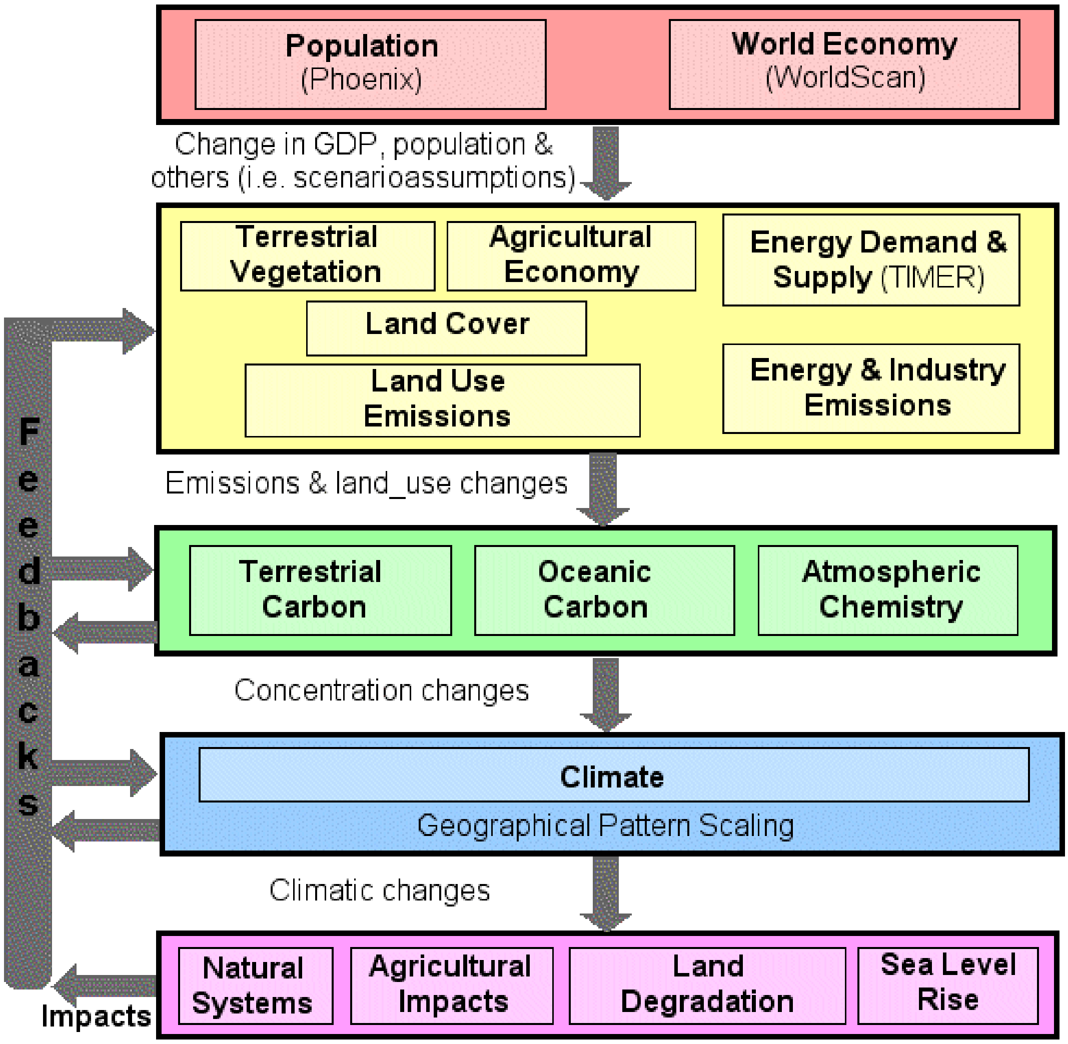


Figure 2.1. The framework of the IMAGE 2.2 model (IMAGE-team, 2001).

The impact models include those describing sea-level rise and land degradation risk. In addition, effects of climate change on natural and agro-ecosystems are simulated by the ecosystem and crop models. The ecosystem models also simulate migration of vegetation as a result of climate change and associated effects on the C-cycle (Van Minnen et al., 2000).

Although IMAGE 2.2 is global in application, it performs many of its calculations either on a high-resolution terrestrial 0.5 by 0.5-degree grid (crop yields and crop distribution, land cover, land-use emissions and terrestrial C cycle) or for 17 world regions indicated in Appendix E (population, energy, trade, industry and their emissions). This approach allows to link the different socio-economic and environmental dimensions and scale levels.

Historical data for energy and industry CO_2 emissions (Marland and Boden, 2000) and concentrations (Etheridge et al., 1998; Keeling and Whorf, 2001) over the 1765-1970 period are used to spin up the C cycle and climate system. Data from many different sources are used to calibrate the energy, climate and land-use variables over a period from 1970 to 1995. The IMAGE 2.2 scenario simulations cover the 1995-2030 period in this study.

2.1.2 Agriculture, land use and land cover modelling

The *Land Cover model* of IMAGE 2.2 simulates changes in land cover on a terrestrial grid (0.5 by 0.5 degree) until regional demands for land use are satisfied (Figure 2.2). The main input to the Land Cover model comes from the Agricultural Economy model and the Terrestrial Vegetation Model of IMAGE 2.2.

The *Agricultural Economy model* calculates the regional demand for all the products that are explicitly modelled by the Land Cover model. These products are the seven different food crops (temperate cereals, rice, maize, tropical cereals, pulses, root and tuber crops and oilcrops), animal feed (crops, residues and grass), four different modern biofuel crops (sugar cane, maize, woody biomass and nonwoody biomass), traditional biofuels (fuelwood and charcoal) and timber products (pulpwood and particles, sawlogs, veneer and industrial roundwood) (Table 2.1).

Table 2.1. Categories used in IMAGE 2.2 for livestock, food crop, biofuel crop production and for animal feedstuffs and timber products.

Livestock categories	Food crops	Biofuel crops	Animal feed	Timber products
Nondairy cattle	Temperate cereals	Maize	Grass	Pulpwood and particles
Dairy cattle	Rice	Sugar cane	Food crops	Sawlogs
Pigs	Maize	Woody biofuels	Residues (from food crops)	Veneer
Poultry	Tropical cereals	Nonwoody biofuels		Industrial roundwood
Sheep and goats	Pulses	Traditional biofuels		
	Root and tubers			
	Oilcrops			

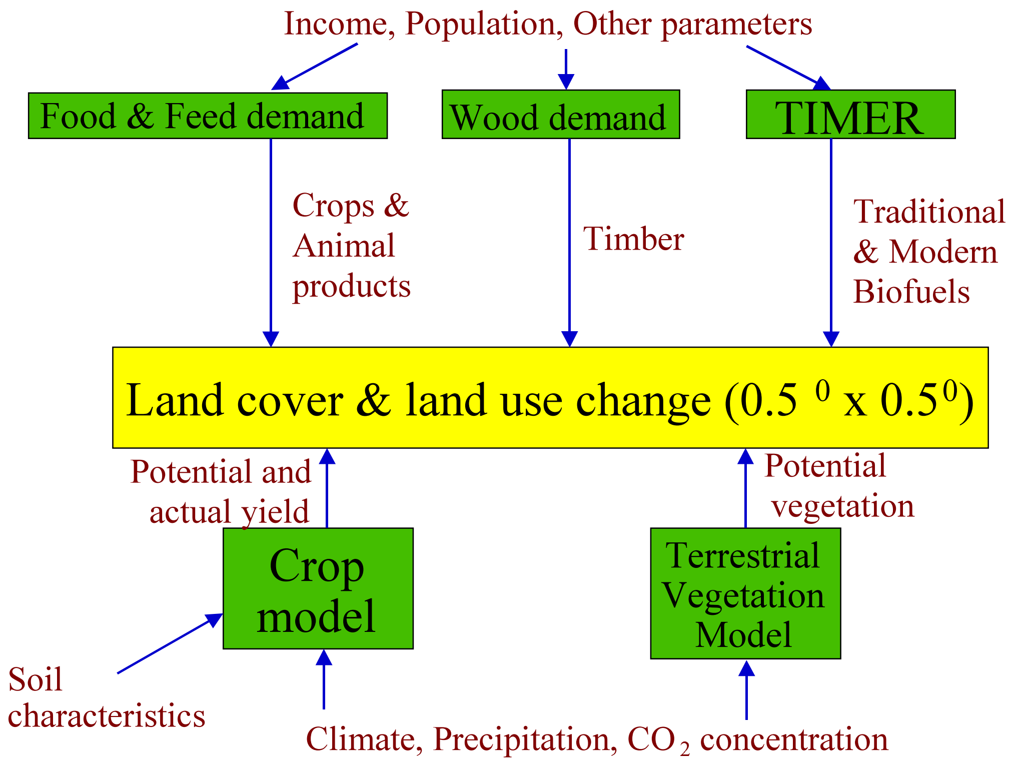


Figure 2.2. Scheme representing the interrelations between the Agricultural Economy, TIMER, Land Cover, Terrestrial Vegetation and Carbon Cycle models of IMAGE 2.2.

Generally food consumption patterns change along with economic growth, with a higher share of animal products with increasing incomes in developing countries, and more or less stable shares of animal products in the human diet in developed countries. Population growth determines the total volume of the regional demand (Stengers, 2001).

The *Terrestrial Vegetation model* computes the potential distribution of natural vegetation and crops. It also computes the potential yield of crops. The BIOME model (Prentice et al., 1992) is used to determine the potential distribution of major plant types (e.g. needle-leafed vs. broad-leafed, deciduous vs. evergreen, trees vs. shrubs and grasses). These plant types are combined into biomes (large-scale vegetation complexes), which describe the potential natural vegetation patterns.

Biome patterns are updated every five years during each simulation. The BIOME model calculates an instantaneous equilibrium response to climate change (temperature and precipitation) by shifting potential natural biome patterns. Plant species need time to migrate. Grasses and shrubs probably migrate more rapidly than long-lived species such as trees. The speed of migration not only depends on the plant and land-cover types involved but also on the distance from propagule sources. In the terrestrial vegetation model the migration process is a function of the rate of climate change, original and new vegetation types and the distance to the nearest location where the new vegetation type already exists (Van Minnen et al., 2000).

The Land Cover model and Terrestrial Carbon model explicitly deal with four land cover transitions:

1. Natural vegetation to agricultural land (either cropland or pasture) because of the need for additional agricultural land;
2. Agricultural land to other land cover types because of the abandonment or unsuitability (under climate change) of agricultural land;
3. Forests to ‘regrowth forests’ because of timber and fuelwood extraction, and;
4. One type of natural vegetation to another because of climate change and/or increased water use efficiency.

These transitions are important in the assessment of C sink potential, as will be explained further on (sections 2.1.3 and 2.1.4).

Finally, vegetation patterns are influenced by atmospheric CO_2 concentrations. The water use efficiency (WUE) of plants increases with rising CO_2 concentration. Consequently, it allows plants to grow under more arid conditions (Körner, 1995). In IMAGE 2.2 enhanced WUE broadens the extent of forests and grasslands and decreases the extent of deserts.

The crop production model (Leemans and van den Born, 1994) is based on the FAO Agro-Ecological Zones Approach (FAO, 1981). This model calculates ‘constraint-free rainfed crop yields’ accounting for local climate and light attenuation by the canopy of the crop considered. The climate-related crop yields are adjusted for grid-specific conditions by a soil factor with values ranging from 0.1 to 1.0. This soil factor takes into account three soil quality indicators: (i) nutrient retention and availability; (ii) level of salinity, alkalinity and toxicity; and, (iii) rooting conditions for plants.

A key aspect of the Land Cover model is that it uses a crop- and regionally-specific *management factor* to represent the gap between the theoretically feasible crop yields simulated by the Terrestrial Vegetation model, and the actual crop yield which is limited by less than optimal management practices, technology and know-how. Regional management factors are used to calibrate the model to regional estimates of crop yields and land cover for the period 1970-1995 from FAO data (FAO, 2001a). For years after 1995 the management factor is a scenario variable (see section 2.3), which is generally assumed to increase with time as an indication of the influence of technological development on crop yields.

The Land Cover model allocates the agricultural demand (including wood demand) grid cell by grid cell within each region, giving preference to cells with the highest potential for satisfying this demand. The preference ranking of grid cells is based on 'land use rules'. Grid cells are given a higher ranking for agricultural production if they:

1. are close to existing agricultural land or fallow forest land;
2. have high potential crop productivity;
3. are close to large rivers or other water bodies;
4. a random factor.

For timber rules 1 and 3 are used, and instead of rule 2 IMAGE 2.2 uses the biomass production per unit area in the form of stems and branches, as computed by the Terrestrial Carbon model.

2.1.3 Carbon cycle modelling

The *Terrestrial Carbon model* simulates the actual C fluxes between the terrestrial biosphere and the atmosphere, considering changes in atmospheric CO_2 concentrations and climate, and the effects of land cover transitions on net primary production (NPP) and net ecosystem production (NEP). It is described in detail elsewhere (Klein Goldewijk et al., 1994; Alcamo et al., 1998; IMAGE-team, 2001). A refined calibration, especially because of a better oceanic carbon model, has led to an improved parameter setting for the different land cover types.

Land cover types are divided into living biomass (leaves, branches, stems, roots) and non-living biomass (litter, humus, charcoal) components. NPP is partitioned over the different living biomass compartments using allocation fractions. Living biomass is transformed into litter on the basis of land-cover specific lifetimes. Litter finds its way to humus and inert soil C (charcoal) using humification and carbonization fractions. During the various transformations part of the C is lost to the atmosphere in the form of CO_2 through soil respiration, which is computed as a function of soil temperature and moisture.

The Terrestrial Carbon model is driven by NPP. The actual level of NPP in any grid cell is a complex function of the land cover type, atmospheric CO_2 concentration, soil and climate as described in Leemans et al. (2002). NPP is calculated for each month and aggregated to an annual value.

In the tropics the expansion of agricultural land releases large amounts of CO_2 as a result of deforestation. Part of the branch and stem pools is used to satisfy wood demand and a small fraction of the living biomass enters the soil pool. In temperate regions, all wood is used and all other living biomass enters the humus compartment. When agricultural land is abandoned or becomes unsuitable under climate change, the natural vegetation emerges again. The content of the agricultural root and litter pools shift to the humus compartment and NPP is assumed to recover, following a logistic-type curve towards the NPP of the natural land cover type (Dewar, 1991). For forests, the land-cover type is initially listed as regrowth – or secondary – forest, but when its NPP reaches at least one-half the value of the NPP of the natural land cover, the regrowth forest is assumed to shift to the natural land cover type. When timber or fuelwood is extracted, the forest recovers in a similar way.

During climate and WUE induced transition of one vegetation type to another NPP and NEP will probably not be in equilibrium. We have implemented a lagged response using a linear interpolation that parameterizes different vegetation transitions. If the transition only involves the disappearance of BIOME's plant types from a land cover type, transitions occur rapidly; if plant types have to enter a region the transition should be much slower. Furthermore, it is assumed NPP cannot change as long as the actual vegetation has not been replaced by the new vegetation (Van Minnen et al., 2000).

2.1.4 Modelling of carbon sinks

In the base-line scenario C sequestration (or C loss) is calculated for re-growing vegetation in former agricultural areas taken out of production. C loss may occur in periods shortly after abandonment, due to the decomposition of soil C and litter. After this initial period the uptake by vegetation dominates the loss. In abatement scenarios these and other suitable areas may be planted with fast growing high-productive trees to stimulate the C uptake. Here we present the Carbon Sink module that was developed for the GECS project to calculate the C sequestration by carbon plantations largely on the basis of Onigkeit et al. (2000).

We apply the FAO definition for forest plantations (FAO, 1998)[3]. In addition to this definition we assume that the purpose of carbon plantations is CO_2 sequestration. We do not consider forest plantation for other purposes such as the production of biofuel. Since wood demand is already satisfied in the baseline scenario, its contribution to C sequestration is not considered here.

Conversion of natural vegetation to carbon plantations is not considered on the basis of the assumption that in the GECS scneario conservation of biodiversity has a higher priority than C seqestration. As a consequence, two land cover types remain that can be converted to forest plantations:

1. Abandoned agricultural land, including marginal areas
2. Forest areas cleared for commercial logging

In the GECS baseline scenario the natural vegetation type regrows on abandoned agricultural land and commercial logging areas. However, these areas can also be planted with fast growing trees used for C sequestration in carbon plantations (CP). The net C sequestration by the plantation is calculated as the Surplus Potential Productivity (SPP) according to the scheme in Figure 2.3. SPP represents the net C sequestration by the plantation minus that of the original vegetation.

[3] Forest stands established by planting or/and seeding in the process of afforestation or reforestation. They are either introduced species (all planted stands), or intensively managed stands of indigenous species, which meet all the following criteria: one or two species at plantation, even age class, regular spacing.

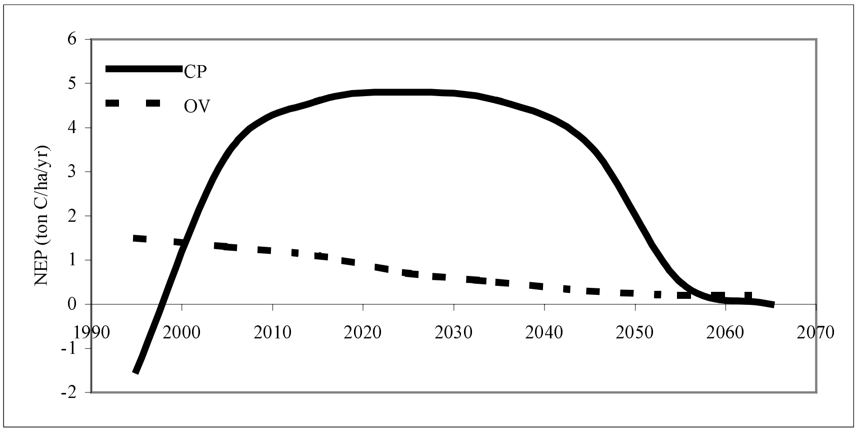


Figure 2.3. Schematic presentation of the calculation of the Surplus Potential Productivity (SPP) as the difference between the NEP for the carbon plantation (CP) and that for the situation in the baseline scenario (original vegetation, OV). The negative NEP for the carbon plantation in the initial years is the result of decomposition of litter and soil organic matte following clearing of the original vegetation.

Carbon plantations are assumed to be implemented in areas which have no other use during a 50-year period starting in any year in the period 1995-2030 (i.e., the GECS scenario period). This 50-year period is the time period for which we assume that the 50-year mean SPP for different grid cells can be compared for different tree species (Figure 2.3). This implies that for a plantation started in 1995 the area will not be available for other land uses until 2045, while planting in 2030 means that the area will have no other uses up till 2080.

For the plantations we consider eight tree species (Table 2.2). Each species has specific climatic requirements determining its NPP. For each grid cell the species with highest NPP, in the first year of selection is selected. Prior to planting the trees, the existing vegetation needs to be cleared. We assume that the C stored aboveground biomass of the existing vegetation is used and, hence, is not released into the atmosphere as CO_2 in the plantation lifetime of 50 years. Below ground biomass, litter and some soil organic matter are decomposed during the first years after clearing, and lost as CO_2 to the atmosphere. The respiration rate is dependent of soil, climate and tree type.

The effect of C sequestration by carbon plantations on the atmospheric CO_2-concentration is neglected in the present study. For the scenario period considered (1995-2030) this will probably not lead to important errors as long as C sequestration is only a small fraction of the total CO_2 emissions from fossil fuel combustion and deforestation.

Table 2.2. Tree species considered for C plantations and their temperature requirements in the Carbon Sink module of IMAGE 2.2.

Species	Preferred climate	Temperature requirement (^oC)		
		Minimum	Optimum	Maximum
Eucalyptus camaldulensis	Dry tropical	0	25	50
Ecalyptus grandis	Wet tropical	0	25	50
Pinus radiata	Relatively dry tropical and subtropical	0	20	40
Acacia mangium		0	25	50
Populus clones	Temperate	-5	20	40
Picea high yield	Temperate	-5	20	40
Abies		-5	20	50
Larix		-10	15	40

2.2 Calculation of land-use related greenhouse gas emissions

2.2.1 General

CO_2 emissions represent the bulk of the GHG emissions in the long-term. They are currently modelled in detail by most models (IPCC, 2000; De Vries et al., 2000; EU, 1999). Recently, there is good evidence that the over-all costs of stabilizing greenhouse-gas concentrations at levels which pose no serious risks may be lower if also other GHGs than CO_2 are included (UNFCCC, 1997). Such a multi-gas or 'what' flexibility – besides 'where' and 'when' flexibility – is an important element in climate change policies. The sources and species of GHGs that are identified in the Kyoto Protocol are listed in Table 2.3.

The non-CO_2 GHGs like CH_4 and N_2O are more potent greenhouse-gases than CO_2. For comparison the so-called Global Warming Potential (GWPs) is generally used (Table 2.4). The GWPs express the radiative forcing of a gas in comparison to an equivalent amount of CO_2 – so-called equivalent CO_2-emissions. GWPs are partly determined by the atmospheric lifetime of a gas and therefore depend on the time horizon used. For example, the GWP for CH_4 for a 20 year period is about 9 times higher than the GWP for a 500-year period. In the GECS project we use the 100 year GWPs.

CH_4 and N_2O are significant contributors to the total greenhouse gas emissions expressed in CO_2-equivalent emissions in Europe in 1998 (Table 2.4). Land-use related (including natural) sources are the major contributors to the emissions of CH_4 and N_2O.

Table 2.3. GHG species and sources that are commonly considered.

Gas species	Source
Carbon dioxide (CO_2)	Energy sector Cement industry Deforestation Carbon sinks
Methane (CH_4)	Energy sector (losses from natural gas production, transportation and distribution, coal mines Landfills Agricultural production (ruminants, rice crops, biomass burning)
Nitrous oxide (N_2O)	Agriculture (fertilizer use) Biomass burning Adipic and nitric acid production
Other GHGs	HCFC (aerosols/propellants, foams, cooling, fire extinguisher) HFCs (hydrofluorocarbons), substitutes for CFCs and HCFCs PFCs (primary aluminium and semiconductors), substitutes to CFCs) SF6 (magnesium and semiconductors, electrical equipment)

Table 2.4. Anthropogenic emissions of CO_2, CH_4 and N_2O for OECD Europe in 1995.

GHG	Emissions ($Mtonne\ yr^{-1}$)	GWP [a] (-)	CO_2 equivalent ($Mtonne\ yr^{-1}$)
CO_2	965	1	965
CH_4	21.8	23	137
N_2O	0.61	296	77

Source: IMAGE-team (2001). CO_2 is expressed as C, CH_4 as CH_4, N_2O as N.

[a] From IPCC (2001a). GWP represents the cumulative radiative forcing between the present and some chosen time in the future caused by a unit of gas emitted, related to a unit of CO_2 (mass basis). As agreed in the GECS project we use GWPs for a 100-year time horizon.

2.2.2 Land Use Emission Calculations in IMAGE 2.2.

The *Land Use Emissions* model in IMAGE 2.2 covers the following gas species: carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), nitrous oxide (N_2O) and volatile organic compounds (VOC). The flux of CO_2 from the terrestrial biosphere is calculated separately as described in section 2.1.3. The sources considered in the Land Use Emissions model and the way they are computed are listed in Table 2.5. In general the emissions for a specific GHG are calculated as:

$$E_t = A_t \cdot EF_t \tag{2.1}$$

with:
E_t = emission of GHG considered at time t
A_t = the activity level, e.g. fertilizer use, feed intake, amount of biomass burnt, at time t
EF_t = emission factor, i.e. the emission per unit of the activity at time t.

Exceptions to this general approach are some sources for which the emission is a global estimate (see Table 2.5 for the geographic detail) and N_2O emissions from soils under natural vegetation (calculated with a regression model, see below).

Methane emissions stem from a variety of sources. A major source is microbial decomposition of organic material under anaerobic conditions occurring in natural wetlands, wet rice cultivation and landfill sites for solid waste dumping. Methane is also formed in the digestive tract of ruminating animals and by various insects, the major species being termites (10-50 Tg CH_4 per year). The burning of biomass is another source, coming next to fossil or non-living CH_4 from CH_4 hydrates.

For CH_4 emissions from cattle a model approach is used based on EPA (1994). In this approach CH_4 emissions are directly related to the feed intake. The feed intake is a function of the energy requirement for maintenance (based on body weight), for obtaining feed (grazing), growth, work and calving and other factors. Hence, the CH_4 generation is calculated on the basis of the scenario for animal productivity considered, and no additional assumptions are needed. For the other animals (sheep and goats, pigs and poultry) a different approach is taken. Here it is assumed that emission factors of livestock in developing countries slowly evolve to those of industrialized countries.

Nitrous oxide is formed in soils during nitrification and denitrification. The precise dynamics of N_2O emissions are largely unknown, but are related to several sources, such as N-fertiliser use, animal manure and biomass burning, aquatic sources (oceans and coastal waters, sewage treatment, freshwater systems, aquifers and irrigation) and global warming, which accelerates biological N_2O forming processes.

The land-use related N_2O emissions stem from application of synthetic N fertilizers and animal wastes to croplands and grasslands, animal waste management systems, grazing, soil incorporation of crop residues and cultivation of leguminous crops, as well as indirect sources caused by leaching of N and by human sewage. All these sources are calculated on the basis of IPCC (1997).

The calculation of N_2O emissions from soils under natural vegetation is based on a modification of the regression model (using NPP, soil moisture, oxygen and fertility) described in Bouwman et al. (1993) and Kreileman and Bouwman (1994). The regression now includes more measurement data covering a wider range of ecosystems and explains about 70% of the variability in reported measurements (IMAGE-team, 2001).

Table 2.5. Calculation of GHG emissions associated with agricultural activities in IMAGE 2.2.

Source	Species	Geographic detail	Activity level / key assumptions	Origin of input data
Biomass burning (deforestation)	CH_4, CO, N_2O, NO_x, VOC	Grid	Related to C burning (C fluxes)	Land Cover model
Savanna burning	CH_4, CO, N_2O, NO_x, VOC	Grid	Related to C burning (fixed C flux per unit area)	Land Cover model
Agricultural residue burning	CH_4, CO, N_2O, NO_x, VOC	Grid	Related to crop production + burning fraction (based on EPA, 1994, Bouwman et al., 1997; Smil, 1999) and emission factors from IPCC (1997).	Land Cover model
Landfills	CH_4	Regional	Urban population.	Scenario
Domestic sewage	CH_4, N_2O	Regional	Human population	Scenario
Wetland rice fields	CH_4	Grid	Related to area of irrigated, rainfed and deepwater rice (harvested areas) from FAO (2001a). Regional emission factor for 1970-1995 from Neue (1997).	Scenario
Animals (non-dairy cattle, dairy cattle, pigs, poultry and sheep & goats)	CH_4	Grid	Related to feed intake (cattle) and total number of animals according to Alcamo et al. (1998). For other animals emission factors from IPCC (1997).	Scenario/ Land Cover model
Animal waste (animal categories see above)	CH_4, N_2O	Grid	Related to total number of animals. Emission factors from IPCC (1997). N, P and K contents for manure by animal category from Bouwman (1997).	Scenario/Land Cover model
Arable land (temperate cereals, rice, maize, tropical cereals, pulses, root and tuber crops, oil crops and other crops)	N_2O,NO_x	Grid	-N_2O: related to N fertilizer use (synthetic fertilizer + animal manure), N fixing crops (pulses, soybeans), and crop residue incorporation; crop residues are below ground parts + total aboveground residues minus biofuel use, agricultural waste burning and feed use of residues (see feed for animals). Modified from IPCC (1997).	Scenario/Land Cover model
			-NO_x: related to N fertilizer use (see above) emission factor from Veldkamp and Keller (1997).	Land Cover model
Indirect sources	N_2O	Region	Related to fertilizer use (synthetic fertilizers and animal waste) and population, according to IPCC (1997); includes leaching (related to N inputs)	Scenario
Post-clearing effects	N_2O, NO_x	Grid	Related to forest clearing (deforestation) and natural N_2O/NO_x emission	Land Cover model

Deforestation (i.e. land clearing) may lead to accelerated decomposition of litter, root material and soil organic matter in the first years after disturbance, causing a pulse of N_2O emissions. This effect is taken into account only for tropical rain and seasonal forests, where in the first year after clearing, the N_2O flux amounts to five times the flux of the original ecosystem, which then decreases linearly to the flux of the new ecosystem in the subsequent 10 years; this is usually lower than the flux from the original forest.

In contrast to Kreileman and Bouwman (1994), most calculations for agricultural emissions follow the IPCC Methodology for National Emission Inventories (IPCC, 1997). To make calculations consistent with this methodology, some additional sources were included, such as the indirect sources of N_2O. Also, we included NO_x emission calculations for agricultural fields and natural ecosystems. In the case of rice fields, we had to follow the approach of Neue (1997) due to lack of data on organic amendments in rice cultivation (required for IPCC methodology).

2.3 Scenario assumptions for land use and associated emissions

Except for those sources where a global estimate is used, emissions from all sources vary according to the scenario considered. For example, the CH_4 emissions from cattle per unit of product decrease with increasing productivity. Natural N_2O emissions change according to land cover and climate changes. Fertilizer-induced emissions change according to the scenario of fertilizer use and substitution of synthetic fertilizers by animal manure.

IMAGE scenarios for land use vary on the basis of differences in scenario assumptions on trade in agricultural products, and characteristics of livestock and crop production systems. For the GECS baseline scenario the following scenario assumptions were used:

- *Trade*. For each product (see Table 2.1), trade is based on the self-sufficiency ratio (SSR, i.e., the ratio between regional production and consumption), and the desired self-sufficiency ratio (DSSR). The term 'desired' refers to the fact that exporting regions determine the volume of food that can be traded and, therefore, determine the maximum amount that can be imported by regions with DSSR<1. If for a certain food product SSR>1 in 1995, i.e. if the region considered was an exporter, export is assumed to increase in the future by multiplying the so-called export fraction (i.e. SSR in 1995 minus 1) by a factor of 3 in 2025, and a factor of 4 in 2050. Contrary, SSR values remain unchanged up till 2030 if for the product considered SSR≤1 in 1995. Furthermore, DSSR is assumed never to exceed a value of 2. In other words, the regional export will never exceed the regional consumption. The following exceptions to these general rules were made:
  - More export is assumed for South America, because this region has large areas of potential agricultural land that are currently not used.
  - Eastern Europe and the former USSR become larger exporters than following from the general rules above. Eastern European countries will probably become members of the European Union and therefore their agricultural sector will modernize and focus more on export. For the USSR, modernization combined with positive effects of climate change, allows for higher exports in the future.
  - Less export is assumed for OECD-Europe, because many studies indicate a decrease in agricultural production, at least in the next few decades.
  - More import is assumed for the African regions, the Middle East, South Asia (i.e. India) and East Asia (China) to ascertain food consumption. In particular, it is generally expected that India and China will import large amounts of food to meet the increasing demands of a growing and wealthier population.
- *Livestock production*. For animal production assumptions are made on the carcass weight at slaughtering, the off-take rate (the percentage of the animal population that is slaughtered each year) and the feed efficiency (the amount of feed required to produce one kg of product, i.e. milk or meat) for the animal categories nondairy

Table 2.6. Production targets for livestock production characteristics. Target year is 2025 in the GECS baseline scenario.

Characteristic	Nondairy cattle	Dairy cattle	Sheep and goats	Pigs	Poultry
-Carcass weight	OECD Europe 1995 level	OECD Europe 1995 level	Oceania 1995 level	OECD Europe 1995 level	110% of OECD Europe 1995 level
-Off-take rate	110% of OECD Europe 1995 level	110% of OECD Europe 1995 level	110% of OECD Europe 1995 level	110% of OECD Europe 1995 level	-
-Feed efficiency	Depending on energy for maintenance, grazing, growth, work and calving based on EPA (1994). Target for number of pregnant animals OECD Europe 1995		OECD Europe 1995 level	OECD Europe 1995 level	OECD Europe 1995 level
-Fraction grass in diet	OECD Europe 1995 level	OECD Europe 1995 level	OECD Europe 1995 level	OECD Europe 1995 level	OECD Europe 1995 level
-Fraction residues in diet	OECD Europe 1995 level	OECD Europe 1995 level	OECD Europe 1995 level	OECD Europe 1995 level	OECD Europe 1995 level

Table 2.7. Maximum values of the management factor for pasture and fodder species and food and biofuel crops.

Crop	Region[1]	Maximum value of management factor (-)
Pasture and fodder species	Canada, USA, Southern Africa, East Asia, Oceania	0.1
	Central America, South America, Northern Africa, Western Africa, Eastern Africa, former USSR, Middle East, Southeast Asia, Japan	0.2
	OECD Europe, Eastern Europe, South Asia	0.6
Temperate cereals	All regions	0.9
Rice	All regions	1.2
Maize	All regions	0.9
Tropical cereals	All regions	0.7
Pulses	All regions	0.7
Root and tuber crops	All regions	1.2
Oilcrops	All regions	0.9
Biofuel crops	All regions	1.0

[1]For regions see Appendix E.
[2] Maize, sugarcane, woody and nonwoody biofuels.

cattle, dairy cattle, pigs, poultry and sheep and goats (Table 2.6). In general the assumption is that when countries reach the 1995 OECD Europe income level, their productivity and feed efficiency will also reach the OECD Europe level of 1995.

– *Crop production.* The land productivity in grass and crop production is determined by the development in the so-called 'management factor' used to describe crop yields (Tables 2.7 and 2.8), and the cropping intensity, i.e. the ratio harvested land : total arable land (Table 2.9). The management factor represents the gap between the theoretically feasible crop yields simulated by the Terrestrial Vegetation model, and the actual crop yield which is limited by less than optimal management practices, technology and know-how (see section 2.1.2). For the management factor scenario-independent maximum values are assumed for different crops, because the maximum

achievable yields under practical conditions, which are assumed to be independent of economic growth, are the same for all scenarios. However, the rate at which regions advance towards these maximum values depends on the scenario (Table 2.8). Growth paths are specified on the basis of the storyline and relative differences in economic growth between regions.
In temperate regions the cropping intensity is generally less than 1, because part of the arable area is fallow (Table 2.9). In some tropical regions with an important share of irrigated crops, the cropping intensity exceeds unity, indicating that more than one crop is grown each year. Regional cropping intensities move towards region-specific maximum values (Table 2.9). Each scenario has a specific target year in which the maximum value is reached. Increasing cropping intensities reduces the need for expansion of the agricultural area used.

- *Fertilizer use*. For crops the maximum nutrient input (fertilizer plus animal manure) is 300 kg NPK $ha^{-1}yr^{-1}$, which is 90% of the rate in OECD Europe in 1995. Industrialized regions are assumed to move in a linear fashion towards this rate in 2025. The growth in less industrialized regions is according to a logarithmic function based on GDP. The fraction of synthetic fertilizers applied to grass and fodder species is assumed to grow towards the fraction of OECD Europe in 1995. N in synthetic fertilizer is a fixed regional fraction of NPK (generally 50-60%). The fraction of animal manure that is available for application to crops and grasslands (i.e., stored manure, which is all manure excluding excretion during grazing and manure used as fuel) is assumed to approach the 1995 OECD Europe level when regions approach the 1995 per capita GDP of OECD Europe. This is to simulate intensification of livestock production whereby more animal manure becomes available. This way animal manure gradually substitutes synthetic fertilizer.

Table 2.8. Annual growth percentages for the management factor for groups of world regions[a].

Year	1,2,9,16,17	3,4,5,12,14,15	6,7	8,13	10,11
1995	1.0	1.0	0.0	1.0	0.0
2000	1.0	1.0	1.0	1.0	0.5
2010	1.5	2.0	2.0	1.5	1.0
2025	1.5	1.5	2.5	2.0	2.0
2050	1.0	1.5	2.0	2.0	2.0

[a] See Appendix E. 1 = Canada; 2 = USA; 3 = Central America; 4 = South America; 5 = North Africa; 6 = Western Africa; 7 = Eastern Africa; 8 = Southern Africa; 9 = OECD Europe; 10 = Eastern Europe; 11 = former USSR; 12 = Middle East; 13 = South Asia; 14 = East Asia; 15 = Southeast Asia; 16 = Oceania; 17 = Japan.

Table 2.9. Maximum values of cropping intensity and the growth path towards this maximum value for different regions.

Region[1]	Maximum cropping intensity	Target year
Annex I countries [2]	110% of 1995 value	99% of maximum is reached in 2050
Central America	0.8	
South America	0.9	
Southern and Northern Africa and Middle East	1.0	
Western Africa	1.3	99% of maximum is reached in 2100
Eastern Africa	1.1	
South Asia	1.3	
East Asia and Southeast Asia	1.3	

[1] Appendix E.
[2] Canada, USA, OECD Europe, Eastern Europe, former USSR, Oceania and Japan.

Table 2.10. Assumptions on changes in CH_4 emissions from agricultural waste burning, landfills and wetland rice cultivation.

Agricultural waste burning	OECD-regions: fraction of crop residues burnt in the field changes towards 1995 OECD Europe level in 2025 Non-OECD regions: fraction of crop residues burnt in the field changes towards 1995 OECD Europe level when GDP reaches the 1995 OECD Europe level
Landfills	OECD-regions: production of organic waste moves towards the 1995 OECD Europe level in 2025 Non-OECD regions: production of organic waste moves towards the 1995 OECD Europe level when GDP reaches the 1995 OECD Europe level
Wetland rice	All regions: emission factor moves to the 1995 USA level in 2020.

- *Emissions*. For CH_4 emissions from agricultural waste burning, landfills and wetland rice assumptions are used as indicated in Table 2.10.

2.4 GECS baseline scenario results for agriculture, land cover and associated emissions

In general terms the developments in the GECS scenario are driven by fast economic growth leading to fast changes in the demand for food. In developing countries the demand for meat and milk increases strongly along with rising incomes. In developed countries the consumption patterns do not change much with increasing incomes, and meat and milk consumption may even decrease. On top of the changes in demand caused by economic growth, the total volume of the demand changes as a result of population growth. We present base-line scenario calculations for a number of characteristics of crop and animal production systems (sections 2.4.1 and 2.4.2, respectively), and for emissions associated with landfilling of human organic wastes and sewage (2.4.3).

2.4.1 Crop production

Agricultural productivity also strongly increases in the GECS baseline scenario. Despite this increase there is a fast world-wide expansion of the arable area. Most of the expansion occurs in developing countries where population and economic growth and a continuing towards more livestock products in the human diet lead to increasing demand for food products.

Figures 2.4a-e show the implications for arable areas, crop yields, fertilizer inputs and emissions of N_2O in the GECS baseline scenario for the world and for four selected regions varying in their GDP and degree of industrialization. These elements are presented here, because they are also the factors to be used for assessment of emission reductions. In crop production these relate to the efficiency of fertilizer use, crop yields and associated N_2O emissions.

2.4.2 Livestock production

We present some of the characteristics of the milk production system and associated emissions of CH_4 to illustrate the results for animal production On the basis of demand and trade projections for milk the model calculates the domestic regional milk production. The required number of animals (Figure 2.5a) results from this domestic production (Figure 2.5b). The amount of animal feed required for this production is related to the efficiency of feed use per kg of milk produced, which tends to increase along with economic development (Figure 2.5c). The CH_4 emission associated with enteric fermentation is shown in Figure 2.5d. It is clear that CH_4 emissions show a slow increase in most developed regions and is a fast increase in most developing regions.

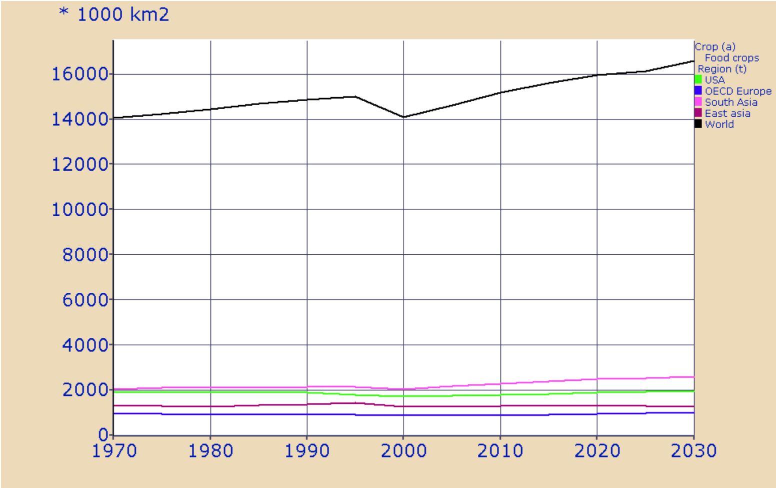


Figure 2.4a. Areas of arable land in OECD Europe, USA, South Asia and East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

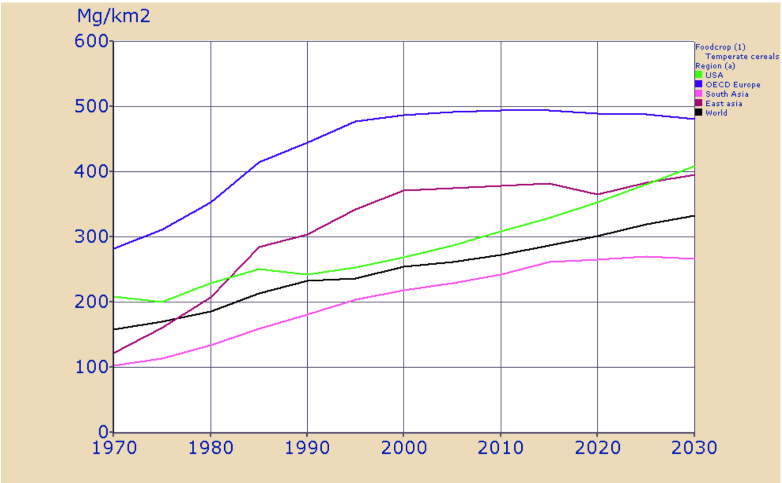


Figure 2.4b. Yields of temperate cereals (mainly wheat) in OECD Europe, USA, South Asia, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

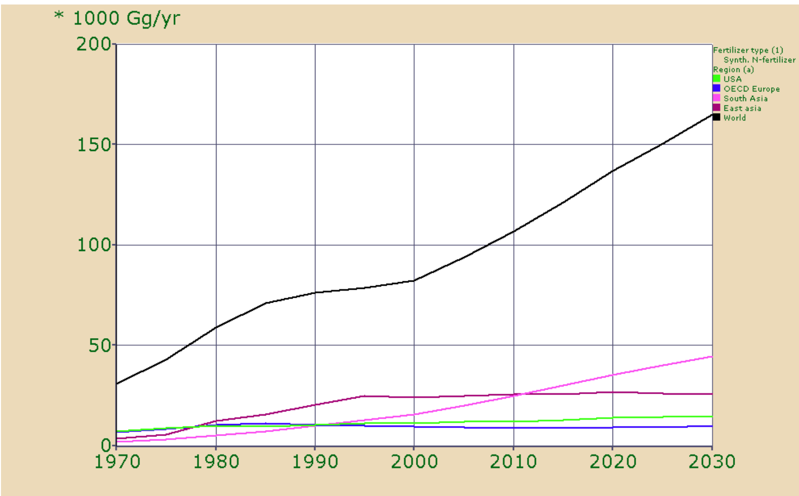


Figure 2.4c. Use of syntheticN fertilizers crop production in OECD Europe, USA, South Asia, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

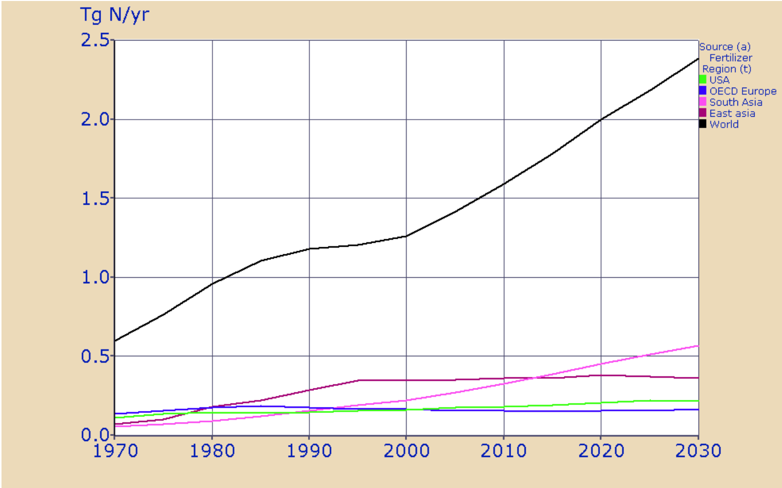


Figure 2.4d. Direct emission of N_2O from the use of synthetic fertilizers and animal manure in OECD Europe, USA, South Asia, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

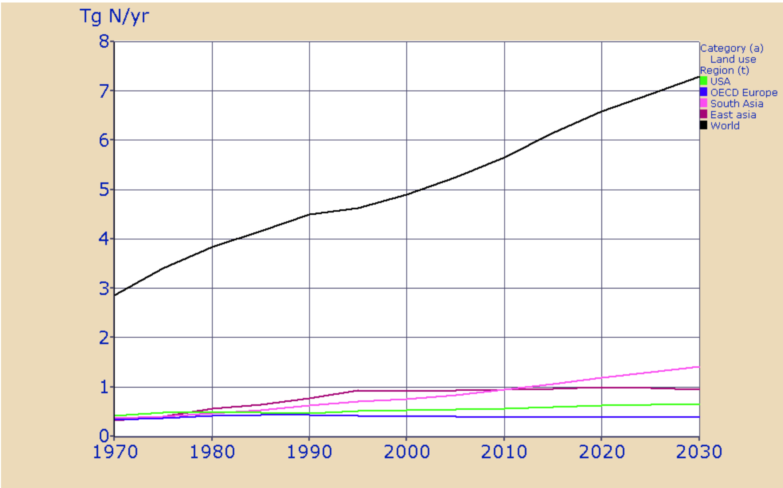


Figure 2.4e. Total land-use related emission of N_2O for OECD Europe, USA, South Asia, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

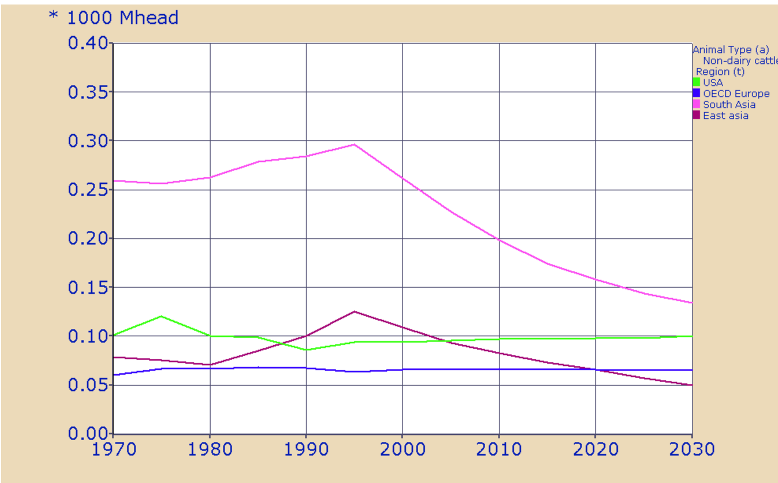


Figure 2.5a. Number of dairy cows in OECD Europe, USA, South Asia and East Asia for the period 1970-2030 in the GECS baseline scenario.

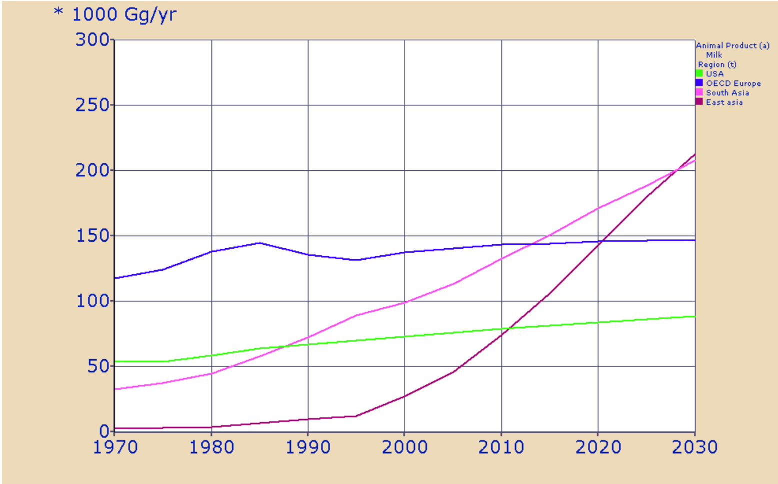


Figure 2.5b. Milk production in OECD Europe, USA, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

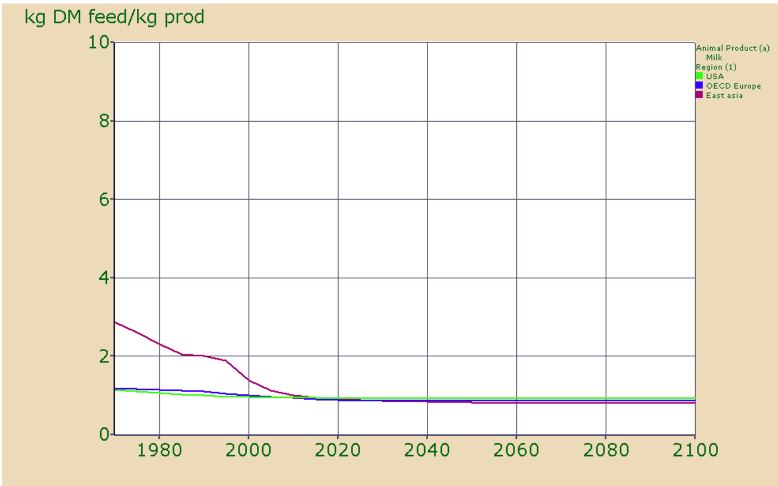


Figure 2.5c. Feed requirement for milk production in OECD Europe, USA, East Asia and the world for the period 1970-2035 in the GECS baseline scenario.

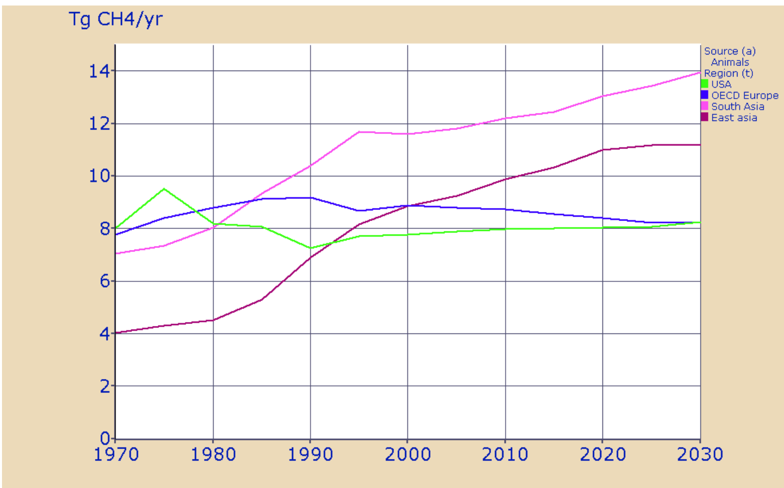


Figure 2.5d. CH_4 emissions from enteric fermentation for OECD Europe, USA, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

2.4.3 Landfilling and sewage

Anual emissions of CH_4 from sewage amount to 28.9 Mton CH_4 in 2000 (Figure 2.6), thus accounting for 5.4% of total CH_4 emission. This slowly increases to 32.5 Mton CH_4 meaning 5.5% in 2010 (which is 9% of total global anthropogenic CH_4 emissions). The projected emission for 2030 is 38.7 Mton CH_4 accounting for 6% of total emissions (and close to 10% from total global anthropogenic CH_4 emissions originated from energy, industry and land use related sources). This agrees with earlier estimates (Thorneloe, 1993). A large part of the total N_2O emissions are from on-site wastewater treatment, Asia being the largest contributor (De Jager et al., 2001).

Emissions of CH_4 from landfills change along with the development in the urban population showing a slight increase in OECD Europe and a more pronounced one in the USA, while in developing regions such as South Asia and China CH_4 emission from landfills increase strongly in the coming decades (Figure 2.6a). Emissions of CH_4 and N_2O from sewage show only a slight increase in developed countries, and a fast increase in most developing regions, along with population growth and continuing urbanization.

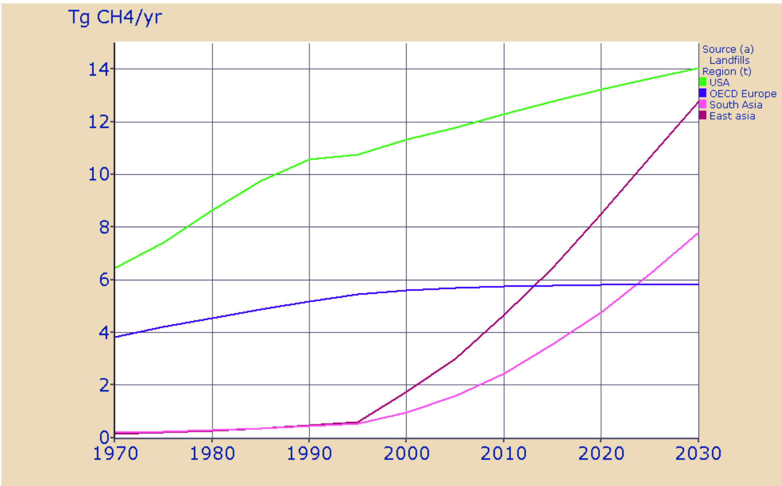


Figure 2.6a. Emissions of CH_4 from landfills for OECD Europe, USA, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

As for CH_4, the estimates for N_2O emissions from waste water and its treatment are highly uncertain. Following the GECS baseline scenario, annual global N_2O emissions from sewage amount to 0.25 Mton N in 2000 (Figure 2.6b), thus accounting for 2% of global N_2O budget. In the baseline scenario this slowly increases to 0.3 Mton N in 2010 and slightly more in 2030.

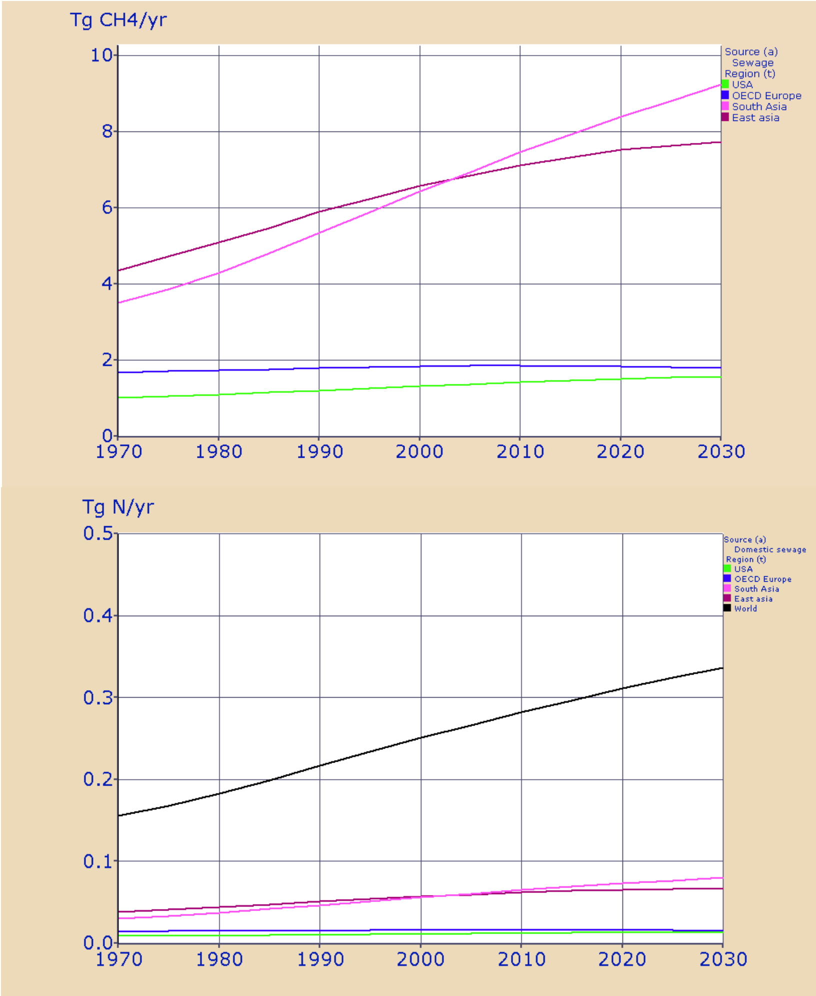


Figure 2.6b. Emissions of CH_4 (top panel) and N_2O (bottom panel) from sewage for OECD Europe, USA, South Asia, East Asia and the world for the period 1970-2030 in the GECS baseline scenario.

3. Emission abatement and costs in the IMAGE 2.2 framework

3.1 Methodology

3.1.1 General

The scale of IMAGE 2.2 land-use modelling is regional with grid-based calculations of C cycling. In addition, in agricultural production many products have been aggregated in IMAGE 2.2. In livestock and crop production systems, IMAGE 2.2 considers aggregated categories indicated in chapter 2 (Table 2.1). This implies that cost calculations of Emission Reduction Measures (ERM) also need to be made at this aggregated level.

For the purpose of the GECS project we made a list of greenhouse-gas (GHG) emissions and the associated activities (Appendix B) that will be included in cost-calculations for GHG abatement options matching the IMAGE model. CIRAD and RIVM have agreed upon a division of tasks as indicated in Appendix B.

The marginal abatement cost (MAC) curves will be developed for two view years, i.e. 2010 and 2030. This study will concentrate on the direct effects of ERMs on emissions of GHGs and the associated costs only. The indirect costs of ERMs and non-climate related environmental benefits are not taken into account. Such indirect costs are, for example, second-order economic consequences of ERMs such as decreasing employment and price-effects (Vringer and Hanemaaijer, 2000). Non-climate related environmental benefits of GHG reductions include, for example, reduction acidification through reduction of NO_x emissions and deposition.

GHG emission abatement options may interact through mutual influence on the effectiveness or costs. Different forms of interaction can be distinguished based on Vringer and Hanemaaijer (2000) (see Chapter 2):

- *Exclusiveness*, when one option excludes another one. For example, waste incineration excludes the possibility of composting the same amount of waste.
- *Simultaneous and interacting options*, when the effect of an option depends on options already implemented. For example, CH_4 collection from landfills requires capping of the landfill to prevent uncontrolled escape of CH_4.

It is difficult to estimate the effects and costs of such interactions quantitatively due to scarcity of data. Interactions will, therefore, be dealt with in a qualitative manner. For example options can be ranked according to their individual cost-effectiveness, and when two measures exclude each other, the most cost-effective one will be selected.

The basis for the cost calculations varies for the different activities. Generally the activity indicators presented in Table 2.1 are used as the key parameter in cost calculations, but in a number of cases cost calculations are indirect and more complicated.

For landfilling and sewage the regional emission is taken as a basis for cost calculations, since IMAGE does not produce estimates of the volume of organic wastes dumped in landfills. For C sinks the potential area of carbon plantations is taken into account, based on the GECS baseline scenario. In all cases we use the bottom-up engineering approach for estimating costs of abatement (see also 3.1.2).

The costs taken into account in this analysis are confined to the capital and operational (labour, materials) costs of ERMs using a bottom-up approach. Costs are always assessed as additional costs with respect to a baseline development. The implicit assumption is that these additional costs are reflected in the product prices. These cost estimates are derived where possible from information on specific abatement projects ERMs. The so-called non-private or external costs/benefits are ignored in this study. This does not imply that external costs are negligible. However, external costs are borne by different groups of actors and often only in an indirect way, i.e. elsewhere and with varying delay. The same is true for the benefits resulting from the ERMs considered, which are often difficult to measure.

The following steps need to be taken for constructing MAC curves:

1. Generation of the reference emission development scenario for view years (2010 and 2030) with the IMAGE 2.2 model;
2. Construction of the list of ERMs for abatement of greenhouse gases CO_2 (but only non-energy related CO_2), CH_4, N_2O. This gives a matrix of abatement options ERM_j (j=1, 2,.., n) for greenhouse gases GHG_i (i=1, 2, .., n).
3. Following the proposed bottom-up costing methodology, this comprises the following steps (COHERENCE/ECOFYS/NTUA/ECOSYM, 1999; Bates, 1998a,b; VROM, 1999):
   (i) collection of estimates of the relevant model parameters for each option, i.e. the fraction of the GHG emission that is abated and the costs of the ERMs. These costs include investment costs, and operation and maintenance costs. *Investment costs* are the costs of investments in the GHG-abatement technologies or measures, implying annual recurring costs of depreciation of the assets. *Operation and maintenance costs* are the annual recurring costs for having the installations and machinery working properly. Part of this category consists of labour costs for managing the installations or in general managing the abatement activities;
   (ii) The operational lifetime of an abatement option; the lifetime determines the capital cost via the annuity applied;
   (iii) The appropriate discount rate; in the GECS project a discount rate of 4% is used; and,
   (iv) The annual quantity of greenhouse gas i GHG_i (i=1..3) abated by a particular option ERM_j (j=1..n) in the year considered.
4. Annuitize the present value of the total cost stream of each option over its operating life. The total cost stream consists of an investment and an operation and maintenance component. The resulting expression for the annual cost is:

   $$COST_i^{TOT} = \alpha \cdot COST_i^{INV} + COST_i^{O\&M} \qquad (3.1)$$

   with:
   $COST_i^{TOT}$ = yearly total costs to implement ERM_j to reduce greenhouse gas *i*
   $COST_i^{INV}$ = yearly investment flow
   $COST_i^{O\&M}$ = yearly operation and maintenance costs
   α = annuity factor: $r/(1-(1+r)^{-n})$, r being the discount rate (% yr^{-1}) and n the depreciation period (yr).
5. Calculate the net marginal costs for each ERM, that is, the total costs per ton abated minus the cost savings per ton abated from the ERM. *Savings* are avoided costs on

the one hand, like for example the avoided costs for landfilling. On the other hand, they represent the revenues or cost decreases due to the adjusted use and management of techniques. Examples are the revenues from paper recycling or energy sales from landfill gas collection and use for generation of electricity. These are savings of direct costs:

$$COST_i^{NET} = COST_i^{TOT} - COST_i^{SAV} \tag{3.2}$$

with:
$COST_i^{NET}$ = net costs of emission reduction of substance *i* (Euro/tonne/year)
$COST_i^{TOT}$ = costs of emission reduction of substance *i* (Euro/tonne/year)
$COST_i^{SAV}$= costs avoided of emission reduction of substance *i* (Euro/tonne/year)

6. Assess the amount of GHG abated for the view years (2010 and 2030) compared to the emissions projected for the same year. This consist of four steps:
   (i) Start with the GHG emission of the source in IMAGE before implementation of the ERM;
   (ii) Consider the *share of the particular source in the emission in the IMAGE-sector*, to which the ERM will apply;
   (iii) Estimate the (technically) *maximum reduction potential* of the ERM; this has always been set at 100% in the cases considered.
   (iv) Estimate the *degree of implementation* of the ERM in the view year, accounting for lags in implementation and adoption of ERMs. The result will be ΔE_i, the quantity of greenhouse gas *i* abated in year *t*.
7. Normalize the annuitized cost of each option to the resulting emission reduction. This yields the following equation:

$$MAC_i = \left(\alpha \cdot COST_i^{INV} + COST_i^{O\&M} - COST_i^{SAV}\right) / \Delta E_i \tag{3.3}$$

8. For cost calculations we use 1999 EUROs, represented as €99. €99 equals US$ of 1995, represented as \$95. The € to ECU rate is 1.0. For other years the appropriate (industrial producer) price index is used to obtain €99.

3.1.2 Specific cost-aspects of carbon plantations

Some cost-aspects of carbon plantations need special attention. In line with the approaches for landfills and sewage we used the bottom-up approach, which is the most common method to calculate the costs of specific technological options in a given region. For carbon plantations one key variable in this approach is the cost of the land. For land costs a range of estimators are used, such as land rent and opportunity costs. Comparison of bottom-up studies is often difficult, mainly because data on land costs are difficult to obtain. Often land costs are therefore ignored. In addition, lack of standardization of the treatment of C yields and timing of C sequestration is leads to discrepancies between studies.

Two other approaches exist to estimate the costs of C sequestration in carbon plantations:

1. Sectoral optimization studies endogenize key variables such as land-owner decisions and prices and consider dynamic effects of sequestration. These models link forestry and agriculture sectors allowing for assessment of leakages occurring when a sequestration program leads to increased prices of agricultural products. This may lead to conversion of forests to agriculture.
2. Econometric studies consider past landowner behaviour to predict future behaviour on the basis of land use studies and the time path of sequestration (Richards and Stokes, 1999).

We use the Levelled Costs/Discount Method (LCDM) approach for discounting the costs of C sequestration in carbon plantations. In LCDM the present costs are annuitized over the period of C sequestration and divided by the average annual rate of C sequestration. Hence, C sequestered is discounted to the present value (IPCC, 1996).

Two other approaches exist, i.e. the Flow Summation Method (FSM), the Average Storage Method (ASM). In FSM the net present value of costs is divided by the total C sequestered over the period considered. In ASM the costs of C sequestration are calculated by dividing the present value of implementation costs over the plantation period by the C stored in one management rotation.

3.2 Emission abatement options

Appendix B presents the list of the emission abatement options considered. We distinguish three levels to assess the marginal abatement costs of ERMs, the clustering of which is not sharp and largely dependent on the actual ERMs under consideration:

- Add-on technology (AOT) or end-of-pipe (EOP) oriented ERMs
- Integrated measures or packages of measures, for instance the introduction of biotechnology and changes in food trade and consumption patterns
- Fully mixed measures (i.e., mixes of the above two types)

3.3 Regional aspects

For several regions data on specific activities such as waste handling and sewage treatment, and abatement strategies and associated costs or benefits are scant or not available. In such cases the regional outcomes should be adjusted on the basis of other regions with adequate data. The underlying assumption is that regions are similar in several respects – which may not be correct for agricultural production – and may converge in the future to even more similar practices and options. Factors which may be considered in adjusting regional data include:

- Relations between factor costs and productivity (labour, capital and land)
- The shares of industry, services, agricultural sectors in the regional economy
- Structural differences in the society/economy/land use
- Regional environmental conditions
- Path-dependence lock-in or system-inertia may increase marginal abatement costs
- Actual GHG-emissions related to land use
- Historical efforts to mitigate land-use related GHG emissions already implemented
- Environmental policies without GHG-mitigation objective already implemented, but with impact on GHG-emissions
- Functioning of factor and good markets, which nowhere function perfectly
- Role of institutions influencing the functioning of markets, prices and incentives
- The importance of the so-called informal and formal economy.

In practice, the feasible adjustments are constrained by the data used and model approach in the IMAGE model. The IMAGE 2.2 model includes a number of factors that can be used to translate cost curves to other regions, for example, the management factor, cropping intensity, fertilizer use, land-use (arable), availability of land, food efficiency, demand for animal products (see chapter 2).

4. MAC curves for abatement of CH_4 emissions from landfills

4.1 Abatement options

4.1.1 General

Waste comprises a mix of materials of varying composition. When deposited in a landfill, a proportion of the organic waste fraction will begin to degrade through biological and chemical processes. Bacteria decompose the organic fraction, via an anaerobic phase to several products. Degradation results in biochemical breakdown products, water and the liberation of landfill gas, which is a mixture of CH_4 and CO_2. Waste components that contain significant biodegradable fractions include food and garden waste, paper and cardboard, and waste from animals (Bates, 1998a).

Waste degradation is a dynamic and variable process. Because of the diversity in type of waste (with different degradable fractions) and the differences in conditions within a landfill, processes vary within a landfill and between landfills. Processes also vary in time. Generally the CH_4 production increases after about two months if circumstances are suitable and generally reaches its maximum within two years. In years 2-20 the processes are more or less constant, and after about 20 years the CH_4 production decreases, particularly under more aerobic conditions prohibiting the methanogenesis. The primary factors determining CH_4 emissions include the age of the landfill site, the form and depth of the site, the way of filling and management of the site. Important differences occur in the organization and technologies applied to landfill sites.

Two major categories of options for reducing and controlling CH_4 emissions from landfills need to be distinguished (Bates, 1998a) and Figure 4.1. The first category aims at reducing the mass of waste to be landfilled by recycling or treatment of the waste. The second category aims at reducing CH_4 emissions from landfill sites in place. Both approaches can be used independently or in combination (Figure 4.1). The first category of options will abate future emissions, while the second category has a direct effect starting from the time these options are implemented.

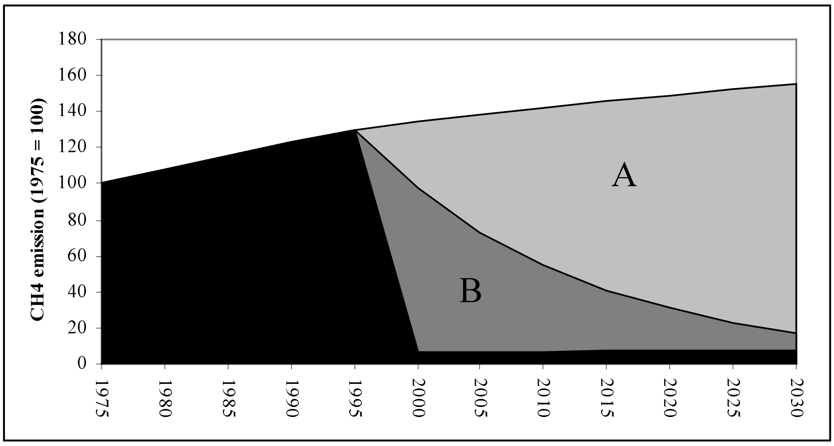


Figure 4.1. CH_4 emission from landfills from OECD Europe in the GECS baseline scenario. Emissions that potentially can be avoided is A + B. A is the emission avoided when landfilling in current sites is halted by, for example, incineration of waste. B represents the case when gas is collected from existing sites.

Table 4.1. Disposal of solid municipal waste in the EU for 1996.

Country	Landfill	Incineration	Composting (%)	Recycling	Other
Belgium	39	52	2	7	0
Denmark	18	58	1	22	1
France	45	45	6	4	-
Germany	42	25	10	22	1
Greece	94	0	0	6	0
Ireland	99	0	0	1	0
Italy	85	7	0	4	4
Luxembourg	24	47	1	28	0
Netherlands	40	28	15	17	0
Portugal	35	0	10	1	54
Spain	83	6	10	1	0
UK	85	10	0	5	0
Total	58	22	5	10	5

Source: (Bates, 1998a).

Hence, the complementarity of the two categories decreases with time, depending on the rate of implementation of the ERMs. Over a longer time period the two categories are exclusive. For the scenario period 1995-2030 covered in this study the two categories are considered to be complementary.

4.1.2 Options to reduce landfilling of organic waste

The emissions on the one hand and the potential for reduction on the other hand are largely determined by the existing system. Most EU member states still rely on landfills as the major way of disposal their solid waste. Table 4.1 shows the percentage of waste landfilling, incineration, composting and recycling for 12 EU countries in 1996. The most important options (paper recycling, composting, anaerobic digestion and incineration) are discussed below.

Paper recycling. Recycled paper will normally return in the process of paper and board production. In 1997 about 44% of paper waste was recycled in the EU member countries (Bates, 1998a). Paper makes up 27% of Municipal Solid Waste (MSW) in the EU and about 60 to 70% of biodegradable C in MSW (Bates, 1998a). Some 58% of the total waste disposal flow goes into landfills (Table 4.1). This is 64.4% of the non-recycled flux including paper and board waste. Hence, the fraction of paper and board waste in the total volume of waste landfilled is 17.4% (0.27×0.644).

Paper and board flows not going to landfills are assumed to have zero CH_4 emissions, so that the emission reduction of CH_4 is expected to be 100% for recycled paper. Bates (1998a) assumed that 25% of landfilled paper waste can be recycled by 2010, and 50% by 2020. We therefore assumed that the potential for abatement of CH_4 emissions from landfills for 2010 is 25% of the current 17.4%, or 4.4%. For 2030 we assumed 50% abatement, which is 8.7% of the current landfill emission.

Composting. The degradable organic fraction of the waste can be composted to stabilize the organic matter. The residue is then landfilled or, if the feedstock waste is uncontaminated, the composted product can be used as fertilizer. In practice composting requires pre-sorted waste or waste which is free of contamination. Several countries within Europe are now collecting organic wastes from households for organic waste treatment.

Different systems are available for composting organic waste. Current large-scale centralized systems are energy intensive and require sorting and multiple handling of the waste using machinery. Estimates of the energy use within composting facilities range from 20 to 70 kWh/t (Bates, 1998a).

The MSW consists of about 32% (own estimate) of organic waste (ranging from 20 to 49% according to Bates). It is estimated that 30-50% of the waste will be turned into compost while 25% of the material is residue, which may be landfilled with negligible CH_4 generation potential. The remaining part is lost as water and CO_2 during composting. Since these materials and products stem from agricultural products they are neutral with respect to global warming. Data on costs vary significantly between different studies and range from 40 – 290 € per tonne.

An alternative for centralized composting is home composting, which does not require transport and processing. Because of the small scale of operations and thus high surface to volume ratio most of the degradation is aerobic. Hence, CH_4 emissions are minimal (Bates, 1998a).

Anaerobic digestion. Anaerobic digestion is primarily a method of energy recovery based on the natural decomposition of organic material in the absence of oxygen. Anaerobic digestion normally occurs in landfills, but this ERM involves optimization of the process to decrease the period of gas generation to about three weeks rather than three or more decades in uncontrolled landfills.

The process is carried out in an enclosed system. It produces biogas, a mixture of CH_4 and CO_2, which is burnt to allow energy recovery, either through the generation of electricity or for the production of heat. A significant part of the energy generated will be needed to facilitate the fermentation process. A possible surplus of energy in the form of biogas – which therefore requires purification – or electricity might be delivered to the grid, in which case there is a small benefit in the form of avoided CO_2 emission and some revenues from sales.

Besides biogas, the process yields a solid residue that can be applied on the land as a soil organic amendment. Only part of it (about half) of the solid residue produced may be of adequate quality. Another by-product is a liquid residue consisting of a large portion of the nutrients in the waste and can be used as a fertilizer.

Incineration. During waste incineration the municipal waste is burnt and the energy released is used for heat or electricity production. In the EU, incineration is one of the most common options for pre-treating biodegradable wastes prior to landfilling. Incineration reduces the waste volume to 30% of its original volume and produces an inert residue suitable for landfilling. Incineration can be used to treat all fractions of MSW. Therefore, theoretically, all CH_4 emissions from newly formed waste can be avoided when all the waste is incinerated. Waste already stored in landfills will potentially cause substantial emissions after 2010 and probably even small amounts after 2030 (Figure 4.1).

4.1.3 Options to reduce methane generation from landfills

Whereas the previously discussed options lead to a reduction in landfill size, thus avoiding future CH_4 emissions, there are a number of options for existing landfills which cause an immediate reduction of CH_4 emissions. These options include capping, flaring, and oxidation and other treatments.

Capping of landfill sites. Where controlled landfills are in operation, improved site engineering can help to reduce uncontrolled emissions of CH_4 from the site. Installing a barrier system prevents lateral migration of landfill gas from the site and its subsequent escape to the atmosphere. Improving the capping and restoration layers of a landfill site is a relatively low-cost option to reduce CH_4 emissions. Capping of landfills with an impermeable clay layer reduces CH_4 emission by providing a physical barrier. Over many years, the clay cap may deteriorate or crack under dry weather conditions. However, if the restoration layers above the clay cap are also engineered to take advantage of biological CH_4 oxidation activity, the CH_4 emissions are relatively unimportant. It is assumed that 80% of the landfill gas can be collected and combusted for all modern landfills (Bates, 1998a). The remainder of the CH_4 produced by the waste (20%) will pass through the restoration layer during which 90% is oxidized biologically.

Flaring of landfill gas. Gas collection systems can be installed to prevent leakage of CH_4 from landfills. Gas collection and combustion can dramatically reduce uncontrolled CH_4 emissions to atmosphere. The technology for landfill gas collection and combustion for either flaring or energy recovery is well established in many EU countries (Bates, 1998a). Modern flares are designed to work continuously. Combustion efficiency generally exceeds 99% for CH_4. Costs of landfill gas collection can only be calculated on a site by site basis because of site-specific factors such as waste type, depth and area. Costs of flaring depend on local regulations and best practice requirements. Only where no suitable end use can be found and/or the project cannot achieve sufficient financial returns, flaring of CH_4 is the most suitable option. We assume that the CO_2-emissions are negligible, because CO_2 has a much lower global warming potential than CH_4.

Direct use of landfill gas. Landfill CH_4 can be used directly in boilers or indirectly for electricity generation or process heating. If direct combustion of landfill gas is not a viable option at a site, the most likely alternative is to generate electricity, with or without heat recovery. Electricity generation from landfill gas is a successful demonstration technology within the EU; currently more than 200 schemes are in operation. An electricity generation scheme requires a prime mover and generator, associated civil works to house the generation plant, electrical and control equipment, access to the distribution grid, and annual running costs including the operation and maintenance of the plant.

Methane oxidation in topsoils. When landfill gas diffuses through the top layer, part of the CH_4 is oxidized to CO_2 by methanotrophic bacteria. The share in the CH_4 emissions that is oxidized varies strongly between landfills. In some landfills the CH_4 oxidation is negligible while in other landfills oxidation is close to 100%. CH_4 emissions from landfills can be reduced by optimization of the conditions for oxidation by modifying the level of biological activity, the availability of nutrients, structural aspects of the cover material, etc. (De Jager et al., 2001). Global CH_4 emissions from landfills could be reduced by an estimated 10 to 20% as a result (De Jager et al., 2001). An economically interesting way to increase CH_4 oxidation is the addition of waste materials to the top-layer. Extensive large-scale experiments have not been made so far. The effect of the different specific ERMs is therefore uncertain.

Methane oxidation may be applied in old landfills without extraction system as these are significant CH_4 emitters. Recently closed landfills are another interesting group of landfills, where CH_4 fluxes still may quite significant. Abatement via oxidation can also be achieved in landfills that are still in exploitation (De Jager et al., 2001).

Aerobic landfilling with biological-mechanical pre-treatment. Methane in landfills is generated under strictly anaerobic conditions. Small amounts of oxygen in a landfill will inhibit the methanogenesis process and limit CH_4 generation. One way of maintaining the aerobic conditions in the landfills is a process where air enriched with oxygen is compressed and injected into the landfill, through specific needles. This method is proven in technology in different European countries (De Jager et al., 2001).

A further way the aerobic pre-treatment to reduce the CH_4 emission potential of the waste upon landfilling. This is generally part of mechanical-biological pre-treatment of waste, comprising: (i) mechanical treatment with separation (paper, plastics), size reduction and homogenization; (ii) biological pre-treatment generally with a composting step and (iii) waste incineration.

Another method has long been used in many European countries. Waste was first collected in small heaps near the homes, and after some time it was relocated to larger more managed landfill sites (De Jager et al., 2001). Reduction in volume and humidity, and reduction of emissions to soil and groundwater are additional advantages. In modern cities this pre-storage is no longer practicable.

4.2 Potential emission reduction

The potential emission reduction by the ERMs identified is estimated on the basis of the following elements:

1. *Emission scenario* which is the GECS baseline scenario (see chapter 2). In the baseline scenario no autonomous emission reduction is considered over the implementation time path of the ERMs;
2. *Sectoral share* (section 3.1.1);
3. *Potential emission reduction*. Emission reductions exceed 100% when, in addition to the reduction per se, also substitution of fossil fuels occurs, for example in the case of electricity generation using landfill gas, and;
4. *Implementation degree* (section 3.1.1). The implementation begins at a low level and increases over time to the maximum level. The implementation depends on many variables and is therefore based on exogenous assumptions. For certain ERMs, the degree of implementation in 2030 is higher than in 2010 to reflect the technical and economic constraints which have to be overcome gradually. Such constraints are considered to be independent of the carbon value.

Table 4.2 presents the emissions for 2010 and the above three factors determining the reduction potential in the 17 IMAGE regions for the GECS baseline scenario for the year 2010 and 2030. In Appendix D the assumptions made for the parameters in Table 4.2 are listed. Adjustments can easily be made in the spreadsheet model according to changed interpretations.

The USA, OECD Europe and East Asia are the regions with the highest potentials for emission reduction in 2010 (Figure 4.2). This can partly be explained by the fact that these regions also have the highest emissions.
The estimated reduction potentials for the year 2030 indicate that in the currently industrialized world regions the reduction potential will roughly double. The growth of emissions and hence the increase in reduction potential in the GECS baseline scenario is much larger in the less developed than in industrialized countries, as their share in the total emission reduction potential increases from 48.3 % in 2010 to 66.5 % in 2030 (Figure 4.3). This growth is largely due to the higher growth rates in the less developed regions in the GECS scenario.

Table 4.2. CH_4 emission from landfills for 2010, the share in sector, emission reduction, implementation degree and the total emission reduction for the 17 IMAGE regions.

IMAGE region[1]	Emission projected for 2010 (Mton $CH_4\ y^{-1}$)	(Mton $CO_2\ y^{-1}$)	Share in sector	Potential emission reduction[2] (%)	Implementation degree	Emission reduction in 2010 (Mton $CO_2\ y^{-1}$)
1 Canada	1.4	33.2	17-80	45-110	10-75	12.0
2 USA	12.3	282.9	17-80	45-110	10-75	102.4
3 Central America	1.7	40.2	17-80	45-110	5-75	14.6
4 South America	3.4	78.0	17-80	45-110	5-75	28.2
5 Northern Africa	0.5	10.4	17-80	45-110	5-75	3.7
6 Western Africa	0.4	11.0	17-80	45-110	5-75	4.0
7 Eastern Africa	0.2	4.1	17-80	45-110	5-75	1.5
8 Southern Africa	0.4	8.4	17-80	45-110	5-75	3.0
9 Oecd Europe	5.8	132.3	17-80	45-110	10-75	47.9
10 Eastern Europe	1.0	23.2	17-80	45-110	5-75	8.4
11 Former USSR	2.7	63.2	17-80	45-110	5-75	22.9
12 Middle East	1.5	33.5	17-80	45-110	5-75	12.1
13 South Asia	2.4	55.8	17-80	45-110	5-75	20.2
14 East Asia	4.7	107.3	17-80	45-110	5-75	38.8
15 Southeast Asia	1.2	27.0	17-80	45-110	5-75	9.8
16 Oceania	0.5	10.5	17-80	45-110	10-75	3.8
17 Japan	1.6	36.3	17-80	45-110	10-75	13.2
World	41.6	957.4	17-80	45-110	5-75	346.5

[1] Appendix E.
[2] Reduction of > 100% results from CO_2 mitigation due to fossil fuel substitution.

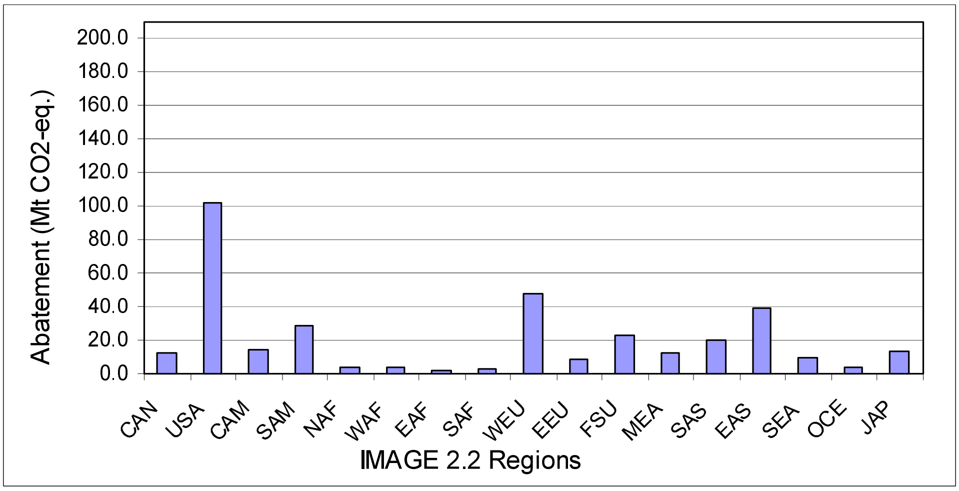


Figure 4.2. Potential CH_4 emission abatement for landfills for 2010 for the 17 IMAGE regions (see Appendix E).

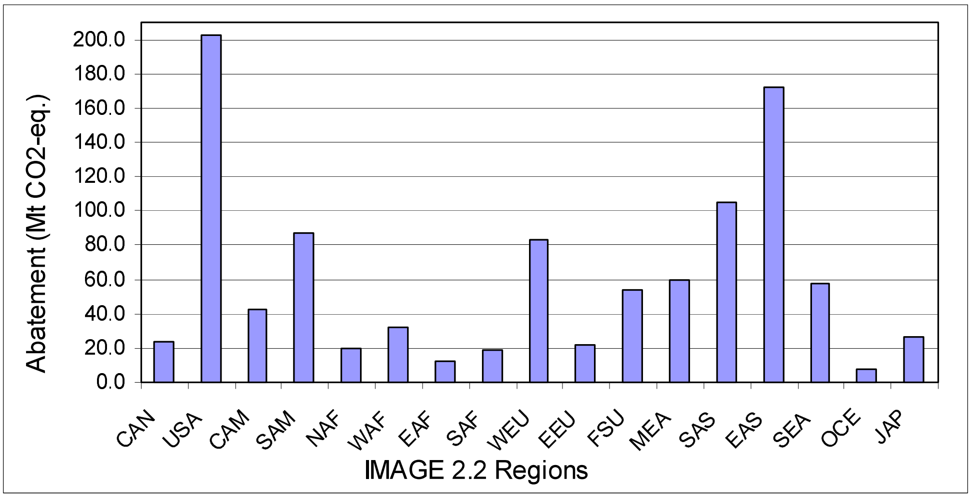


Figure 4.3. Potential CH_4 emission abatement for landfills for 2030 for 17 IMAGE regions (see Appendix E).

Table 4.3. Costs of waste-related ERMs in Europe in the mid-1990s.

Emission Reduction Measure (ERM)		1995€/t CH_4	1995€/t CO_2-equiv
Paper Recycling	Best estimate	-2208	-105
	Range	-2669 to –1747	-127 to - 83
Composting (turned windrow, UK)	Best estimate	1033	49
Variation due to:			
– Uncertainty in source separation costs	Range	812 to 1180	39 to 56
– Zero revenues from residue		1171	56
– Zero avoided cost of disposal		2197	105
Composting (tunnel composting, NL)	Best estimate	1794	88
Variation due to:			
– Uncertainty in source separation costs	Range	1495 to 2093	71 to 100
– Zero revenues from residue		2139	102
– Zero avoided cost of disposal		4013	191
Anaerobic digestion	Best estimate	1858	87
Variation due to:			
– Uncertainty in source separation costs	Range	1627 to 2013	77 to 96
– Zero revenues from residue		2216	105
– Zero avoided cost of disposal		3575	169
Incineration	Best estimate	1423	68
– Zero avoided cost of disposal		3130	149
Capping of Landfill	Best estimate	592	28
	Range	446 to 790	21 to 38
Flaring Landfill Gas	Best estimate	23	1
	Range	15 to 31	0.7 to 1.5
Direct Use of Landfill Gas	Best estimate	- 76	- 3.6
	Range	- 73 to – 77	- 3.5 to - 3.7
Generation electricity from Landfill Gas	Best estimate	44	2
	Range	- 14 to + 104	- 1 to - 5

Source: Bates (1998a). Negative values indicate net income generated by ERMs.

4.3 Costs of ERMs

For each ERM we consider investment costs of the additional installations, plants and other facilities and the operation and maintenance costs and savings (see chapter 3). We first estimated costs for European countries on the basis of several studies on emission reduction and associated costs (Bates, 1998a; De Jager et al., 1999; Gerbens and Zeeman, 2000; Harnisch and Hendriks, 2000; Bates, 2001; Bates and Haworth, 2001; De Jager et al., 2001) The costs of ERMs for CH_4 from solid waste disposal from the literature is presented in Table 4.3. The most cost-effective ERM is paper recycling, followed by ERMs involving the direct use of landfill gas (Bates, 1998a). These options are in fact no-regret options, as the benefits from gained energy like heat or avoided expenditures for landfilling, for example, more than offset the operational and annualized capital costs of the ERMs.

Flaring of landfill gas and electricity generation from landfill gas are both cost-effective options (22 and 36 €99 /tonne CH_4, respectively). The cost of abating CH_4 by capping landfills is an order of magnitude higher than that of options involving the recovery of landfill gas. Apart from paper recycling, the options involving diversion of organic waste from the waste stream all have significantly higher costs of abatement (>1000 €99 /tonne CH_4).

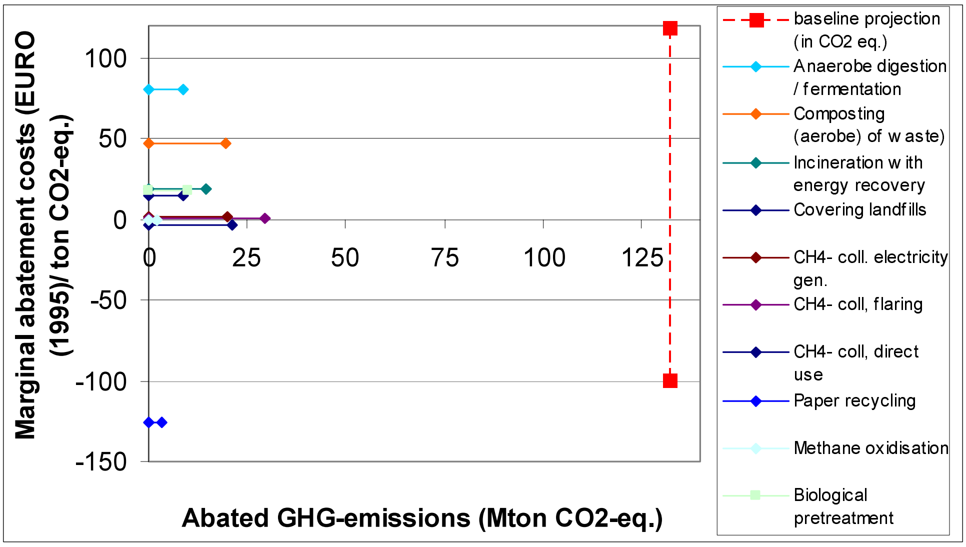


Figure 4.4. Costs of individual measures to reduce CH_4 emissions from landfills in 2010 for OECD Europe.

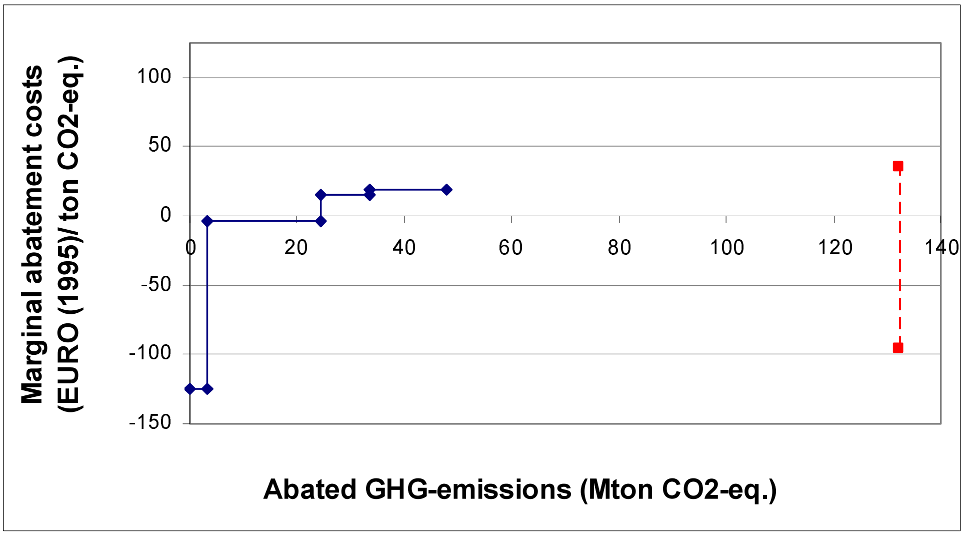


Figure 4.5. Cost of the mix of ERMs to reduce CH_4 emissions from landfills for OECD Europe for 2010. The red broken line is the CH_4 emission from landfills for OECD Europe for 2010 in the GECS baseline scenario.

Table 4.4. Regional economic indicators used for the construction of the MACs in 2010.

IMAGE region[1]	Annual investment indicator (OECD Europe = 1)	Annual O&M costs denominator (OECD Europe = 1)	Energy price index
1 Canada	1.0	1.0	0.7
2 USA	1.0	1.1	1.0
3 Central America	1.1	0.7	0.9
4 South America	1.1	0.8	1.0
5 Northern Africa	1.2	0.7	0.3
6 Western Africa	1.2	0.7	0.5
7 Eastern Africa	1.2	0.7	2.3
8 Southern Africa	1.2	0.7	1.8
9 Oecd Europe	1.0	1.0	1.0
10 Eastern Europe	1.1	0.8	1.0
11 Former USSR	1.2	0.7	0.6
12 Middle East	1.1	0.7	0.3
13 South Asia	1.2	0.7	1.2
14 East Asia	1.1	0.7	1.4
15 Southeast Asia	1.2	0.7	0.8
16 Oceania	1.1	0.9	0.7
17 Japan	0.9	1.2	2.1

[1] Appendix E.

Costs were first estimated for each ERM separately. The ERMs are combined on the basis of their cost-effectiveness. In some cases specific combinations of ERMs are selected. For example, CH_4 collection is always combined with capping of the landfill. The resulting set of ERMs selected for 2010 for OECD Europe is shown in Figure 4.5.

For other regions data are often more difficult to find and more uncertain and the cost calculations were based on the following assumptions:

- Greenhouse gas mitigation has lower priority in lower per capita income regions.
- The composition of waste depends on the structure of the economy, whereby industrialized economies differ from agriculture or service sector dominated economies.
- Costs of capital, labour and energy vary across regions.

To account for these differences, we use multiplication factors which indicate the relative cost as compared to OECD Europe (Table 4.4). The discount rate is kept the same for all regions, namely 4%.

- *Annual investment costs per region*. We assumed that investment criteria such as the 'Internal Rate of Return' (IRR) or the 'pay-back period' (PBP) tend to be higher in low-income regions where capital is scarce than in high-income regions, particularly for the ERMs considered here. On the basis of these considerations, the following multipliers are applied for the relative ERM investment cost in the world regions (Table 4.4):

- 0.9 for regions with GDP >150 % of that of OECD Europe (see: Appendix E)
- 1.0 for regions with GDP of 50%-150% of that of OECD Europe
- 1.1 for regions with GDP of 10-50% of that of OECD Europe
- 1.2 for regions with GDP of 0-10 % of that of OECD Europe.

- *Regional labour costs*. We used regional GDP per capita relative to that of OECD Europe to estimate relative labour costs (Table 4.4). The base level for each region is 0.7. The ratio of the regional GDP per capita to that of OECD Europe is multiplied by 0.3 and added to the base level – hence OECD Europe has a value of 1.0. The results among regions vary from 0.7 for African regions with the lowest labour cost to 1.1 for Japan with the highest labour costs. This factor is applied to the annual operation and maintenance costs.

- *Regional energy savings/revenues.* For those ERMs which give a net energy gain which can be sold on the market, we used the price of the energy carrier 'natural gas' as simulated in the TIMER model for the GECS baseline scenario (Table 4.4). We used natural gas because energy in the form of CH_4 gas from landfill sites matches natural gas more closely than coal and oil. For example, the prices used for the different regions vary from 0,77 €99/GJ for Northern Africa and 0,88 €99/GJ for the Middle East to 6,78 €99/GJ for Eastern Africa and 6,0 €99/GJ for Japan in 2010. Similarly, in 2020 and 2030 TIMER simulations show the high prices of natural gas in some regions (such as Japan) resulting in high values for the energy price indices (Table 4.5).

Table 4.5. Regional economic indicators used for the construction of the MACs in 2030.

IMAGE region[1]	Annual investment indicator (OECD Europe = 1)	Annual O&M costs denominator (OECD Europe = 1)	Energy price index
1 Canada	1.0	0.9	1.0
2 USA	1.0	1.1	1.2
3 Central America	1.1	0.8	1.0
4 South America	1.1	0.8	0.9
5 Northern Africa	1.1	0.7	0.4
6 Western Africa	1.2	0.7	0.4
7 Eastern Africa	1.2	0.7	1.1
8 Southern Africa	1.2	0.7	1.2
9 Oecd Europe	1.0	1.0	1.0
10 Eastern Europe	1.1	0.8	0.8
11 Former USSR	1.1	0.8	0.5
12 Middle East	1.1	0.8	0.2
13 South Asia	1.2	0.7	1.1
14 East Asia	1.1	0.8	1.4
15 Southeast Asia	1.1	0.7	0.9
16 Oceania	1.1	0.9	0.7
17 Japan	1.0	1.1	1.6

[1] Appendix E.

4.4 Cost curves

4.4.1 Cost curves for 2010

The combination of the emission reduction potential and costs for the different ERMs is presented for the 17 IMAGE regions (Figure 4.6) showing the CH_4 emission reduction in each region. A small amount of emissions can even be reduced at negative costs by paper recycling. Such options are interesting even without climate policy. Other ERMs show significant emission reduction potential over the different regions, at low to average costs. In many cases the options cost less than 22 €99/ton CO_2-equivalent. The results show that emission reductions may take place as a result of current policies. For example in Europe some ERMs have already been implemented.

4.4.2 Cost curves for 2030

In the GECS baseline scenario the CH_4 emissions from landfills strongly increase in most world regions between 2010 and 2030. As a result, the potential emission reduction also increases. This means that for a certain amount of reduction in tonnes CO_2-equivalent units the costs will decline. For the estimation of the implementation degree we made assumptions based on - where possible - estimates or expert judgements from the literature (Appendix D). Some considerations are important in this respect. We assumed that in 2030 there has been more time to implement ERMs so that the implementation degree of the various ERMs is higher than in 2010, particularly for ERMs requiring investments in high-tech installations. Furthermore, we assumed an increasing public concern for environmental quality and climate change, coinciding with rising incomes.

Finally, for certain ERMs the potential emission reduction may increase over time as technologies improve. However, when an increasing part of the reduction potential has been achieved it may become increasingly difficult and costly to achieve further reductions. For some ERMs we assumed a slight improvement in effectiveness over time and for other ERMs no change. In the spreadsheet model adjustments can be made to describe the net effect of these two bi-directional phenomena. The resulting aggregated cost curves are presented in Figures 4.6a and 4.6b.

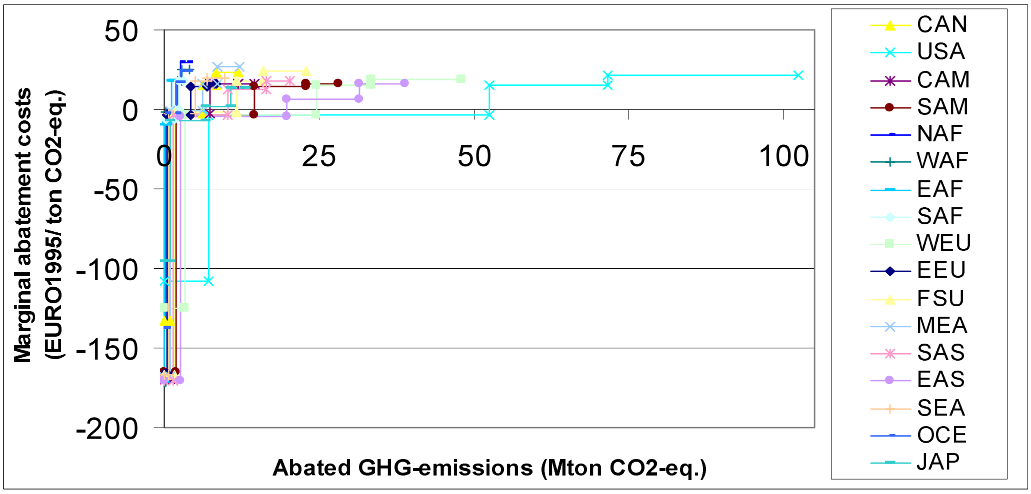


Figure 4.6a. Aggregated Cost curves for reduction of CH_4 emissions from landfills for 2010 for the 17 IMAGE regions (see Appendix E).

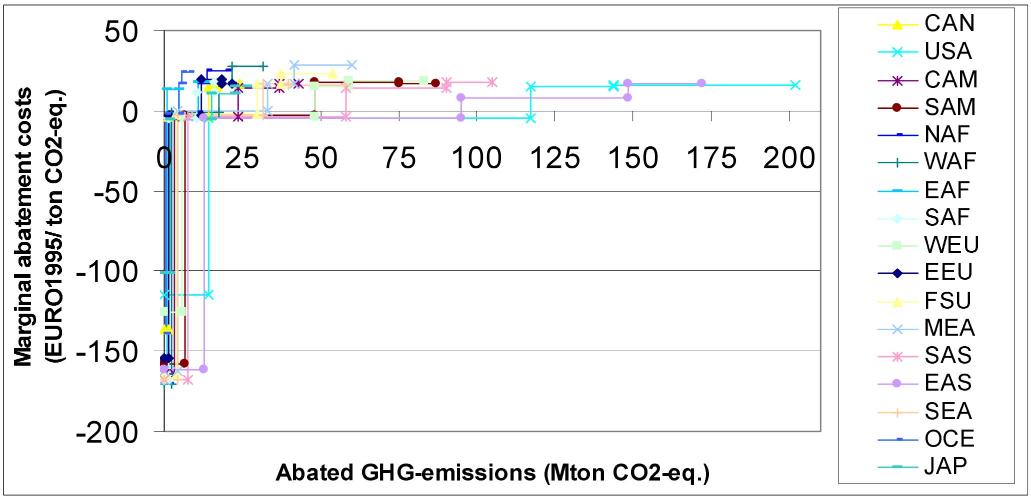


Figure 4.6b. Aggregated cost curves for reduction of CH_4 emissions for 2030 for the 17 IMAGE regions (see Appendix E).

4.5 Comparison with other studies

Our results combine the findings from a small selection of studies, and will therefore not always match exactly with each separate study. For example in addition to the categories of ERMs distinguished in the study of Bates (1998a), we considered two additional ERMs (CH_4 oxidation and biological pre-treatment) which were considered by De Jager et al. (2001). A difference with the study of (De Jager et al., 2001) is the sequence in the approach. De Jager et al. (2001) based the implementation degree on expert judgements. In our study we first estimate the maximum implementation that under given circumstances could be expected for each separate measure. After that, a selection takes place according to the lowest reduction costs per unit of abated CO_2-equivalent, and subsequently by choosing ERMs that can be combined. It is clear that the different approaches will lead to different outcomes, in particular with regard to the selected individual ERMs.

Some of the differences with other studies may also be caused by differences in the assumptions made in the GECS baseline emissions scenario for landfills and the discount rate used (Figure 4.4). The period of projections and trends differ from the study of Bates (till 2030). Differences also may occur due to definitional differences. Some studies, like Bates (1998a) use a ‘business as usual’ baseline scenario including current plans for abatement of greenhouse gases, while in this study we compare abatement measures with a ‘without climate policy’ baseline scenario.

Despite these differences and considering the large uncertainty in emission estimates for landfills, our results for the abatement are comparable to those of De Jager et al. (2001) (Table 4.6). Bates (1998) however have comparable results for the emission levels but significant higher estimates for the abatement. Beyond 38% abatement the associated costs strongly increase according to our approach thereby limiting the realized abatement, since abatement in other sectors would be more cost-effective.

Table 4.6. Comparison of reported estimations of CH_4 emissions from landfills and potential emission abatement for EU 15 and OECD Europe in 2010, 2020 and 2030.

Region	(Bates, 1998a)[a]	(De Jager et al., 2001)	This study[b]
		Emissions in 2010	
EU 15	7		
OECD Europe		24 [c]	6
		Emissions in 2020	
EU 15	8		
OECD Europe		24 [d]	6
		Potential abatement in 2010	
EU 15	5		
OECD Europe		1	2
		Potential abatement in 2020	
EU 15	7		
OECD Europe		3	3
		Potential abatement in 2030	
EU 15			
OECD Europe			4

Emissions and abatement in Mton CH_4 y^{-1}.
[a] Business-as-usual scenario.
[b] GECS baseline scenario.
[c] This figure refers to CH_4 formation in landfills, not actual CH_4 emission.
[d] For the year 2025.

5. MAC curves for abatement of CH_4 and N_2O from wastewater

5.1 Abatement options

5.1.1 General

Wastewater is produced in increasing quantities as a result of the growing world population and economy (see section 2.4). Two major sources of wastewater are distinguished:

1. Domestic and urban waste water stemming from toilets (black wastewater), kitchens and bathrooms; and combined wastewater (domestic wastewater combined with urban run-off water).
2. Industrial wastewater. Wastewater from the food and beverage industry contains by far the highest concentrations of organic compounds; further important sources are the petrochemical and the iron and steel industries.

Anaerobic conditions are needed for CH_4 formation. In waste streams with high organic concentrations available oxygen is quickly depleted by decomposition of organic matter (EPA, 2001). Therefore, the CH_4 generation potential of wastewater is determined by the amount of organic material in the wastewater as indicated by the biochemical oxygen demand (BOD). BOD, expressed in milligrams of oxygen per litre, represents the amount of oxygen that would be required to completely oxidize the organic matter contained in the wastewater. Further factors that regulate methanogenesis are temperature, pH, and age of the sludge.

Untreated domestic waste streams typically have a BOD ranging from 110 to 400 mg/l, while food processing facilities (such as fruit, sugar and meat processing plants and creameries) and breweries produce untreated wastewater with a BOD of 10.000 to 100.000 mg/l (Thorneloe, 1993).

In treatment plants in developed countries N is removed to meet the N discharge levels. N removal is achieved by nitrification and subsequent denitrification, whereby N_2 is the main product. N_2O and NO are intermediate products of denitrification which may escape to the atmosphere. The main controlling factors of N_2O formation are temperature, pH, BOD, and N concentration (EPA, 2001). For sewage the amount of proteins consumed by humans and for industrial effluents the N content of the organic material determines the nitrogen concentration in wastewater. The emission from municipal wastewater treatment is generally about 0.001% of N_2O-N from the aeration tank and 0.04% of N_2O-N from the nitrification/denitrification units (De Jager et al., 2001).

A century ago wastewater from houses, municipalities and industry was not treated, and effluents were simply discharged to surface waters or allowed to percolate into the soil. Nowadays, in many countries (part of) the wastewater is treated to remove soluble organic matter, suspended solids, pathogenic organisms and other chemical contaminants. Soluble organic matter is generally removed by micro-organisms which consume the waste for nutrition. The residual biomass sludge is removed from the wastewater prior to discharge and may be further biodegraded under aerobic or anaerobic conditions.

Rural areas rely on cess pits, open or simple pit latrines or septic tanks, which are more likely to produce CH_4 as a result of anaerobic degradation. In rural areas both liquid and sludge wastes are commonly applied to agricultural land for irrigation and fertilization (IEA GHG, 1998).

The CH_4 produced during anaerobic treatment can be collected and either flared or combusted for energy, although some of the CH_4 may escape to the atmosphere. Aerobic treatment of the sludge, next to anaerobic treatment of the wastewater, can result in significant reductions of CH_4 (Lexmond and Zeeman, 1995a).

Treatment methods (Figure 5.1) and CH_4 and N_2O emissions vary considerably between systems (IEA GHG, 1998). In most developed countries, most municipal and industrial wastewater is collected and treated in an integrated sewage system. After treatment the residue is disposed of on land or discharged into aquatic environments such as rivers or lakes. Integrated systems are not common in developing countries.

The highest potential for reducing CH_4 emissions from wastewater is in developing countries, where waste streams are often unmanaged or maintained under anaerobic conditions without control of CH_4 (De Jager et al., 2001). In OECD countries most municipal and industrial wastewater is collected and treated in integrated sewage systems. Treatment involves an aerobic degradation step resulting in small CH_4 emissions (OECD/IEA, 2000). Industrial sources generate the majority of CH_4 emissions in OECD countries, especially food processing, pulp/paper and chemical industry. Very little is known about the CH_4 emissions from untreated wastewater in OECD countries (OECD/IEA, 2000).

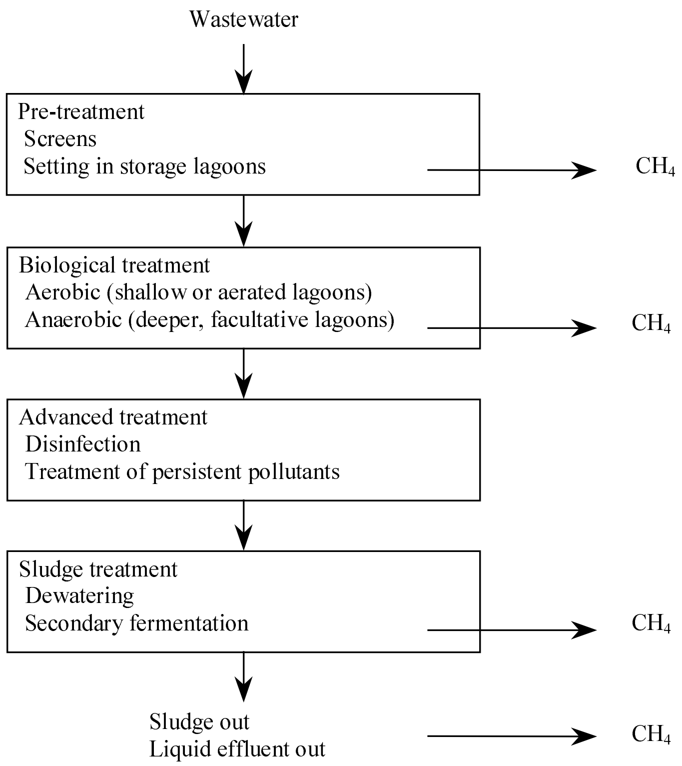


Figure 5.1. Wastewater treatment systems and CH_4 production. From Lexmond and Zeeman (1995b).

5.1.2 Options to reduce emissions from wastewater

- *Methane*. The CH_4 formed in integrated sewage systems prior to full stabilization of the sludge can be collected and flared or used as a fuel. Therefore, the available abatement options are similar to the ones for landfills. Several ERMs are available:

- Aerobic wastewater treatment
- Upgrading of existing overloaded wastewater treatment plants or plants with sub-optimal aeration
- Anaerobic treatment to stimulate CH_4 generation, which can be collected and re-used as fuel. An additional benefit is the substitution of fossil fuels.

Most abatement options for CH_4 have give reductions of close to 100% (Gerbens and Zeeman, 2000). Theoretically full implementation of wastewater treatment could reduce annual global greenhouse gas emissions from raw discharged wastewater and latrine and septic tank wastewater by about 78% (De Jager et al., 2001). Several technologies are available to prevent or reduce CH_4 emissions from residual sludge from wastewater treatment by controlled sludge treatment or disposal under aerobic conditions (De Jager et al., 2001).

Anaerobic digestion is a common practice in developing countries such as India and China, where several millions of household have installations to produce gas for domestic lighting, cooking and heating (IEA, 1998). Anaerobic treatment for GHG mitigation can result in both favourable and undesirable situations, depending on the use of the biogas produced (Lexmond and Zeeman, 1995b). Caution should therefore be taken when stimulating anaerobic treatment.

- *Nitrous oxide*. The following ERMs can be distinguished to reduce N_2O emissions from wastewater (Gerbens and Zeeman, 2000):

- N_2O emission can be prevented by using N enriched wastewater in crop production systems to reduce the use of synthetic N fertilizers
- Reduction of N_2O losses from denitrification by closely controlled N removal at wastewater treatment plants (Gerbens and Zeeman, 2000). N_2O emissions can be reduced by anaerobic denitrification in existing large scale and centralized treatment plants. In Europe most sewage treatment plants are optimized to achieve maximum N removal, with no consideration of the end-product (N_2O or N_2). Optimizing the N removal process to achieve more complete reduction of NO_3^- to N_2 rather than to N_2O (Table 5.1) could reduce N_2O emission by 50% (Hendriks et al., 1998). Here we assumed that optimization of these processes could reduce N_2O formation by one-third during nitrification and by two-thirds during denitrification. The total reduction in an aerobic-anaerobic system is about 40%. As a consequence of the increased N removal rates, the N load of surface water from sewage treatment plants is decreased significantly. In the following we mainly will focus on the latter strategy as it will have largest impact.

Table 5.1. Optimal process conditions in wastewater treatment for minimal N_2O formation.

Process parameters	Nitrification	Denitrification
Oxygen concentration	> 2.0 mg dm^{-3}	< 0.5 mg dm^{-3}
pH	neutral	neutral
Organic matter content	low	BOD/N > 4
Age of sludge	high	high

Source: Hendriks et al. (1998).

5.2 Potential emission reduction

We use the following elements to calculate the potential emission reduction by the various ERMs:

1. *Emission scenario* which is the GECS baseline scenario (see chapter 2) giving projections for CH_4 and N_2O emissions from both treated and untreated domestic and industrial waste water. No autonomous emission reduction is considered over the implementation time path of the ERMs;
2. *The share in the sector* (see section 3.1.1);
3. *Emission reduction*, which is the fraction from the baseline emissions of a sector share that can be reduced by the specific ERM under consideration. Emission reductions exceed 100% when, in addition to the reduction per se, also substitution of fossil fuels occurs;
4. *Implementation degree* (see section 3.1.1). For certain ERMs, the degree of implementation in 2030 is higher than in 2010 to reflect technical and economic constraints which are gradually overcome. These constraints are considered to be independent of the carbon value.

- *Methane*. On the basis of the above elements we estimated the reduction potential for 2010 for CH_4 (Table 5.2) from wastewater in the 17 IMAGE regions. Data for 2030 are not presented in this report but are available in the underlying spreadsheet. The most important reductions CH_4 emissions from sewage can be achieved in the USA and OECD Europe. Other important regions for CH_4 and N_2O reduction from sewage are South and East Asia and Japan. Stimulation of better management of treatment plants to reduce emissions of CH_4 will require regulation by enforcement or incentives. Effective governmental efforts are required, while success largely depend on the local circumstances. Since such governmental actions involve non-private costs, the private costs of the ERMs are low or sometimes zero.

We assumed that in 2010 only part of the maximum theoretical potential can be implemented. The reduction potential is related to the baseline scenario emissions. Thus, in Japan, Eastern Europe and OECD Europe where CH_4 emissions decline in the period 1995-2030, the reduction potential also declines. For the world as a whole the CH_4 emission from sewage (and reduction potential) strongly increase.

For developed countries we assumed a lower degree of implementation as less sanitation and wastewater treatment plants are in place. For 2030 we assume that for certain regions a maximum degree of implementation of 60% can be achieved. We also assume slight improvement in the effectiveness of CH_4 emission reduction over time, increasing from 60% in 2010, to 70% in 2020 and 80% in 2030.

- *Nitrous oxide*. On the basis of the above elements we estimated the reduction potential for 2010 for N_2O (Table 5.3) from wastewater in the 17 IMAGE regions. Generally abatement measures for N_2O are not expressed in quantitative terms because of large uncertainties and lack of quantitative information (Gerbens and Zeeman, 2000; De Jager et al., 2001; Bates, 2001b). Therefore, we use conservative estimates for the reduction effectiveness.

We first considered the share of the sewage N that is being treated in treatment plants using regional data from WHO (WHO/UNICEF, 2001) on the sanitation coverage (i.e., the fraction of the population being connected to a sewage system) and the fraction of sewage being treated in a treatment plant. We assumed that abatement focuses on centralized sewage water treatment plants already in place. Abatement options at the (household) level of pits and septic tanks is assumed to be much more difficult to implement, and primary based on human health and general hygiene rather than climate change considerations.

The different elements that determine the effectiveness of the measures are presented in Table 5.3 for 2010. We assumed a maximum of 20% reduction of the N_2O emission from treated wastewater in 2010, 30% in 2020 and 40% in 2030. Emission reductions are lower in high-income than in low-income regions, assuming that ERMs are already in place in many treatment plants.

For 2010 the assumed implementation degree is 30% of its potential in high-income regions (>50% of OECD European per capita GDP), 20% for medium-income regions (10-50% of OECD European GDP) and 10% for low-income regions (<10% of OECD-European GDP). For 2020 the values for the implementation degree are 50% for high-income regions, 30% for medium-income and 20% for low-income regions. For 2030 the values for implementation degree are 70%, 40% and 30%, respectively.

5.2.1 Costs of ERMs

In general the costs differ between systems and vary on the basis of local conditions for various reasons:

- Because of economies of scale there is an important difference in costs between (community) on-site, small-scale and (centralized) large-scale wastewater treatment (De Jager et al., 2001).
- The more advanced wastewater treatment systems should be applied for removal of toxic substances or pathogens to meet public health objectives; this implies high costs of GHG emission reduction.

Table 5.2. CH_4 emission from wastewater for 2010, the share in sector, emission reduction, implementation degree and the total emission reduction for the 17 IMAGE regions.

IMAGE region[1]	Emission projected for 2010 (Mon CH_4 y^{-1})	(Mton CO_2 y^{-1})	Share in the sector	Emission reduction (%)	Imple-mentation degree	Emission reduction in 2010 (Mton CO_2 y^{-1})
1 Canada	0.2	3.3	35	60	40	0.3
2 USA	1.4	29.6	35	60	40	2.7
3 Central America	0.9	19.8	7	60	25	0.2
4 South America	1.8	38.8	7	60	25	0.4
5 Northern Africa	0.8	17.0	8	60	15	0.1
6 Western Africa	1.9	40.2	0	60	15	0.0
7 Eastern Africa	1.1	24.5	0	60	15	0.0
8 Southern Africa	0.9	19.1	0	60	15	0.0
9 OECD Europe	1.8	38.7	35	60	40	3.6
10 Eastern Europe	0.6	12.0	8	60	25	0.1
11 Former USSR	1.4	29.5	8	60	15	0.2
12 Middle East	1.4	29.6	8	60	25	0.4
13 South Asia	7.5	156.7	5	60	15	0.7
14 East Asia	7.1	149.3	5	60	25	1.2
15 Southeast Asia	2.8	58.4	7	60	15	0.4
16 Oceania	0.2	3.4	33	60	40	0.3
17 Japan	0.6	12.6	35	60	40	1.2
World	32.5	682.6	0-35	60	15-40	11.9

[1] Appendix E.

Table 5.3. N_2O emission from wastewater for 2010, the share in sector, emission reduction, implementation degree and the total emission reduction for the 17 IMAGE regions.

IMAGE region[1]	Emission projected for 2010 (Kton $N_2O\ y^{-1}$)	(Mton $CO_2\ y^{-1}$)	Share in the sector	Emission reduction (%)	Imple-mentation degree	Emission reduction (Kton $CO_2\ y^{-1}$)
1 Canada	1.6	0.5	35	10	30	4.9
2 USA	18.9	5.6	35	10	30	58.6
3 Central America	12.6	3.7	7	20	20	10.0
4 South America	25.1	7.4	7	20	20	20.0
5 Northern Africa	11.0	3.3	8	20	10	5.4
6 Western Africa	26.7	7.9	0	20	10	0.0
7 Eastern Africa	15.7	4.7	0	20	10	0.0
8 Southern Africa	12.6	3.7	0	20	10	0.0
9 OECD Europe	25.1	7.4	35	10	30	78.1
10 Eastern Europe	7.9	2.3	8	20	20	7.0
11 Former USSR	18.9	5.6	8	20	10	8.8
12 Middle East	18.9	5.6	8	20	20	18.0
13 South Asia	102.1	30.2	5	20	10	29.0
14 East Asia	97.4	28.8	5	20	20	54.2
15 Southeast Asia	37.7	11.2	7	20	10	16.7
16 Oceania	1.6	0.5	33	10	30	4.7
17 Japan	7.9	2.3	35	10	30	24.4
World	441.6	130.7	0-35	10-20	10-30	339.8

[1] Appendix E.

- Upgrading of existing overloaded treatment plants or plants with sub-optimal aeration may be one of the most cost-effective techniques, but the costs depend on the local situation and are therefore difficult to estimate.

Cost estimates for sewage treatment are scarce. Some studies assume low or even at zero costs. Other studies (IEA GHG, 1998) estimated a (private) cost of CH_4 abatement in the waste sector of around 50-100 US$ per ton CH_4 abated (2.5 €99 per ton CO_2 equivalent). The estimate made by De Jager et al. (2001) for the private abatement cost is 100 US$90/ton CH_4 or about 117 US$95/ton CH_4 (about 5.1 €99 per ton CO_2 equivalent).

For methane, we used aggregated cost estimates from the literature for the ERMs for OECD Europe (De Jager et al., 2001) and distributed the total costs over capital (25%), operation and maintenance (60%) and energy costs (15%) according to Gerbens and Zeeman (2000). The operation and maintenance costs include those for treatment and sludge disposal. We used the corrections for regional labour and capital costs which were discussed earlier in section 4.3 (Tables 4.4 and 4.5).

The measures for N_2O can be applied against low or zero costs (Hendriks et al., 1998), and are so-called no-regret options.

5.3 Cost curves

In the GECS baseline scenario the CH_4 emissions from sewage strongly increase in most of the world regions between 1990 and 2030. As a result, the potential emission reduction also strongly increases for most regions. Depending on the assumed implementation degree this leads to a strong increase in the emission reduction between 1995 and 2030. The aggregated cost curves are presented in Figure 5.3.

The measures for N_2O can be applied against low or zero costs (see above). Hence abatement options for N_2O from sewage are so-called no-regret options (Figure 5.4).

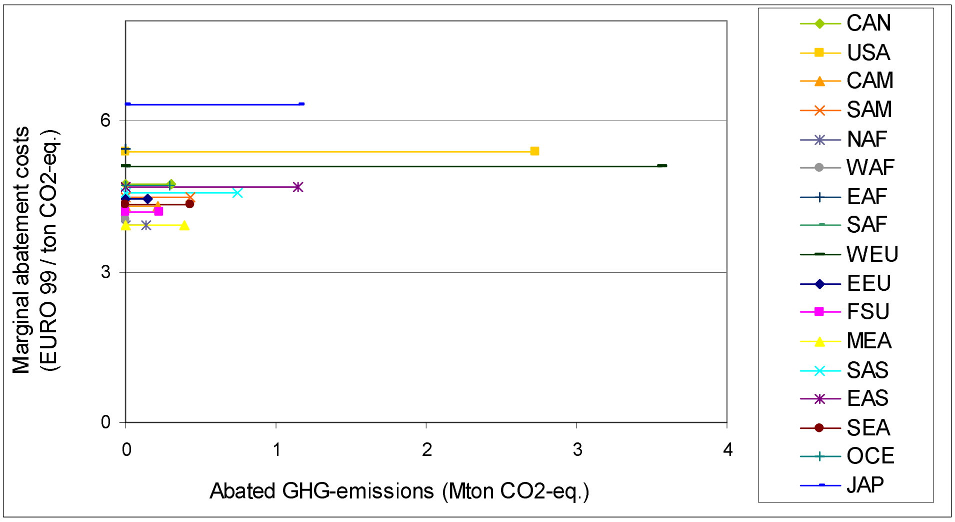


Figure 5.3a. Costs of ERMs to reduce CH_4-emission from wastewater for 2010 for the 17 IMAGE regions (see Appendix E).

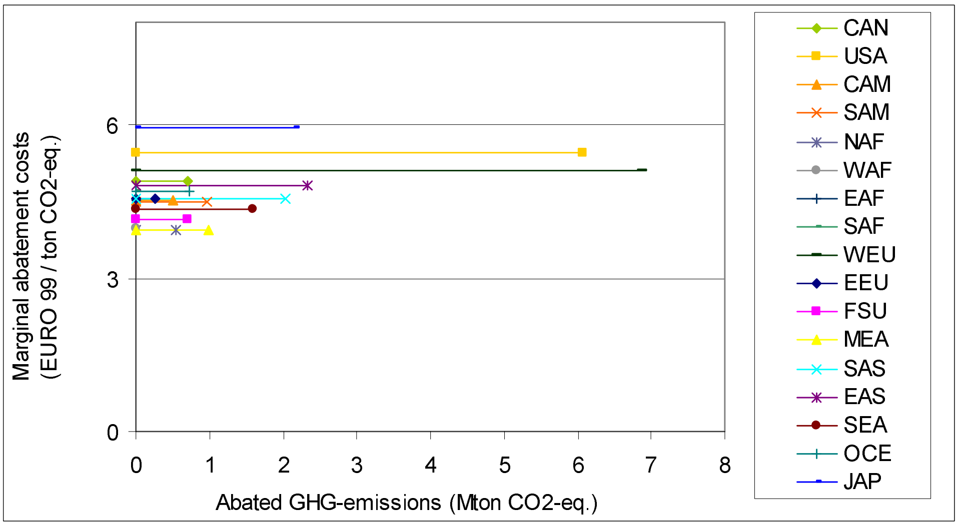


Figure 5.3b. Costs of ERMs to reduce CH_4-emission from wastewater for 2030 for the 17 IMAGE regions (see Appendix E).

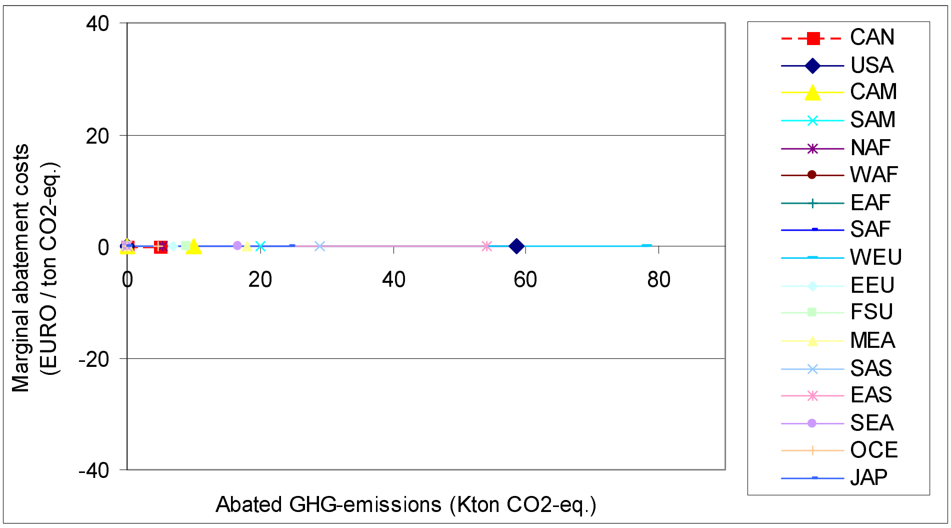


Figure 5.4a. Costs of ERMs to reduce N_2O emission from wastewater for 2010 for the 17 IMAGE regions (see Appendix E).

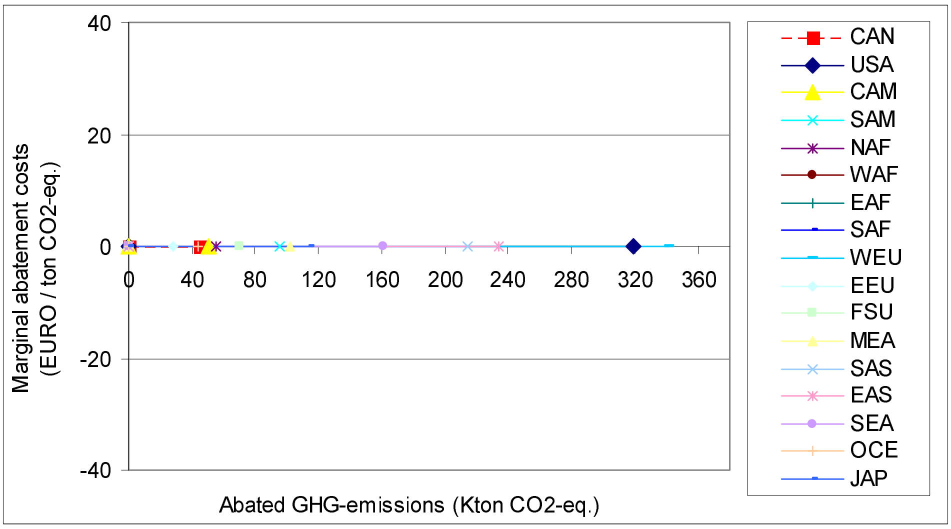


Figure 5.4b. Costs of ERMs to reduce N_2O emission from wastewater for 2030 for the 17 IMAGE regions (see Appendix E).

5.4 Comparison with other studies

We compared our estimated CH_4 emissions for the GECS-baseline scenario with those from other studies (Table 5.4). The comparison is difficult in some cases, because estimates refer to different years while in other cases it is not clear to which year the estimates correspond. However, our estimated emissions are within the range of uncertainty in the estimates of EPA (2001), Gerbens and Zeeman (2000), IEA (1999) and De Jager et al. (2001).

Our estimates for abatement of CH_4 emissions differ strongly from some other studies. Hyman (2001) assumed much more optimistic CH_4 emission abatement with a maximum of almost 50% from total emissions for the U.S.A. for 2010. For comparison, our results indicate an abatement of only about 10% for the U.S.A. for 2010. This is based on the strong increase in abatement costs beyond 30% abatement, whereby more cost-effective ERMs are implemented in other sectors.

Some studies are compared in Table 5.4. Gerbens and Zeeman (2000) assumed a full implementation (100%) of the technical measures for the EU (Table 5.4), while the estimate of IEA (1999) is also based on more optimistic assumptions on the implementation degree than our study (Table 5.4). De Jager et al. (2001) applied a degree of implementation for the EU increasing from 20 to 60% in the course of time, and their estimate closely matches the results of our study.

Another explanation of the differences between our results and the literature stems from our assumption that improved aerobic and anaerobic treatment is only possible for the sewage that is actually being treated in treatment plants. In addition, wastewater collection and sewage treatment systems will probably not be developed for reasons of GHG mitigation only. Generally such systems are implemented for reasons of public health.

For N_2O the opportunities for comparison of our estimates with other studies are limited, as there are no studies that specify emissions and abatement for this gas.

Table 5.4. Comparison of reported estimations of CH_4 emissions from sewage and potential emission abatement for Europe, the USA and the world for 1990/1995 and 2020.

Region	EPA (2001)	Gerbens and Zeeman (2000)	IEA (1999)	This study [a]
		Emissions in 1995		
Europe		1.1 [b,c,d]	4.8	1.8
USA	0.6 [e]	0.4 [b,c]	2.4 [f]	1.3
World		11.1 (4.3-22.6) [b,f]	35.0 [g]	26.9
		Emissions in 2020		
Europe				1.8
USA				1.5
World		17.2 [h]	58.0 [i]	35.9
		Abatement in 2010		
Europe				0.2
USA				0.1
World		8.7 (3.4-17.8) [j]	10.0 [k]	0.5
		Abatement in 2020		
Europe				0.2
USA				0.2
World			19.4 [k]	0.8

Emissions and abatement are indicated in Mton CH_4 y^{-1}.

[a] GECS baseline scenario and abatement compared to GECS baseline scenario.

[b] All data for 1990 unless stated otherwise.

[c] Emissions from industrial wastewater treatment are not included.

[d] Countries included in the region Europe are not specified; for simplicity we compare the estimates with the IMAGE 2.2 OECD Europe region.

[e] Estimates the whole of North America.

[f] Emissions from treated and untreated domestic (8.4 Mton) and industrial wastewater (2.7 Mton).

[g] Emissions from sewage treatment dominated by the industrial emissions.

[h] Based on the assumption that current practices will not change, annual emissions would grow to 12.8 Mton CH_4 from domestic sources Mton and 4.4 Mton CH_4 for industrial sources in 2020

[i] For no change in current practices. Considering improvements in sewage treatment would result in annual emission of 32 Mton CH_4.

[j] For full (100%) implementation. De Jager (2001) used an implementation degree increasing from 20% to 60% in the course of time.

[k] In their 'example' mitigation scenario estimates are compared to a 'baseline scenario' that show a significant increase of annual emissions over time from 35.0 Mton CH_4 in 1990 and 51.6 Mton CH_4 in 2020.

6. Emission abatement by carbon sequestration

6.1 Potential carbon sequestration

The potential C sequestration is calculated on the basis of the Surplus Potential Productivity (SPP) as discussed in section 2.1.4. The Carbon Sink module of IMAGE 2.2 generates the SPP and area for each 0.5 by 0.5 degree grid cell, the potential and actual yield for the different crops indicated in Table 2.1, the original vegetation and the planted tree species for specific years. This information is aggregated to the level of the IMAGE 2.2 regions, resulting in a physical C sequestration curve.

Between 1995 and 2030, the GECS scenario period, those areas that will be abandoned from their original agricultural or forestry use are added to the potential plantation area if they remain unused during at least the next 50 years. Hence, we need to consider years after the GECS baseline scenario. For projections of land use changes after 2030 we used the SRES A1B scenario (IMAGE-team, 2001) which most closely matches the GECS storyline and the population and economic scenarios.

In this study we do not consider the conversion from primary and secondary natural vegetation to carbon plantations. This is based on the assumption that the concern about nature conservation and biodiversity has a higher priority in the GECS scenario than abatement of climate change through C plantations. In addition, in most cases the SPP for conversion from existing natural vegetation will be much lower than for conversions from agricultural land to C plantations, leading to much higher costs than conversion of agricultural land with much higher SPP.

Figures 6.1 and 6.2 present the physical C sequestration potential as a function of the area planted for 2010 and 2030, respectively, for both abandoned agricultural land and, for comparison, abandoned commercial logging areas. It is clear that the potential C sequestration is much larger in the abandoned logging areas. However, for reasons indicated above, these were not included in all further calculations.

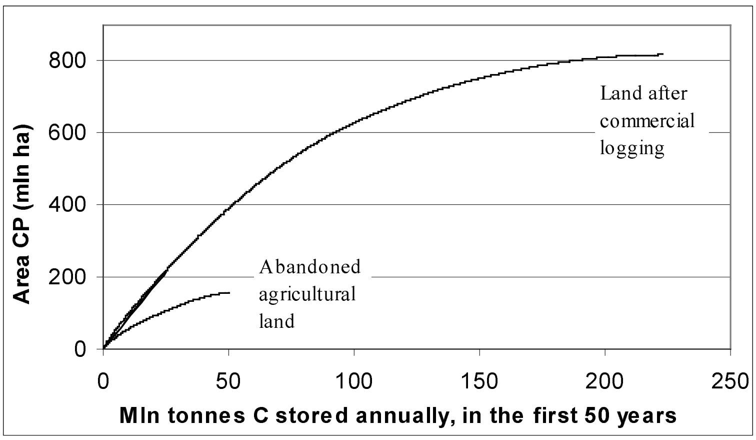


Figure 6.1. Potential global C sequestration for 2010.

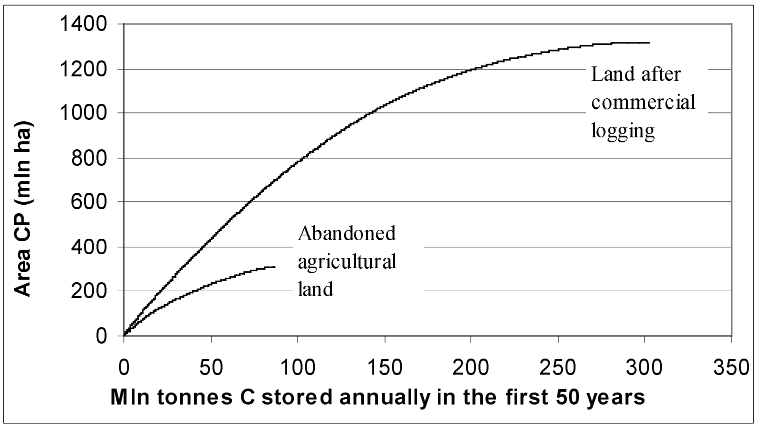
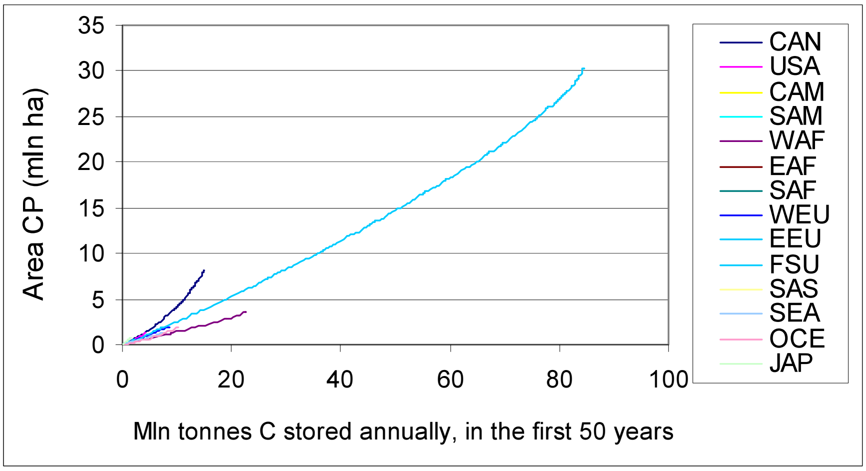


Figure 6.2. Potential global C sequestration for 2030.

Figures 6.3 and 6.4 show the same results for C sequestration in abandoned agricultural areas for all IMAGE regions for 2010 and 2030, respectively. Since the area of abandoned agricultural land in the former Soviet Union in the period 1990-2000 is very large, the potential C sequestration in this region dominates that of the whole world. The bottom graphs of Figure 6.3 and Figure 6.4 indicates the same results as the top graph excluding the former Soviet Union.



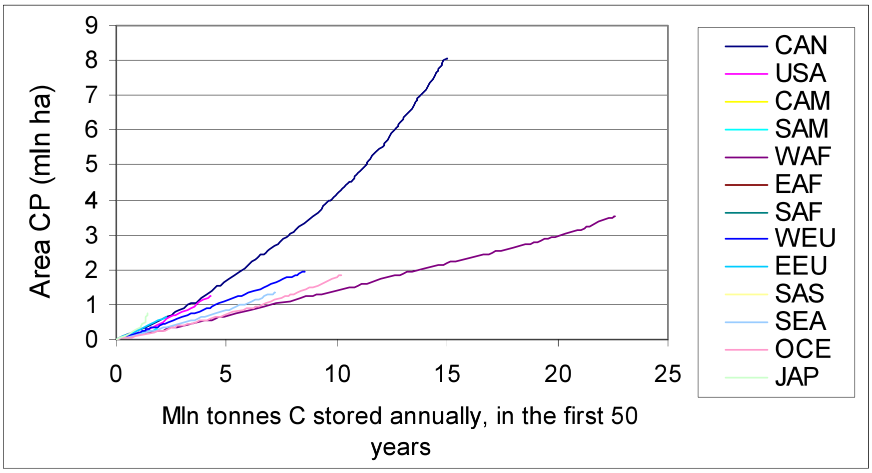
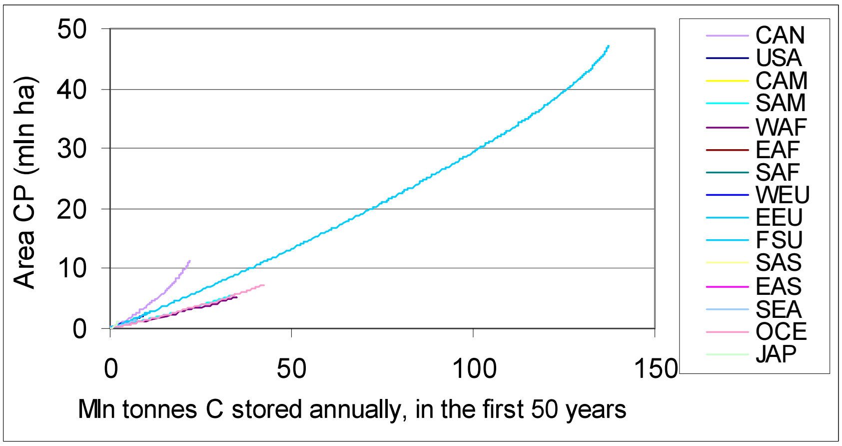


Figure 6.3. Regional contribution to the global potential C sequestration in C plantations on abandoned agricultural land in 2010 including (top) and excluding (bottom) the former Soviet Union (FSU).



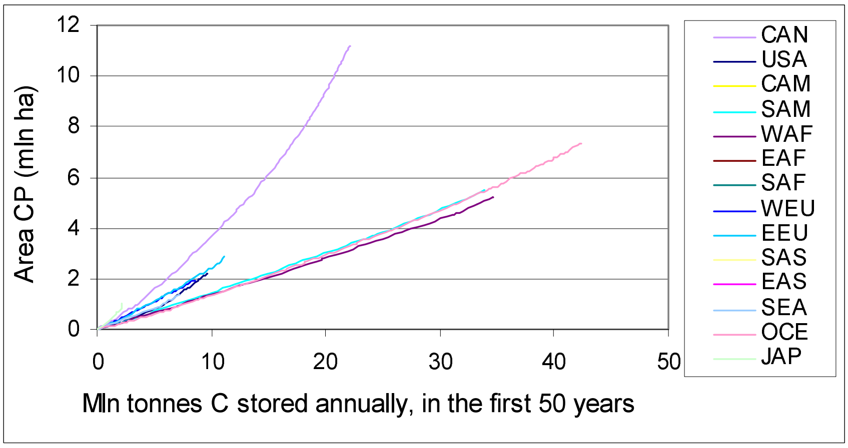


Figure 6.4. Regional contribution to the global potential C sequestration in C plantations on abandoned agricultural land in 2030 with (top) without former Soviet Union (FSU) (bottom).

6.2 Costs of sequestration

6.2.1 General

Various categories of costs and benefits related to C plantations can be considered (Table 6.1). Here, a selection has to be made that fits the aims of the Kyoto Protocol article 3.3, based on the following considerations:

– For the GECS scenario period we do not consider the revenues from the wood produced in the carbon plantation.

Table 6.1. Costs and benefits of C plantations.

Costs	Revenues/benefits
– Land costs, based on: - market prices for agricultural land -lost income from agricultural activities (opportunity costs) - lost employment - cost increase due to higher prices for agricultural products for consumers – Land clearing, soil preparation, planting material, etc. – Management and maintenance – Harvesting – Transaction costs	– Standing biomass – Sale of wood for building material, paper or other purposes – Sale of wood for energy purposes – Several other, often not quantified, benefits from forest such as reduced losses due to climate change, reduced land degradation by rainfall or wind erosion, recreation, biodiversity, and products for the local communities.

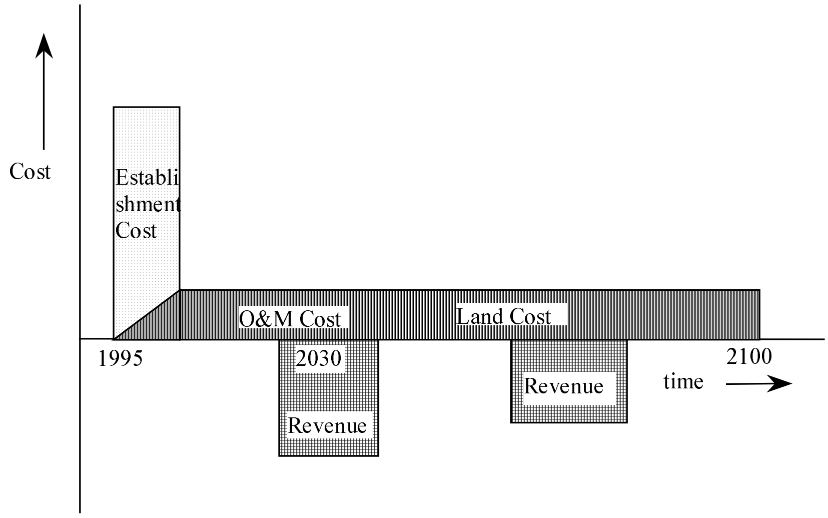


Figure 6.5. Phasing of the different costs and revenues of C plantations in the course of time.

- The other benefits indicated (Table 6.1) can not be quantified and are therefore not included. Such secondary benefits could significantly reduce the net costs.
- Transaction costs, costs of monitoring or certification of sinks are not considered, as these are assumed not to be part of the private costs.
- Regarding the costs of land we assume that the owners of abandoned, fallow agricultural land will be compensated in the form of land rent. This seems reasonable when the land owners have no alternatives to fallow except forest plantation.

Initial treatment or establishment costs are generally expressed as a capital outlay, where the maintenance costs, are expressed as annual costs. Figure 6.5 illustrates the development over time of the different cost categories.

On the basis of the above considerations we will take the following cost categories into account for carbon plantations:

- Land costs
- Forest establishment costs, including costs for land clearing, land preparation and plant material and planting
- Operation and maintenance costs including management

6.2.2 Land costs

Since we consider abandoned agricultural land, the use of opportunity costs is not correct, because the land has no alternative use. Where the agricultural land is still in use for food and fibre production, the compensation would have to be equal to the opportunity costs or lost net income, i.e., the market value of the crop minus production costs. In such cases this compensation would be an incentive for the agricultural sector (farmers or land owners) to increase productivity and efficiency elsewhere on the farm or within the country or region.

Therefore we need to base the land cost estimates on the equivalent of land prices. Country-level data on agricultural land prices are scant. For example, FAO provides data on land prices and land rent for a small number of primarily developing countries (FAO, 1997). Even within regions these data show a wide range and cannot be used to establish average values for land price or land rent. In addition, even if local price data are available, land markets are often so distorted that meaningful outcomes across countries and regions are uncertain.

We therefore used World Bank data on land values (Kunte et al., 1998), which are consistently based on land values derived from the present discounted value of the return to the land. This return to the land is computed as the difference between the world market value of the output crops and crop-specific production costs. This land value was recalculated to obtain the annual cost for 1995, 2000, 2010 and 2030.

The IMAGE Land Cover model assumes that abandoned agricultural areas have a lower productivity than the average for agricultural areas. We use the ratio between the lowest productivity of abandoned cells within each IMAGE region and the average regional productivity. This ratio expresses the value of abandoned agricultural areas relative to the mean regional land values from Kunte et al. (1998). The results are presented in Table 6.2.

Hence, in the applied methodology differences in prices of land result from differences in land and soil quality as computed in IMAGE 2.2. The marginal costs of C sequestration in forest plantations vary within the IMAGE regions as a result of variation in SPP for grid cells (see section 2.1.4). Grid cells with high SPP values have lower costs per tonne of C sequestered than grid cells with a low SPP value.

6.2.3 Other costs

Operation and management costs, land costs and opportunity costs are annual recurring costs. Establishment costs and revenues need to be discounted to obtain the annual costs. The method for discounting (Levelled Costs/Discount Method, LCDM) is discussed in chapter 3.

For operation and maintenance costs it is difficult to obtain reliable estimates. Forest establishment costs include costs of nurseries to produce seedlings, land clearing and planting. Costs of land clearing depend on the original type of vegetation and other (landscape and soil) factors. In this study, we consider abandoned agricultural land, for which costs of land clearing are assumed to be lower (roughly half) than for any of the transitions from natural vegetation types. In most studies no annual operation and maintenance costs are considered, but only the establishment costs. These are pre-planting costs and costs during the first year, but a small part may also occur over the lifetime of the plantation. Therefore we have made conservative estimates for establishment costs and annual recurring costs.

We used regional information on establishment costs summarized by IPCC (1996) and translated this to the IMAGE 2.2 region level (Table 6.2). For annual operation and maintenance costs of carbon plantations we therefore use a standard value of €95 25 per hectare for OECD Europe. For the other regions the maintenance costs were varied on the basis of per capita incomes, as costs of maintenance operations primarily involve labour costs (Table 6.3).

No variation in costs within the regions is considered due to scarcity of data. In reality, differences in establishment and management costs could be the result of differences in the distance to populated areas or existing forestry and agricultural activity.

Table 6.2. Estimates of establishment costs involved in forest plantations derived from IPCC compared with the estimates used for this study for the 17 IMAGE world regions.

IMAGE region[a]	Average and range based on IPCC[b] (1990 US $ ha^{-1})	Average for this study [d] (€99/ha)
1 Canada	400 (300-500)	456
2 USA	415 (140-690)	473
3 Central America	Latin America: 150 – 800 Mexico: 475 (387 – 700)	542
4 South America		433
-Temperate	Afforestation 259; reforestation 357	
-Tropical	Agroforestry 454, reforestation 450, average 380	
5 Northern Africa	Africa: 400 (30-1400)	456
6 Western Africa		456
7 Eastern Africa		342[c]
8 Southern Africa		456
9 OECD Europe	308 (afforestation 259, reforestation 357)	351
10 Eastern Europe	308 (afforestation 259, reforestation 357)	351
11 Former USSR		388
-Boreal	Reforestation 324	
-Temperate	Reforestation 357	
12 Middle East	Agroforestry 454, reforestation 450, average 452	515
13 South Asia	459 (367-550)	523
14 East Asia	437 (46 –828)	498
15 Southeast Asia	452 (agroforestry 454, reforestation 450)	515
16 Oceania		433
-Temperate	357 (afforestation 259, reforestation 357)	
-Tropical	452 (agroforestry 454, reforestation 450)	
17 Japan	308 (afforestation 259, reforestation 357)	351

[a] Appendix E.
[b] Estimates are based on IPCC (1996) (p. 248 and 349).
[c] Lower than African average because of lower per capita GDP.
[d] These cost represent full cost, including the costs for clearing. The US dollar deflator has been applied (1990 - 1995).

Table 6.3. The cost components used for C plantations in this study.

Region[1]	Annual Land costs	Forest establishment costs (€99 /ha)[2]	Operation and maintenance costs
1 Canada	65	228	22
2 USA	86	237	33
3 Central America	56	270	3
4 South America	55	217	5
5 North Africa	27	228	1
6 West Africa	23	228	0.3
7 East Africa	21	171	0.2
8 Southern Africa	29	228	1
9 OECD Europe	132	176	25
10 Eastern Europe	77	176	4
11 Former USSR	26	194	2
12 Middle East	31	258	4
13 South Asia	106	261	0.5
14 East Asia	145	249	2
15 Southeast Asia	181	258	2
16 Oceania	15	217	18
17 Japan	651	176	44

[1] Appendix E.
[2] Establishment costs exclude the clearing costs because we consider forest establishment on abandoned agricultural land or recently logged forest areas.

Barriers may prevent the realization of C plantations. A barrier is defined as any obstacle that can be overcome by policies, innovative projects, demonstrations and financial arrangements (IPCC, 2001b). We considered socio-economic barriers. The risk involved in C plantations due to, for example, drought, pests and fire, may be rather high. This risk can be accounted for by using a discount factor of 10%, instead of the 4% used for other abatement options.

Further barriers include lack of planting material as a result of, for example, limited availability of nurseries, which could lead to a significant delay in the plantation activities. In this study, however, we ignore these aspects and assume that plantation can take place in any year from 1995 onwards. Other barriers such as lack of knowledge, lack of experience in forest management, unavailability of credit facilities, land tenure and distrust in governmental policies are, however, more difficult to implement.

These barriers may cause a reduction of the area that is actually planted. Implementation degrees can only be arbitrarily chosen. In a study on forestry activities to sequester carbon in the framework of the Clean Development Mechanism (CDM) (Waterloo et al., 2001), a list of eight criteria are distinguished, like additionality, verifiability, compliance, sustainability. Each criterion reduces the area and thus the sequestration by a certain percentage. If all eight criteria are considered, Waterloo et al. (2001) estimated that only about 8% of the potentially available area is actually planted. This could serve as a minimum value for CDM-projects in non-Annex I countries. For Annex I countries other barriers may play a role (see above).

We have not attempted to generate estimates of the implementation degree for each region, because implementation will largely be determined by considerations in agriculture (farmers), the food production chain, nature conservation and biodiversity. Since in the AGRIPOL model of CIRAD the balance between forestry, agriculture and GHG mitigation activities is modelled in an integrative fashion on the basis of farmers risk attitude, decisions regarding the implementation degree of C plantations cannot be made in isolation. Instead, they should be based on considerations of all competing activities with land claims and costs.
Therefore, in this study we compare 100% implementation of the potential for both 2010 and 2030 with an implementation degree of 10% for 2010 and 30% for 2030. Lower implementation degrees appeared to give estimates of plantation areas that are consistent with current plantation areas according to FAO inventories (FAO, 2001b).

6.3 MAC curves

The costs of C sequestration are obtained by combining the annuitized costs per hectare for each region as described in 6.2 with the per hectare average annual C sequestration rate. Annual C sequestration rates are calculated as the mean sequestration rate during a 50-year period. First we consider the potential C plantation area (see 6.1). The results are presented in Figure 6.6.

It is clear that the former Soviet Union by far has the highest potential and that West Africa, Oceania, Former USSR and Eastern Europe has the lowest cost per tonne of C sequestered. Japan has the highest costs followed by East Asia (due to the limited potential plantation area), Southeast Asia, OECD Europe, Canada and United States. The differences are primarily caused by the difference in annual land costs per hectare.

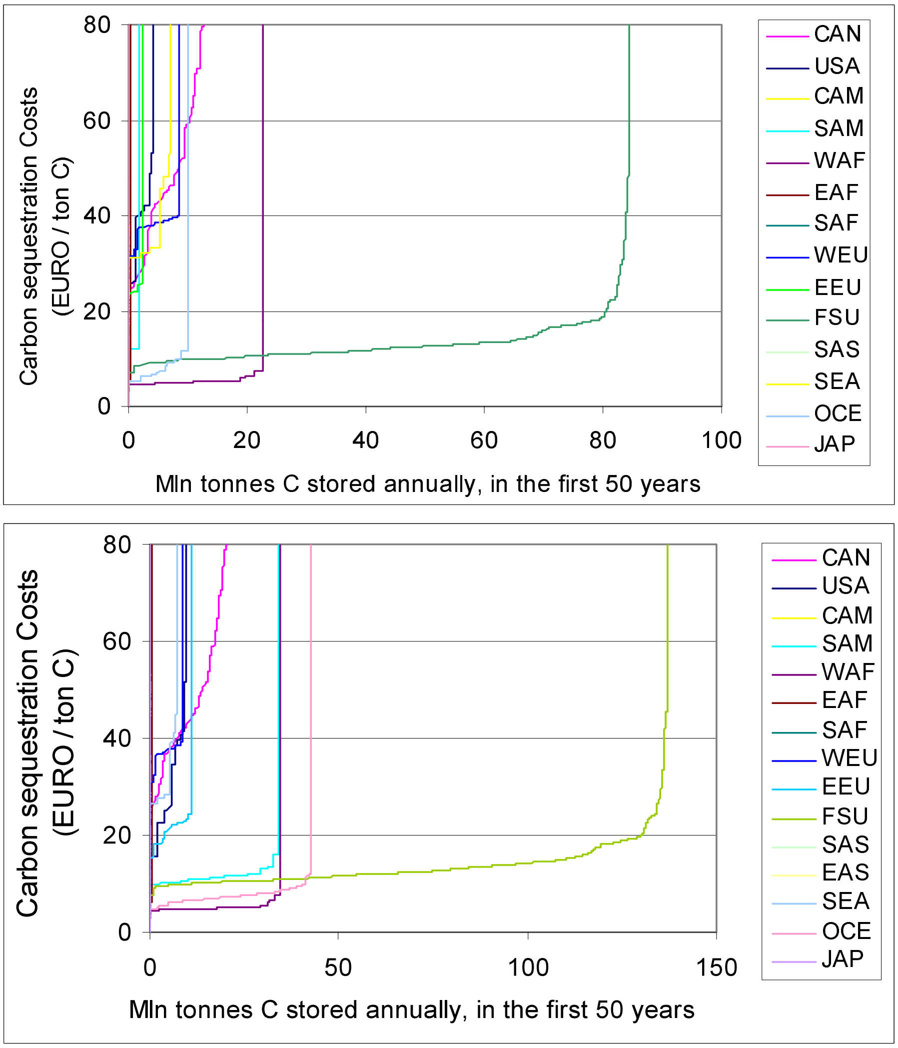


Figure 6.6. Aggregated cost curves for the 17 IMAGE regions (see Appendix E) for C plantations established on agricultural land only in 2010 (top) and 2030 (bottom).

The former USSR has the highest potential in 2010 (53% of the world's potential), followed by West Africa and Canada. Together these regions contribute 77% of the world's potential in 2010. The results for all regions are shown in Figure 6.7.

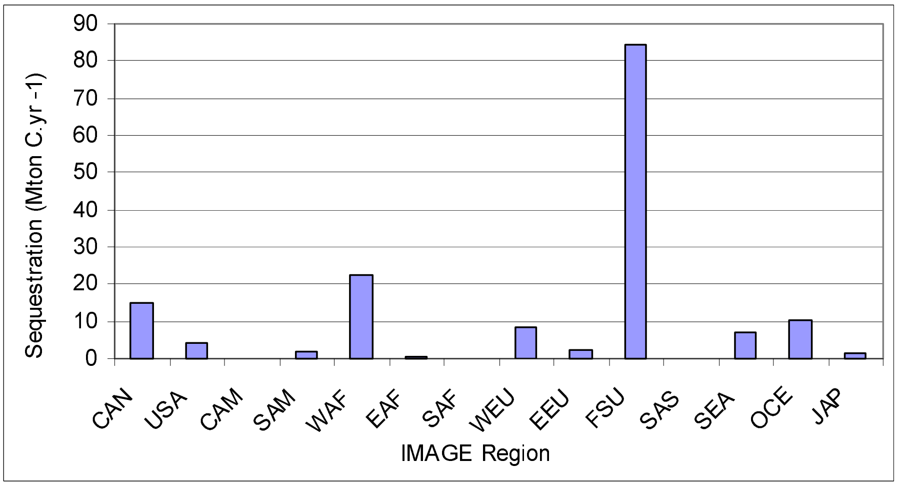


Figure 6.7. Average potential annual C sequestration for the 17 IMAGE regions by C plantations established on agricultural land for 2010.

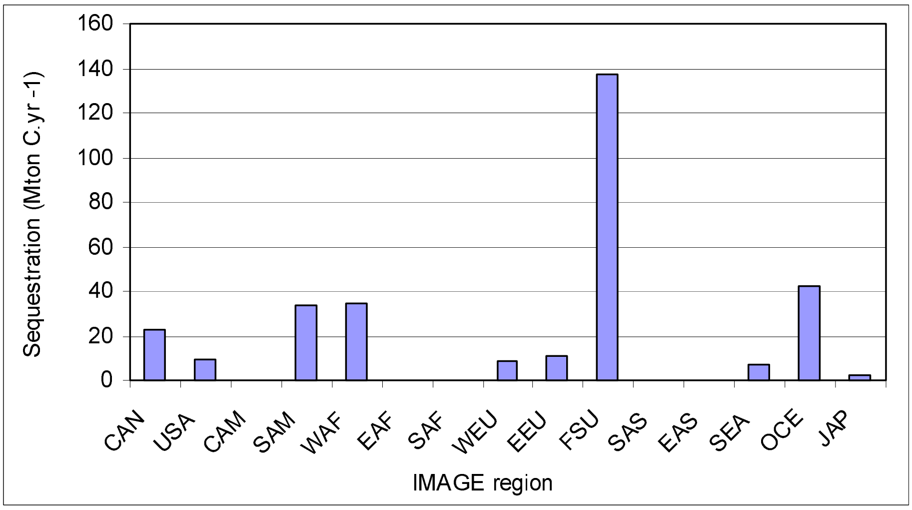


Figure 6.8. Average potential annual C sequestration for the 17 IMAGE regions by C plantations established on agricultural land for 2030.

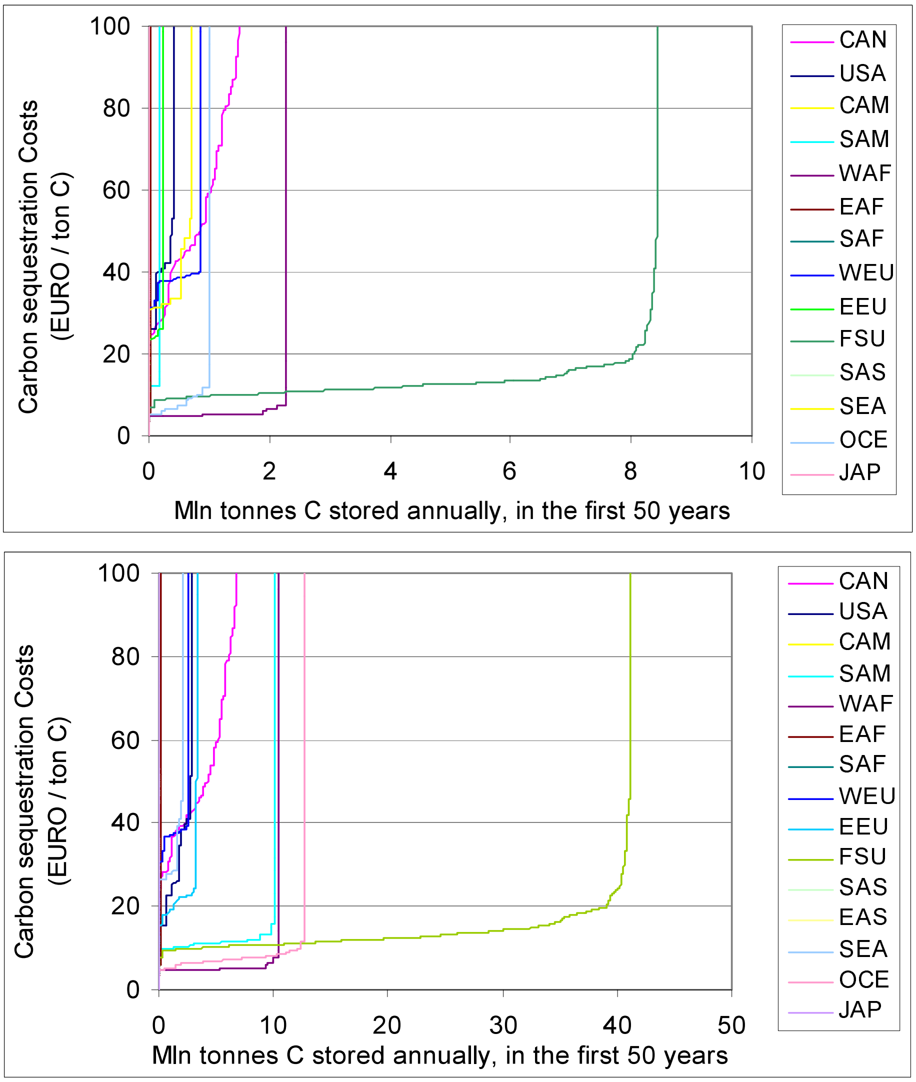


Figure 6.9. Aggregated cost curves for the 17 IMAGE regions (see Appendix E) for C plantations established on agricultural land only in 2010 (top) and 2030 (bottom) using a low implementation degree (10% in 2010 and 30% in 2030).

For 2030 the former USSR also has the highest potential followed by Oceania, West Africa and South America. Together these regions contribute about 80% to the world's potential in 2030 (Figure 6.8).

We compared our results with the current area of forest plantations and its annual change. The area of forest plantations according to FAO (FAO, 2001b) for 2000 is 187 Mha world-wide, while the area that is currently planted each year is 4.5 Mha. Therefore, two variants for 2010 and 2030 are presented to illustrate the ranges of marginal abatement costs of carbon plantations. Lower implementation degrees reflect the effect of certain socio-economic and other barries that may prevent the realization of carbon plantations. Using an implementation degree of 10% and 30% for 2010 and 2030, respectively (Figure 6.9), results in annual plantation of forests for carbon sequestration of 5.0 and 15.0 Mha, respectively. Particularly for the years 1995-2005 these estimates are in good agreement with the area of forest plantations of 4.5 Mha reported by FAO (2001b) for 2000.

The annual carbon sequestration on abandoned agricultural land for the world as a whole is 16 Mton C for 2010 for the low implementation degree (10%). For 2030 an implementation degree of 30% results in annual global carbon sequestration of 93 Mton C for abandoned agricultural land.

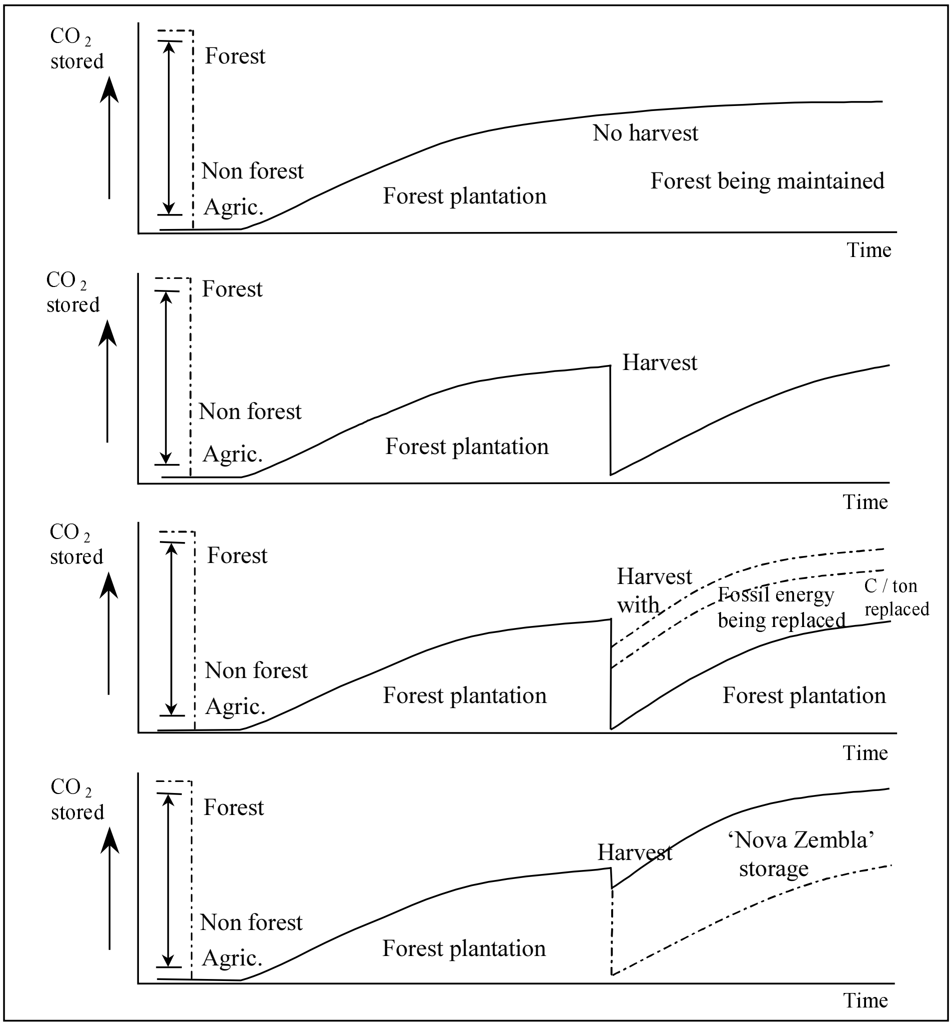


Figure 6.10. Alternative uses of C plantations.

6.4 Revenues

We have not considered revenues in the present study. Our approach is represented in the top schematic graph of Figure 6.10. Revenues from harvesting the carbon plantation, although taking place in periods beyond the GECS scenario time frame, could change the cost-effectiveness of carbon plantations considerably. The use of the wood for purposes such as building material and paper (the situation in Figure 6.10, second graph) is not considered, because the demand for wood is already satisfied by production in existing forests. Revenues from carbon plantations can be generated by using the wood as biofuel to substitute fossil fuels, thus reducing CO_2 emissions. This option is indicated in the third graph of Figure 6.10.

6.5 Comparison with other studies

In a study on the Clean Development Mechanism (CDM) the potentials and costs were estimated for around 70 developing countries and some aggregated regions (Waterloo et al., 2001). The estimated potential area for additional forest plantation was 24 Mha over a 100-year period or 10 Mha for the first 12 years. If we compare our estimate of 49.9 Mha representing the maximum global potential plantation area for 2010 to this potential CDM area for a selection of countries (mainly non-Annex-I countries), it is not surprising that our estimate is somewhat higher.

Waterloo et al. (2001) estimated that the potential sink is 0.1 Pg C in the first commitment period (2008 to 2012). However, they considered only CDM projects, while in our case we analyze the effect of carbon price on activities leading to C sequestration.

Comparison with a review of several studies on carbon sequestration (Hourcade et al., 1996) shows that differences stem primarily from differences in assumptions and calculation methods. For example, the estimates presented by Hourcade et al. (1996) include areas of natural ecosystems. It is therefore not surprising that for some world regions the estimates of potential plantation areas and carbon sequestration are not in close agreement. Unfortunately Hourcade et al. (1996) did not specify for which year the estimates were made. Most of the studies that have been used by Hourcade et al. (1996) cover the early 1990s.

Table 6.4. Comparison of the C sequestration in forest plantations from different studies.

Region	Area available for plantation (Mha)	C sequestration rate (ton C $ha^{-1}yr^{-1}$)	Total C sequestration (Mton C yr^{-1})	Source[a]
Global	465-510	0.8-6.2	280-2900	1
Global 2030	86 [b]	3.6 [b]	310	2
Africa	178	n.s.	13600	1
Africa 2030	5 [b]	6.6 [b]	35	2
USA	102-114	0.0-10.9	400 [c] –640	1
USA 2030	2 [b]	4.3 [b]	10	2
Canada	8.6		6	1
Canada 2030	12	1.9 [b]	22	2
China	111	22-146	8500	1
East Asia 2030	0 [d]	n.r.	0	2

n.s. = not specified, n.r. = not relevant.

[a] 1 = Hourcade et al. (1996) who based estimates on several studies on carbon sequestration; 2 = this study (based on 100% implementation degree).

[b] Average calculated over the total carbon sequestration curve (Figures 6.3 and 6.4).

[c] Average for a 100-year period.

[d] In East Asia China is the largest and dominant country.

7. Additional work

For downscaling the MAC curves developed in work package 2b from 17 IMAGE 2.2 regions to the 38 regions of the POLES 4.0 model (Criqui, 1997), data were collected on arable land and grassland, forest areas, production and trade of rice, other cereals, pulses, oilseeds and root and tuber crops, and emissions from landfills and sewage. These data were made available to the partners in the GECS project.

In addition to the work described in the previous sections, RIVM also contributed to work package 2a. This involved the collection of historic emission estimates of non-CO2 greenhouse gases from energy and industry-related sources from the EDGAR 3.2 database at the POLES regional aggregation level (Olivier et al., 2001).

8. Concluding remarks

This report presents the costs of abatement of greenhouse gas emissions in the form of so-called Marginal Abatement Cost (MAC) curves of methane (CH_4) emissions associated with landfills, CH_4 and nitrous oxide (N_2O) emissions from sewage and carbon (C) sequestration in forest plantations. The main conclusions drawn on the basis of this study relate to the uncertainty of emissions associated with land use and food production systems (section 8.1), the uncertainty in the cost estimates (8.2) and the use of MAC curves (8.3).

8.1 Uncertainty in emission estimates

The uncertainties of emissions associated with land-use and food production systems and thus of estimates of potential emission reductions are much greater than those for energy and industry systems. These uncertainties are related to the availability and reliability of statistical and other information on agricultural production systems and land use. In addition, land-use related emissions are difficult to quantify because they are diffuse with a great variability in space and time. In contrast, energy and industry systems are generally point sources of emissions.

The emission reduction options and measures considered (Table 8.1) are largely based on existing knowledge on technologies and expectations with regard to technology improvement and the degree of implementation. As a result, generally conservative estimates for incremental technology improvement are made, because revolutionary technological or organisational improvements are difficult to take into account. As a result the presented projections for emission reductions may be conservative.

8.2 Uncertainty in cost estimates and implementation

Costs of different ERMs include investment, operation and maintenance costs, and possible savings and revenues. These costs and revenues vary on the basis of regional estimates of costs for investments and labour, and savings and revenues. The data underlying these estimates is, however, scant.

A key variable in this study and bottom-up costing studies in general is the degree of implementation of ERMs. The degree of implementation, presumably changing over time, directly determines the cost-effectiveness of ERMs and the level of abatement, and thus the shape of the MAC curve. Therefore, any uncertainty in the current and future degree of implementation of ERMs directly influences the achieved emission reduction.

Table 8.1. Emission reduction measures (ERMs) considered for landfills, sewage and C plantations.

Landfills	-	Reduction of the volume of waste landfilling.
	-	Reduction of CH_4 generation from landfills.
Sewage	-	Aerobic wastewater treatment.
	-	Upgrading of existing overloaded wastewater treatment plants or plants with sub-optimal aeration.
	-	Anaerobic treatment to stimulate CH_4 generation, which can be collected and re-used as fuel. An additional benefit is the substitution of fossil fuels.
C plantations	-	Land costs.
	-	Forest establishment costs, including costs for land clearing, land preparation, plant material, planting.
	-	Operation and maintenance costs of the plantation, including management.

8.3 The use of MAC curves

The potential emission abatement and the degree of implementation of ERMs for the scenario period 1995-2030 was based on the GECS baseline scenario for agriculture and land use implemented with the IMAGE 2.2 model. The MAC curves presented can, therefore, not be directly used in combination with different scenarios, since both the potential emission abatement and the degree of implementation of ERMs need to be adjusted to the different scenario context.

The cost curves developed in this study and in other bottom-up costing studies are generally discontinuous, because ERMs are implemented one-by-one on the basis of their cost-effectiveness. In many cases MAC curves are used in macro-economic models. For that purpose the step-wise discontinuous 'abatement cost curves' are translated to continuous curves.

However, macro-economic models generally ignore negative net costs (revenues) since ERMs with net revenues (no-regret options) are believed to be introduced even in the absence of climate policies. In reality, barriers and considerations that are not purely economic may prevent the adoption of cost-effective solutions or no-regret options. Ignoring no-regret options in the context of climate policy scenarios may lead to significant misjudgements. One way to deal with negative cost options is to subtract the reductions associated with no-regret options from the emissions in the baseline scenario to obtain a new baseline with potential emission abatement. However, this may result in overoptimistic estimates for emission reduction.

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Appendix A. GECS work package 2.b.

WP2b. GHG emissions and sequestration associated to land-use and agriculture

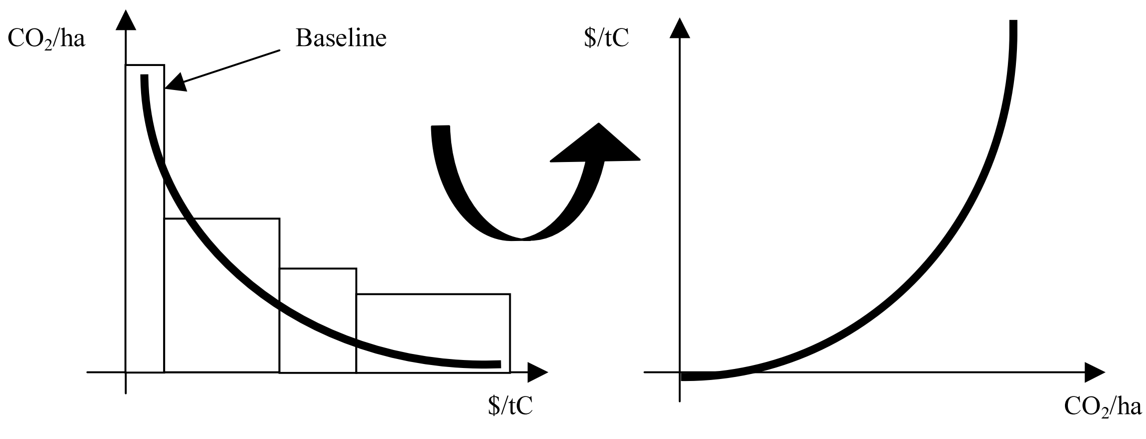
WP2.A3. Changes in Land-use, by world region
Based on exogenous trajectories for economic growth and population, the IMAGE-model at RIVM simulates the demand for energy and food. The Energy-Industry-System (EIS) generates a projection for energy demand, fossil fuel use and the use of biomass-derived fuels. The Agriculture-Economy-System (AES) converts the demands for food, fodder and biofuels into emissions of gases relevant for the enhanced greenhouse effect. The EIS does the same for the combustion of fossil fuels and industrial activity. The four SRES-IS99 scenarios for the IPCC provide a good context for more detailed, regional scenario analyses.

In this part of the project, projections in land-use change until 2030 will be will be performed by RIVM for at least two (A1 andB1) of the four SRES scenarios, using the corresponding assumptions on economic and population growth, dietary patterns, consumer preferences, agricultural practices and biofuel use. It will be explored how the resulting land-use changes at the 0.5 x 0.5 ° level can be characterised and presented in a comprehensive way. They will be compared with other projections and expectations.

The presently used GHG emission coefficients will be evaluated and adjusted to the latest insights. The result will be a series of emission profiles for the greenhouse-gases considered (see Annex 3) at the regional level and in relation to scenario assumptions.

WP2.A4. Emission functions from different types of land-use and agricultural practices
As a follow-up to the previous activity, an inventory will be made of the costs at which land-use related GHG emissions can be reduced per unit of activity in Western Europe, and, though less detailed, for the other world regions.

Jointly with RIVM, the CIRAD will take in charge the treatment of the resulting information in order to construct static Marginal Abatement Costs curves, which indicate the emission reduction potentials in carbon-equivalent values. Part of the analysis will focus on the interaction between various end-of-pipe oriented emission abatement measures and on the relation with changes in the food system such as agro-technology, food trade and consumption patterns.



The resulting continuous MAC curves will then be introduced into the different models, POLES, GEM-E3 and IMAGE. In this process, dynamic regional GHG emission MAC curves will be constructed and compared with similar curves for the energy-industry related GHG emissions, in order to identify least-cost abatement strategies with different schemes of 'What' flexibility.

Appendix B. List of abatement strategies for N_2O, CH_4 and CO_2 for various land-use related activities

The activities printed in grey are covered by RIVM.

List of abatement strategies for N_2O, CH_4 and CO_2 for various land-use related activities.		
Activity	**Practice**	**Abatement strategy**
		Gas species: N_2O
Crop production	Fertilizer management	- Soil testing to evaluate N requirement - Split application of fertilizer to match N input with plant requirement
	Advanced fertilizer management	- Use of controlled-release fertilizers, nitrification inhibitors - Foliar application in certain crops - Modification of application mode (injection or deep placement instead of broadcasting)
	Manure management	Manure re-use in crop production, by collection, transport and application of manure
	Crop management	- Crop selection for high N-efficiency - Reduce crop residue burning where possible for N conservation
	Soil Management	- Improve soil aeration by reducing soil compaction and surface sealing
	Land use	- Price support - Subsidies for set-aside of less productive land
Livestock production	Feeding	- Dietary manipulation to achieve low N excretion - Breeding of N efficient livestock
Human waste management	Sewage treatment	N removal from sewage by water treatment
		Gas species: CH_4
Crop production	Rice growing	– Move to other cultivars with lower CH_4 emissions – Water management – Less organic amendments (rice straw) – Using different fertilizers (e.g. ammonium sulphate instead of urea)
	Residue burning at field scale	Reduced field burning
Livestock production	Enteric fermentation	– Increased level of feed intake – Improved feed conversion efficiency – Replacement roughage with concentrates – Feed additives (like lipids) to enhance the molecular percentage of Propionic acid – Feed quality / composition (less fibers) – Probiotic additives / adding antibiotics Etc.
	Manure management	– Prevention of fermentation during stabling – Aerobic treatment – Anaerobic digestion to biogas
Human waste handling	Sewage treatment	Aerobic wastewater treatment, upgrading of existing overloaded treatment plants, collection of CH_4
	Landfilling	CH_4- collection and use in energy recovery Flaring
	Waste processing	Reduced landfilling – via composting (aerobe) of waste – via (paper) recycling – via anaerobe digestion / fermentation – Incineration with energy recovery – Direct combustion
Large-scale biomass burning[1]	Savanna/grassland burning, deforestation	Reduced burning / burning prevention by e.g. extension
		Gas species: CO_2
Forestry	Forest plantation	Carbon plantation

[1] Reduction of large-scale biomass burning was not considered in the present study, because mitigation options would involve external costs only which are borne by governments.

Appendix C. Cost categories

Private cost categories for investments for abatement of GHG emissions. The cost categories printed in grey and bold are those covered by RIVM in this project.

A. Private costs

Costs related to the investments

- **Annual investment** (or capital) costs, to be calculated from annuitized project or specific investment costs (€/unit), economic and technical lifetime (yr), interest rate.
- **Operational costs** (such as additional labour costs due to an abatement option)
- **Maintenance costs** (related to specific machinery or building facilities, partly also labour costs)
- **Costs and/or benefits in the form of sales of by/coproducts**, additional and/or lost material inputs
- **Avoided input costs** (such as avoided energy or waste treatment costs)
- Monitoring costs for measuring emission abatement which need to be performed by an entrepreneur/ farmer
- Overhead costs (engineering and contracting costs, interest during construction delays etc.).

B. Non-private or external costs:

- Costs for implementation the ERM (to stimulate awareness and acceptation)
- Program costs (all costs for authorities as a result of specific ERMs)
- Costs for marketing the program
- Costs for education/training/information (to stimulate people to deal with a specific issue)
- Costs for extension service (to overcome lacks in awareness)
- Costs for monitoring/compliance (to determine the effect of ERMs on emissions)
- Costs for certification (certification of the amount of GHG abated)
- Overhead costs (legal costs, etc.)
- Impacts on market prices (food, land, etc.) and market distortions.

Appendix D. Share in the sector, emission reduction and implementation degree for landfills for 17 IMAGE 2.2 regions for different ERMs [1]

YEAR:	2010			2020			2030		
Regional factors of: 1. Share in the sector 2. Implementation degree 3. Emission reduction									
Region[2]	1	2	3	1	2	3	1	2	3
1. Reduced landfilling, via (paper) recycling									
# All regions	17%	100%	15%	17%	100%	20%	17%	100%	25%
2. Reduced landfilling, via incineration with energy recovery									
# All regions	33%	110%	30%	33%	110%	40%	33%	110%	50%
3. Reduced landfilling, via composting (aerobe) of waste)									
# All regions	33%	90%	50%	33%	90%	50%	33%	90%	50%
4. Reduced landfilling, via anaerobe digestion / fermentation									
# All regions	33%	100%	20%	33%	100%	20%	33%	100%	20%
5. Covering of landfills									
# All regions	20%	45%	75%	20%	45%	80%	20%	45%	90%

[2] See Appendix E

6. CH_4 collection and use in energy recovery flaring									
1 Canada	80%	40%	70%	80%	45%	80%	80%	50%	90%
2 USA	80%	40%	70%	80%	45%	80%	80%	50%	90%
3 Central America	80%	40%	50%	80%	45%	80%	80%	50%	70%
4 South America	80%	40%	50%	80%	45%	80%	80%	50%	70%
5 Northern Africa	80%	40%	50%	80%	45%	80%	80%	50%	70%
6 Western Africa	80%	40%	50%	80%	45%	80%	80%	50%	70%
7 Eastern Africa	80%	40%	50%	80%	45%	80%	80%	50%	70%
8 Southern Africa	80%	40%	50%	80%	45%	80%	80%	50%	70%
9 OECD Europe	80%	40%	70%	80%	45%	80%	80%	50%	90%
10 Eastern Europe	80%	40%	50%	80%	45%	80%	80%	50%	70%
11 Former USSR	80%	40%	50%	80%	45%	80%	80%	50%	70%
12 Middle East	80%	40%	50%	80%	45%	80%	80%	50%	70%
13 South Asia	80%	40%	50%	80%	45%	80%	80%	50%	70%
14 East asia	80%	40%	50%	80%	45%	80%	80%	50%	70%
15 Southeast Asia	80%	40%	50%	80%	45%	80%	80%	50%	70%
16 Oceania	80%	40%	70%	80%	45%	80%	80%	50%	90%
17 Japan	80%	40%	70%	80%	45%	80%	80%	50%	90%
7. CH_4 collection and use direct use / combustion									
1 Canada	80%	40%	50%	80%	45%	65%	80%	50%	80%
2 USA	80%	40%	50%	80%	45%	65%	80%	50%	80%
3 Central America	80%	40%	50%	80%	45%	65%	80%	50%	70%
4 South America	80%	40%	50%	80%	45%	65%	80%	50%	70%
5 Northern Africa	80%	40%	50%	80%	45%	65%	80%	50%	70%
6 Western Africa	80%	40%	50%	80%	45%	65%	80%	50%	70%
7 Eastern Africa	80%	40%	50%	80%	45%	65%	80%	50%	70%
8 Southern Africa	80%	40%	50%	80%	45%	65%	80%	50%	70%
9 OECD Europe	80%	40%	50%	80%	45%	65%	80%	50%	80%
10 Eastern Europe	80%	40%	50%	80%	45%	65%	80%	50%	70%
11 Former USSR	80%	40%	50%	80%	45%	65%	80%	50%	70%

YEAR:	2010			2020			2030		
Regional factors of: 1. Share in the sector 2. Implementation degree 3. Emission reduction									
Region[2]	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
12 Middle East	80%	40%	50%	80%	45%	65%	80%	50%	70%
13 South Asia	80%	40%	50%	80%	45%	65%	80%	50%	70%
14 East asia	80%	40%	50%	80%	45%	65%	80%	50%	70%
15 Southeast Asia	80%	40%	50%	80%	45%	65%	80%	50%	70%
16 Oceania	80%	40%	50%	80%	45%	65%	80%	50%	80%
17 Japan	80%	40%	50%	80%	45%	65%	80%	50%	80%

[2] See Appendix E

8. CH_4 collection and use for electricity generation									
1 Canada	75%	40%	50%	75%	45%	65%	75%	50%	80%
2 USA	75%	40%	50%	75%	45%	65%	75%	50%	80%
3 Central America	75%	40%	50%	75%	45%	65%	75%	50%	70%
4 South America	75%	40%	50%	75%	45%	65%	75%	50%	70%
5 Northern Africa	75%	40%	50%	75%	45%	65%	75%	50%	70%
6 Western Africa	75%	40%	50%	75%	45%	65%	75%	50%	70%
7 Eastern Africa	75%	40%	50%	75%	45%	65%	75%	50%	70%
8 Southern Africa	75%	40%	50%	75%	45%	65%	75%	50%	70%
9 OECD Europe	75%	40%	50%	75%	45%	65%	75%	50%	80%
10 Eastern Europe	75%	40%	50%	75%	45%	65%	75%	50%	70%
11 Former USSR	75%	40%	50%	75%	45%	65%	75%	50%	70%
12 Middle East	75%	40%	50%	75%	45%	65%	75%	50%	70%
13 South Asia	75%	40%	50%	75%	45%	65%	75%	50%	70%
14 East asia	75%	40%	50%	75%	45%	65%	75%	50%	70%
15 Southeast Asia	75%	40%	50%	75%	45%	65%	75%	50%	70%
16 Oceania	75%	40%	50%	75%	45%	65%	75%	50%	80%
17 Japan	75%	40%	50%	75%	45%	65%	75%	50%	80%

9. CH_4 oxidation in top-soils									
1 Canada	80%	10%	20%	80%	15%	30%	80%	20%	40%
2 USA	80%	10%	20%	80%	15%	30%	80%	20%	40%
3 Central America	80%	10%	10%	80%	15%	15%	80%	20%	25%
4 South America	80%	10%	10%	80%	15%	15%	80%	20%	25%
5 Northern Africa	80%	10%	10%	80%	15%	15%	80%	20%	25%
6 Western Africa	80%	10%	10%	80%	15%	15%	80%	20%	25%
7 Eastern Africa	80%	10%	10%	80%	15%	15%	80%	20%	25%
8 Southern Africa	80%	10%	10%	80%	15%	15%	80%	20%	25%
9 OECD Europe	80%	10%	20%	80%	15%	30%	80%	20%	40%
10 Eastern Europe	80%	10%	10%	80%	15%	15%	80%	20%	25%
11 Former USSR	80%	10%	10%	80%	15%	15%	80%	20%	25%
12 Middle East	80%	10%	10%	80%	15%	15%	80%	20%	25%
13 South Asia	80%	10%	10%	80%	15%	15%	80%	20%	25%
14 East asia	80%	10%	10%	80%	15%	15%	80%	20%	25%
15 Southeast Asia	80%	10%	10%	80%	15%	15%	80%	20%	25%
16 Oceania	80%	10%	20%	80%	15%	30%	80%	20%	40%
17 Japan	80%	10%	20%	80%	15%	30%	80%	20%	40%

10. Aerobic landfilling with biological pretreatment									
1 Canada	80%	95%	10%	80%	95%	20%	80%	95%	35%
2 USA	80%	95%	10%	80%	95%	20%	80%	95%	35%
3 Central America	80%	95%	5%	80%	95%	15%	80%	95%	30%
4 South America	80%	95%	5%	80%	95%	15%	80%	95%	30%
5 Northern Africa	80%	95%	5%	80%	95%	15%	80%	95%	30%
6 Western Africa	80%	95%	5%	80%	95%	15%	80%	95%	30%
7 Eastern Africa	80%	95%	5%	80%	95%	15%	80%	95%	30%

YEAR:	2010			2020			2030		
Regional factors of: 1. Share in the sector 2. Implementation degree 3. Emission reduction									
Region[2]	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
8 Southern Africa	80%	95%	5%	80%	95%	15%	80%	95%	30%
9 OECD Europe	80%	95%	10%	80%	95%	20%	80%	95%	35%
10 Eastern Europe	80%	95%	5%	80%	95%	15%	80%	95%	30%
11 Former USSR	80%	95%	5%	80%	95%	15%	80%	95%	30%
12 Middle East	80%	95%	5%	80%	95%	15%	80%	95%	30%
13 South Asia	80%	95%	5%	80%	95%	15%	80%	95%	30%
14 East asia	80%	95%	5%	80%	95%	15%	80%	95%	30%
15 Southeast Asia	80%	95%	5%	80%	95%	15%	80%	95%	30%
16 Oceania	80%	95%	10%	80%	95%	20%	80%	95%	35%
17 Japan	80%	95%	10%	80%	95%	20%	80%	95%	35%

[1] The indexes given here can be adjusted in the spreadsheet model.
[2] See Appendix E

Appendix E. Definition of the IMAGE 2.2 regions

01 Canada (CAN)
Canada
02 USA
Saint Pierre and Miquelon
United States of America
United States Minor Outlying Islands
03 Central America (CAM)
Anguilla
Antigua and Barbuda
Aruba
Commonwealth of the Bahamas
Barbados
Belize
Bermuda
Cayman Islands
Republic of Costa Rica
Republic of Cuba
Commonwealth of Dominica
Dominican Republic
Republic of El Salvador
Grenada
Guadeloupe
Republic of Guatemala
Republic of Haiti
Republic of Honduras
Jamaica
Martinique
United Mexican States
Montserrat
Netherlands Antilles
Republic of Nicaragua
Republic of Panama
Puerto Rico
Saint Kitts and Nevis
Saint Lucia
Saint Vincent and the Grenadines
Republic of Trinidad and Tobago
Turks and Caicos Islands
British Virgin Islands
Virgin Islands of the United States
04 South America (SAM)
Argentine Republic
Republic of Bolivia
Bouvet Island
Federative Republic of Brazil
Republic of Chile
Republic of Colombia
Republic of Ecuador
Falklands Islands (Malvinas)
French Guiana
Republic of Guyana
Republic of Paraguay
Republic of Peru
South Georgia and the South Sandwich Islands
Republic of Suriname
Eastern Republic of Uruguay
Republic of Venezuela
05 Northern Africa (NAF)
People's Democratic Republic of Algeria
Arab Republic of Egypt
Socialist People's Libyan Arab Jamahiriya
Kingdom of Morocco
Republic of Tunisia
Western Sahara
06 Western Africa (WAF)
Republic of Benin
Burkina Faso
Republic of Cameroon
Republic of Cape Verde
Central African Republic
Republic of Chad
Republic of the Congo
The Democratic Republic of the Congo
Republic of Côte d'Ivoire
Republic of Equatorial Guinea
Gabonese Republic
Republic of the Gambia
Republic of Ghana
Republic of Guinea
Republic of Guinea-Bissau
Republic of Liberia
Republic of Mali
Islamic Republic of Mauritania
Republic of the Niger
Federal Republic of Nigeria
Saint Helena
Democratic Republic of Sao Tome and Principe
Republic of Senegal
Republic of Sierra Leone
Togolese Republic
07 Eastern Africa (EAF)
Republic of Burundi
Islamic Federal Republic of the Comoros
Republic of Djibouti
Eritrea
Federal Democratic Republic of Ethiopia
Republic of Kenya
Republic of Madagascar
Republic of Mauritius
Mayotte
Réunion
Rwandese Republic
Republic of Seychelles
Somali Democratic Republic
Republic of the Sudan
Republic of Uganda
08 Southern Africa (SAF)
Republic of Angola
Republic of Botswana
Kingdom of Lesotho
Republic of Malawi
Republic of Mozambique
Republic of Namibia
Republic of South Africa
Kingdom of Swaziland
United Republic of Tanzania
Republic of Zambia
Republic of Zimbabwe
09 OECD Europe (WEU)
Principality of Andorra
Republic of Austria
Kingdom of Belgium
Kingdom of Denmark
Faroe Islands
Republic of Finland
French Republic
Federal Republic of Germany
Gibraltar
Hellenic Republic
Holy See (Vatican City State)
Republic of Iceland
Ireland
Italian Republic
Principality of Liechtenstein
Grand Duchy of Luxembourg
Republic of Malta
Principality of Monaco
Kingdom of the Netherlands
Kingdom of Norway
Portuguese Republic
Republic of San Marino
Kingdom of Spain

OECD Europe, continued
- Svalbard and Jan Mayen
- Kingdom of Sweden
- Swiss Confederation
- United Kingdom

10 Eastern Europe (EEU)
- Republic of Albania
- Republic of Bosnia and Herzegovina
- Republic of Bulgaria
- Republic of Croatia
- Czech Republic
- Republic of Hungary
- The former Yugoslav Republic of Macedonia
- Republic of Poland
- Romania
- Slovak Republic
- Republic of Slovenia
- Federal Republic of Yugoslavia

11 Former USSR (FSU)
- Republic of Armenia
- Azerbaijani Republic
- Republic of Belarus
- Republic of Estonia
- Georgia
- Republic of Kazakstan
- Kyrgyz Republic
- Republic of Latvia
- Republic of Lithuania
- Republic of Moldova
- Russian Federation
- Republic of Tajikistan
- Turkmenistan
- Ukraine
- Republic of Uzbekistan

12 Middle East (MEA)
- State of Bahrain
- Republic of Cyprus
- Islamic Republic of Iran
- Republic of Iraq
- State of Israel
- Hashemite Kingdom of Jordan
- State of Kuwait
- Lebanese Republic
- Sultanate of Oman
- State of Qatar
- Kingdom of Saudi Arabia
- Syrian Arab Republic
- Republic of Turkey
- United Arab Emirates
- Republic of Yemen

13 South Asia (SAS)
- Islamic State of Afghanistan
- People's Republic of Bangladesh
- Kingdom of Bhutan
- British Indian Ocean Territory
- Republic of India
- Republic of Maldives
- Kingdom of Nepal
- Islamic Republic of Pakistan

South Asia, continued
- Democratic Socialist Republic of Sri Lanka

14 East Asia (EAS)
- People's Republic of China
- Hong Kong
- Democratic People's Republic of Korea
- Republic of Korea
- Macau
- Mongolia
- Taiwan, Province of China

15 Southeast Asia (SEA)
- Brunei Darussalam
- Kingdom of Cambodia
- East Timor
- Republic of Indonesia
- Lao People's Democratic Republic
- Malaysia
- Union of Myanmar
- Republic of the Philippines
- Republic of Singapore
- Kingdom of Thailand
- Socialist Republic of Viet Nam

16 Oceania (OCE)
- American Samoa
- Australia
- Christmas Island
- Cocos (Keeling) Islands
- Cook Islands
- Republic of Fiji
- French Polynesia
- French Southern Territories
- Guam
- Heard Island and McDonald Islands
- Kiribati
- Republic of the Marshall Islands
- Federated States of Micronesia
- Republic of Nauru
- New Caledonia
- New Zealand
- Niue
- Norfolk Island
- Commonwealth of the Northern Mariana Islands
- Republic of Palau
- Papua New Guinea
- Pitcairn
- Independent State of Western Samoa
- Solomon Islands
- Tokelau
- Kingdom of Tonga
- Tuvalu
- Republic of Vanuatu
- Wallis and Futuna

17 Japan (JAP)
- Japan

18 Greenland
- Greenland

19 Antarctica
- Antarctica

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