FINAL REPORTS SUMMARIES

SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY SPSD 1

Practical achievements of sustainable development require constant effort at both international and national levels, and call for an integrated approach of the social, economic and environmental fields between all levels of competency and decision-making.

Implementation of a policy focused on sustainable development also depends on the presence of effective scientific support at various levels, as was recommended by Agenda 21 adopted at the Rio Summit in 1992.

In this context the first "Scientific support plan for a sustainable development policy" (SPSD I) was approved by the Federal Government on 7 March 1996 on the proposal of the Minister of Science Policy and has been implemented by the Federal Office for Scientific, Technical and Cultural Affairs within the framework of a co-operation agreement between the State and the Regions.

This scientific support plan deals with several important aspects of the commitments made by Belgium with respect to sustainable development.

The programmes of this Plan covered various fields :*"Sustainable management of the North Sea", "Global change and sustainable development", "Antarctica", "Sustainable mobility", "Prenormative research in the food sector", "Levers for a sustainable development policy", "Earth observation by satellite", "Supporting actions"*. They were developped to support the scientific potential, to increase knowledge and to reduce incertainties in the concerned fields in order to incorporate aspects of the sustainable development concept into the design of concrete political measures.

The research's summaries of this programme are published in order to serve as a basis for reflection, as well as means of communication of the results, to better integrate research into a strategy of sustainable development of our societies.

SPSD I ended in 2001 and is followed by a second "Scientific support plan for a sustainable development policy" (SPSD II), which was approved in March 2000 by the Federal Government and which covers a period of six years (2000-2005).

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GLOBAL CHANGE AND SUSTAINABLE DEVELOPMENT

SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY FINAL REPORTS SUMMARIES

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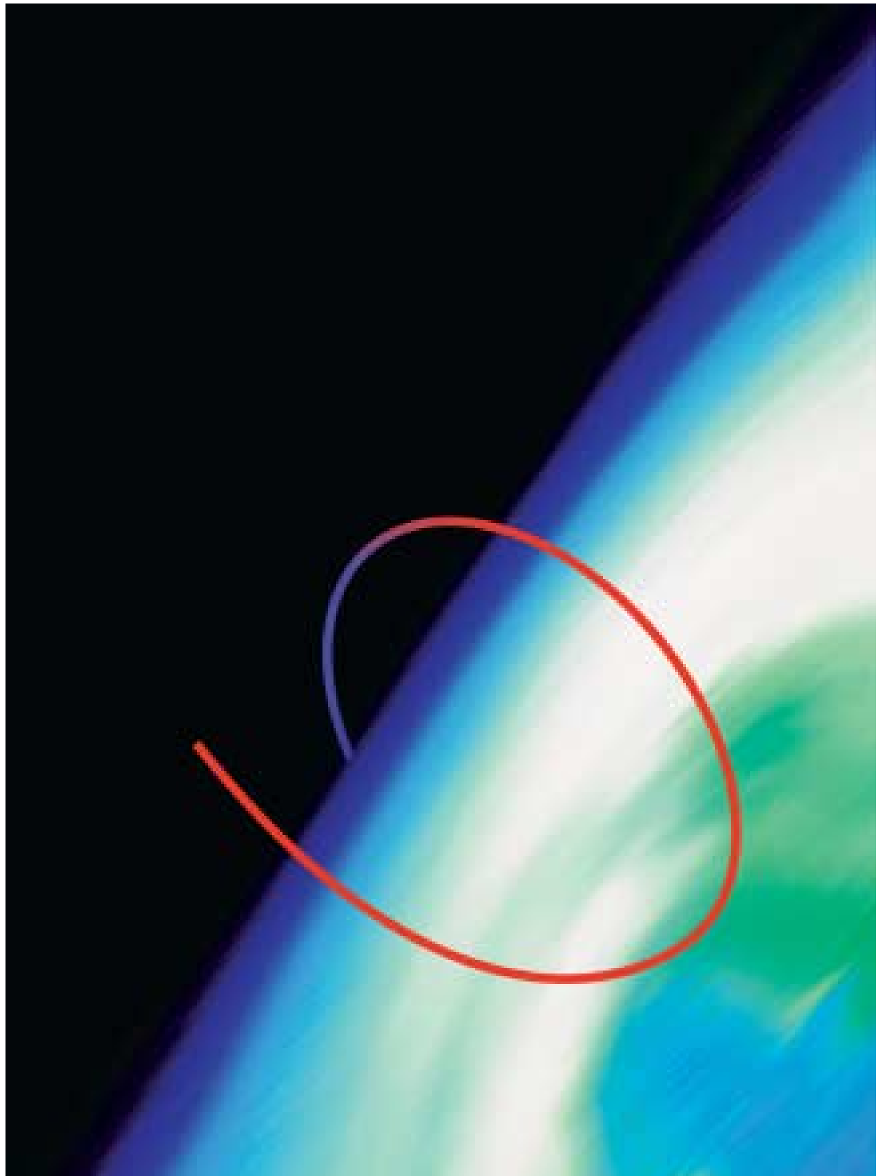
GLOBAL CHANGE AND SUSTAINABLE DEVELOPMENT



SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY SPSD 1

FINAL REPORTS

SUMMARIES

GLOBAL CHANGE AND SUSTAINABLE DEVELOPMENT

SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY SPSD 1

This booklet is realised in the framework of the Scientific Support Plan for a Sustainable Development Policy (SPSD I). The available publications are :

- *"Antarctica"*
- *"Levers for a sustainable development policy"*
- *"Earth observation by satellite" TELSAT 4*
- *"Pre-normative research in the food sector"*
- *"Global change and sustainable development"*
- *"Sustainable management of the North Sea"* (available from spring 2003)
- *"Sustainable mobility"* (available from spring 2003)
- *"Supporting actions"* (available from spring 2003)

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INTRODUCTION

The programme "Global change and sustainable development" in context

Global change is regarded as one of the most significant threats to sustainable development around the world. The term refers to changes in the make-up of the atmosphere and changes to biological, geological and hydrological systems. These changes may be manifested locally, but have consequences all around the world (deforestation, desertification, etc). Alternatively they may be world-wide changes that impact at the local and/or global level (particularly the increased greenhouse effect, the problem of tropospheric ozone, depletion of the stratospheric ozone layer, etc). Our research programme relates mainly to the latter problems.

The phenomena of climate and global change are extremely complex, and our understanding of them is still incomplete. We are still very uncertain about the importance of these global environmental problems, what their consequences and long-term impact will be and the likely risks for the terrestrial system. We are also unsure of the extent to which man – or his lifestyle and living conditions, society, economic and demographic growth and technological change – have caused these problems.

It is in this context of uncertainty and controversy that we have to plan a response so we can pass on a viable environment and adequate resources to future generations. Our political leaders have to cope with this uncertainty, and should adopt the precautionary principle.

The awareness of world-wide environmental problems has lead to certain international and European agreements a.o. the Framework Convention on Climate Change signed in Rio and the Kyoto protocol, the Vienna Convention, the Montreal Protocol and the LRTAP (*Long Range Transboundary Air Pollution*) Convention and the 5th European action programme *"Towards Sustainability"*. These agreements, but also the Convention on Biological Diversity , the Convention to Combat Desertification, and others have acted as a real stimulus for research into *Global Change*.

However, Belgium must first develop a reliable base of scientific and technical knowledge before it can take its responsibility seriously, meet its international commitments and actively participate in international research work. The *Global Change and Sustainable Development* programme is designed to contribute to this process. The very nature of this problem, and its scope and time-scale, require a change in the type of research, which has traditionally been confined to certain academic disciplines. It must be reorganised in a more international context. It must be integrated, holistic and multi- and interdisciplinary. It must bring together physicists, biologists, chemists, economists, sociologists and many other experts.

Concept and organisation of the programme

The programme will concentrate primarily on the needs arising from the Convention on Climate Change.

It establishes a balance between the basic research needed to resolve uncertainty and more urgent research designed to support the political decision-making process.

The research is carried out by networks made up of several teams of scientists (2 to 4 on average). These scientists are based at different Belgian universities and research institutions, and are studying specific problems from different angles.

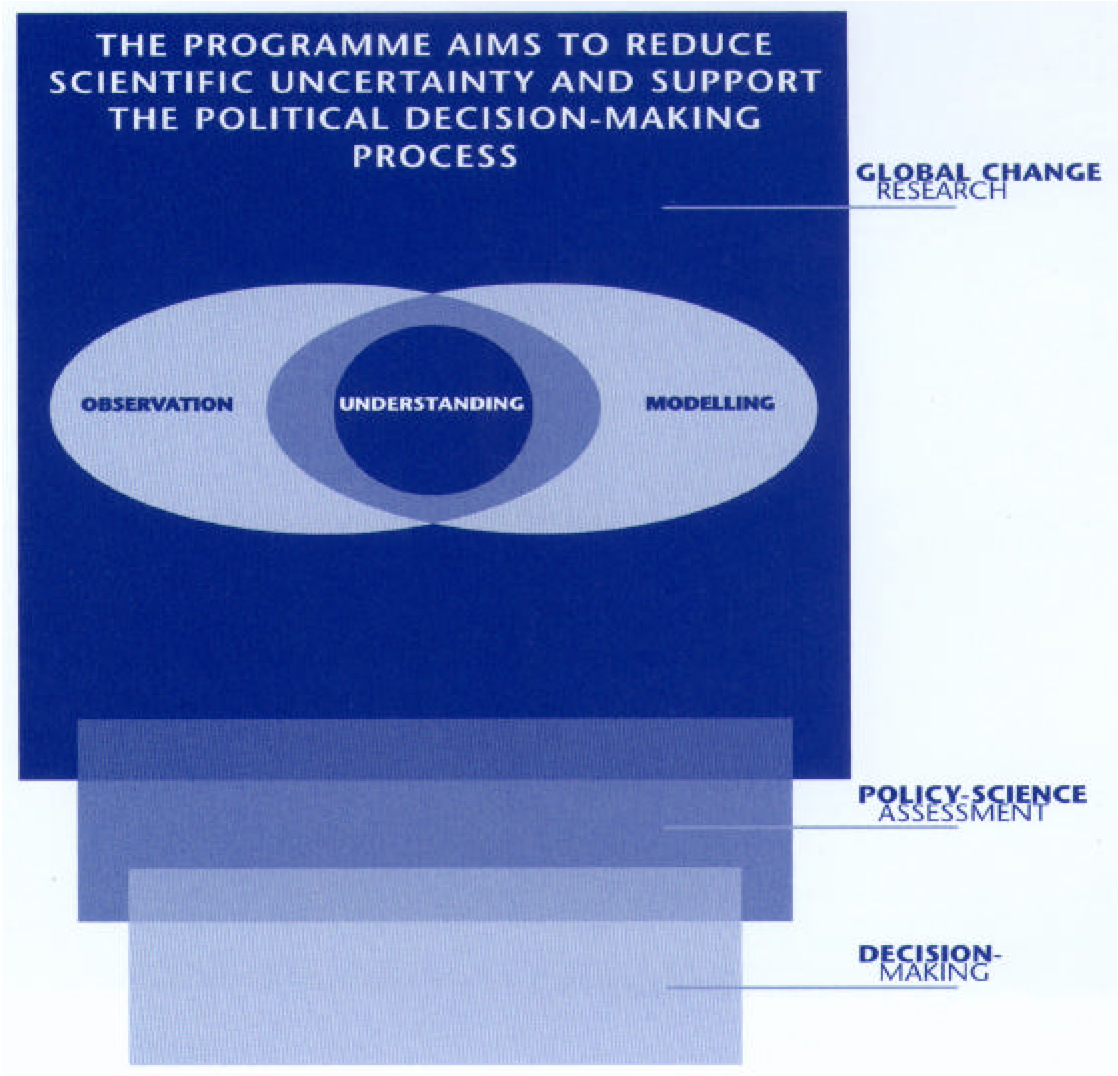
The networks have established links and exchange information with one another. Their work aims both to describe the current situation (observation, experiments) and to predict future changes (modelling). In this way, it will provide a better understanding of the current environmental and socio-economic system within the context of climate change.

This knowledge, however incomplete or full of uncertainty and controversy, is the basis for the short-term decision-making and should help to meet long-term objectives.

To be useful the knowledge is summarised, integrated and evaluated before being incorporated into the decision-making process. Several scientists on the programme are involved in these assessment exercises at both the national and the international level.

The programme is also designed to promote interaction between “research” and “policy” by involving the potential users of these results in certain projects and by establishing a steering committee to monitor the programme. This body is made up of representatives from the federal and regional departments affected by the problems under consideration.

The scientific aspect is just one of the elements involved in decision-making, however. There are also social, ethical, economic and legal choices. These fall outside the scope of the programme, but still have to be considered when choosing between political options and determining how they are to be applied, monitored and evaluated.

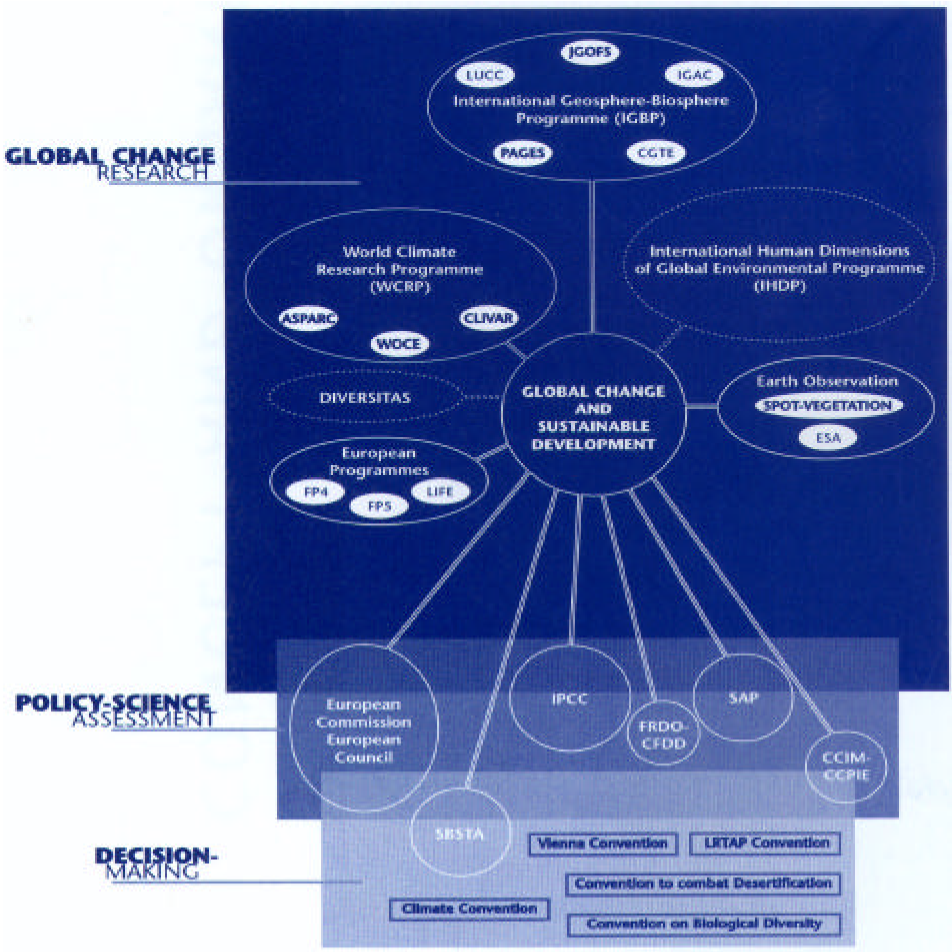


The Scientific Support Plan for a Policy of Sustainable Development

The *Global Change and Sustainable Development* programme is part of a larger project known as the "Scientific Support Plan for a Sustainable Development Policy". The plan was approved by the Council of Ministers on 7 March 1996, and covers other relevant programmes associated with Global Change, such as *Sustainable Management of the North Sea, Scientific Research on the Antarctic, Earth Observation by Satellite, Sustainable Transport and Mobility.* Themed workshops, integration reports and the involvement of certain research teams in many of these programmes enabled us to build bridges and create synergy between them, leading to a holistic view of the problem of *Global Change*.

The *Global Change and Sustainable Development* programme was set up for 4 years, starting from 1 December 1996. Most projects ran through to 30 November 2000 and some to the 30th of June 2001. It was granted a budget of 16 million ECU, covered 24 projects and involved 67 teams.

The programme within a national and international political and scientific context

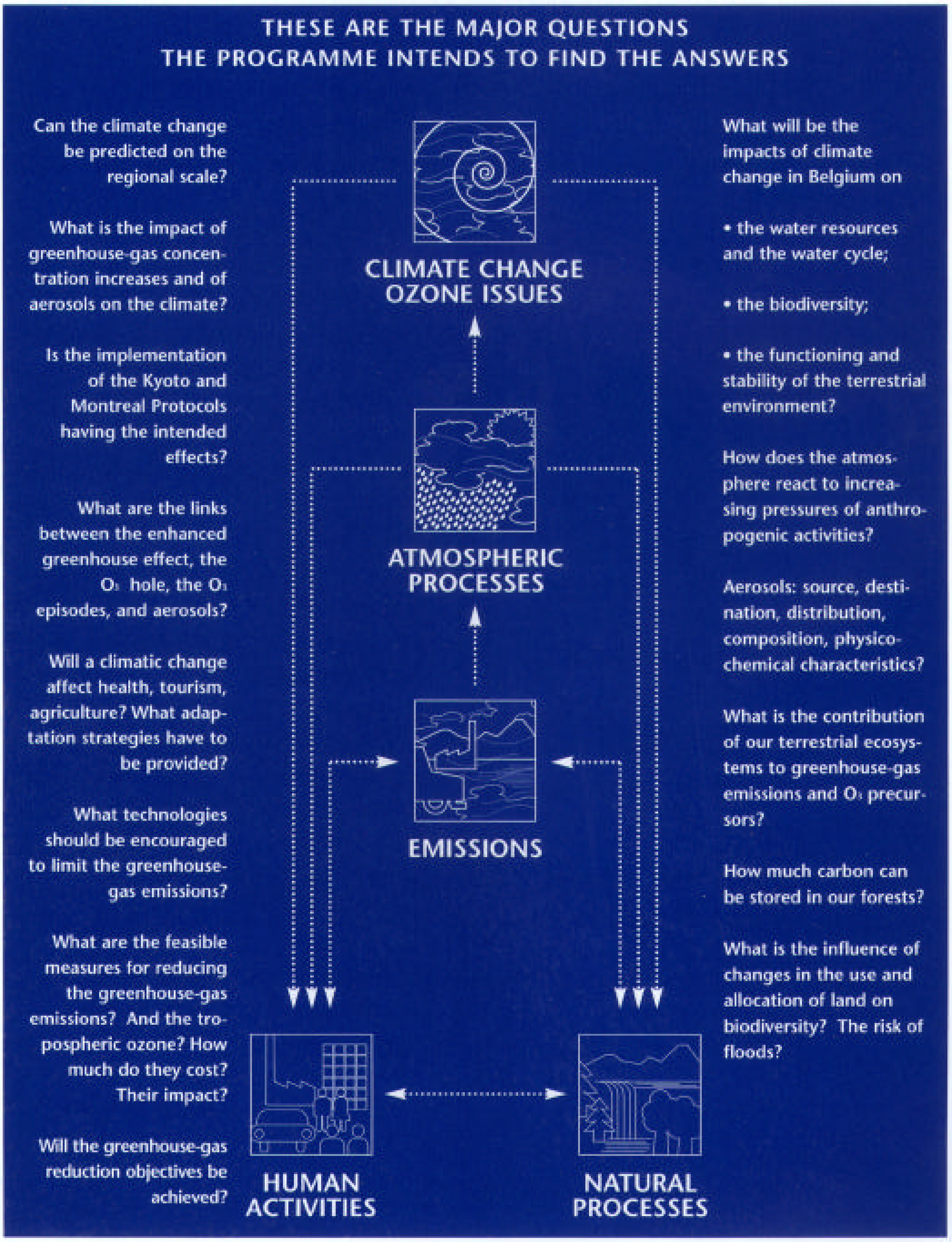


The scientists involved in the programme are well known, both in Europe and further afield, for their research into *Global Change*. They include a number of Belgian experts involved in *core projects* of the *International Geosphere and Biosphere Programme* (IGBP) (*Land Use and Land Cover Change* (LUCC), *International Global Atmospheric Chemistry* (IGAC), *Joint Global Ocean Flux Study* (JGOFS)), in the World Climate Research Programme (WCRP), EUROTRAC 2 projects, the 5th framework programme (Energy, Environment and Sustainable Development), etc.

Others are involved in an advisory capacity or -working parties on scientific evaluation and integration committees, as part of the *Intergovernmental Panel on Climate Change* (IPCC) or the Scientific Assessment Panel of the Vienna Convention on the protection of the ozone layer. They are contributing to the various reports, either as co-ordinators, co-authors or reviewers of specific chapters.

Through national, European and international discussion groups and -councils, the programme managers and some of the scientists working on the programme are involved in the political negotiations concerning the implementation of international conventions.

The objectives, structure and content of the programme



1. To reduce uncertainty

To understand changes in the climate system, the processes and composition of the atmosphere and the interaction between the climate and the natural environment: terrestrial ecosystems and water cycles.

Atmospheric processes and the climate system

Objectives

- To determine the atmosphere's tolerance thresholds and the impact of man's activity on atmospheric changes with a view to taking the most suitable political action concerning climate change in the short, medium and long term, within a national and international context.

- To develop models that will help us to understand the processes underlying the climate system and to predict climatic changes in our regions.

Research subjects

Atmospheric processes and radiative forcing:

- To study chemical, physical and optical properties, the chemical balance and the local, regional and global distributions of active radiative gases and aerosols in the atmosphere.
- Stratospheric ozone:
    - To quantify the ozone balance and study the mechanisms responsible for the trends observed in the ozone of the lower stratosphere and upper troposphere.
    - To study the causes of ozone depletion at the middle latitudes by better quantifying mass transfers.
    - To study the changes in UV radiation and to produce UV-B forecasts for Belgium.
- Tropospheric ozone:
    - To quantify the global and regional balances of hydrocarbons and oxides of nitrogen.
    - To study the mechanisms by which tropospheric ozone is formed and, more specifically, the photochemical degradation of hydrocarbons at different NO concentrations.

- To study changes in the atmosphere's oxidation ("self-cleaning") capacity in response to the disturbances caused by human activity and natural phenomena, with particular attention to the role of the hydroxyl radical.

- The climate system
  - To improve the various modules of the different global climate models.
  - To develop appropriate methods and techniques for analysing the climate, its variability and predictability.
  - To reconstruct past climatic conditions on a regional and/or global scale.
  - To develop models of the carbon cycle as input for climate models.
  - To consolidate the data needed to validate these climate models.

Terrestrial ecosystems and water cycles

Objectives

- To evaluate and predict the effects of climate change, possibly combined with other environmental changes (e.g. changes in the use and ownership of the land), on the natural environment (terrestrial ecosystems, water cycles and water resources) in order to provide a sound basis for developing adaptive strategies.

- To evaluate the contribution of terrestrial ecosystems to emissions of greenhouse gases and ozone precursors.

Research subjects

- To study the physical, biological and chemical processes associated with natural emissions of greenhouse gases (N_2O, CH_4, O_3 precursors).
- To develop and improve methods of quantifying natural emissions of greenhouse gases.
- To evaluate emissions, the storage and dynamic behaviour of carbon and the associated nutrients in pasture, wet land, coniferous and decidious forest ecosystems.
- To provide an overall evaluation of carbon exchange on all the vegetation in Belgium.
- To analyse the impact of climate change and any other environmental factors (tropospheric ozone, acid rain, changes in the availability of nutrients or water) on the functioning (primary productivity, decomposition, nutrient cycle) of terrestrial

ecosystems, specifically in Belgium, and on their complexity (stability, resilience, adaptability, diversity, etc).

- To develop, integrate and validate hydrological models in order to predict the effects of climate change on:
- the dynamics of the water cycle at the basin and sub-basin level.
- Belgian underground water resources.

2. To provide scientific support for Belgian politics concerning climate change

To provide some of the answers to questions arising from the establishment and application of policies relating to the United Nations Framework Convention on Climate Change, the European Union Council Decision concerning the monitoring of CO_2 and other greenhouse gas emissions and the national programme of adaptive and preventive measures (to reduce emissions of CO_2 and other greenhouse gases).

To reduce emissions of greenhouse gases

The ultimate objective is twofold:

1. To define medium and long-term objectives for reducing greenhouse gas emissions in Belgium, given the risks of climate change and their consequences, as measured by the cost of damage and the resources needed to control such emissions.

2. To evaluate the instruments and actions needed to reduce greenhouse gas emissions in our country, taking account of the problem's international dimension.

To this end, we must develop and improve the tools (methods and models) that will enable us to:

- evaluate the instruments and measures needed to reduce greenhouse gas emissions on the basis of criteria such as:
    - their effectiveness in reducing emissions,
    - their cost,
    - their impact on the economy (economic growth, jobs, inflation, private consumption, etc) and on the natural environment (conservation of resources, reduction of other pollutants, etc),
    - their sustainability.

- evaluate how well the various European, Federal or Regional measures work together;

- contribute to the burden-sharing debate;

- analyse the possibility of setting up joint activities with different part of the country.

These tools are the fruit of many different approaches, including micro- and macro-economic models, sector studies, cost/benefit analyses, etc. They were developed by research teams whose experts were drawn from various disciplines (scientific, technical, economic, legal).

Tropospheric ozone: reducing the background concentration and preventing peaks

The objective is to integrate all the scientific and economic knowledge, and thus provide an aid to decision-making. This will then enable us to evaluate the socio-economic impact of the various instruments and political measures and their effect on the background concentration of ozone and the prevention of ozone peaks.

PART 1: REDUCING UNCERTAINTIES

Atmospheric processes and the climate system

CG/DD/01A
CG/DD/01B
CG/DD/01C
CG/DD/01D

EXPERIMENTAL STUDIES OF ATMOSPHERIC CHANGES (ESAC)

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1. SCIENTIFIC RATIONALE AND RESEARCH OBJECTIVES

The composition of the Earth's atmosphere is changing as the concentrations of a number of radiatively and chemically active atmospheric constituents emitted at the surface are rapidly increasing, mainly due to man-made activities. These increased emissions influence atmospheric ozone, the Earth's radiative balance, hence climate, and modify the oxidising capacity of the atmosphere. It has become clear also that the upper troposphere / lower stratosphere is a region of high interest, because it controls the exchange of gases between the troposphere, where the sources are, and the stratosphere, and it controls to a great extent the radiative balance of the atmosphere.

A better knowledge of atmospheric composition and chemical processes, from the ground up to the stratosphere, is fundamental to assess the present state and changes and predict the future evolution of the Earth's environment, so that regulatory decisions about mankind practices can be identified on the basis of firm scientific grounds. This can only be achieved by a comprehensive series of complementary measurements including ground-based observations, aeroplane and balloon-borne campaigns, and global satellite missions, by improving the probing capabilities in the troposphere, and by comparing and integrating the observational data with numerical models.

ESAC has contributed to the objectives of investigating the behaviour of ozone and many key stratospheric and tropospheric species at four stations in Europe, complemented by global satellite observations. This investigation has included long-term monitoring and the evaluation of radiative, dynamical, and chemical mechanisms underlying the observed variabilities and changes. The four stations are Ukkel (Belgium, 50.5°N, 4.3°E), Jungfraujoch in the Swiss Alps (46.5°N, 8°E), Harestua (Norway, 60.2°N, 10.7°E), and Observatoire de Haute Provence (France, 44°N, 6°E); they are part of the international Network for Detection of Stratospheric Change. Additionally it was tasked to improve the acquisition of tropospheric data, and in particular, to pursue the analysis of earlier ATMOS/Space Shuttle observations to assess the possibilities to study the upper troposphere by infrared remote sensing from space. Long-term monitoring of the spectral UV irradiance has been performed at Ukkel, in compliance with the international quality standards. The atmospheric observations have been supported by numerical modelling of the atmosphere and by laboratory experiments that provide the fundamental spectroscopic and radiative data needed in the models and in the spectral data analyses.

The research is embedded in various European and international research programmes.

2. PARTNERSHIP

The project was carried out by four Belgian research groups, that work in close collaboration with international partners. They are the Royal Meteorological Institute of Belgium, the “Groupe Infra-Rouge de Physique Atmosphérique et Solaire” of the Université de Liège, the “Laboratoire de Chimie Physique et Moléculaire” of the Université Libre de Bruxelles, and the Belgian Institute for Space Aeronomy that co-ordinated the project. A close collaboration among the partners was achieved, through the sharing of manpower and instruments for performing observations, and the exchange of data and expertise concerning the analysis and interpretation of measurements.

3. RESULTS

The ESAC project has enabled the Belgian partners to continue long-term monitoring of the atmospheric composition with ground-based instruments at the four European stations mentioned above. The instruments used are Fourier transform spectrometers, UV-visible Differential Optical Absorption Spectroscopy (DOAS) instruments, UV-visible radiometers including Dobson and Brewer instruments and ozone sondes. Existing time series of atmospheric data have been updated, in a consistent way. Revisions and homogenisations have been implemented where necessary. The synergy with satellite data has been explored. Accurate laboratory data of relevance to the atmospheric research have been acquired.

3.1 Jungfraujoch long-term observations

At the Jungfraujoch, time series date back to 1985, with some data going back to the mid seventies or even to 1950. They have proven to be of utmost importance to identify and quantify variabilities and long-term changes of a large number of atmospheric species, among which ozone, key stratospheric species that are involved in the processes leading to ozone destruction, like the halogens, a number of radiatively active gases (the so-called greenhouse gases) that impact the Earth’s climate, like methane and carbon dioxide, and source gases emitted at the surface, often by human activities, like the CFC and HCFC. Important features in the atmosphere’s evolution that could be detected at the Jungfraujoch and investigated during the ESAC project are:

- The turn around of the rate of change of the total inorganic chlorine loading in the stratosphere, in 1997-1998. Knowing that it takes 3 to 5 years for the long-lived chlorine-bearing source gases to leave the troposphere and reach the mid-stratosphere, this observation is in agreement with the observed decrease in the total organic chlorine in the troposphere (that is representative of the chlorine-bearing source gases) after mid-1994. The observations agree with model calculations that take into account the reductions of emissions according to the Montreal Protocol and its successive Amendments.

- The continued rise, although slowed down, of the inorganic fluorine concentration in the stratosphere, contrary to the decrease of chlorine. At present this observation cannot be understood, in comparison with model predictions and correlative observations.

- The decrease of the NO_2 column abundance by about 45% at maximum at the beginning of 1992, due to the aerosol load injected in the stratosphere by the eruption of the Mt. Pinatubo volcano in the Philippines in July 1991, and its subsequent recovery, until the end of 1994.

- The now apparent long-term increase of NO_2 by about 0.6%±0.2% per year. At present, the trends of HNO_3 (-0.2%±0.2% per year) and NO_2 don't seem to be consistent with the one observed for the N_2O source gas, that is of order 0.30%±0.01% per year. This is related to the difficulty to quantify the long-term changes, due to the very large natural variability of HNO_3 and the perturbation by Mt. Pinatubo aerosols that disrupted the time series.

- Observations of the rate of increase of the major radiatively active gases that are controlled by the Kyoto Protocol: CO_2 (0.41%±0.01% / year), CH_4 (slowing down from 0.74%/year in 1987 to 0.1%/year in 2000), N_2O (0.30%/year), SF_6 (slowing down from 14%/year in 1987 to 5%/year in 2000).

- Tropopause heights appear to rise in the eighties, and lower in the nineties. This may correlate with changes in the radiative balance in the atmosphere. The tropopause changes may explain part of the N_2O rise and may also correlate with the slow down in the nineties of the negative total ozone trend that was observed in the eighties. Has a recovery of ozone been observed after 1994? The question whether this signature is due to interannual variability or to a steady trend will be answered by extending the times series in the future.

3.2 The evolution of Ozone at Ukkel

The time series of ozone vertical profile data between 0 and 35 km altitude, obtained from soundings at Ukkel, extends from 1969 to present. It has been re-evaluated to correct for instrumental artefacts and changes with time. Trends have been revised concurrently. The main features are: a pronounced long-term decrease of ozone in winter and spring in the lower stratosphere, an increase of tropospheric ozone in all seasons, and a strong increase of ozone in the planetary boundary layer in March to September and decrease during the other months. All-year round trend values for ozone are positive in the troposphere of order +0.35 to 0.85%/ year (depending on altitude), negative in the lower stratosphere between -0.2 and –0.5%/ year (at 15 km altitude). It appears that the photochemical production of ozone has increased significantly during recent years.

3.3 OClO and BrO observations at Harestua and OHP

Growing time series of BrO at Harestua and OHP and of OClO at Harestua have improved our knowledge about the diurnal, seasonal and latitudinal variations of both species. Events of enhanced OClO values are observed in cold winters when vortex air passes over Harestua. Largest BrO amounts are observed in winter, especially in conditions of denoxification for which the conversion to the reservoir $BrONO_2$ is reduced.

The synergistic exploitation of the ground-based, balloon-borne and satellite (GOME/ERS-2) observations of BrO has led to the conclusion that there exists a non-negligible tropospheric background of BrO, on a global scale. Its sources are still to be identified.

Using the coupled radiative transfer and photochemical box model PSCBOX (see below) for comparisons with observations, Our actual knowledge of the halogen chemistry has been questioned, because twilight observations of OClO under weak chlorine activation conditions cannot be reconciled with the PSCBOX model results. More investigations are in progress.

3.4 UV spectral irradiance measurements at Ukkel

Having acquired now about 11 years of UV spectral irradiance data, an UV climatology has been developed. The key factors that influence the UV dose at ground level are the occurrence of clouds and the amount of ozone: their impact has been studied. Because of their variability, it is found too early to distinguish a reliable UV trend.

An operational UV index forecasting procedure has been developed and implemented: UV Index forecasts are now disseminated daily to the public in the late spring and summer months.

3.5 Synergy with satellite data

The consistencies and complementarity between various satellite, balloonborne, ground-based remote sensing and *in situ* data sets have been investigated and exploited, in particular for the derivation of an NO_2 profile climatology from the ground up to 70 km altitude and for the verification of an improved algorithm for the ATMOS/Shuttle experiment extending the derived molecular profiles down into the free troposphere.

3.6 Process Studies

Several campaigns have been conducted, to study tropospheric and planetary boundary layer ozone, at Ukkel, the occurrence of ozone and other pollutants (NO_2, SO_2, benzene, toluene, formaldehyde, night-time NO_3) at ground level in the urban area of Brussels (1997) and the chemical composition in the troposphere – planetary boundary layer in summer 1998 in the Jungfraujoch area.

Four components in the ozone budget in the boundary layer (up to 2km on average) could be identified and quantified: accumulation in the layer due to local production, transfer from the boundary layer to the free troposphere, deposition at the surface and horizontal advection. It has been found that good estimates of the O_3 concentration can be made using only meteorological parameters (wind speed and direction, humidity, irradiance, …), but that they can be improved upon including estimates of NO and NO_2 concentrations. The measurements in the Jungfraujoch area were mainly of technological interest, proving the new measurement concept of altitude-differential measurements (see below). Fast variations of CO with a 1-hour timescale have been observed, in agreement with correlative local *in situ* observations. Also tropospheric boundary layer C_2H_6 varies rapidly from day to day, whereas CH_4 and N_2O are quite stable in a 1-month time frame.

3.7 Laboratory data

The molecules for which new or more accurate spectroscopic data (absorption cross-sections, line positions and intensities) have been obtained are: O_2 and its collision complexes O_2-X with X=N_2, Ar, or O_2 itself), NO_2 and its dimer N_2O_4, H_2O and its isotopomers HOD and D_2O, C_2H_2, OCS, HOCl and HCFC-22 and HFC-152a. They were measured under different conditions of temperature and pressure in the near and mid infrared, visible and UV ranges using Fourier transform spectroscopy. Compared to previous studies, the aim in many cases was to acquire data at pressure, temperature and concentration conditions that are 'atmosphere-like', and/or to resolve discrepancies existing in actual literature data. In particular for the water molecule, it is important to characterise the large amount of weak absorption features in the UV-visible to identify their contribution to the radiative balance of the atmosphere.

4. PROGRESS IN INSTRUMENTS, DATA ANALYSIS AND INTERPRETATION

To achieve the objectives and to obtain the above results, various new developments and improved methods have been implemented. We cited already the *UV Index forecasting* and the *differential-altitude measurements*. The latter is one method to acquire data in a distinct altitude range in the boundary layer – lower troposphere. It is based on simultaneous measurements at two different observation altitudes of the total column abundance of a target species, to derive from the difference between the observed columns the concentration in the layer in between both observations sites.

Vertical inversion algorithms provide an alternative method to acquire altitude information from ground-based measurements. One has been developed for high-resolution Fourier Transform infrared measurements like the Jungfraujoch observations. The principle of the inversion is the variation of the absorption line shape with altitude, due to its dependence on pressure and temperature. The inversion algorithm has been validated extensively for ozone. Preliminary results have been obtained for HCl and HF. It will be possible in the near future to re-analyse existing long-term series to study the distinct behaviour of the atmospheric composition in various altitude ranges back to the last decades.

In the UV-visible DOAS method, the tropospheric information content increases if one makes quasi-simultaneous observations of the diffuse sunlight scattered at different zenith angles in the sky, e.g., the zenith and an angle close to the horizon. This is called the *DOAS off-axis method*. New instruments have been built and made operational, and preliminary results as to tropospheric BrO and formaldehyde have been obtained at the Observatoire de Haute Provence.

Software developments have contributed to a better and easier analysis of atmospheric and laboratory spectra. *WinDOAS* is a much advanced software package for the analysis of UV-visible DOAS spectra; *Wspectra and bFit* serve the analysis of absorption line parameters in high resolution Fourier transform laboratory spectra.

PSCBOX is *a coupled radiative transfer/chemical box model* that has been developed for the geophysical interpretation of fast varying species like OClO and

BrO: it has contributed to a better understanding of the twilight chlorine and bromine chemistry in the stratosphere.

A new correction procedure has been developed for the ozone sonde measurements, that takes into account various correction factors. In particular, a new correction profile for the sonde pump efficiency has been implemented. The whole O_3 time series of soundings at Ukkel has been homogenised considering this new procedure.

It has been found also that reference standard atmosphere models commonly used in the community are outdated, incomplete, or lacking information about the natural seasonal and latitudinal variations. In several occasions, new climatological models have been developed for particular purposes, e.g., for O_3, based on the Ukkel soundings and local tropopause altitudes, for NO_2, based on the synergy between satellite and ground-based data and models, and for HF, HCl and CH_4, based on HALOE satellite data.

5. VALORISATION

The usual dissemination channels have been used extensively: publications, international symposia, workshops, public information activities, and integration in various European and international projects. Particular valorisation activities to be mentioned are the archiving of atmospheric and spectroscopic data in international geophysical and spectroscopic databases, respectively, via which these data become accessible to the world-wide scientific community for further exploitation including satellite validation activities, the participation of some partners in International Assessment exercises, and the distribution of software (WinDOAS) to other research groups. It has been demonstrated once more that the uninterrupted continuation of long-term monitoring supported by fundamental research (e.g., laboratory work) plays a key role in atmospheric research focusing on global changes in atmospheric chemistry, dynamics and climate.

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ANTHROPOGENIC AND BIOGENIC INFLUENCES ON THE OXIDISING CAPACITY OF THE ATMOSPHERE

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1. PROJECT SUMMARY

The oxidizing capacity of the atmosphere consists in its own ability to cleanse itself from a number of pollutants. It determines the fate and lifetime of a large number of chemical compounds, including greenhouse gases. For example, the abundance of methane (one of the major greenhouse gases) is largely controlled by its chemical reaction with the hydroxyl radical (OH). It follows that any perturbation affecting the concentration of this OH radical will also influence the abundance of methane as well as of many other gases. In fact, many other chemical compounds present in the atmosphere influence the oxidizing capacity of the atmosphere. These include hydrocarbons, carbon monoxide and the nitrogen oxides. All these compounds have both biogenic and anthropogenic sources. In other terms, human activities have a very large impact on the concentration of these gases. Industrial activities, the burning of fossil fuels, deforestation, the burning of savannas and forests and the use of fertilizers in agriculture are among the most prominent processes responsible for the emissions of these pollutants, causing their atmospheric concentration to increase significantly. It is therefore of great importance to understand the budget (sources and sinks) of these chemical species, and also to quantify how human activities might have influenced them.

The biosphere (vegetation, soils, and oceans) has also a large influence on the chemical composition of the troposphere. For example, the emissions of very reactive non-methane hydrocarbons (NMHCs) by vegetation are believed to have a significant impact on the budget of species like carbon monoxide, ozone, the hydroxyl radical, and aerosols. The emissions as well as the complex oxidation mechanisms of these hydrocarbons are still not well understood and quantified, however. Additional investigations aiming at the elucidation of these processes are therefore required in order to better characterize the natural environment in which the human perturbation takes places.

In this project, the impact of anthropogenic and biogenic emissions on the formation of tropospheric ozone and other oxidants has been investigated through a combination of modelling activities and laboratory studies. Atmospheric models are the best tools available in order to estimate the impact of anthropogenic emissions on harmful pollutants (like ozone) and radiatively important compounds (like methane, ozone, and aerosols). These models are a simplified representation of the real atmosphere. They take into account most of the physical and chemical processes influencing the tropospheric composition at the global scale. The confrontation of the model results with observations and the continuous improvement of the model parameterizations are important aspects of this project. Another very important aspect of this project is the development and application of new measurement techniques appropriate to the elucidation of key chemical reactions of biogenic non-methane hydrocarbons. The studies conducted using these techniques are crucial in order to narrow the uncertainties related to the chemistry of biogenic hydrocarbons.

2. OBJECTIVES

The major objectives of our project are the following:

- to narrow the uncertainties in the processes influencing the global composition of the troposphere; more specifically, to quantify the impact of biogenic volatile organic compounds; even more specifically, determine the products and yields of the reaction of important biogenic hydrocarbons (the monoterpenes α- and β-pinene) with the hydroxyl radical (OH).
- to quantify the influence of human activities on the composition of the global troposphere (in particular, oxidants) and on its oxidizing capacity.

3. RESULTS

Our results are in line with the objectives stated above:

Narrowing the uncertainties

We contributed to the elucidation of the chemical degradation of two important biogenic non-methane hydrocarbons (α-pinene and β-pinene) in their reactions with hydroxyl radicals. Several reaction products not known before have been identified, and reaction schemes explaining their formation have been proposed.

The following results were obtained:

1. In the case of α-pinene, carbon dioxide, carbon monoxide, and acetone were identified and quantified via on line mass spectrometric analysis. The product yields were found to be strongly pressure dependent, indicating that the fate of the initially formed α-pinene-OH adduct is determined by its stabilisation rate.

2. The more important products are the semi-volatile compounds, for which new analytical detection methods have been developed. These products were first collected on a liquid nitrogen trap and subsequently identified by mass spectrometry.

The analysis showed that campholenealdehyde and pinonaldehyde were formed as oxidation products for the α-pinene reaction, with pinonaldehyde being the main product. In the case of the β-pinene reaction, the measurements showed nopinone as the main oxidation product.

3. A new sampling method has been applied for the detection of light carbonyl compounds. In this way, formaldehyde, acetaldehyde and acetone could be determined for the α-pinene system. For the β-pinene system, the following products have been detected: nopinone, acetone, acetaldehyde, formaldehyde and for the first time trans-3-hydroxynopinone, perillaldehyde, perilla alcohol and myrtanal. The latter four compounds are possibly good sensors for unravelling the degradation mechanisms of β-pinene.

4. Mechanisms have been proposed explaining the formation of these products. We concluded that the current Master Chemical Mechanism (MCM) describing the degradation of terpenes is unable to explain the observed product yields and will have to be adjusted accordingly.

In addition, and in collaboration with international research teams, we completed the development and validation of two comprehensive chemical-transport models of the global troposphere, the IMAGES and MOZART models. Both models are valuable tools, which have been used by several international teams in order to quantify the processes controlling the composition of the troposphere, and in particular ozone and its precursors. For example, these models were used to determine the influence of various emission processes (biomass burning, lightning, etc.) on the distribution of chemical compounds. The budget of ozone and the respective contributions of various chemical processes to its formation and loss have been quantified.

New techniques have been proposed and applied in order to understand how the observations of chemical compounds can be used in order to provide useful constraints on the emissions of ozone precursors. In future studies, these developments will be the basis for the exploitation of satellite measurements of tropospheric compounds.

Quantify the influence of human activities

Both the IMAGES and MOZART models have been used in order to provide quantitative assessments of the anthropogenic impact on the tropospheric composition. These results were obtained in part in the framework of international assessments (IPCC).

The impact of the subsonic aircraft emissions on tropospheric ozone and on the oxidizing capacity of the atmosphere has been evaluated. These emissions are found to enhance ozone concentrations by about 6% during the summer in our latitudes. The impact of aviation is expected to increase in the future according to the models.

The future impact of industrialisation and of increased energy demand and population has been estimated, based on scenarios for the anthropogenic emissions of ozone precursors in the 21st century. The possible impact of dimatic changes on tropospheric chemistry has also been estimated. The calculated increases in surface level ozone concentrations are found to be very large in the heavily populated areas in the Tropics. These ozone levels will represent a major threat to public health and agriculture in these areas. Important differences between the predictions by different models have been noted, however.

4. VALORISATION

Our results have been made available by communications in international conferences and publications in international journals, as well as e.g. via an EUROTRAC programme website.

The laboratory results of our project have been incorporated in the European Environmental Research Programme EUROTRAC 2, within the project "Chemical Mechanism Development" (CMD).

The model results on the future impact of aviation and industrialisation on the tropospheric composition are a contribution to two assessment reports of the Intergovernmental Panel for Climate Change (IPCC).

5. RECOMMENDATIONS

Given the widely accepted importance of tropospheric chemistry in outstanding issues such as climate change and air quality, and because of the large remaining uncertainties in the processes involved, we strongly recommend that the Belgian and European research efforts be sustained and possibly enhanced in this area.

More specifically, noting the importance of the biosphere in the climate system as well as the very large remaining uncertainties in the quantification of biospheric emissions and impacts, we recommend that research efforts be sustained in this area.

Because the emissions of non-greenhouse gases like carbon monoxide, nitrogen oxides, and non-methane hydrocarbons are known to enhance the abundance of ozone (a greenhouse gas) in the troposphere, we believe that these emissions should be considered in future efforts to mitigate climate change.

Noting that tropospheric ozone levels are expected to increase to very high values in many heavily populated areas of the world, thereby representing a considerable threat to human health and agricultural yields in these areas, we recommend that strategies be elaborated in order to reduce the emissions of ozone precursors (carbon monoxide, nitrogen oxides and hydrocarbons), not only in our countries, but also in the rest of the world.

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SOURCES, PHYSICO-CHEMICAL CHARACTERISTICS, AND CLIMATE FORCING OF ATMOSPHERIC AEROSOLS

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SYNTHESIS OF THE FINAL INTEGRATED SCIENTIFIC REPORT

For the 4-year period from 1/12/1996 until 30/11/2000

The overall goal of the project was to contribute to the reduction of the uncertainties in our knowledge of the sources, spatial distribution, and characteristics of the tropospheric aerosols that are of importance for climate. This was accomplished by performing studies at sites which are representative for large regions or are situated within (or downwind of) areas where it is expected that the radiative forcing by anthropogenic aerosols is very substantial. The studies were done (a) at selected sites in Europe within the framework of the EUROTRAC-2 AEROSOL subproject, (b) at sites in the eastern Mediterranean and in the Arctic, which are receptor areas of the European pollution plume, and (c) in tropical and subtropical regions.

The specific objectives of the project were:

(1) to provide a comprehensive physico-chemical characterisation of the fine (submicrometer-sized) aerosol in the areas of study;

(2) for some study areas, to complement this with purely physical aerosol measurements, with the determination of in-situ optical aerosol parameters and of vertical-column aerosol characteristics, and with measurements of atmospheric trace gases;

(3) to determine the relative contributions of the three aerosol types (fine sulphate, organic aerosols, and mineral dust), which are mainly responsible for the aerosol forcing on climate; to differentiate between the natural and anthropogenic contributions to the fine sulphate and the organic aerosols; and to assess the sources, source processes, source areas, and transport mechanisms for the three important radiatively active aerosol types;

(4) to investigate to which extent the fine aerosol mass can be reconstituted on the basis of the measured aerosol types, and thus aerosol chemical mass closure can be obtained;

(5) to interrelate the various aerosol data sets and to utilise them for model calculations of optical aerosol characteristics or radiative forcing.

The project involved the development and implementation of novel methods and approaches for aerosol collection, for “bulk” and individual particle analysis, and for data interpretation and interrelation.

With regard to methodology, we implemented and evaluated a thermal-optical transmission technique for the determination of organic carbon and elemental carbon in aerosols. We participated in the EUROTRAC-2 AEROSOL Carbon Shootout Stages I and II and in other round-robins, which were organised to compare the methods of the various participants and to arrive at improved methods for the determination of and differentiation between organic carbon and elemental carbon. We improved and evaluated methods for extracting organic compounds from aerosols for subsequent detailed analysis by capillary gas chromatography - flame ionisation detection and gas chromatography/mass spectrometry. We started developing a method for the quantitative determination of levoglucosan (which is a general marker for wood combustion) and related monosaccharide anhydrides in aerosol samples, and we implemented various types of derivatisations and solid-phase extraction in combination with gas chromatography/mass spectrometry for the characterisation and structure elucidation of unknown compounds that were present in notable concentrations in urban and tropical aerosols. Methodological development work was done for transmission electron microscopy with selected area electron diffraction, and for two other microscopical analytical techniques, namely microprobe X-ray fluorescence with laboratory and synchrotron radiation sources and static secondary ion mass spectrometry.

Our contribution to the EUROTRAC-2 AEROSOL subproject includes the development, evaluation and application of analytical methods for organic carbon and elemental carbon and for detailed organic compounds. During 1998, the methods were evaluated and applied to aerosol samples collected in Gent, during two different seasons (winter and summer). In both seasons, daily samples were taken with three types of filter collection devices. Particulate mass was determined for all filters by weighing, and all quartz fibre filters were subjected to analyses for organic carbon and elemental carbon; selected filters from one sampler were analysed for detailed organic compounds by capillary gas chromatography - flame ionisation detection and gas chromatography/mass spectrometry. About two thirds of the PM10 (that is particles smaller than 10 µm) aerosol mass was contained in the fine (<2 µm) size fraction at Gent during the sampling campaigns. During both winter and summer, total carbon (that is the sum of organic carbon plus elemental carbon) was responsible for around one quarter of the aerosol mass and elemental carbon represented about 25% of total carbon. Considering that the organic aerosol also contains other atoms (such as hydrogen, oxygen, nitrogen) besides carbon, the organic carbon data have to be multiplied by a conversion factor in order to obtain organic aerosol mass. Multiplication factors of 1.4 are commonly used for urban aerosols. Using this factor, one arrives at a percentage of carbonaceous aerosol (that is the sum of organic aerosol plus elemental carbon) of one third of the particulate mass. By the detailed analyses for organic compounds, over 100 compounds belonging to different classes could be identified. Their total mass represented on average only 3% of the mass of the organic aerosol, though. *n*-Alkanes and fatty acids were the prevailing organic compounds in both seasons, but the distribution patterns of individual components within each class showed seasonal differences. The *n*-alkane pattern for summer aerosols was clearly affected by emissions from the vegetation, while that of fatty acids revealed a lower relative abundance of unsaturated fatty acids in summer than winter, that can be related to more extensive atmospheric oxidation of unsaturated fatty acids during summer. Concentrations of dicarboxylic acids and related products that are believed to be oxidation products of hydrocarbons and fatty acids were highest in summer aerosols. Some individual compounds in the latter class could only be detected in summer samples and showed the highest concentrations on hot summer days that were characterised by maximum temperatures above 25°C and increased ozone concentrations. The latter compounds included novel, recently identified glutaric acid derivatives. Several compounds were found that are markers of wood combustion, including diterpenoic acids, lignin pyrolysis products, and levoglucosan. The quantitative results obtained for diterpenoic acids and lignin pyrolysis products indicated that contributions from wood combustion are more important in winter than in summer. There was evidence that both soft and hard wood burning contribute to the organic aerosol, but that hard wood burning prevails during winter. Polyaromatic hydrocarbons were also more prevalent in winter than in summer.

Besides work on organic carbon, elemental carbon, and detailed organic compounds, our contribution to the AEROSOL subproject includes the intercomparison and evaluation of methods for measuring important aerosol parameters, such as the particulate mass and carbon, the determination of the detailed mass size distribution for the particulate mass, organic carbon, elemental carbon and other important aerosol species, chemical mass closure work, and source (type) apportionment. Various intercomparisons were made at Gent of filter collections and in-situ measurements for the aerosol particulate mass and elemental/black carbon (all for the PM2.5 aerosol, that is for the particles smaller than 2.5 µm). The in-situ instruments were a Rupprecht and Patashnick tapered element oscillating microbalance (TEOM) for the particulate mass and a Magee Scientific aethalometer for black carbon. The TEOM value was on average only two thirds of the gravimetric mass derived from quartz fibre filters. Discrepancies between TEOM and gravimetric aerosol data have been observed by others and are attributed to the heating to 50°C (and loss of semi-volatile aerosol) in the TEOM. Comparisons of gravimetric fine particulate mass determinations were also done with filter holders that used different types of filters. It was found that the fine particulate mass derived from Nuclepore polycarbonate filters and Teflo filters was only around 75% of that derived from the quartz fibre filters. The difference may be due to the loss of semi-volatile aerosol for the Nuclepore and Teflo filters or to the collection of gaseous species by the quartz filters or to a combination of both. Further investigations should clarify this. In fall 1999, we examined the detailed mass size distribution of the particulate mass, organic carbon, elemental carbon, and various elements at Gent, and used the data for aerosol chemical mass closure calculations as a function of particle size. Six aerosol types were considered in the mass closure calculations: (1) organic aerosol, (2) elemental carbon, (3) ammonium sulphate, (4) sea salt, (5) crustal matter, and (6) biomass smoke. The major aerosol types in the submicrometer size fraction were organic aerosol (on average responsible for 32% of the particulate mass), ammonium sulphate (27%) and elemental carbon (10%). In the supermicrometer size range, organic aerosol (28% of the particulate mass) and crustal material (24%) prevailed; ammonium sulphate and sea salt were responsible for about 10% each. On average, 74% of the gravimetric particulate mass was accounted for by the aerosol types considered. The unexplained mass is likely attributable to ammonium nitrate and water.

We also participated in the INTERCOMP 2000 experiment of the EUROTRAC-2 AEROSOL subproject. The field work for INTERCOMP 2000 took place in April 2000 at the Institute for Tropospheric Research (IfT) research station Melpitz, about 50 km north-east of Leipzig, Germany.

A large part of our project dealt with comprehensive studies on chemical, physical, and optical (radiative) aerosol properties in the eastern Mediterranean and the assessment of the direct radiative forcing by aerosols in the area. These studies were performed in close co-operation with foreign research groups, especially with the Biogeochemistry Department of the Max Planck Institute for Chemistry, Germany. Both long-term and intensive aerosol measurements were conducted at Sde Boker in the Negev desert, Israel. The long-term measurements started in January 1995 and are still going on. The intensive measurements were conducted during two campaigns (of about 4 weeks each), the first one, called ARACHNE-96, in June-July 1996, the other, ARACHNE-97, in February-March 1997. In the long-term measurements, aerosol samples are collected with a Gent PM10 stacked filter unit sampler according to a 2-2-3-day schedule and analysed for the particulate mass, black carbon, and over 40 elements. From December 1995 through September 1997, an integrating nephelometer was used for the continuous measurement of the aerosol scattering and backscattering coefficients at 3 wavelengths (450, 550, and 700 nm), and it was then replaced by a unit which only measures the scattering at 550 nm. Furthermore, measurements of the vertical column-integrated aerosol optical depth and other aerosol properties are conducted at the site on a nearly continuous basis with an automatic tracking combined sunphotometer/sky radiometer. During the intensive campaigns, a wide array of instruments were used for measuring the aerosol chemical, physical, and optical (radiative) properties and for measuring selected atmospheric trace gases (CO, CO_2, SO_2, O_3). Comprehensive articles on the ARACHNE-96 and ARACHNE-97 campaigns were published. During ARACHNE-96, the average aerosol dry single scattering albedo (ω_0) characterising polluted conditions was 0.89, whereas during "clean" periods ω_0 was 0.94. The direct radiative effect of the pollution aerosols was estimated to be cooling. With regard to the long-term measurements, the data from the 3-wavelength nephelometer and the Gent PM10 stacked filter unit sampler were interrelated. This was done for the period December 1995 through September 1997. The total scattering coefficient at 550 nm showed a median of 66.7 Mm^{-1}, typical of moderately polluted continental air masses. Values of 1000 Mm^{-1} and higher were encountered during severe dust storm events. Mass scattering efficiencies were obtained by multivariate regression of the scattering coefficients on dust, sulphate, and residual components. An analysis of the contributions of the various aerosol components to the total scattering observed showed that anthropogenic aerosol accounted for about 70% of the scattering. The rest was dominated by the effect of the large dust events mentioned above, and of small dust episodes typically occurring during mid-afternoon. The radiative forcing by anthropogenic aerosols in the study region at the top of the atmosphere was estimated using two different approaches. The most detailed one of these yielded an all-sky radiative forcing of 2.5 and 4.9 Watt per square meter over desert and ocean surfaces, respectively. These data are in good agreement with predictions from global models of aerosol radiative forcing. Overall, we concluded that our data provide a strong support for a negative radiative forcing due to anthropogenic aerosols in the eastern Mediterranean region, and that the magnitude of this forcing is in good agreement with current model predictions. Further with regard to the long-term collections, we applied trajectory statistics in order to assess the source regions of some important aerosol constituents. The stacked filter unit data set for the 3-year period from 1995 through 1997 was used for this purpose. The air masses, which arrived at Sde Boker slightly above ground (i.e., at a level corresponding to 950/960 hectoPascal), originated mainly from the north-west, and had remained in the atmospheric boundary layer (below 2000 meters) during the 5 days preceding their arrival. The same was true for the 900 hectoPascal arrival level. The highest levels of fine sulphur were associated with air masses that originated in the North; the dominant source region appeared to be Ukraine, followed by the West coast of the Black Sea, and Greece. In contrast, fine vanadium and fine nickel (two indicators of residual oil burning) were from local/regional origin, including from the power plants along the Israeli coast. Russia seemed to be the major source area of fine zinc.

Coarse calcium, an indicator for the carbonate mineral dust, was highest for air masses coming from the south-east and west, consistent with the location of the desert source regions

Our aerosol research in tropical and subtropical regions included studies in Africa (the Republic of Congo, Zimbabwe, South Africa), the Brazilian Amazon region, northern Australia, and Indonesia. It involved both long-term and campaign-type measurements. The emphasis in the studies was placed on the impact of biomass burning and of natural biogenic emissions on the climatically active fine aerosol. Part of our work for Brazil was performed within the framework of the “Smoke, Clouds, Aerosols and Radiation - Brazil (SCAR-B) Experiment” and the “Large Scale Biosphere-Atmosphere Experiment in Amazonia” (LBA), and some of our research in South Africa was done as part of the “Southern African Regional Science Initiative” (SAFARI 2000).

With regard to the valorisation of our work, this is partly done through traditional channels, such as publications in international journals and presentations at international conferences. For our research that is done within intensive campaigns, we also relate our data with results of the other participants, which leads to joint publications and presentations. The results are further used in workshops, activities and reports that aim at transfer of knowledge to policy advisers and policy makers. Our long-term and other data sets with concentrations and compositions of fine atmospheric aerosols for various European sites are being used for advice to the European Commission, in particular within work for the 2003 revision of the EU Particulate Matter Directive.

Our research has shown that the determination of seemingly simple aerosol parameters, such as the particulate mass, is much less straightforward than usually thought. The measurement of the particulate mass is complicated by both positive and negative artifacts. Work on the control, elimination, and assessment of the artifacts is needed. This work will assist regulatory bodies which are setting and imposing guidelines for particulate matter. Carbonaceous particles make up a very large fraction (often over 30%) of the aerosol in many areas. Yet, our knowledge on the detailed molecular composition of the carbonaceous aerosol, its sources, and its effects on human health and climate is still quite poor. Further research on these topics is highly recommended. There are still large uncertainties associated with the radiative forcing of aerosols on climate. In the past few years, much progress has been made with regard to the *direct* radiative aerosol forcing. However, with regard to the *indirect* radiative forcing (that is through the effects of aerosols on clouds) much work remains to be done.

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MODELLING THE CLIMATE AND ITS EVOLUTION AT THE GLOBAL AND REGIONAL SCALES (CLIMOD)

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The overall objective of the research project CLIMOD (CLImate MODelling) was to contribute to the international research effort leading to an improved understanding of the climate system and to a better assessment of the impact of human activities on the global and regional climates. Two main tools were used to reach this goal: modelling and data analysis.

Four Belgian research teams have participated to this project: the *Global Climate Modelling Group* and *Regional Climate Modelling Group* of the *Institut d'Astronomie et de Géophysique Georges Lemaître*, the *Geografisch Instituut* of the *Vrije Universiteit Brussel,* and the *General Climatology Section* of the *Royal Meteorological Institute of Belgium*.

At the beginning of the project, members of the research network CLIMOD had at their disposal a global coupled atmosphere–ocean general circulation model, a thermomechanical model of the Greenland ice sheet, and a regional atmospheric model. Each of these complex three-dimensional models was run by a different team in a different location. At the end of the project, a community model, to which each team has contributed a component, is accessible to all in a common computer environment.

Several improvements were made to the atmosphere–ocean general circulation model and to the Greenland ice-sheet model to stay in line with the latest advances of the climate-modelling science. Radiation, clouds, oceanic vertical mixing, and oceanic density-driven downslope flows have received a particular attention in the atmosphere–ocean general circulation model, with the aim of reducing the drift observed with similar models. The Greenland ice-sheet model has been improved in the areas of mass balance, iceberg calving, and bedrock isostasy. Once the validation of the updated models completed, the two models were coupled together.

A climate-change experiment covering the period 1970–2100 was then conducted with the coupled global model. In this experiment the model was driven by the Intergovernmental Panel on Climate Change's (IPCC) scenario SRES B2 for both greenhouse-gas concentrations and sulphate-aerosol loading. This scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, intermediate levels of economic development, and moderate technological changes. It is noteworthy that no flux correction was utilised in the model. By the end of the 21st century, the model simulates a global surface warming of 2.3°C and an increase in precipitation of 3%, which fall within the range of estimates obtained with other climate models. The global mean rate of temperature change is predicted to be 0.15°C per decade, i.e., 1.5 times the rate of change that many of the more sensitive ecosystems are thought to be capable of surviving. The upper panel of Figure 1 shows the regional patterns of the projected warming for the end of the 21st century. Note that nearly everywhere warms. Western Europe experiences an annual mean warming ranging between 2 and 6°C. According to our simulation, there is expected to be in 2100 increased precipitation in mid- and high-latitude regions, especially in winter, and in parts of the Intertropical Convergence Zone (see lower panel of Figure 1). Decreases in precipitation are likely in many parts of the subtropics. The projected rise in sea level due to thermal expansion reaches 22 cm at the end of the experiment. Regarding the Greenland ice sheet, its area shrinks by about 1% and its volume decreases by an amount equivalent to 4 cm in global sea-level rise. The enhanced freshwater flux from the ice sheet (more than 50% by the end of the 21st century) does not seem to affect the simulated climate, as revealed by an additional climate-change experiment with no interactive ice-sheet component. However, this result must be taken with caution since the strength of the North Atlantic thermohaline circulation decreases with time in the control run performed with the model.

In addition to this work, a more advanced atmosphere–ocean general circulation model has been developed within CLIMOD, and its validation has begun.

With present-day computing resources, it is still not possible to carry out global prediction experiments to the high resolution required for regional impact studies. A regional model, nested within the global model, has therefore been set up over Western Europe. This has a resolution of 50 km $\times$ 50 km, which is to be compared with the 560 km $\times$ 360 km resolution of the global model at mid-latitudes.

A series of modifications were made to the original regional model to make it suitable for climate studies. Missing physical processes such as deep convection and a snow albedo dependent on snow-metamorphism processes have been added. The refined model was then thoroughly validated by nesting it in the European Centre for Medium Range Weather Forecasts' re-analyses. We found that the model produces satisfying results over Western Europe. In particular, the simulated mean sea-level pressures, temperatures, and humidities are in general agreement with the re-analysis data. The observed day-to-day variability is also quite well reproduced. It should be noted that we also evaluated the capability of a finer-resolution version of the model (10 km $\times$ 10 km) limited to Belgium to simulate wind gusts and other extreme events. The model was then nested in the outputs of the control run conducted with the atmosphere–ocean general circulation model for a limited time period. Furthermore, a test of the nesting procedure was done under climate-change conditions. While more simulations are needed before any climate-change assessment can be done over

Western Europe, the regional model shows an encouraging ability to refine the results of the global model. In parallel to this work, a version of the regional model was applied over Greenland with the aim of further improving the mass-balance model employed by the Greenland ice-sheet model. The refinement proposed did not improve significantly the mass-balance results. So, it was decided to use the original formulation in all the experiments performed with the ice-sheet model. This study also revealed that the regional model is capable of reproducing the main features of the observed Greenland climate.

A new climatological database for Belgium made up of time series of daily extreme temperatures (maximum and minimum) and daily amount of precipitation has also been built within CLIMOD. Such a database allows a better characterisation of the present Belgian climate at the regional scale. In the same time, it constitutes an invaluable tool to assess the performance of regional climate models over Belgium. Moreover, the reconstruction of 100-year-long climatic time series gives the opportunity for studying the evolution of the Belgian climate over the 20th century.

All these aims require time series of high-quality data. The data initially available at the Royal Meteorological Institute of Belgium have all been examined in depth using successive steps to improve the global quality of the climatic database. First, we searched in the original monthly reports from observers the missing data and the precise locations of the stations. A better knowledge of the station locations also contributes to improve the results of spatial interpolation methods. These methods are needed to estimate missing data, when appropriate. Comparisons between actual data and their estimation by interpolation were made to detect and correct obvious outliers. Finally, non-climatic heterogeneities in the time series were detected and corrected using adequate statistical methods. Instrument or station relocation, change of instrument or observational schedule, instrumental drift, systematic observer bias, local environmental effects, … can indeed lead to artificial discontinuities when considering the temporal evolution of a climatological element. As a result, numerous corrected, completed, and homogenised climatic series have been produced. For the last 50 years, 125 daily series for precipitation and 45 daily series for extreme temperatures are included in the new database. Furthermore, for the last 100 years, 16 daily series for precipitation and 9 daily series for extreme temperatures have been reconstructed from original monthly reports and subjected to a quality control.

As regards the 1961–1990 period, the monthly and annual normals for extreme and mean temperatures and for precipitation have been computed, enabling a regional characterisation of the present mean Belgian climate. For the last 50 years, 8 regions were delimited to characterise homogeneous regional climates. The main trends for precipitation and extreme temperatures were studied inside each of these regions. Globally, the extreme temperatures exhibit a warming trend (between 2 and 2.5°C per century), mainly operating in summer. A particularly warm period started abruptly after 1988 (average warming of about 1°C). The most significant regional warming trends are observed in the coastal region for the maximum temperature and in the centre of the country and in regions of highest altitude (Haute Ardenne) for the minimum temperature. As far as the annual precipitation is concerned, no significant trend is detected. A notable negative trend is found however in summer for the regions Polders, Vlaanderen, and Brabant. Overall for Belgium, the mean daily intensity of precipitation shows a positive trend over the last 50 years.

The evolution of the Belgian climate over the 20th century has been further investigated using a few 100-year-long daily series of extreme temperatures and precipitation. The minimum temperature exhibits a relatively coherent warming trend over the country (0.9°C per century), with an abrupt increase around 1988. The results for the maximum temperature are less clear. Concerning this temperature, the very reliable measurements made at the station Uccle-Ukkel reveal a significant warming trend over the century, in contrast to the other 9 stations, which present a cooling trend. It is worth mentioning that the measurement of maximum temperature is very sensitive to the screen employed to protect thermometers from radiation. Several changes of screen have been made in the climatological network (but not at Uccle-Ukkel) between 1900 and 1930, but their quantitative impacts on the temperature trend have not yet been estimated. Regarding precipitation, a positive trend is found over the whole country. This trend is largely attributable to an increase that occurred during the 1900–1935 time period. The largest trend is encountered in the region Haute Ardenne (+240 mm per century) and the smallest one in the region Gaume (+100 mm per century). A change of pluviometer in the climatological network around 1910 may, at least partially, explains the observed trend in precipitation.

The results discussed above have been widely disseminated through presentations in international scientific meetings, publications in peer-reviewed scientific journals, and a number of vulgarisation activities. The research network CLIMOD consisted of scientists deeply involved in the IPCC's activities and in international research programmes on climate change such as Climate Variability and Predictability (CLIVAR) and Arctic Climate System Study / Climate and Cryosphere (ACSYS/CliC), which are two subprogrammes of the World Climate Research Programme. In particular, two members were lead authors of two different chapters of the IPCC's Third Assessment Report, and a third one was contributing author of another chapter. This has enabled the dissemination of the CLIMOD results both to scientists involved in studying climate change and to the communities involved in impact studies. Note, however, that the climate-change projections conducted within CLIMOD are not included in the IPCC's Third Assessment Report because they have been completed too late. It must also be mentioned that one of us contributed actively to the work of the Belgian Federal Council for Sustainable Development.

The work made within the framework of CLIMOD is a contribution to the ongoing international scientific effort to better understand how human activities impact the climate system at the global and regional scales. This is needed in order to provide a sound basis for policies designed to address the challenge of climate changes. The problem will not go away quickly, and is most likely to become more and more important. Each Party to the United Nations Framework Convention on Climate Change (UNFCCC) has committed itself to "promote and cooperate in scientific (...) research (...) related to the climate system and intended to further understand and reduce the remaining uncertainties (...)." (UNFCCC, Article 4.1(g)).

The sustained funding of this kind of research is required both at the international and national levels, so that the appropriate scientific capacity is available in as many countries as possible. Two areas that require particular attention are (1) the improvement of the representation of physical processes in global climate models and (2) the downscaling of results from global climate models to the European and Belgian scales through nested regional models and increased spatial resolution at these scales. This will allow addressing the specificity of the European and Belgian climates, while improving the overall quality of climate simulations at the global scale and reducing the remaining uncertainties. So that the Belgian research effort becomes better integrated in the European and international research programmes, the appropriate support should be given to facilitate participation to the existing and planned model-intercomparison programmes. These allow the different modelling laboratories to confront their methods and results to each other, so that the origin of differences can be better understood. This will lead to better models, enhance capacity building, and help integrate the Belgian research efforts. For the same reasons, participation of Belgian modellers to interdisciplinary research dealing with the impacts and mitigation of climate change is of high value, and collaboration to the work of the IPCC should be encouraged.

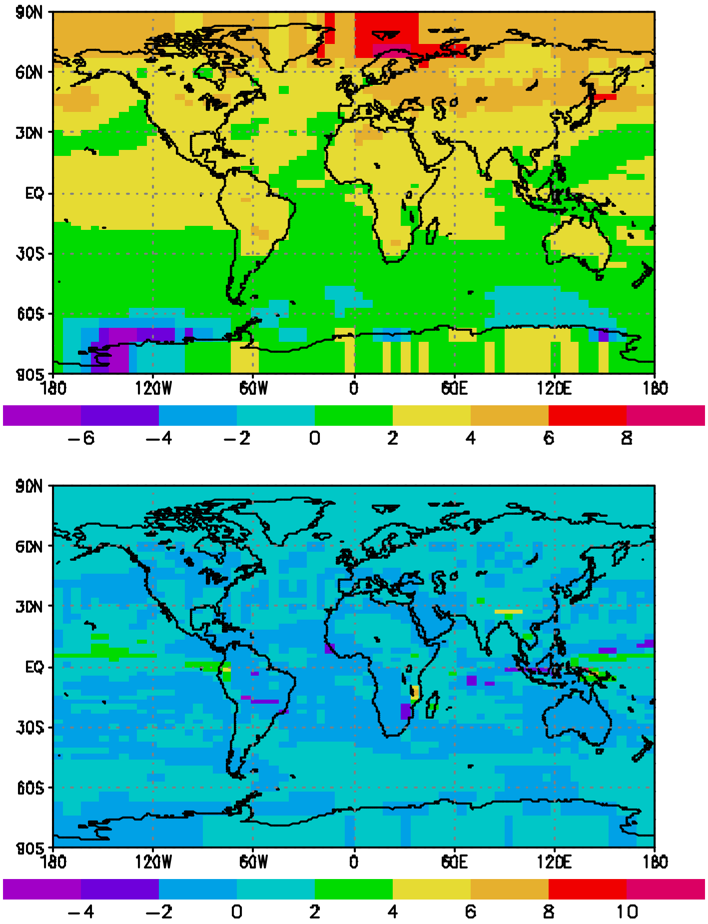

Figure 1: *Changes in annual mean surface air temperature (in °C; upper panel) and precipitation (in mm per day; lower panel) between 1970 and 2100 as simulated by the global climate model developed within CLIMOD.*

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RECENT ENSO AND PALEO ENSO OF THE LAST 1000 YEARS IN LAKE

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Lake Tanganyika is one of the oldest lakes in the world. Its present limnological cycle shows that it is very sensible to climate variability (Coulter, 1991; Plisnier *et al.*, 1999). The winds and the air temperature fluctuations influence the mixing of the lake, allowing access of nutrient-rich deeper water toward the surface where biotic production takes place. When organisms die, they accumulate into layers at the bottom of the lake, where some of them may be identified and related to the lake conditions prevailing at the time of their deposit.

Global signals of oceanic/atmospheric origin affect the local climate in East Africa and probably the hydrodynamic and the biotic environment of Lake Tanganyika. Its sediments could thus archive paleoclimatic variability partially related to world climatic variability such as ENSO (El Niño/Southern Oscillation). ENSO is a major climatic/oceanographic event characterised by the apparition every 2-10 years of a warm current in the Pacific Ocean and numerous climatic anomalies around the Pacific Ocean and in many others areas of the world. The influence of El Niño stretches across the Indian Ocean to southern Africa where it brings droughts and to equatorial Africa where it brings flooding (WMO-UNDP, 1993; IPCC, 1990).

The objective of the project was to check the possible influence of climate variability on Lake Tanganyika at two scales of time: the recent period (+/- last 50 years) and the last 1000 years. For the recent period, the project studied the teleconnections (correlation with remote climatic or proxy data) between ENSO and various data (oceanic, climatic, remote sensing, hydrological, fisheries catches...) in the Lake Tanganyika area. For the last 1000 years, paleo-signals were studied in the sediments of the lake. The finely laminated sediments were studied particularly using diatom composition and thin sections analysis to detect variability of organisms as possibly related to limnological and climatic variability.

For the study of the recent period, available climate data in the Lake Tanganyika area (Tanzania, Burundi, Zambia and R.D.Congo), were processed using various statistical methods for the 1981-94 period at different time lags. The results of teleconnections with climate data were compared with remote sensing data from NOAA/AVHRR (National Oceanic and Atmospheric Administration / Advanced Very-High Resolution Radiometer) using the same procedures.

Significant ENSO teleconnections were found with average air temperature, maximum and minimum air temperature, humidity, rainfall, winds, pressure and radiation. The strongest teleconnections were found between monthly air temperature anomalies with the sea surface temperature anomalies in the west equatorial Pacific Ocean. A time lag of 4-6 months generally gave the strongest correlation (e.g. in the range of R=0.6). ENSO events were characterised by average air temperature increase (+0.26°C) while extreme air temperature could reach +/- 0.8°C as observed during a strong El Niño event for the recent period. During ENSO events, winds decreased but air pressure and radiation increased. The stability of the water column was reconstructed for the last 40 years using water temperature profiles and air temperature data. The results suggested a +/- 20% variability range of stability for the upper 100m of the lake. Catches per unit of effort of the main pelagic fishes were partially correlated with ENSO for the last 30 years in two stations of Lake Tanganyika. Hypotheses of changes in hydrodynamic and upwelling intensity have been presented to explain this. More winds and lower temperature seem favourable for clupeids fishes (and possibly phytoplankton and zooplankton) while *Lates stappersi* catches are lower maybe because of lower transparency unfavourable to this visual predator.

One of the major findings of this project is that several climate and land surface attributes show a partial correlation with the fluctuation of the Pacific sea surface temperature (SST) index. These different variables are not all teleconnected to ENSO in the same way, which leads to a complex impact of ENSO on the ecosystem. The SST anomalies in the Pacific Ocean induce changes in climate variables. These ENSO-driven changes in climate induce changes in vegetation activity, as measured by changes in several remote-sensing measured variables (a vegetation index, the surface temperature etc…). The exact response of the vegetation to the ENSO-induced climate variations depends on the land cover type.

The project showed that the ENSO impact is highly differentiated in space in the investigated East African area. Many previous studies have postulated a single, region-wide impact of ENSO. It appears that the direction, magnitude and timing of this impact is controlled by the climate system at a regional scale and at a more local scale – e.g. as influenced by the presence of large lakes, local topography or proximity to the coast. Surface attributes, as determined by geology, soil and vegetation might also influence the magnitude and the time lag of the ENSO impact. Hence different zones are recognised in the East African area studied, each subject to different combinations of ENSO induced climate variations.

ENSO is however not the only source of inter-annual variability in climate conditions in the region. The changes of the variables studied, not taken into account by ENSO, could be related to the variability of neighbouring oceans as well (Saji *et al.*, 1999). Beside ENSO, a warming was observed in the recent decades in the air temperature at Lake Tanganyika (>0.7-0.9°C). This was apparently linked to a water temperature increase and a higher stability of the lake. Decreased winds and changes in fish catches were observed during the same period for the clupeids fishes and *Lates* *stappersi*. Those observations suggest that the lake is sensitive to other climate variability such as the recent global temperature increase besides ENSO.

In order to study the sediments of Lake Tanganyika, an expedition was organised in collaboration with the EAWAG-team from Switzerland (Dr. M. Sturm). During this expedition, 16 cores were retrieved in the southern basin of the lake, between 330 and 1200m water depth. All cores were taken in deep water where permanent anoxic conditions exist and where bioturbation is minimal.

Thin section analysis was performed on parts of the sediments of the two cores taken on the Kalemie Ridge in 424 and 428m water depth and of one core taken in the southern basin in 1200m water depth. Both laminated as well as homogeneous layers are present in all cores. The laminated layers result from the settling of alternating organic sedimentation and terrigenous sediments. Homogeneous parts in the sediment cores probably correspond to periods with a steady settling of a continuous rain of debris.

The results of the thin section analyses support the hypothesis that the laminated sediment, present in the sediments of Lake Tanganyika, reflects a varying biogenic production. More intense winds prevailing apparently in La Niña years could possibly have favoured this increased production. Because the laminations were not continuous in the entire core and are difficult to count reliably, we do not expect them to provide a comprehensive annual reconstruction of the ENSO-signal. However, it seems possible to produce a reconstruction of the primary productivity related to the strongest ENSO events. An accurate chronology for the sedimentary records is necessary to test this hypothesis.

Sediment material for dating was taken from a core recovered near Kasaba in 500m water depth and from a core taken near Kipili in 1200m water depth. The results for the Kasaba core are the only one available at the moment. ^{14}C AMS dating indicates that the sediments between 10.5 and 11.5cm are from the historical period (830 (±40) BP), corresponding to a sedimentation rate of about 0.134mm/y during recent periods. The sediments between 48 and 52cm depth are much older (8060 (±60) BP), which would correspond with a very low sedimentation rate of 0.06mm/y. It is known that sedimentation rates in Lake Tanganyika have not been constant and vary considerably in the sedimentary record (Coulter, 1991). Mean reported sedimentation rates in Lake Tanganyika vary between 0.4 and 0.6mm/y (Haberyan and Hecky, 1987; Tiercelin *et al.,* 1988; Coulter, 1991). Extremely low sedimentation rates (±0.05-0.25mm/y) were only reported from the Kalemie Ridge, a bathymetric high that separates the northern and southern basin (Cohen and Palacios-Fest, 1999). The extremely low sedimentation rate, calculated for deeper parts of core taken near

Kasaba and the absence of a layer rich in *Aulacoseira* (*Melosira*) species, a layer reported earlier for sediment cores from the southern basin of Lake Tanganyika (Tiercelin *et al*., 1988), may suggest that part of the sediment is missing, possibly because of sediment-sliding events.

High-resolution diatom analyses were performed on the upper parts of both of the above-mentioned cores. The upper 11cm of the Kasaba core consist of dark finely laminated sediments; the laminations in the upper 18cm of the Kipili core are mostly diffuse. These upper layers were analysed at a vertical resolution of 100µm and 500µm, respectively. Deeper parts of the Kasaba core were also studied at a lower resolution.

Although 230 diatom taxa were observed in the two cores studied, only a few taxa were relatively abundant. In the upper finely laminated sediments "long" *Nitzschia's* and *Gomphonema clevei* were relatively the most important diatoms, followed by *Nitzschia lancettula*, *N. vanoyei*, *N. frustulum, N. fonticola* and *Gomphonitzschia spp*. The high species diversity was due to the numerous benthic taxa; although individual abundancies were generally low, these benthic taxa dominated the fossil assemblage in certain layers.

The diatom record revealed a cyclicity, with a provisionally estimated period of about 200 years, in the Kasaba core. This might be related to a 200 years cycle in the sun activity but this needs to be confirmed by data from longer or more time series. Among the diatoms, "long" *Nitzschia* spp. most clearly demonstrate this cyclicity. They are pennate, planktonic species which can replace *Cyclostephanos spp*. (centricate planktonic diatoms) in the plankton of East African lakes when Si/P ratios decrease (Haberyan and Hecky, 1987).

Benthic diatoms are potentially good indicators of lake level fluctuations, indicating the presence of nearby littoral zones (Barker, 2001). In the Lake Tanganyika cores the significant changes in the proportion of benthic diatoms may likewise indicate lake level changes. In addition, our data suggest that the interpretation of the benthic diatom assemblages might be more complicated. A notable change in the benthic assemblage was the dominance of *Gomphonema clevei* in the lower part of the sediment section studied for the Kasaba core, while in the upper layers other species were abundant. Although this pattern may reflect changes in the littoral environments in Lake Tanganyika, more needs to be known about the ecology of key taxa. Similarly, further investigation of the ecology of planktonic and facultative planktonic key-taxa, e.g. "long" *Nitzschia's*, *Nitzschia lancettula*, *N. vanoyei*, *N. frustulum*, *N. fonticola* and *Gomphonitzschia spp*., is needed to permit a detailed interpretation of the L. Tanganyika sediments.

The present data and work in progress illustrate the unique potential of these cores. It seems feasible to infer records of historical changes in paleo-ENSO intensity, as well as longer-term variation in regional and global climatic conditions.

The recent ENSO signal confirms thus the hypothesis that ENSO may impact significantly the climate in the Lake Tanganyika area and the mixing conditions of the lake in the actual period. It is recommended that a multidisciplinary database using recently collected information in various fields (climate-hydrodynamics-phytoplankton-fisheries) at regular sampling intervals, could provide the required information to interpret the various sediments signals and decrypt the coded information stored in the sediments.

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THE GLOBAL CARBON CYCLE AND THE FUTURE LEVEL OF ATMOSPHERIC CO_2

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1. INTRODUCTION

The atmospheric partial pressure of carbon dioxide (CO_2) has increased from ~280 ppmv in 1800 to ~360 ppmv today and is expected to reach 900 ppmv before the end of the 21st century. The climatic implications of this change in radiative forcing of the planet are still a matter of debate. Rising CO_2 levels are clearly an anthropogenic effect, largely driven by emissions of fossil fuel CO_2.

In this research, we focused on some key aspects important for the understanding of the global carbon cycle and its perturbation by human activities.

- The past and future evolution of the biosphere in conditions of changing climate conditions and CO_2 level;
- The ability of remote sensing techniques to build vegetation cover maps and to derive quantitative information on the carbon content of the biosphere;
- The role played by coastal regions as sources or sink of CO_2 and in the balance of the global carbon budget;
- The role of the open ocean in the exchange of CO_2 with the atmosphere.

2. BIOSPHERIC MODELING

Besides emissions of fossil fuel CO_2, changes in the terrestrial biospheric CO_2 fluxes have played a complex role in changing atmospheric CO_2, with emissions from changing land use, largely in the tropics, re-growth in Northern Hemisphere temperate forests, and some additional terrestrial sinks. While there may be a general consensus towards *global* carbon fluxes from observations and models from terrestrial, atmospheric, or oceanic systems, there are still large uncertainties in the geographic and temporal distribution of those fluxes at local to regional scales. The inter-annual and seasonal variations of carbon fluxes between the terrestrial biosphere and atmosphere are largely driven by the interaction between climate variability and disturbances at local scales. The net effect of observed carbon fluxes are the result of complex interactions between physical and biological phenomena. Satellite remote sensing is a promising tool toward providing information on vegetation phenology and net carbon exchange. However, biospheric models are the only integrative tool that can simulate future carbon fluxes under global environmental change.

In order to study the contribution of the terrestrial biosphere to the atmospheric CO_2 budget, we used CARAIB (CARbon Assimilation In the Biosphere). CARAIB is a model of the carbon cycle in the terrestrial vegetation and soils. It was developed in an earlier phase of the "Global Change" Programme. As a test of the ability of this model to correctly represent the net CO_2 exchange flux, the mean **seasonal cycles of CO_2 concentrations and d^{13}C isotopic anomaly** over the period 1980-1993 were calculated for different monitoring stations. A good agreement was found between the observed and simulated seasonal cycles. Simulations of atmospheric CO_2 transport performed on the basis of monthly fluxes from several terrestrial biospheric models and net monthly fluxes from an ocean carbon model did not reveal substantial influence of the oceanic carbon fluxes on the seasonal atmospheric signal.

CARAIB participated in the **GAIM/IGBP Potsdam'95 model inter-comparison**. The main objective was to analyze the relative importance of the different latitudinal zones in the control of the seasonality of atmospheric CO_2. Most Terrestrial Biospheric Models (TBMs) predict that the seasonal amplitude of the net CO_2 flux varies dramatically with latitude, while the pattern in soil respiration (R_H) is more muted. All of the TBMs agree well on the phasing of the Net Primary Productivity (NPP) and the Soil Respiration in the north temperate zones. Here most TBM produce a maximum NPP in June or July and maximum R_H in July or August. Minimum R_H generally takes place in January. In the tropics, the maximum NPP from all models lags the maximum precipitation, which occurs in August and January in the northern and southern tropical bands respectively. Similarly, the minimum NPP from all the models lags the minimum precipitation, which occurs around six months after the humid season. Comparison with selected monitoring stations indicates that the modeled seasonal amplitudes in the north are generally too low. The phases of CARAIB in the northern hemisphere are generally close to the observations. In the tropics, the effect of the ocean and the fossil fuel burning on the month of the CO_2 minimum varies among the TBMs. The effect of the ocean is generally larger than that of fossil fuel.

LPAP also participated in the **ECLAT-2 workshop** help in Potsdam in October 1999 devoted to "Climate scenarios for agricultural, ecosystem and biological impacts". In order to estimate the influence of crops on the biospheric carbon budget, we analyzed more specifically the differences between simulated steady states of the present vegetation and a vegetation without crops. Impact of CO_2 fertilization was also estimated. A 'no crop world' scenario was built from the present vegetation distribution, by replacing crops with forests. Fertilization of the biosphere by increasing atmospheric CO_2 concentration was estimated by comparing biospheric steady states simulated at two levels of CO_2 concentration. In the assessment of the present results, we focused on the direct impacts of crops and CO_2 fertilization and deliberately neglected any inter-annual climatic change, including greenhouse warming. Below 280 ppmv of CO_2, the estimated global annual NPP sink was reduced by 21% ; a value of 53 Gt C yr^{-1} was calculated whether the considered biosphere was the 'no crop world' or the present vegetation. When the atmospheric CO_2 concentration was doubled from 330 ppmv to 660 ppmv, the simulated NPP increased by 67 %, an amount exceeding the 20 to 40% range measured in small-scale experiments. This increase might be reduced due to insufficient water or nutrients (IPCC, 1995). The biospheric carbon increase induced by CO_2 fertilization was found to prevail on the loss of carbon due to the substitution of crops for forests. The net result of these transitions was an increase of 712 Gt in the global amount of biospheric carbon.

The total increase of the atmospheric CO_2 level due to the use of fossil fuels shows **year-to-year variations**. This so-called “anomaly” in CO_2 increase is, on the average, about 2 Gt C/year. The combination of measurements of the CO_2 concentration and $^{13}C/^{12}C$ isotopic ratio makes it possible to show that a significant part of this anomaly is due to some temporal variation of the net CO_2 exchange flux between the atmosphere and the biosphere. The relative importance of Gross Primary Productivity (GPP), Plant Respiration (R_A) and R_H during the period 1980-1993 was assessed with CARAIB. The contribution of the main ecosystem types to the total anomaly was also evaluated. The comparison with the values computed on the basis of CO_2 concentration measurements shows a good agreement for the amplitude of the CO_2 biospheric fluxes as well as their time evolution. It also indicates that temperature is the most significant forcing controlling the anomalies of the CO_2 flux from the biosphere. The model predicts the largest value of the flux anomaly to the atmosphere for El Niño years 1983 and 1987 corresponding to positive annual temperature anomalies. Conversely, the calculated assimilation by the biosphere is maximum in 1989, 1992 and 1993. 1992 and 1993 were are characterized by negative temperature anomalies, probably related to the global cooling due to the aerosols released by the Pinatubo eruption (June 1991). An analysis of the contribution of the exchange flux of CO_2 by zones of latitude and ecosystems indicates that the tropical zones are the major contributors to the CO_2 anomaly. Moreover, tropical rain forests and savannas play a dominant role both in the positive and negative contributions to the global CO_2 flux anomalies. In savannas the inter-annual changes are mainly exerted by the control of the amount of available soil water on the gross primary productivity. In rain forests, the variations of the CO_2 exchange fluxes are due to changes in the GPP as well as in the respiration rate.

Ice-core measurements document significant fluctuations of the atmospheric CO_2 level during **glacial-interglacial climate transitions.** Large amounts of carbon were redistributed between the atmosphere, the ocean and the continental biosphere during these transitions. CARAIB was also used to study carbon flows, stocks and isotope balances at the last glacial maximum (LGM, –21,000 years) and mid-Holocene (–6,000 years), using sets of climatic inputs from two different climate models. The calculated changes relative to present range from –132 to +92 GtC for the mid-Holocene and from –710 to +70 GtC for the LGM, depending on the climatic set used and whether the "CO_2 fertilization" effect was included or not. At the LGM desertic and semi-desertic areas were more extended, at the expense of forests and grasslands. It appears that the CO_2 fertilization effect is responsible for most of the increase in NPP, vegetation and soil carbon stocks which occurred from the LGM to the present, since the increase associated with the climate warming was largely offset by a decrease linked to the sea level rise and the corresponding reduction in land area.

3. OCEAN MODELING

The ocean sets up the CO_2 atmospheric pressure by two different processes: the solubility and the biological pumps. The large-scale or overturning circulation (wind-driven and thermohaline) leads to a dynamic equilibrium between three reservoirs: the atmosphere, which can be considered as well-mixed with respect to the oceanic sphere; warm surface waters cooling down on their journey to the poles, hence taking up CO_2 ; and deep waters, not in contact with the atmosphere for centuries, which finally surface releasing their excess CO_2 . The exchange rates between the three pools determines the strength of the solubility pump. Under pre-industrial conditions this results in pulling the atmospheric p_{CO2} from 700 ppm (the value that would be achieved in a still ocean scenario) down to 450 ppm. However the pre-industrial atmospheric p_{CO2} was about 280 ppm and not 450 ppm. This extra decrease is due to biological activity. Photosynthetic assimilation of carbon in the upper sunlit layers of the ocean and the export of dead material to great depths result in lowering the CO_2 partial pressure at the ocean surface. Generally accepted values of this “biological pump” or “export production” range from 8 to 12 GtC yr^{-1} across 150m depth.

Hence any perturbation in the overturning or productivity rates, will bear consequences on atmospheric CO_2 levels. Past studies are used to understand the degree at which such phenomena may be invoked to explain observed excursions in the record of atmospheric CO_2. Studying these events is also important for prediction of the future climate in case of a breakdown of the overturning circulation, a probable scenario for the not-so-far future.

The net air-sea CO_2 fluxes cannot be directly measured due to their low value with respect to gross exchange rates. Modeling the oceanic carbon cycle is one way of overcoming this difficulty. Other indirect methods based on isotopic techniques or atmospheric gas ratio measurements provide further understanding.

The 3D Ocean Carbon Cycle Model, LOCH, was developed in a former phase of the “Global change” program and is among those participating to the Ocean Carbon Intercomparison Project (OCMIP, an international GAIM initiative). Present-day distributions of various oceanic tracers are reproduced satisfactorily. Forcing the model with atmospheric CO_2 values over the industrial period leads to a oceanic CO_2 uptake for 1990 ranging from 2.1 to 2.4 GtC yr^{-1}, depending on the circulation field driving the transport. These results are in accordance with other model studies. After the steps of calibration and verification our scientific work was aimed at examining the sensitivity of the carbon cycle to circulation changes either driven by external conditions (the LGM) or by changing the tool (numerical scheme). Sensitivity studies also addressed the bomb radiocarbon methods.

Once the equations pertinent to the problem have been defined, building up a model consists in the temporal and spatial discretization of these equations. This critical step fully defines the numerical model, i.e. different models addressing the same set of mathematical equations with different discretization procedures behave differently. Among other results our studies showed how the numerical scheme influences the deep water oxygen content, which in turn affects the biological carbon pathway.

At LGM the overturning circulation was slower resulting in different pathway for the water masses when compared to the present-day state. Consequences on the carbon cycle were an enhanced North Atlantic CO_2 sink, together with lower and higher sources in the equatorial Pacific and Atlantic respectively. These changes are caused by modifications both in the exchange rates with the atmosphere (the solubility pump) and in the nutrient distribution among the main ocean basins affecting the biological pump. Most of our results meet conclusions from proxy studies.

One often uses bomb radiocarbon for estimating the uptake of anthropogenic CO_2 by the ocean. Though both have different input function in the atmosphere and different equilibration time with the ocean, useful conclusions may be reached. However various studies resulted in very different number for the oceanic uptake of the bomb radiocarbon. A careful study of the methods used in modeling this flux allowed the conclusion that **most studies overlooked the critical importance of spatial patterns in air-sea carbon fluxes.** Assumptions of local air-sea equilibrium and of a negligible role of the biosphere lead to under- and over-estimated values of the oceanic bomb radiocarbon uptake. Figures obtained in a comprehensive modeling allow to **reconcile both the current number of ocean CO_2 uptake and the atmospheric bomb radiocarbon balance.**

4. REMOTE SENSING

Within the integrated project, VITO (the Flemish Institute for Technological Research) accomplished the tasks related to "Remote Sensing", i.e. the analysis and interpretation of images registered by digital cameras (sensors) on board of earth observation satellites. This satellite information was practically used to derive land cover maps (a crucial input for the CARAIB-model) and to check the quality of the model predictions.

As to the type of sensor, we mainly used data of the American meteorological system NOAA-AVHRR, which already became active in the late seventies. While the NOAA-satellite moves along a near-polar orbit, the AVHRR-sensor systematically scans the earth surface and stores the optical measurements in an endless image strip with a width of about 2500 km and a spatial resolution (pixel size) of 1x1 km. The system is synchronized in such a way that the entire earth surface is registered once a day – although each ground station only receives the local data registered in the surroundings of the antenna. Much time was devoted to the development of a software chain for the pre-processing of raw AVHRR-images. This chain upgrades the individual registrations into calibrated, atmospherically corrected, geometrically registered and quality-checked image products, ready for use in any application. This effort could later be valorized in many other projects in Europe and abroad (mostly China). For instance, thanks to this experience VITO still performs the pre-processing of the European AVHRR-data registered in Berlin, for the MARS-programme of the European Union (Monitoring Agriculture by Remote Sensing).

However, for this project we needed images with global coverage. In the case of AVHRR this requirement can only be achieved if several ground stations spread over the world collaborate and "composite" their results into periodic (mostly 10-daily) and global image mosaics. In 1997, when our project started up, there only existed two such image sets, both derived from AVHRR and produced by the United States Geological Survey (USGS): the Global Land 1km AVHRR Data Set still has the original pixel size of 1x1km but it is restricted to the year 1992, the PathFinder Data

Set covers a much longer period (1981-2000) but has a deteriorated resolution (8x8km). However, in March 1998 the SPOT4-satellite was launched, a French initiative with a significant Belgian contribution. Amongst other sensors, SPOT4 carried (and carries) the VEGETATION-instrument which strongly resembles AVHRR but with the crucial advantage that all data are stored on-board and are systematically transmitted to one single antenna close to the North Pole (Kiruna, Sweden). From there, the images are transmitted to VITO where they are pre-processed with standardized procedures, immediately composited into global mosaics (one per day and/or per decade) and distributed among the scientific user community.

The project research related to remote sensing was mostly carried out with these three global image sets (Global Land, PathFinder, VEGETATION) and it covered three quite different subjects. In the first place, several data enhancement procedures were developed for the elimination of the noise due to cloudy measurements and for the computation of new images with more precise information on the general state of the vegetation (vegetation indices, start and length of the green season, etc.). A special problem concerns the high data volumes. To give an idea: one yearly cycle of 10-daily VEGETATION-composites occupies about 360 Gb of disk space. Special data reduction procedures were developed which compress the imagery (down to 8% of the original size) and eliminate the redundant information, thereby allowing to process the global sets at full resolution.

The second topic concerns the extraction of maps with the distribution of the general ecosystems (so-called biomes), which are needed by the CARAIB-model. By means of digital classification algorithms, several such maps could be established. From the PathFinder-set we derived three global maps at 8 km-resolution, depicting the situation in the years 1987, 1992 and 1997. Later on the VEGETATION-data could be used as well for the preparation of actual land cover classifications (1998-1999) at 1km-resolution, first of Central-Africa but recently also of the entire world.

The third and last subjects concerned the evaluation of the CARAIB-model. As a test criterion we selected fAPAR, the fraction of PAR-radiation absorbed by the vegetation (PAR: the solar energy in the wavelength band between 400 and 700 nanometer which can be absorbed by plant pigments and used for the photosynthesis), because it is computed by CARAIB and it can also be estimated fairly well from the satellite images. The comparison of both fAPAR-estimates thus gives an idea of the quality of the model. This exercise was performed for the situation in 1992 and by means of the Global Land 1km AVHRR Data Set. The general conclusion was that CARAIB systematically over-estimates fAPAR, but on the other hand it correctly grasps the phenologic behaviour of the vegetations (start / culmination / end of the growing system).

5. COASTAL OCEANIC REGIONS

According to the IPCC 1995 report, the anthropogenic flux of CO_2 to the atmosphere represented 7.1 ± 1.1 $GtC.yr^{-1}$ in the early nineties of which 2.0 ± 0.8 GtC were annually transferred to the ocean. This transfer is partly related to the marine primary production driven by sunlight and by the supply of nutrients into the surface layer of the ocean. The total primary production in this upper illuminated layer (the "photic zone") can be partitioned into two fractions: (1) the **recycled production** supported by the degradation of organic matter and the associated release of nutrients, and (2) the **new production** supported by nutrients entering the photic zone, primarily from the deep ocean, but also from the atmosphere and from land in the coastal zone. The **biological carbon pump** is the process by which a fraction of the carbon is exported from the ocean surface layer as organic matter by settling to the deeper water, thus reducing the total carbon dioxide in the surface layer. Most of the settling carbon is remineralized at depth (except a small fraction which is deposited and buried in the sediments), but considering the properties of the general circulation of the ocean, one may assume that carbon transferred below 500 m depth will not be restored to the surface ocean before several hundred years and can thus be considered as scavenged at this time scale.

Besides **light**, which is the main factor controlling photosynthesis, primary production in oceanic systems is most often limited by the **availability of nutrients**. By contrast to the open ocean, marine productivity is much larger on the continental shelf, driven by a complex pattern of nutrient fluxes including river discharge, atmospheric deposition, diagenetic processes in the sediments and transfer of deep ocean water across the shelf break by upwelling or vertical mixing. The high nutrient fluxes at the boundaries of the coastal zone lead to a much large fraction of new production. Shelf seas thus contributes significantly to the biological pump process. However, as stated in the 1995 IPCC report, "*the contribution of continental margins to global estimates of total export oceanic production may not have been properly estimated*".

The first step of our research was therefore to collect the most recently published data, to get a better evaluation of the relative importance of the continental margins in the global ocean carbon cycle. We mainly focused on nitrogen fluxes, which are thought to be the limiting nutrient in most parts of the ocean. Ammonia may be used as a tracer to evaluate the recycled production. In contrast, nitrate provided by deep waters to the photic zone sustains the new production. Unfortunately, the nitrogen cycle is quite complex and a number of processes other than primary production are enhanced in the coastal waters (N_2 fixation, nitrification, denitrification).

The nitrogen fluxes required to sustain total primary production were estimated to reach 41 $gNm^{-2}yr^{-1}$, of which more than 40% is related to new production (18 $gNm^{-2}yr^{-1}$). A large part of the nitrogen involved in primary production is either exported as organic particulate N to the open ocean (15 $gNm^{-2}yr^{-1}$) or deposited in the coastal sediments (12.9 $gNm^{-2}yr^{-1}$). However, about 80% of the depositional flux of N is recycled to the water column under the action of diagenetic processes (10.6 $gNm^{-2}yr^{-1}$). **Pelagic-benthic coupling** is thus important for the shelf N cycle. The remaining 20% are almost completely lost as N_2 by denitrification. Only a minute fraction of N is stored in the sediments by burial (0.38 $gNm^{-2}yr^{-1}$). The present- day values for river input (2.3 $gNm^{-2}yr^{-1}$) and atmospheric deposition (0.38 $gNm^{-2}yr^{-1}$) show that the continental inputs, although enhanced by anthropogenic activities, are secondary N sources for the shelf and are therefore totally insufficient to maintain the nitrogen requirements of the planktonic activity. Our estimation of the import flux of nitrogen at the shelf break (14.6 $gNm^{-2}yr^{-1}$) confirms that, **at the global scale, the new production of the coastal zone is mainly supported by the transfer of nutrients from the open ocean**.

The second step in our research was to develop a coupled 1-D hydrodynamical-ecological model describing the carbon and nitrogen fluxes at the ocean margin. The two central objectives of this development were (1) to assess the respective contribution of new and recycled primary production and (2) to provide a model which could be applied to similar situations at a global scale and allow a better evaluation of the biological carbon pump at the boundaries of the open ocean. The model development was focused on *La Chapelle Bank* an area of the bay of Biscay situated at the shelf break of the Celtic sea. This area is influenced by strong internal waves which contribute to the vertical mixing in the area of the shelf break.

Because new production is basically driven by the supply of fresh nutrients from the deep water layers, the description and quantification of vertical exchanges in the water column is a first necessary step in order to account for nitrate inputs into the photic zone. A numerical 1-D (vertical) model has therefore been developed in order to provide a full description of turbulence-induced exchanges along the vertical, leaning on the concepts of local turbulent kinetic energy and momentum diffusivity. The vertical turbulent mixing is controlled, at the seasonal scale, by the balance between heating (which leads to stratification) and wind mixing (which tends to homogenize the water column) at the atmosphere-ocean interface. These meteorological factors are introduced into the model via forcing conditions.

As shown by a comparison with data from the ICES database, our model correctly reproduces the vertical temperature distribution in the first 300m of the water column, both in time and space. The eddy diffusivity, which is the central “coupling” variable between the physical and the ecological models, is large enough to mix the first 200 m of the water column during the winter months. Stratification appears in spring (April-May) and remains during all summer and part of fall. The net heat budget is balanced to within less than 6% of the incoming solar energy flux.

An analysis of model results shows that the start of the spring bloom is a very critical phenomenon which is strongly dependent on the photosynthetic parameters of the phytoplankton. The evolution with time of the phytoplankton biomass is mainly controlled by the rate of grazing by zooplankton but also by its mortality rate and vertical mixing. All these processes influence the concentration of dissolved nitrogen and thus the ratio of recycled to new production. The model is extremely sensitive to small fluctuations of the parameters: for example, a small variation of the maximum phytoplankton growth rate has a drastic influence both on the beginning of the bloom and on the accumulation of the phytoplankton biomass in the system over the rest of the year. The validity of the model has been tested by comparing the vertical distribution of the various variables with observed values. The agreement is reasonable good, the only main discrepancy corresponds to the beginning of the phytoplankton bloom.

The total computed primary production amounts to 148 gCm^2yr^{-1}, which is a typical value for the area above the slope. The new production supported by nitrate imported from the deep ocean is equal to 89 gCm^2yr^{-1}, and the recycled production supported by ammonium resulting from the respiration of zooplankton and bacteria amounts to 74 gCm^2yr^{-1}. The ratio of new to total primary production (the so-called “f-ratio”) thus ranged between 50 and 60%, in agreement with the values obtained by field investigations in the bay of Biscay. According to the model, roughly 40% of the phytoplankton production is used by the zooplankton and included in a higher trophic food level, also in accordance with previous estimations for areas with a high nutrient input. Interestingly, 20% of the phytoplankton is lost by vertical mixing of surface water with deep water. This export is relatively high and probably explains why the primary production is not even larger than the one observed. Some slowly sinking particles of dead phytoplankton are also transferred to the deep water by the same process. Finally, about 50% of the vertical flux of particles is due to the sinking of large particles (fecal pellets and dead zooplankton).

CG/DD/12

NATURAL HOLOCENE CLIMATE VARIABILITY AND RECENT ANTHROPIC IMPACT IN BELGIUM

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ABSTRACT

The main objective of the project is the reconstruction of the natural climate variability during the Holocene from the study of travertine sequences located in Belgium.

Pollen, ostracod paleoecology and geochemistry are the main proxy data used for paleoenvironmental reconstitution. Statistical analyses have been performed using the ostracod assemblages of the travertine sequence located at Annevoie-Rouillon, near Namur. These results show past changes in the hydrodynamic of the system. The Mg contents in three fossil ostracod species were determined. In this state of the research, we hypothesise that the observed variation in the ostracod Mg/Ca ratios mainly reflect precipitation changes. On the other hand, the end of the travertine edification should be related to a drastic increase of the precipitation, both with an increase of an erosion activity. Such reconstruction is now in progress for an other travertine sequence, located at Treignes.

The project involves the development of the ostracod geochemistry method. Several laboratory experiments and field collections provided a better understanding of the variability of partition coefficients.

1. INTRODUCTION

The main objective of the project is the reconstruction of the natural climate variability during the Holocene, and the detection of a possible human impact on the environment.

To achieve this goal, two travertine sequences located in south of Belgium were sampled. The study of the Annevoie-Rouillon sequence, located between Namur and Dinant along the Meuse, is finished. The work is in progress for the travertine located at Treignes (Viroin valley).

In Belgium, travertine deposits are important archives for reconstructing past hydrology and environmental changes during the Holocene. Travertine are built by calcium carbonate precipitation mainly due to C02 degassing. The decrease of CCh content in water is linked to physico-chemical (temperature and pressure) and biological (photosynthetic activity) processes.

In this project, mainly two proxy-data are used: pollen and ostracods (aquatic micro crustaceans). Pollen is used to reconstruct past vegetation landscapes and may be useful for detecting human activities such as farming, forest clearance,... The study of ostracod assemblages may provides local and regional information linked to the hydrological conditions (precipitation) and water temperature. Moreover, geochemical study of trace-element contents incorporated in the calcite of the ostracod shells offers the opportunity to quantify water chemistry and temperature changes. As this method is relatively new, laboratory experiments and field collections of ostracods are driven in order to provide a better understanding of the links between trace-element contents of ostracods and physical, chemical, and biological factors.

2. OSTRACOD GEOCHEMISTRY: LABORATORY EXPERIMENTS

Several studies have shown that the trace-element composition of the ostracod valves is controlled by the chemistry and the temperature of the water in which calcification occurs (Chivas et al., 1986; Wansard et al., 1999). Newly-identified factors modifying the traceelement partitioning between ostracod shells and water have been recently reported (Xia et al., 1997; Wansard et al., 1998). Particularly, we hypothesised that typical freshwater species do not show a Mg-temperature relationship (Wansard & Roca, 1997; Wansard et al., 1999).

In order to test this hypothesis, several experiments have been realised in controlled laboratory conditions. To assess our preliminary results (cf. annual SSTC report 1998), new experiments using *Candona neglecta* and *Heterocypris incongruens* species were recently achieved.

3. THE TRAVERTINE ANNEVOIE-ROUILLON SEQUENCE

Preliminary results based on ostracod and pollen data were provided in the two first annual reports. Here we provide new results based on statistical analysis of ostracod assemblages and trace-element contents in ostracod shells (Figure 1).

3.1 Statistical analyses

Correspondence analysis (CA) is used in treating ostracod distribution. The results of the CA analysis shows that axis 1 separates species and samples (Fig. IA) in a gradient that can be interpreted in terms of environmental conditions. The species - P. *zenkeri, C. neglecta, C. candida* and *Herpetocypris sp.* are present at one end of the first axis, and *Pseudocandona zschokkei, S. triquetra, F. brevicomis, C. vavrai* and E. *Pigra* are present at the other end of the axis 1 (Fig. IA).

The plot of the percentage of each species in each sample as a function of the coordinate on the first axis reveals the quality of the gradient or relay index (RI) (Fig. 1B). According to the ecological preference of the species, the RI depicts the changes in the ostracod habitat:

- low RI values characterise a slow, or even stagnant, water regime;

- medium RI values correspond to a typical spring regime;

- high RI values depicts an hyporheique habitat.

Theses habitats can be related to the level of energy in the environment, and partially to the hydrological regime. An other evidence is the increase of the grain size of the sediment with the RI. Past changes in the hydrodynamic of the system is illustrated by the RI variations along the whole studied sequence (Fig. 1C).

3.2 Ostracod geochemistry

Fig 1C shows the variation in the ostracod Mg/Ca ratio for three species along the whole section. The ostracod Mg/Ca ratio is mainly a function of the water Mg/Ca ratio (Wansard et al., 1998). The Mg/Ca curve shows several fluctuations, with the lowest Mg/Ca ratios in ostracods corresponding to the higher flow regime (RI).

Generally, the changes in the water chemistry is mainly due to the aquifer discharge in the travertine system, and hence to the precipitation regime. The greater the discharge (precipitation), the more diluted the water. In this state of the research, we hypothesise that variation in ostracod Mg/Ca ratios reflect precipitation changes. On the other hand, the end of the travertine edification should be related to a drastic increase of the precipitation, both with an increase of an erosion activity.

Several datations are necessary to quantify the apparent cyclicity observed in the Mg/Ca curve. Until now, only one date (14C) is available: 7290 ± 50 y BP at 1.4 m depth (Cors et al., 1998).

4. THE TREIGNES SEQUENCE

The study of the travertine deposited at Treignes started two months ago. The stratigraphic log of a 4 m long sequence and the sampling were realised. One datation is submitted. This travertine sequence is characterised by the presence of peat layers, and charcoals. This should let to a good chronological framework.

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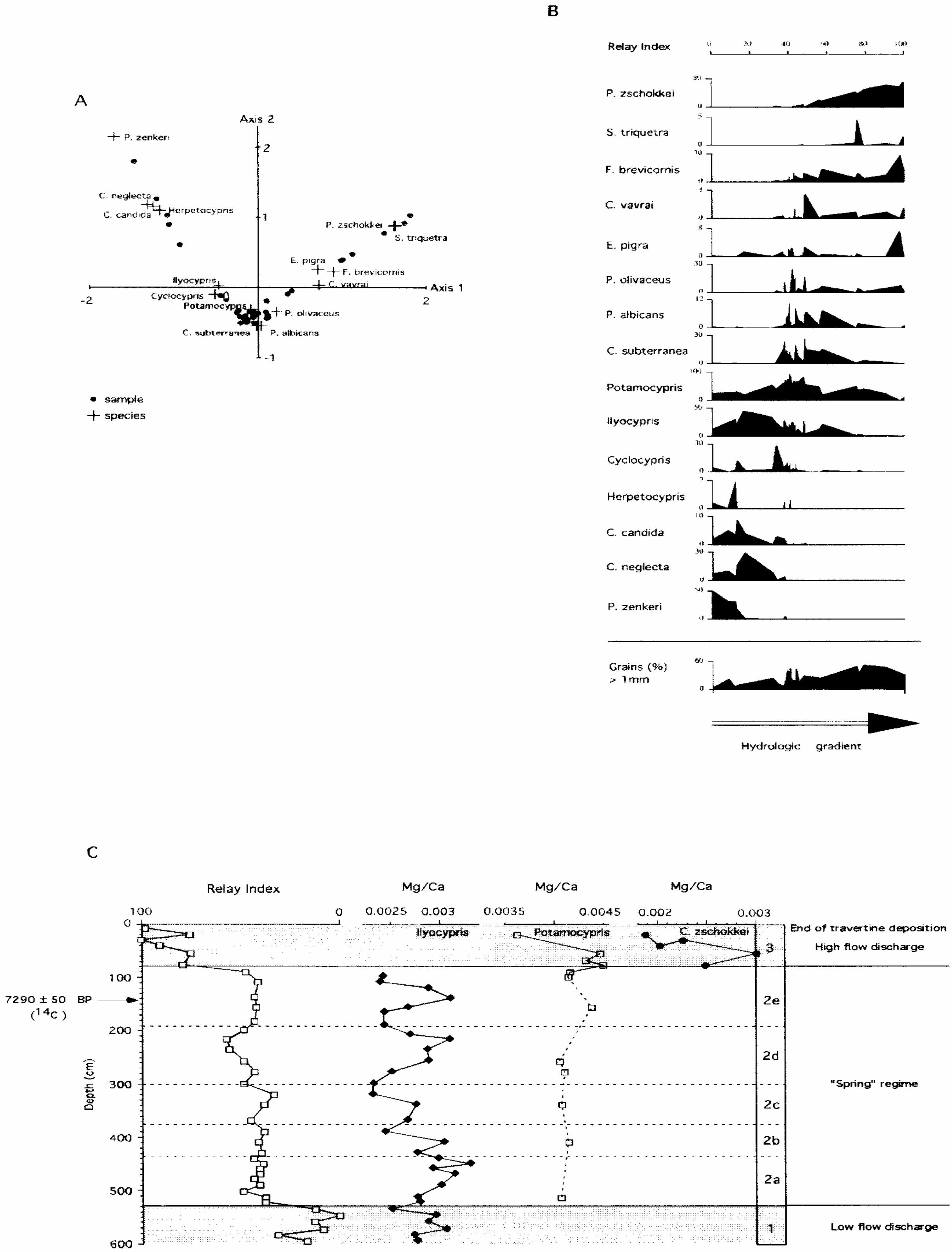

FIG. 1: The ANNEVOIE-ROUILLON sequence: a synthesis of the ostracod study.

CG/DD/13

UNDERSTANDING THE DECADAL-CENTURY-TO MILLENNIA CLIMATE VARIABILITY BY SIMULATING EXTREME PALEO-CLIMATIC SITUATIONS

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The climate model designed in Louvain-la-Neuve for palaeoclimate purposes (Gallée et al., 1991; 1992) has been improved in two different directions. It has been coupled to a model representing the dynamics of the vegetation. Two types of vegetation are represented, i.e. trees and grass. Desert is a potential third type of land cover. Vegetation change is determined according to climate, more precisely temperature (growing degree-day, GDD0) and precipitation. Vegetation impacts on climate through the surface albedo.

The second improvement is related to the ocean representation. The ocean was represented by its upper mixed layer in the original version of the climate model. This representation has been replaced by a dynamic ocean model.

This new version of the model, called MoBidiC, allows us to investigate the short-term climate variability in the climate system. Therefore we studied the climate changes during the last millennium and more specially the impact of different origin for this variability either natural sources (volcanic activity, solar forcing) or human activities (greenhouse gases, sulphate emission, land cover change). Before the industrial period, climate variability can largely be explained by the natural forcing effect. In particular, the temperature reconstruction can largely be explained by the variation in total solar irradiance. However during the industrial period (from 1765 up to now) the natural forcing alone is not able to explain the climate change and the anthropogenic forcing must be taken into account to simulate the observed climate changes.

Secondly we investigated climate change during older periods. We studied the conditions under which abrupt climate change can be simulated by the model either in interglacial or glacial periods. We derived the timing and amplitude of the different events following an initial freshwater input. In particular it is shown that after a freshwater input in the North Atlantic thermohaline circulation first shuts down and then resumes in one step during interglacial periods and in two steps in glacial periods.

At last, we analysed the stability of the climate through the Holocene. This study highlights the importance of the vegetation, especially in the high latitudes. Indeed it can induce there a further temperature change of a few degrees during the spring time over the Holocene.

PART 1: REDUCING UNCERTAINTIES

Terrestrial ecosystems and water cycles

CG/DD/04A
CG/DD/04B

SPECIES DIVERSITY: IMPORTANCE FOR SUSTAINABILITY OF ECOSYSTEMS AND IMPACT OF CLIMATE CHANGE

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1. PROJECT SUMMARY

In this project we investigated (1) the importance of plant diversity for the functioning and stability of temperate grassland ecosystems; (2) the interactions between plant diversity and climate change; and (3) how plant diversity in grasslands can be optimized through agricultural management techniques. Research themes include the possible linkages between the species diversity of biotic communities and their ecological responses to disturbance, the single-factor and combined influences of elevated atmospheric CO_2 concentration and increased air temperature on productivity in stands with different levels of plant diversity, and the effects of nutrient supply and mowing frequency in species-poor vs. species-rich grasslands.

With techniques of controlled assemblage, artificially synthesized, model ecosystems were created from seeds, either in containers, in the field, or in controlled environments. One of the sets of plant communities contained 1, 2, 4 or 8 species of cool-temperate, perennial grasses, and another contained 1, 2 or 3 functional groups (cool-temperate perennial grasses, nitrogen-fixing dicots and non nitrogen-fixing dicots). In order to distinguish between effects arising from diversity (number of species or number of functional groups) and effects arising from identity (which particular species or functional groups are present?), each level of biodiversity was represented by a range of plant communities with different composition. Functional groups are here defined as groups of organisms performing a similar role in the ecosystem. For example, all symbiotically nitrogen-fixing species are functionally similar in the respect that they supply atmospheric nitrogen to the system, while other species do not. At UIA, replicates of the series with 1, 2, 4, 8 grasses (72 different communities) were exposed to simulated climatic perturbations in the field (heat wave + drought). With this set-up we determined stability-related properties like resistance (deviation from equilibrium) and resilience (rate of recovery after perturbation). The heat waves were generated by controlled infrared irradiation (Free Air Temperature Increase system), aiming to recreate the most extreme hot weather events of the past decades. At RUG, both the series with 1, 2, 4 or 8 grasses (24 communities) and the series with 1, 2 or 3 functional groups (24 communities) were exposed to two atmospheric CO_2 concentrations (ambient and approximately doubled) and two temperature regimes (ambient and +4°C) during an entire growing season, using sunlit, air-conditioned enclosures. A field trial at RUG investigated the effects of plant diversity (four levels of species numbers plus bare soil) under different levels of nitrogen fertilisation (three levels) and mowing frequency (two levels) as anthropogenic factors.

The results show that functional diversity (number of functional groups) promotes productivity and this across a range of nitrogen availabilities and mowing frequencies. Increasing the number of species in communities with only grasses, on the other hand, has only limited effects on productivity. Elevated CO_2 and increased air temperature did not interact with plant diversity in either of these cases (which means the effects were additive), although the relative abundance of species changed significantly. Several mechanisms can explain increased productivity in more diverse systems. For example, in the functionally more diverse systems we oberved enhanced interception of photosyntheticallly active radiation due to a higher total foliar surface per unit ground area, and in the case of growth under elevated temperature also due to a more efficient light capture per unit leaf area. Another possible explanation is that having more species increases the degree of complementarity in the system with respect to the use of resources like radiation or nutrients. Species can be complementary for example in space or in time, and a larger species pool could provide access to more or to a wider range of resources. Although in the communities with only grasses the overall biomass responded little to the imposed variation in plant diversity, internal shifts in the biomass production of the composing species did occur. In particular, those species which were most productive in monoculture tended to dominate the mixtures, and this effect became more pronounced as species richness increased.

A mathematical model was developed to explain the results. One model showed that different components of plant diversity have positive, but different, influences on the productivity and nutrient uptake of plant communities. One component of diversity was species richness (number of species in the community), which had a saturating effect on these processes. By contrast, another component of plant diversity, i.e. the degree to which the species differed in growth rate, had an exponential influence. This implies that small effects of plant diversity on productivity can be expected when the species are highly similar (cf. the results with only cool-temperate grass species, which can be considered functionally equivalent). On contrast, large effects can be expected in the opposite case (cf. the significant increase in productivity with higher numbers of functional groups, if we assume that species belonging to different functional group are more different than species belonging to the same functional group).

When grasslands with various species numbers were experimentally exposed to climatic extremes (heat wave simulation), mortality after the heat wave was higher in the species-rich communities. A probabilistic model was developed to interpret the outcome of these experiments. Under the assumption that every species has a constant - but not the same - probability to go locally extinct following the heat wave, the model predicted enhanced plant survival in the more diverse plant communities, which was opposite to the observations. The contradiction could be explained by the fact that, in the experiment, the low-diverse communities effectively reduced the intensity of the climatic extreme by consuming less water. Consequently, the apparent sensitivity of the species to the extreme event was lower and their probability of survival higher. The consequences of this were further analysed by considering the spatial mortality patterns that arose in the grass communities after the heat wave had ended. The higher mortality in the species-rich systems increased the number of gaps per unit area formed after the extreme event, as well as the size of these gaps.

At the end of the project we made an inventory of those processes in the grassland ecosystems that were affected by plant diversity. Effects were classified according to magnitude and sign (positive/negative) of the response, and the sensitivities of the different processes to diversity were combined in a weighted index. The latter expresses how the basal processes in a grassland (productivity, nutrient uptake, water consumption,...), as well as the sensitivity of these processes to disturbance, vary with diversity. The index can be used as a quantitative tool to assess the consequences of having higher or lower diversity (in the current and in a future climate), so that the ecosystem impact of management options which affect diversity can be evaluated.

2. VALORISATION OF THE RESULTS AND RECOMMENDATIONS

Do changes in the global climate affect biodiversity in grasslands?

In our one-year greenhouse experiments with grassland communities of various plant diversity, exposure to elevated CO_2 concentration, to increased air temperature, or to the combination of both, did not lead to diversity losses. Nevertheless, the significant changes in the relative abundance of the species that were observed in response to these changes, indicate that a number of species of these mixtures will disappear in the longer term. To prevent such biodiversity losses, further increases of CO_2 concentration and air temperature should therefore be minimised. In the experiments, symbiotically nitrogen-fixing species were promoted most strongly in response to elevated CO_2, followed by the cool-temperate grasses, while non-nitrogen-fixing dicots responded the least. This suggests that the risk of local extinction is highest for small populations of species belonging to the latter functional group.

Can trends of altering species composition in response to climate change be mitigated by adapting current management practices?

In principle, several techniques could be applied to counteract the evolution towards a larger fraction of nitrogen-fixing species in future grasslands growing at elevated CO_2 concentration. First, increased nitrogen fertilisation (minimum 350 kg ha^{-1} y^{-1}) would constrain the nitrogen-fixers, creating a benefit for the grasses. However, the environmental effects of such a solution (ground water pollution through nitrogen leaching) are not acceptable, and the well-fertilised grasses would also outcompete many of the non-nitrogen-fixing dicots. Second, the timing of nitrogen supply could be adjusted at the expense of the nitrogen fixers. In spring, the grasses dominate, while the proportion of nitrogen fixing plants is small. During summer, nitrogen fixers grow relatively better than grasses. Enhanced nitrogen supply in spring would thus further favour the grasses. However, also the non-nitrogen-fixing dicots will suffer greatly from such a redistribution of fertilisation, which is likely to further reduce diversity rather than to restore it. As a third option, potassium supply could be reduced to favour the grasses since nitrogen-fixing plants need a lot of this element, but, again, also this method would set back the non-nitrogen-fixing dicots. We conclude that, although negative plant diversity evolutions in grasslands under elevated CO_2 could potentially be mitigated by changes in management, the ecological consequences would be either undesirable or even counterproductive (i.e. biodiversity loss is aggravated instead of repaired).

Will less diverse grasslands be less stable in a future climate with more frequent extreme events?

In controlled experiments, more species-rich grass communities proved to be more susceptible to heat waves of exceptional intensity. In particular, mortality after a heat wave was higher when more species were initially present, and the residual vegetation became more fragmented than in the case of monocultures. The long-term consequences of this remain speculative. Will the higher gap densities created in these initially more species-rich grasslands act as a promotor of diversity, by offering more opportunities for less competitive species to establish after the disturbance? Or will invasive species have increased chances to completely modify the resident plant community? In any case, on the short term, the larger loss of individuals in the more diverse systems following the extreme event effectively reduce their diversity. Enhanced susceptibility to extremes of more diverse systems is a further reason to invest in slowing down climate change, since the more ecologically valuable (diverse) grasslands are likely to be affected most, and more species will be lost from these systems. As far as rare species are concerned, it is evident that their small population size makes them more vulnerable to extremes for stochastic reasons (relatively less buffering of population size to fluctuations). These reasons lead us to believe that a climate with more extreme events will further accelerate the ongoing global erosion of biodiversity.

Which management practices optimise plant diversity in grasslands under the current climate?

Pluri-annual field trials demonstrated that agricultural management (either 100, 250 or 400 kg nitrogen ha^{-1} year^{-1} and either 3 to 4 or 5 to 6 cuts year^{-1}) strongly determines plant diversity. In July the largest species numbers were recorded under the lowest nitrogen supply combined with the highest mowing frequency. One reason for this is the shorter canopy under intense mowing. This results in enhanced illumination of the ground surface, offering more chances for species to germinate. Also, under a given nutrient supply, a higher mowing frequency removes more nutrients, which leads to a less fertile environment. The resulting reduction in growth rates favours in particular the less competitive species, which increases the total number of species in the system. To enhance the species richness of agricultural grasslands in Belgium, low nitrogen fertilisation (100 kg ha^{-1} y^{-1}) is most effective, combined with the highest possible mowing frequency that agricultural practice allows (5 to 6 cuts per year). This implies a shift from intensive to extensive exploitation, with high costs to harvest the relatively small amount of forage. We point out that our results were obtained for continuously mowed grassland, while standard grassland use either combines mowing with grazing, or is limited to grazing only.

Can plant diversity be controlled by sowing?

Whether farmers sow a grass monoculture, or rather a species-richer mixture of ryegrass, timothy, clover and even some dandelion, hardly affects the final species number. The reason for this is that more species can succesfully establish in monocultures than in mixtures. However, the seed mixture used does matter for biomass production: in the experiments during 2000, the species-richer mixtures produced on average 3000 kg ha^{-1} year^{-1} more dry matter than the average of the monocultures, in spite of their similar final species number. Clearly, the sown agricultural cultivars are more productive than the established species. For this reason, it is from an agronomic point of view most appropriate to sow grass-clover mixtures. This option has no implications for species diversity, but the nitrogen-fixing clover species allow one to obtain adequate biomass production rates even under low nitrogen supply. Care should be taken with pastures containing more than 50% clover, which can cause bloat in cattle.

Species diversity vs. species identity

As described above we used specific experimental procedures to distinguish between effects on biomass production of species richness and of species identity. Although species identity was not the focus of this project, it should be clear that both the quantity and quality of grassland production are affected by it. Annual meadowgrass (UK) / annual bluegrass (USA) and broadleaved docks, for example, which occur abundantly under high mowing frequency, greatly reduce the agronomic value of the vegetation. Dandelion, on the other hand, which thrives under high nitrogen supply, is welcomed in pastures for it is appreciated by cattle. Creeping buttercup, more characteristic of lower fertilisation, is slightly toxic, but its toxicity is lost upon conservation. Future adjustment of management practices to optimise biodiversity through fertilisation and mowing will therefore have to consider expansion or decline of particular noxious or beneficial species.

CG/DD/05

BIOGEOCHEMICAL CYCLES OF BELGIAN FOREST ECOSYSTEMS RELATED TO GLOBAL CHANGE AND SUSTAINABLE DEVELOPMENT (BELFOR)

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1. OBJECTIVES OF THE BELFOR PROGRAMME

The goal of the BELFOR programme was to generalise previous and currently obtained experimental observations of impacts of CO_2 and temperature on trees and to evaluate their likely impacts on forest ecosystems in view of their sustainable development. Therefore a detailed experimental and theoretical analysis was made of measured and simulated data of the CO_2, nutrient and water cycles of model forests located in both the North and South of Belgium. Hence, the deliverables of this programme are :

- An extended inventory of the available and acquired data related to carbon, nutrient and water cycles in typical Belgian forest ecosystems (so-called Functional Forest Types or FFTs);
- The modelled and validated information for the corresponding pools and fluxes under current conditions, including the scaling-up to the level of the region;
- The prediction of changes in these pools and fluxes under a series of realistic climatic scenarios in view of a future sustainable development of Belgian forest ecosystems, including the formulation of relevant guidelines;
- The establishment of an integrated database with easy access (CD-ROM), containing all experimental and simulated information on the biogeochemical cycles in Belgian forest ecosystems.

The analysis of carbon, nutrient and water cycles in Belgian forest ecosystems started with the inventory of observations made in 6 different experimental sites, corresponding to the major forest types in Belgium (Functional Forest Types). The sites were selected according to the existing knowledge of ecosystem functioning. A large amount of biogeochemical data was already available for the selected sites, and some of the sites are still operated within the scope of related research projects funded by the EU or by the Flemish and Walloon Governments.

Five Task Forces were established within the frame of the BELFOR network to ensure efficient co-ordination of the research activities. Senior scientists were appointed as Task Force leaders in order to establish communication links between teams and to share expertise on data acquisition, measurement techniques, sampling protocols, data synthesis and data exchange. The Task Forces and their leaders were :

Task Force Carbon : R. Ceulemans, UIA
Task Force Water : E. Laitat, FUSAGx
Task Force Nutrients : N. Lust, RUG
Task Force Modelling : J. Gérard, ULg
Task Force Database : F. Veroustraete, VITO

The general co-ordination of the network was done by R. Lemeur (RUG). He was assisted by ir. I. Vande Walle who was responsible for the day-to-day management and also served as the central info point for the network.

2. DESCRIPTION OF THE FUNCTIONAL FOREST TYPES

The main characteristics of the different Functional Forest Types are given in Table 2.1. The sites belong to different phytosociological domains, which correspond with different climatological conditions, as indicated in Table 2.2.

Table 2.1. *Main characteristics of the Functional Forest Types (FFTs) of the BELFOR network*

Functional Forest Type	Main tree species	Humus type	Soil pH	Age	Number of stems	Standing crop	Annual increment
				(in 1998)	(ha^{-1})	($m^3\ ha^{-1}$)	($m^3\ ha^{-1}\ y^{-1}$)
I - Gontrode							
Oak-beech (Ia)	*Quercus robur L.* *Fagus sylvatica L.*	Moder	3.7 *(1)**	76	345 *(6)*	301.2 *(6)*	5.1
Ash (Ib)	*Fraxinus excelsior L.*	Mull	4.0 *(3)*	76	403 *(8)*	327.3 *(7)*	3.8
II – Brasschaat	*Pinus sylvestris L.*	Mor	3.8 *(2)*	70	542 *(10)*		7.0
III - Balegem	*Populus sp.*	Mull	6.3 *(6)*	15	191 *(5)*	367 *(8)*	24.5
IV - Vielsalm		Dysmoder	4.0 *(3)*				
Douglas fir (IVa)	*Pseudotsuga menziesii (Mirb.)*			65,50,40	39 *(1)*	176.4 *(2)*	
Beech (IVb)	*Fagus sylvatica L.*			60,70,90	116 *(3)*	165.9 *(1)*	
V - Chimay							
Ville de Mons	*Quercus robur L.*	Moder-mull	5.1 *(5)*	107	148 *(4)*	278 *(4)*	
Intensive Monit.Stand	*Quercus petraea Liebl.*	Moder-mull	4.1 *(4)*	116	76 *(2)*	185 *(3)*	

VI - Jalhay/Waroneu							
Catchment	*Picea abies (L.) Karst.*	Hydromoder	4.0 *(3)*	65	370 *(7)*	295 *(5)*	9.7
Intensive Res. Stand.		Hydromoder	4.0 *(3)*	70	462 *(9)*	475 *(9)*	11.0

* ( ) indicates the rank following an increasing order

Table 2.2. *Main climatological conditions in the atlantico-European and medio-European domains (Source : Poncelet and Martin 1947)*

Parameter	**Atlantico-European domain (Gontrode, Brasschaat, Balegem)**	**Medio-European domain (Vielsalm, Chimay, Jalhay/Waroneu)**
Temperature (°C)		
annual mean	9.5-10.0	9.5-10.0
May, June, July	15.5	15.5
January	2.0-3.0	2.0-3.0
Rainfall (mm)		
annual (mean)	750-800	900-1300
May, June, July (mean)	200-210	230-280
Rainfall > 1 mm (days)	160-170	170-200

The six Functional Forest Types are indicated on the map of Belgium presented in Fig. 2.1.

FUNCTIONAL FOREST TYPES

I. Gontrode – Aelmoeseneie forest

Deciduous mixed

Ia : oak-beech; Ib : ash

II. Brasschaat – De Inslag

Coniferous

III. Balegem – Het Ganzenhof

Deciduous monospecific

IV. Vielsalm - Tinseubois

Deciduous – coniferous

IVa : Douglas fir; IVb : beech

V. Chimay

Deciduous mixed

VI. Jalhay - Waroneu

Coniferous monospecific

Fig. 2.1 *Location of the 6 Functional Forest Types of the BELFOR network*

3. TASK FORCE MODELLING

The Task Force Modelling had the objectives to model the fluxes and the pools in forest ecosystems, and to validate simulated results with measured data from the FFTs. Detailed analyses and spatial upscaling were major scientific goals.

3.1 Fundamental analysis and predictive modelling : the ASPECTS model

ASPECTS (Atmosphere-Soil-Plant Exchange of Carbon in Temperate Sylvae) is a mechanistic model built to predict the evolution of carbon fluxes and reservoirs in temperate forest ecosystems. Because cycles of carbon, nitrogen and water are interdependent, the evolution of nitrogen and water reservoirs of the forest ecosystem are also predicted. The carbon reservoirs considered in the ASPECTS model are : (1) sugar and (2) starch reserve, and the dry weights of (3) leaves, (4) branches, (5) stems, (6) coarse roots per soil layer, (7) fine roots per soil layer, (8) non-woody litter per soil layer, (9) woody litter per soil layer, and (10) soil organic matter (SOM) per soil layer. Nitrogen reservoirs are identical to carbon reservoirs (3) to (10), plus a nitrogen reserve and mineral nitrogen content per soil layer. Water reservoirs are snow, and soil water content per soil layer. The evolution of all reservoirs is computed at each time step by solving all differential equations defined between incoming and outgoing fluxes. All reservoirs are computed several times per day at a frequency defined by the time step of the input weather data. Although the integration time step is short, the ASPECTS model is designed to simulate the evolution of carbon, nitrogen and water reservoirs over periods longer than a century. Initial conditions can be defined for a forest of any age, *i.e*. from a stand of seedlings to a mature stand. ASPECTS also simulates tree growth and the evolution of carbon reservoirs and fluxes. The theoretical background of the calculation procedures used in ASPECTS is extensively described in the final report of the BELFOR programme (Vande Walle and Lemeur 2001).

The ASPECTS model uses 4 types of model inputs :

1) the initial condition for each reservoir;

2) the soil characteristics : clay, loam and sand percentages, bulk density, and depths of the soil layers;

3) information on forest management : a management file contains the dates when plots were thinned, and the amount of wood removed from the plots;

4) the hourly or half-hourly meteorological data for the following variables : solar radiation (W m^{-2}), air temperature (°C), precipitation (mm day^{-1}), relative humidity (kg kg^{-1}), wind speed (m s^{-1}) and atmospheric pressure (Pa).

The ASPECTS model generates a large number of outputs, which can be obtained on an hourly, daily, monthly and annual basis. The most important outputs for the carbon cycle are : (1) the gross primary productivity (GPP), (2) the net primary productivity (NPP), (3) the Net Ecosystem Exchange (NEE), (4) the net production of leaves, branches, stem wood, coarse roots and fine roots, (5) the litter produced by leaves, branches, stem wood, coarse roots and fine roots, and (6) decomposition of the litter and mineralisation of the soil organic matter. The most important outputs related to the nitrogen cycle are : (1) nitrate leaching and (2) the net accumulation of nitrogen in leaves, branches, stem wood, coarse roots and fine roots. The output related to the water cycle is : (1) throughfall, (2) canopy interception and evaporation, (3) tree transpiration, given by the water uptake by roots, (4) soil evaporation, (5) drainage and (6) runoff.

The key concept of ASPECTS is that tree growth results from the allocation of photosynthetic carbon produced in excess of tissue respiration. Therefore, the most essential processes to simulate the carbon fluxes and reservoirs are photosynthesis and respiration rate, together with carbon allocation in tree components.

The ASPECTS model was calibrated and validated using experimental data from the Functional Forest Types. The model was applied under present atmospheric conditions. The model appeared to be a powerful tool for gap filling at sites where periods of missing data might bias the results. ASPECTS was also used for the estimation of litter production (both above- and belowground). This is an interesting application as litter production is a major carbon flux in forest ecosystems. Accurate estimation of the amounts of litter being generated by each plant compartment is pivotal to understand the impact of forest management on CO_2 fluxes.

3.2 Spatial upscaling using the C-FIX model

The mathematical C-Fix procedure, as published by Veroustraete *et al.* (1996), attempts to quantify the carbon fluxes on a regional basis by integrating satellite observations into a simplified carbon budget model. The key hypothesis in this approach, is that the evolution of the 'amount' and 'state' of the vegetation are directly inferred from space observations and, hence, no longer need to be estimated by the carbon budget model itself.

For a given point location, the C-Fix model estimates three types of fluxes on a daily basis (expressed in g C m^{-2} d^{-1}) :

i) the *Gross Primary Productivity*, which represents the gross uptake of carbon by photosynthesis;

ii) the *Net Primary Productivity*, which is the flux that accounts for the autotrophic respiratory losses by vegetation, and is mainly related to the conversion of glucose into photosynthates and the maintenance of standing phytomass;

iii) the *Net Ecosystem Productivity (NEP)* which also takes into account the soil respiration flux (R_d), originating from heterotrophic decomposition of soil organic matter.

These carbon fluxes are calculated on the basis of both remote sensing data (NOAA-AVHRR or SPOT4-VGT imagery) and meteorological information (daily incoming solar radiation and mean air temperature). Monthly and yearly average values are subsequently derived by numerical integration (Simpsons' rule) of the daily fluxes over a complete growing period.

Once the NEP is calculated for each pixel of the Belgium territory, the yearly Belgian NEP for all green vegetation is calculated. To generate information for the Belgian forest carbon balance only, a forest probability map is used, expressing the probability of a pixel that it is covered with forest. This probability is expressed as a fractional area coverage (%). The combination of the NEP pixel value with the forest probability map pixel value, finally results in a (Belgian) forest NEP map.

Table 3.1 illustrates the total number of pixels studied and lists some of the results obtained from C-Fix.

Table 3.1. *Total number of pixels selected for Belgium, the corresponding area (km²), the mean net ecosystem productivity (NEP) per unit area and the total net ecosystem productivity in Belgium (total NEP) for different years; for both all vegetation and forests*

	All vegetation		**Forests**	
	1997	**1998 – 1999**	**1997**	**1998 – 1999**
Number of pixels	24917	24920		
Total area [km²]	30589	30593	5693	5693
Mean NEP [ton C ha^{-1} y^{-1}]	4.79	4.76	5.03	5.01
Total NEP [10^6 ton C y^{-1}]	14.64	14.58	2.76	2.75

From Table 3.1 it can be noticed that the forest mean NEP is slightly higher than that for all types of green vegetation together. Another conclusion is that the total NEP for the forests in Belgium is only 19 % of the value for all types of vegetation combined.

C-Fix results were also compared with the eddy covariance flux measurements obtained in two different Functional Forest Types in Belgium (FFT II and IV). The correspondence of simulated and measured results depends on the size of the forest : if the forest size is too small, the flux measurements are sometimes unreliable. Finally, simulations of NEP performed at pixel (or site) level with C-Fix were compared with results obtained from the ASPECTS model. It was found that ASPECTS and C-Fix show a good correlation along the 1:1 line for the Vielsalm site (IV). The correlation between ASPECTS and C-Fix is less good for the Brasschaat site, though still reasonable. A major conclusion in addition to the apparently good correlation between both models, was that the models elicit and describe different types of short-term carbon exchange dynamics. It was suggested that the discrepancies have to be explained by the lack of a water balance description in C-Fix (contrary to ASPECTS which contains a full water balance description). This conclusion should be taken into account for future development of the C-Fix model.

4. TASK FORCE CARBON

The Task Force Carbon aimed at the detailed analysis of the carbon pools and fluxes in some of the Functional Forest Types. Both experimental and simulated data were used for this purpose. Information obtained from previous research programmes were also taken into account.

4.1 Carbon pools in different compartments of the forest (FFTs I, II and IV)

Table 4.1 gives an overview of the carbon stocks determined for different stand compartments of the Functional Forest Types I, II and IV. From this table, it can be concluded that, despite the occurence of different dominant tree species and different soil types (see chapter 2), all FFTs seemed to contain large carbon stocks. The FFTs Ia and Ib at Gontrode and IVb at Vielsalm had similar amounts of total carbon stored, while FFT IVa had the largest carbon reservoir. The smallest amount of carbon was found in the Scots pine forest stand of FFT II at Brasschaat.

***Table 4.1**. Amounts of carbon (ton C ha^{-1}) stored in the soil compartment, in the surface litter layer and in the vegetation compartment of three different Functional Forest Types, i.e. in Gontrode (Ia, oak-beech and Ib, ash stand), Brasschaat (II, Scots pine stand) and Vielsalm (IVa, Douglas fir and IVb, beech stand)*

Compartment	Ia	Ib	II	IVa	IVb
Soil					
Organic matter (1 m depth)	134.8	170.0	114.7		170.2
Root litter	0.2	0.5	3.0		1.0
Subtotal soil	135.0	170.5	117.7		171.2
Surface litter					
Holorganic horizon	33.2	0.1	25.5		69.9
Woody debris	2.5	3.0	1.3		6.0
Subtotal litter	35.7	3.1	26.8		75.9
Vegetation					
Shrub layer	2.4	4.3	0.0	0.0	0.0
Leaves	2.0	1.3	3.0	9.3	0.9
Branches	42.5	26.9	13.5	32.9	15.6

Stems	78.7	86.9	73.3	90.6	49.0
Coarse roots	25.1	22.8	11.8	19.8	12.7
Fine roots	3.4	5.8	2.8	2.3	3.4
Subtotal vegetation	154.3	148.2	104.4	154.9	81.6
TOTAL	**324.8**	**321.6**	**248.9**	**406.8**	**328.7**

The total amount of carbon stored and the distribution between living and non-living forest compartments depended very much on soil type and on tree species. The distribution of carbon over the different stand compartments depended strongly on the forest type (Fig. 4.1). Striking differences were found in the litter layer. While the litter layer in the oak-beech stand at Gontrode (Ia) contained 11.0 % of the total carbon, it only accounted for 1.0 % in the ash stand at Gontrode (Ib). The contribution of the biomass carbon pool ranged from 42.0 % in the Scots pine stand at Brasschaat (II), over 46.0 % in the ash forest at Gontrode (Ib) to 47.4 % in the oak-beech stand at Gontrode (Ia). The contribution of the non-living compartment (soil and litter) ranged from 52.6 % in the oak-beech stand at Gontrode (Ia) over 54.0 % in the ash forest at Gontrode (Ib) to 58.0 % in the Scots pine forest at Brasschaat (II). Partitioning of the carbon over living biomass, litter layer and mineral soil was in agreement with the results reported by Nabuurs and Mohren (1994).

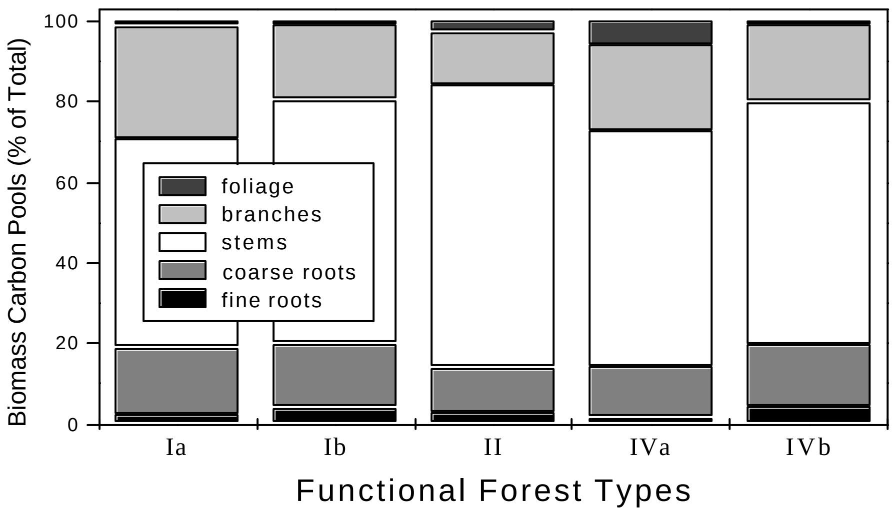

Fig. 4.1. *Relative amounts of carbon stored in the foliage, the branches, the stems, the coarse roots and the fine roots compartments of various forest stands belonging to three different Functional Forest Types : the oak-beech stand at Gontrode (Ia), the ash stand at Gontrode (Ib), the Scots pine stand at Brasschaat (II), the Douglas fir stand at Vielsalm (IVa) and the beech stand at Vielsalm (IVb); values are expressed as percentage (%) of the total carbon pool of the forest biomass*

4.2 Measured carbon fluxes between different compartments of the forest stands (FFTs I, II and IV)

4.2.1. Definition and terminology

Photosynthesis is the most important physiological process in the carbon cycle at the level of the leaves, individual trees and forest stands. The Net Primary Productivity (NPP) is defined as the amount of carbon that plants are able to invest into the production of biomass. The NPP of a forest ecosystem equals the Gross Primary Productivity (GPP or gross photosynthesis) minus the total amount of autotrophic respiration. This net amount of carbon taken up by the vegetation is being allocated to the different biomass components of the ecosystem.

In the soil, CO_2 is produced by (i) the decomposition of organic matter (heterotrophic respiration) and (ii) the growth and maintenance respiration of the roots (autotrophic respiration). The algebraic sum of the heterotrophic soil respiration and the Net Ecosystem Exchange (NEE) gives the Net Primary Productivity (NPP). The NEE is defined as the net amount of CO_2 that is exchanged annualy between an ecosystem and the atmosphere. This NEE equals (i) the gross primary productivity (photosynthesis) minus the total respiration losses or (ii) the NPP minus the heterotrophic respiration. The NEE of forests can be positive or negative and it can fluctuate from year to year. When the NEE is positive – the sum of the autotrophic and heterotrophic respiration losses is lower than the photosynthetic carbon uptake – the forest is a sink of carbon; however when the NEE is negative, the forest is a source of carbon. The total terrestrial carbon sink is estimated to be of the order of 2 $\pm$ 1 * 10^{15} g C per year (Valentini *et al*. 2000) from which EU forests fixed between 0.17 and 0.35 * 10^{15} g C in 1997 (Martin *et al*. 1998).

4.2.2. Carbon fluxes in FFTs I, II and IV

The methods used to determine the various carbon fluxes in the FFTs are described in the final report of the BELFOR programme (Vande Walle and Lemeur 2001). The overview of the carbon fluxes (Table 4.2) showed that soil respiration was the second largest flux in comparison with the photosynthetic carbon uptake in the 4 FFTs examined. The values are similar to what has been reported for most forest ecosystems (Raich and Nadelhoffer 1989). The impact of the forest type on the soil respiration was through litter quality, litter decomposition and soil pH, which all differed among the FFTs (see chapter 2).

Table 4.2. *Overview of measured and simulated carbon fluxes (expressed in ton C ha^{-1} y^{-1}) for 4 Functional Forest Types. For the simulation of the canopy CO_2 uptake of FFT Ia and Ib the species composition of the oak-beech stand (Ia) was assumed 35 % beech and 65 % oak, and of the ash stand (Ib) 83 % ash, 15 % oak and 2 % beech.*

Type of flux	**Ia**	**Ib**	**II**	**IVb**
Carbon fluxes				
- Soil respiration	3.1	4.1	3.1	6.1
- Wood respiration	1.6	1.2	1.0	3.5
- Net canopy CO_2 uptake [1]	11.6	9.0	8.7	
Litter production				
- Aboveground	1.9	1.7	3.4	
- Belowground (measured)[2]	0.2	0.7	0.9	
- Belowground (R and N)[3]	0.2	1.1	-	
Biomass increment				
- Aboveground				
Stem	3.0	3.2	1.5	1.1
Branches	1.5	1.0	0.3	0.6
- Belowground				
Coarse roots	1.0 [1]	1.0 [1]	0.2 [2]	0.3 [1]
- Total biomass increment	5.5	5.2	2.0	2.0

[1] *: simulated*
[2] *: measured by means of ingrowth cores*
[3] *: R and N = method of Raich and Nadelhoffer (1989)*

The woody tissue respiration could only be obtained from scaled-up (*i.e.* indirect) measurements or from model estimations. However, the results indicate that the wood respiratory flux amounted up to ca. 30 % (FFTs Ib and II) or ca. 50 % (FFTs Ia and IVb) of the total soil respiration (sum of autotrophic and heterotrophic respiration). Although wood respiration remains very difficult to measure, and although only model estimates were available, it became clear from this study that wood respiration represented a major flux which cannot be neglected in carbon balance assessments. For all FFTs the net canopy CO_2 uptake was simulated (for 1997) by means of a model, either multi-layer (Ia and Ib), or bi-layer (II) or detailed individual leaf (IVb). Species composition of the oak-beech stand (Ia) was assumed

35 % beech and 65 % oak, and of the ash stand (Ib) 83 % ash, 15 % oak and 2 % beech.

Differences in the aboveground litter production were not significant for FFTs Ia and Ib. The use of two different methods to calculate belowground litter production gave remarkably similar results for FFTs Ia and Ib. The higher production in the ash stand (Ib) could be explained by the higher turnover rate of the litter. Both the different soil respiration and the different belowground litter production rates were indicators of the different characteristics of the FFTs (see also chapter 2).

The total biomass increment can be calculated as the sum of the stem, branch and coarse root increments. The total aboveground biomass increment of FFTs Ia and Ib was of the same order of magnitude, but much larger than the values found for FFTs II and IVb.

For FFTs I, II and IVb the values of NEE, NPP and GPP (only for IVb) for the year 1997 are summarised in Table 4.3. The NEE of all FFTs was positive, which means that all FFTs studied here, were a sink of carbon during 1997. The NEE of the oak-beech forest (Ia) was much higher than the NEE of the other FFTs. In the case of the ash stand (Ib) this could be explained partially by lower photosynthetic rates and partially by higher respiration losses.

Table 4.3. *Summary of the most important carbon fluxes in 4 Functional Forest Types, either measured or derived through indirect techniques. NEE : net ecosystem exchange, NPP : net primary productivity, GGP : gross primary productivity. All values are expressed in ton C ha^{-1} y^{-1} and relate to 1997.*

Parameter	Ia	Ib	II	IVb
NEE	6.90	3.70	1.57[a]	2.10[b]
NPP	8.98[c] - 8.24[d]	6.45[c] - 8.48[d]	8.70[c] – 6.31[d]	
GPP				16.83

[a]measured by eddy covariance technique; [b]derived from carbon allocation and accounting; [c]using the gas exchange method; [d]using the carbon allocation method

The NEE, and thus the rate of carbon sequestration by the forests, varied depending on a number of specific factors that differed among the FFTs. These include the influence of :

- the tree species : in general, fast-growing species (ash, poplar, willow, *etc*...) produce their biomass very quickly, but their carbon density is slightly lower than slower-growing species (as beech and oak). Different tree species also require different management regimes and have different end uses;

- the rotation length : long-term plantations or natural forests generally have lower NEE. So, they sequester carbon more slowly as they age, eventually reaching carbon equilibrium. Repeated cycles of intensively managed fast growing trees could possibly produce a greater carbon benefit, although a recent study (Schulze *et al.* 2000) has cast doubts on this statement.

4.3 Simulated carbon fluxes obtained from mathematical modelling

Fluxes of carbon between different compartments of the forest ecosystem or between the ecosystem and the atmosphere (GPP, NPP, NEE, …) cannot always be measured. Sometimes they must be using a modelling approach. This summary of the final report only gives a short description of the models used by different research teams participating in the BELFOR programme. More detailed information can be found in the final report.

The **FORUG** model, which was used to simulate carbon fluxes in the Aelmoeseneie forest (I), is a process based multi-layer model, composed of several submodels. The forest is divided in five layers : an upper, middle and lower canopy layer, an understorey layer and a soil (and humus) layer. The model simulates both carbon and water fluxes in forest ecosystems. Within the FORUG model, a submodule calculates the CO_2-exchange at the leaf level using two different approaches : (i) the classical Light Response Curve (LRC) and (ii) the Farquhar approach (FA) (Farquhar *et al*. 1980). A seasonal evolution of the photosynthesis parameters is taken into account. Leaf respiration is calculated from a well-known submodel with an exponential temperature function. Gross photosynthesis and leaf respiration are then scaled up to the canopy layer by the LAI of the respective layer. The woody biomass (stem and branches) respiration is calculated according to Ryan (1990), based on stem surface area or sapwood volume. No distinction is made between growth and maintenance respiration. Soil respiration is calculated based on an empirical relationship deducted from measurements in the forest at Gontrode (I). No distinction is made between autotrophic and heterotrophic soil respiration. The time step for the simulations can be chosen (seconds, minutes, hours,…).

The process model used in Brasschaat (II), is called **SECRETS** (Stand to Ecosystem CaRbon and EvapoTranspiration Simulator). It was developed by combining several process submodules from a variety of sources. The internal structure for SECRETS is based on a modified version of the process model BIOMASS (McMurtrie and Landsberg 1992), as adapted by Sampson *et al.* (1996), including site specific adjustments to the water balance and maintenance respiration components. The sun/shade photosynthesis module (de Pury and Farquhar 1997), based on the Farquhar biochemical photosynthesis model (Farquhar *et al.* 1980) was also incorporated in both single- and multi-layer formulations. Soil carbon and nitrogen cycling is represented by the surface and soil module of the Grassland Dynamics simulation model (Thornley 1998) and input parameters for the specific simulations conducted here may be found in Sampson and Ceulemans (1999). SECRETS was written in Digital, visual Fortran 95 and runs on a daily time step, except for photosynthesis which runs on an hourly (or user-defined) time step.

The model **MAESTRA** was used for the 60-year-old beech plot in Vielsalm (IVb). This formulation was based on numerous measurements made at the site to determine the canopy architecture, biomass allocation and microclimate between May and October 1997. Allometric relations were developed to partition the stand biomass at individual tree level, thereby meeting the requirements of the model. The data resulting from the investigation include carbon pools and annual carbon fluxes. The estimates were validated using the eddy flux measurement technique in the study plot. These eddy fluxes were first processed using half hourly measurements in the frame of the EUROFLUX project. The soil respiration was estimated using an Arrhenius equation. A more detailed description can be found in Lefevre *et al*. (2000).

Besides the above-mentioned deterministic models (FORUG, SECRETS, MAESTRA), a **simple black box model** was developed during the BELFOR programme. This black box model can be used to assess the overall dry matter production of a forest stand. The black box approach assumes biomass accumulation to be the integration of the photosynthetic process of light energy conversion over the growing season. The relation between biomass production of plants and the amount of radiation absorbed can be described as follows (Landsberg 1986 and Cannell *et al*. 1987) :

$$B = \int_0^t e \cdot f \cdot I \cdot dt \qquad [4.1]$$

with B : the dry matter produced during the time period dt (g DM m^{-2}),

e : the photosynthetic conversion efficiency (g DM MJ^{-1}),

and $f \,.\, I$: the fraction (f) of the incoming radiation (I) absorbed during the period dt

(MJ m^{-2}).

Once the photosynthetic conversion efficiency e of a specific species is determined, this information can be used to assess the biomass production during a certain time period, if the amount of absorbed radiation is known. The advantage of this simple black box model relies in the fact that the input data set required to assess the biomass production B is quite easy to obtain : information is only needed for the amount of absorbed radiation $f \cdot I$ (I being short wave radiation or PAR). The parameter f is found from the leaf area index; while the photosynthetic conversion efficiency e can be determined from destructive calibration experiments in which both B and I are measured. The black box model is equivalent with the C-Fix model approach (see chapter 3.2). As an example, the photosynthetic conversion efficiency e for oak is given in Table 4.4, for five consequtive periods in the growing seasons 1996, 1997 and 1998.

Table 4.4. *Photosynthetic conversion efficiencies e (g DM MJ^{-1} APAR) for oak in the Aelmoeseneie experimental forest (I). Values are listed for the five periods of the 1996, 1997 and 1998 growing seasons. The seasonal mean for each growing season and the overall mean value for the period 1996-1998 are also given.*

		Period and day numbers					
		1	2	3	4	5	Seasonal mean
Species	**Season**	107-169	170-201	202-226	227-277	278-347	107-347
oak	1996	0.492	0.788	1.133	0.417	0.142	***0.595***
	1997	0.791	0.678	0.665	0.356	1.022	***0.669***
	1998	0.654	1.255	0.850	0.728	0.595	***0.816***
	Overall mean	**0.646**	**0.907**	**0.882**	**0.500**	**0.586**	**0.693**

The results for FFT I indicated that the value of e is not constant during the growing season (see for example the values of e in Table 4.4). This is a very interesting conclusion towards remote sensing applications where a fixed e value is frequently used (*e.g.* the C-Fix model).

5. TASK FORCE WATER

The biosphere strongly interacts with the atmosphere by its control on the return of water back to the atmosphere as evaporation and transpiration. After precipitation, some of the intercepted water returns to the atmosphere and evaporation occurs from the plants. Plants lose water as transpiration when CO_2 is taken up through the stomata. Besides this physiological transpiration process, the evaporation from the soil has to be linked with soil characteristics. It depends on the groundwater table, the structure of the soil in the unsaturated layers and the solar energy reaching the surface. Thus, the presence of vegetation and forest type, determine to a large extent the partitioning of the water into different intermediate reservoirs. The Task Force Water analysed the physiological and physical aspects of evapotranspiration occurring in a forest ecosystem. Therefore, the WAVE model was selected as a basic research instrument. The original version of the model was developed for agricultural crops by Vanclooster *et al*. (1994). Within the scope of BELFOR, it was adapted and implemented for forest ecosystems (Meiresonne *et al*. 1999).

5.1 Experimental and modelling activities

The Task Force calculated the water balance with **WAVE** (**W**ater and **A**grochemicals in soil, crop and **V**adose **E**nvironment). In Balegem (III) and Brasschaat (II), sap flow was measured in all experimental trees using the heat field deformation method with linear radial heating and a combined sensor (Nadezhdina and Cermak 1998, Meiresonne *et al.* 1999). In the Aelmoeseneie experimental forest at Gontrode (I), the calibration of WAVE was based on comparison of simulated and measured soil moisture pressure. In Vielsalm (IV) eddy fluxes were used to assess water vapour exchange between the forest canopy and the atmosphere according to Aubinet *et al.* (2000). In Chimay (V), the thermal Granier method was used (Granier 1987). More detailed information about the measuring techniques can be found in the final report of the BELFOR programme (Vande Walle and Lemeur 2001).

5.2 Water balance terms determined with the WAVE model

Results from WAVE are given in Table 5.1 where ‘Prec.’ stands for precipitation, ‘U-flux’ for upward fluxes, ‘Intercep.’ for interception, ‘Transp.’ for transpiration, ‘Evap.’ for evapotranspiration, ‘D-flux’ for downward fluxes, Runoff, Water storage and finally the ‘Error’ in the budget closure depending on the number of model runs.

5.3 WAVE validation and comparison with other approaches

The terms of the water balance expressed as cumulative amounts or time series were simulated with the WAVE model and compared with results from experiments and other models. Only a brief description of these comparisons is given here. More information can be found in Vande Walle and Lemeur (2001).

For Balegem (III), there was a good fit between the measured (sap flow technique) and the simulated transpiration (WAVE). The water balance model WAVE was calibrated both in Chimay (V) and Balegem (III) using measured soil moisture content. Even at depths with high fluctuations of soil water content, the WAVE model predicted these variations with high accuracy.

Table 5.1. *Cumulative terms of the water balance (mm) as simulated by the WAVE model for the whole soil profile in Gontrode (I), Brasschaat (II), Balegem (III) and Chimay (V)*

	Prec.	U-flux	Intercep.	Transp.	Evap.	D-flux	Runoff	Water stor.	Error
	+	=	+	+	+	+	+	+	+
Gontrode (I) : Period 6/4 – 19/10/1997									
Oak-beech	435.0	0.0	88.3	333.5	66.0	146.0	0.0	-198.8	0
Ash	435.0	0.0	75.0	359.8	102.6	0.0	0.0	-102.4	0
Brasschaat (II) : Period 1/1 – 31/12									
1997	672	248	140	313	206	202	0	+59	0
1998	1042	344	110	322	200	600	0	+156	0
Balegem (III) : Period 1/4 – 31/10									
1997	430	97	91	311	109	57	0	-41	0
1998	510	117	96	288	81	152	1	+9	0
Chimay (V) : Period 1/1 – 31/12									
1997	834	151	100	176	208	-440	77	4.4	-12
1998	1067	74	102	134	188	-599	136	-1.9	-21
1999	1055	122	91	196	222	-493	194	3.2	-17

For FFT II (Scots pine stand in Brasschaat), 3 methods were compared for the quantification of the stand evapotranspiration : the water balance model WAVE, the ecophysiological model SECRETS and the eddy covariance method for the measurement of the latent heat flux. The weekly trends in evapotranspiration (ET) for both models were reasonably well-correlated for 1997 and 1998, although the magnitude in ET varied at times. During summer, WAVE tended to yield higher estimates, while SECRETS gave higher values in the other seasons. The eddy covariance flux measurements were consistently lower in 1997, but came closer to the model data in 1998.

The terms of the water balance were also calculated for both the oak-beech and the ash stand of FFT I (Gontrode) with the FORUG model (Samson 2001) and with the Penman-Monteith approach (De Schrijver 2000). The Penman-Monteith approach yielded lower values for the potential evapotranspiration in comparison with the values obtained with the FORUG model. However, the values for actual evapotranspiration obtained with both methods were very close (Table 5.2). The differences between the results (besides the fact that the FORUG model yields estimates for the total forest Aelmoeseneie (58 % oak-beech and 42 % ash stand) (Samson *et al.* 1996)), can mainly be attributed to differences in parameter values, as both approaches are based on equivalent calculation methods. Actual evapotranspiration is about 50 % of the potential evapotranspiration for the oak-beech stand and for the whole of the Aelmoeseneie forest, whereas for the ash stand it is as high as 75 % (which might be an overestimation). It should however be mentioned that a correct definition of the concept of potential evapotranspiration is of very important (Samson 2001) in order to explain differences between potential and actual evapotranspiration.

5.4 Scientific evidence for water stress in (a) Belgian forest ecosystem(s)

One should not expect that Belgian forests might suffer from drought stress in the present climate conditions, as Belgium has a temperate maritime climate. From June to September 1997, CO_2 exchange and climatic parameters were measured for the Vielsalm experimental site (IV) according to EUROFLUX methodologies (Aubinet *et al.* 2000). Surface conductance was then calculated for both beech and Douglas fir (being the two main tree species) from latent heat flux using the inverted Penman-Monteith equation (see Vande Walle and Lemeur 2001). Analysis of surface conductance data showed a clear decreasing trend for surface conductance against water vapour saturation deficit. Also, a positive correlation between CO_2 exchange in saturating light and surface conductance was found. The preliminary conclusion of this investigation was that, given the relation between water vapour saturation deficit and surface conductance and the correlation between surface conductance and CO_2 exchange, the water vapour saturation deficit indirectly acted on CO_2 exchange via the surface conductance. As such, eddy flux measurements have demonstrated that the Belgian forests may suffer from drought stress in the present climate conditions, and that this stress restricts forest carbon uptake. This finding needs to be confirmed with additional measurements taken at the Vielsalm site.

Table 5.2. *Comparison of the potential (ETpot) and actual (ETact) evapotranspiration obtained by the Penman-Monteith (PM) approach and with the FORUG model (one-layer approach). Results are cumulative values for the period June to September 1997 and for the two forest stands in Gontrode (I)*

Period (1997)	**Total ET_{pot} (mm)**			**Total ET_{act} (mm)**		
	PM Oak-beech stand	PM Ash stand	FORUG	PM Oak-beech stand	PM Ash stand	FORUG
June	118.2	87.6	184.1	50.8	40.1	66.6
July	136.1	107.4	158.6	67.9	80.4	89.5
August	141.9	147.4	181.1	70.1	125.3	91.3
September	77.3	75.7	124.2	60.8	67.3	70.2

6. TASK FORCE NUTRIENTS

Carbon sequestration in forest ecosystems is regulated by a suite of environmental factors, including radiation, temperature and water, and also by nutrient availability. In most forests production of biomass is directly related to nutrient availability and uptake. The global cycles of carbon, nitrogen and other elements are perturbed by human activities in such a way that the transfer from large pools of non-reactive forms to reactive forms (essential to the functioning of the terrestrial biosphere (Norby 1998)) are increased. These cycles are closely linked at all scales, and Global Change analyses must consider C, N and other elements together. The Task Force Nutrients therefore focused on the cycling of the nutritive elements nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and Magnesium (Mg). It is a fact that each of these so-called macronutrients limits forest growth in some locations around the world.

6.1 Quantification of nutrient pools and fluxes

In the Functional Forest Types of the BELFOR programme, different nutrient pools are distinguished : the mineral soil, the forest floor and the above- and belowground vegetation (trees and understorey). Nutrient fluxes comprise i) all fluxes of internal cycling of nutrients and ii) the input and output fluxes. Nutrient inputs from the atmosphere, inputs from rock weathering and nutrient losses are important for the long-term development of soils and ecosystems. On an annual basis however, the nutrient recycling within the ecosystem forms the major source of nutrients for use by plants. The internal nutrient fluxes are :

- the litter flux : the amount of leaves, branches and fruits falling on the forest floor;
- the stem flow : the amount of (elements present in the) precipitation dropping onto the forest floor along the stems;
- crown wash or canopy leaching : the movement of substances derived exclusively from plant tissues to an aqueous solution in direct contact with the vegetation. Leaching may represent the largest transfer pathway from the canopy to the forest floor for mobile elements (Parker 1983, Potter *et al.* 1991);
- the nutrient uptake : the annual elemental increment associated with bole and branch wood plus annual loss through litter fall, leaf wash and stem flow (Cole and Rapp 1981);
- recycling or retranslocation : amount of nutrients that are relocated from the leaves to the wood and bark of the trees before the annual leaf fall.

More information on the measuring techniques and calculation methods used for the quantification of these nutrient pools and fluxes in the Functional Forest Types I, II, IV, V and VI can be found in Vande Walle and Lemeur (2001). For the poplar plantation in Balegem (III), no data on nutrient pools or fluxes were available.

6.1.1. The nitrogen (N) pools and fluxes

The mineral soil pool and the forest floor pool seem to strongly depend on the forest type. The differences in nitrogen-richness of the mineral soil pool can mainly be explained by the soil type on which the forests are situated. The great N pool found in the forest floors in FFTs Ia, II and VI indicate that these forests have a slow litter decomposition, in contrast to the ash stand in Gontrode (Ib), which has a small N pool because of its high decomposition rate. Chimay (V) is the only site where the throughfall water contains less N than the bulk deposition. This means that in Chimay nitrogen uptake takes place through the leaves, while in the other forests all deposited nitrogen is transmitted to the forest floor. Also in Chimay (V), almost no nitrate (NO_3^-) is leaching to the groundwater. This means that the system is closed because no nitrogen is leaving. Contrasting results were found in Gontrode (I) and Brasschaat (II), were very large amounts of nitrogen are leaving the ecosystem.

6.1.2. The phosphorus (P) pools and fluxes

The soil mineral P pool is very high in Chimay (V), intermediate in Gontrode B (Ib), low in Gontrode A (Ia) and very low in Brasschaat (II). The P content in the forest floor can be compared between the different forest types by means of the N/P ratio (see Table 6.1). From this table, it can be concluded that Chimay (V) has the most P rich litter, directly followed by Gontrode B (Ib). The N/P value obtained for Waroneu is extremely high due to a very high N content in the forest floor litter combined with relatively low P contents.

6.1.3. The potassium (K) pools and fluxes

As was the case for P, the K content in the forest floor can be compared between the different forest types by means of the N/K ratio (see Table 6.1). Gontrode B (Ib) has the most K rich litter, directly followed by Chimay (V). The litter of Gontrode A (Ia) and Vielsalm (IVa and IVb) is medium K rich, while the litter in Waroneu (VI) and Brasschaat (II) is very K poor.

In all forest types there is a large enrichment of K in the throughfall water compared to the bulk deposition. Also the crown leaching of K is high in all forest types (see Table 6.2). Although there is some K leaching to the groundwater, a lot of the K is taken up again by the trees. This phenomenon is very typical for K, as it is a very mobile element that moves as a free cation through the plant and remains unbound to any organic compound.

Table 6.1. *The N/P, N/K, N/Ca and N/Mg ratio of the forest floor litter for each Functional Forest Type (FFT)*

FFT	N/P	N/K	N/Ca	N/Mg
Ia	34.5	14.4	2.4	17.1
Ib	20.1	5.9	1.9	6.7
II	29.1	31.0	7.0	41.6
IVa	27.0	20.6	4.2	23.4
IVb	29.9	26.9	12.8	8.2
V	15.2	8.2	4.2	13.6
VI	163.1	28.6	13.6	62.4

Table 6.2. *Crown leaching (kg ha^{-1} y^{-1}) calculated according to Ulrich (1983) for 5 Functional Forest Types (FFT)*

FFT	K	Ca	Mg
Ia	51.3	2.4	1.3
Ib	74.5	26.2	5.9
II	10.8	0.4	0.8
V	14.3	3.6	0.5
VI	20.4	0.4	1.3

6.1.4. The calcium (Ca) pools and fluxes

The Ca mineral soil pool is very high in Gontrode (Ia and Ib) and very low in Brasschaat (II) and Chimay (V). Especially the exchangeable amounts, relevant for plant uptake, are very low in Chimay and Brasschaat. In all forest types there is a Ca enrichment of the throughfall water compared to the bulk deposition.

6.1.5. The magnesium (Mg) pools and fluxes

The soil mineral Mg pools are high in Gontrode (Ia and Ib), the Douglas stand at Vielsalm (IVa) and Chimay (V). The Mg pool in Brasschaat (II) is very low compared with the other forest types. It is however remarkable that in all forest types the exchangeable amounts of Mg are extremely low (especially in Chimay (V) and Brasschaat (II)). The Mg content of the litter is highest in the ash stand at Gontrode (Ib) and the beech stand at Vielsalm (IVb), intermediate in Chimay (V) and the oak-beech stand at Gontrode (Ia), low in the Douglas stand at Vielsalm (IVa) and very low in Brasschaat (II) and Waroneu (VI). The Mg content of the litter is clearly associated with the nature of the tree species.

Generally for all forest types, the Mg enrichment of the throughfall water compared to the bulk deposition is low. It is remarkable that, notwithstanding the low amounts of bulk deposition, rather high amounts of Mg are leaching from the forest soil. This might be due to the soil acidification and high amounts of acid depositions in the different forest types.

6.1.6. Conclusion

The overview of the nutrient pools and nutrient fluxes of the different Functional Forest Types, showed clearly that Brasschaat (II) is in general a very nutrient poor forest. This is mainly due to the soil type (sandy soil – podsol) on which the forest is located. Nitrogen depositions are moderately high in Vielsalm (IV), Chimay (V) and Waroneu (VI), and very high in Gontrode (I) and especially in Brasschaat (II). The consequence of the high N depositions is that all examined forest types – with exception of Chimay (V) – seem to be nitrogen saturated. The forest of Chimay (V) is the only one in which N is the limiting factor for forest growth, which is illustrated by the process of nutrient uptake through the leaves.

6.2 Assessment of the tree nutritive status by means of foliar diagnostics

It is an established fact that, within a certain range of foliar concentrations, positive relationships exist between the concentration of certain nutrients and the growth and outer appearance of plants. In the BELFOR programme, the technique of foliar analysis is evaluated in order to assess the tree nutritive status. Criteria have already been gathered for the assessment of the nutritive status of a number of tree species (as well coniferous as deciduous) based on foliar analysis (Van Den Burg 1985 and 1988). The "Van Den Burg criteria" can only be compared with leaf analyses when specific conditions are fulfilled. For more detailed information on these criteria, the reader is referred to the work of Van Den Burg (1985, 1988), or to the final report of the BELFOR programme (Vande Walle and Lemeur 2001).

Leaf element concentrations (Table 6.3) were determined for the main tree species in the FFTs I, II, IV and V. Gontrode (Ia and Ib) shows an insufficiency in P, as well as Brasschaat (II). However, Brasschaat (II) shows also an insufficiency in Ca and Mg, although the latter is ‘on the edges’. Concerning N, all Functional Forest Types have a sufficient or optimal nitrogen supply for the trees. For Chimay (V) the supply of all elements is sufficient.

Table 6.3. *Leaf element concentrations (ppm) for the main tree species of the Functional Forest Types (* : visual shortage, ** = insufficient, not marked = sufficient and bold = optimal according to the Van Den Burg criteria)*

FFT + species	N	P	K	Ca	Mg
Ia : oak					
1995	25582	1191**	9898	5094	1663
1997	26155	1214**	9381	5302	1398
Ib : ash					
1995	24073	1324**	7665	13605	2220
1997	27639	1336**	8772	15197	2928
II : pine					
1995					
0,5-yr-needles	**23394**	1295**	5782	1684**	687**
1-yr-needles	23804	1132	4451	2828	504
1997					
0,5-yr-needles	**21637**	1327**	5606	1740**	708
1-yr-needles	23076	1131	4291	2514	540
V : oak (summer ’96)	25200	1700	10000	4000	1100

A good nutritive balance of a tree is not only dependent on the absolute foliar concentrations, but also on the element ratios of nutrients in the leaves. Because of the large input of N from the atmosphere, it seems that especially the ratios between the macronutrients and N give a good indication of the nutritive status of the tree (Van Den Burg 1988, Weissen 1990).

For coniferous trees Van Den Burg (1988) established evaluation criteria for the ratios between P, K, Mg and N. The results of the evaluation showed that for Brasschaat (II) the ratios N/P, N/K and N/Mg are insufficient, which means that there is a deficiency in P, K and Mg. Criteria for element ratios in leaves of deciduous trees have not been established by Van Den Burg.

6.3 The nitrogen cycle

6.3.1. Forest soil acidification, nitrogen deposition and nitrogen saturation

As stated before, chronic atmospheric deposition has resulted in N saturation of previously N limited temperate forest ecosystems (De Schrijver *et al*. 2000). A crude way to identify sites that are N saturated is by comparing atmospheric N inputs to annual N leaching losses. However, using a simple input-output approach does not account for the role of internal processes and the release through mineralisation of N accumulated previously in the ecosystem. Based on these considerations, the occurrence of measurable NO_3^- leaching from the soil can be used as an indication that N sources exceed the N sinks in the system (Cole *et al.* 1992).

Within the framework of the European pollution control policy (UN-ECE Convention on Long-Range Transboundary Air Pollution) the 'Critical Loads' approach has been developed. A critical load can be defined as 'the maximum deposition of a given compound that will not cause long-term harmful effects on ecosystem structure and function, according to present knowledge'. The values for the critical loads can be found in De Vries *et al.* (1995) and Vanongeval *et al.* (1998).

In the Functional Forest Types I (Gontrode) and II (Brasschaat) the long-term critical loads are exceeded. For Brasschaat this involves a disturbance of the nutrient uptake, which was also found in the assessment of the tree nutritive status by means of the foliar diagnostics. In Brasschaat there appears to be a shortage of P, Ca and Mg. In Gontrode the current N deposition loads are situated on the edge of exceeding the critical load for nitrate pollution of the groundwater. This becomes also clear by means of the high amounts of nitrate leaching to the groundwater.

6.3.2. Potential net N mineralisation and net NO_3^- production in the Functional Forest Types

Forest ecosystems are characterised by the marked contrast between the total amount of N present, and the quantity actually available for uptake. In fact, 90 % of the N is organically bound, and only 1 % is in inorganic form (NH_4^+, NO_2, NO_3^-), available for plant uptake. The decomposition of this organic N by soil organisms, *mineralisation*, is counteracted by microbial N uptake for biosynthesis, *immobilisation*. The resultant of these two processes is referred to as net mineralisation. *Nitrification* is the oxidation of reduced forms of N into nitrite or nitrate. Nitrification is important in controlling N losses from the ecosystem, as it transforms the relatively immobile cation NH_4^+ to the mobile anion NO_3^-. As NO_2 or NO_3^- are substrates for *denitrification* to gaseous N oxides or N_2, N oxides may also be direct by-products of nitrification. *Nitrogen fixation* is the assimilation of atmospheric N_2 to form NH_3. Mineralisation and nitrification are thus key processes within the nitrogen cycle, controlling the amount of N available for uptake, losses from the ecosystem, and consequently primary production.

The specific aim of this part of the BELFOR research was to evaluate the potential net N mineralisation and net NO_3^- production in the Functional Forest Types. Therefore, three soil cores were taken at each site in March 1998. The treatment of these soil samples, and the analyses performed on them are described in Vande Walle and Lemeur (2001). Finally, net N mineralisation (sum of NO_3^--N and NH_4^+-N) and nitrification are calculated. They are expressed as mg per 100 g dry weight, and the use of cores of a known diameter allowed productions on an areal basis to be calculated.

The production data expressed for 100 g dry soil allow the comparison of the N mineralisation processes between the eight sampling sites. For all sites, the net N mineralisation (except Balegem (III) : not significant) and the net NO_3^--N production (except Balegem (III) and Waroneu (VI) : not significant) were significantly higher in the organic horizon compared to the mineral horizon.

In the organic horizon, Chimay (V) showed highest net NO_3^--N production, whereas Brasschaat (II), Vielsalm beech (IVb), Balegem (III) and Gontrode A (Ia) showed significantly lower NO_3^--N productions. Gontrode B (Ib), Vielsalm Douglas (IVa) and Waroneu (VI) were intermediate, being not significantly different from either site.

In contrast, net N mineralisation was highest for Gontrode A (Ia) and lowest for Balegem (III). In the other horizons, no significant differences in net N mineralisation were detected. In the Ah horizon, Chimay (V) and Brasschaat (II) were also the sites with highest and lowest net NO_3^--N productions, respectively. All other sites showed no significant differences. In the mineral horizon the net NO_3^--N production was highest for Chimay (V) and Gontrode B (Ib) and lowest for Gontrode A (IVa). No significant correlation could be established between the net NO_3^--N production and the net N mineralisation with soil pH.

In contrast to the previous results, production rates expressed on an areal basis take into account soil density. This information therefore characterises the ability of the site to supply nitrogen, rather than giving information on the microbiological process itself. In this case, Balegem (III), Gontrode B (Ib) and Chimay (V) had significantly higher net NO_3^--N production and net N mineralisation than the other sites (Fig. 6.1). These three sites are characterised by respectively a *Fraxinus* (Ib), *Quercus* (V) or *Populus* (III) tree cover and a relatively higher soil pH compared to the other sites.

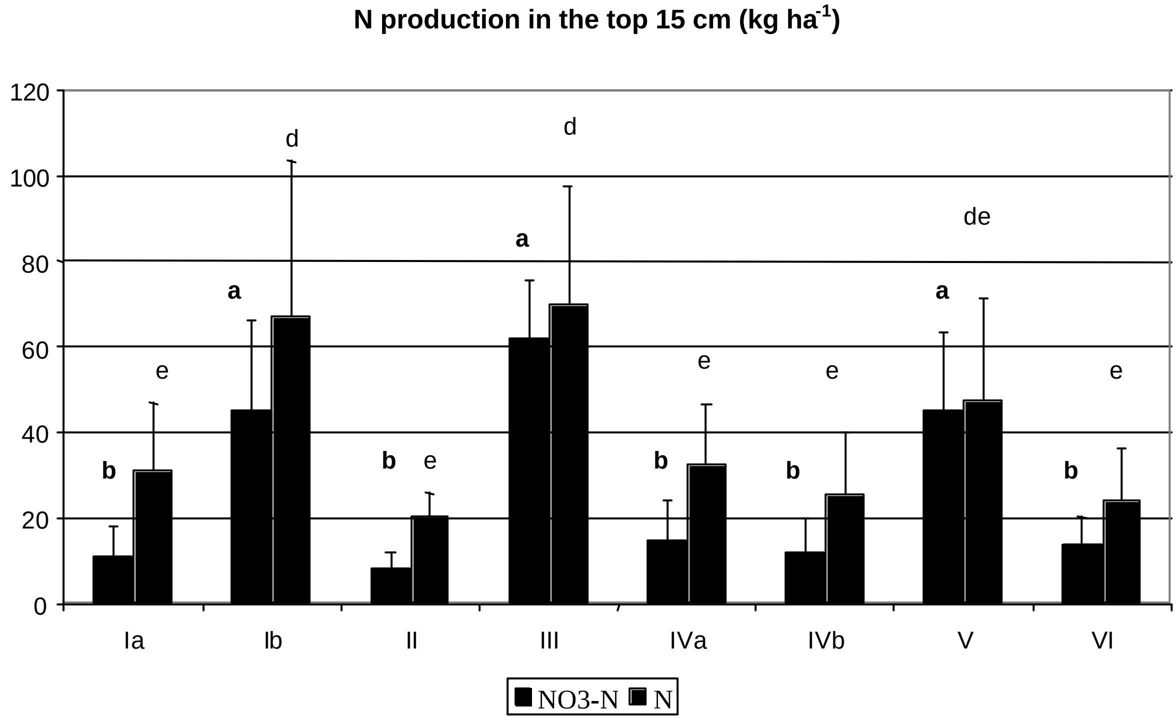

Fig. 6.1. *Net NO_3^--N production and net N mineralisation in the top 15 cm of the BELFOR soils after 6 weeks incubation (kg ha-1); different letters denote significant differences between sites*

7. TASK FORCE DATABASE

An important goal of the BELFOR project is the generalisation of previous as well as new experimental observations of impacts of CO_2 and temperature on trees to evaluate their likely consequences on the Belgian forest ecosystems in view of their sustainable development. For that purpose a database activity was set up which consisted of developing a MetaDataBase (MDB) in which all experimental results were ordered in a systematic way.

The main aims of this BELFOR MetaDataBase can therefore be described as follows :

- to make accessible all geographical and other global change relevant data held by any institute to employees and collaborators of the involved BELFOR institutes;
- by archiving the place where the data are stored;
- to make accessible the corresponding data to the other institutes of the network, together with quality information about it;
- to enable the investigator to survey all available data and to assess its quality and reliability;
- to co-ordinate the ordering of data and storage of metadata to avoid redundancies;
- to enable metadata interchange with national and international institutions by means of a distributed MDB on CD-ROM at the end of the project.

In the frame of the BELFOR programme, it was decided that a decentralised MetaDataBase would be constructed. More information on the main differences between centralised en decentralised databases can be found in Vande Walle and Lemeur (2001).

7.1 Description of the metadatabase implementation and structure

The BELFOR MetaDataBase was developed under Microsoft Access and could be accessed from the WWW by all participants of the BELFOR programme. The basic entities in the database are a site table (describing the site parameters as location, latitude, longitude, area, age,…), a parameter list table (indicating the measured parameters), a method list table (gives all the measuring techniques used) and an actual data set table (with information on the start and end date and the frequency of the measurements). These tables are relationally linked, enabling a structured query of the MDB.

In the MetaDataBase, the actual data are not available online, but presented as a set of descriptions of what has been measured on a specific site with a specified measuring technique. A soft link refers to the owners or authors of the data set(s) (e-mail or addresses) and hard links to the parameter list and method list.

7.2 Contents of the metadatabase

At the 15th of November 2000, 317 parameters were included in the MDB, of which 217 parameters were used by the different teams. A complete overview of these parameters is given in the final report of the BELFOR programme (Vande Walle and Lemeur 2001). In the MDB, 130 measuring methods were described, of which 70 were used. The measuring techniques are also listed in the final report, and literature references are provided. In total, 805 metadata records or data set descriptions are included in the BELFOR MDB. These are distributed over the different BELFOR teams according to Table 7.1.

Table 7.1. *Distribution of the data set descriptions over the BELFOR teams*

	BELFOR Team	*Number of data set descriptions*
1	*RUG – Lab. voor Plantecologie*	*68*
2	*RUG – Lab. voor Bosbouw*	*134*
3	*UIA – Dep. Biologie*	*86*
4	*IBW*	*249*
5	*FSAGx*	*67*
6	*UCL*	*109*
7	*ULg – Lab. Phys. Atmosp. et Plan.*	*n.a.*
8	*ULg – Lab. d'Ecol. Microb.*	*84*
9	*Vito*	*7*

n.a. : not applicable (modelling group)

7.3 Data retrieval and data provision by the WWW

The BELFOR metadata can be accessed via the WWW by the following URL :

http://www2.vito.be/belfor/login.asp

With respect to metadata access, a HTML interface was made accessible through the WWW for input, browsing, editing and listing of the BELFOR metadata for all BELFOR sites. As a result of this, starting from the beginning of 1998, all BELFOR teams were able to input the metadata descriptions at the Vito/TAP (team 9) website for each of the BELFOR sites, according to the agreed data set, parameter and methods descriptions.

A full description on how to look at all or specific records from a specified team (FILTER), how to see a listed view of all the records in the MDB (LIST VIEW), how to correct or remove erroneous records (EDIT SCREEN) and how to add new records (NEW RECORDS SCREEN) is given in the extensive final report (Vande Walle and Lemeur 2001).

7.4 Data requests

Concerning data requests by the teams, as well as the ones by scientists from outside the BELFOR network, but with access to the metadata (*e.g.* 'real' data as distributed through CD-ROM access), it should be mentioned that property rights for the real data have not been specified yet. They will depend on the discussions with the SSTC who owns the data. So in case a request is formulated by mailing to Vito or to another member of the network, a protocol will have to be established. In that case, the SSTC will have to offer the authorisation to the data distributor and data producer to deliver the 'real' data to the requester. This protocol will be subject of a final negotiation between the team leader of the Task Force Database, the BELFOR co-ordinator and the SSTC officials. Once this protocol has been negotiated, the requesters will have to comply with the articles taken up in the BELFOR – SSTC protocol.

7.5 Conclusions

The MDB of BELFOR was successfully implemented and made accessible to the BELFOR teams. It has grown into a landmark of network data management, which is quite unique within the Belgian context. Examples of this approach can only be found at the international level of the global change research community (*cfr*. PIK MDB approach in Germany). Though this task was originally considered as a rather adminstrative activity, the BELFOR MDB has grown into an instrument of enhanced network integration and network efficiency.

8. GLOBAL CHANGE PREDICTIONS AND SCENARIOS

The findings listed here contain the results of both experimental and modelling activities carried out by some BELFOR teams involved in Global Change scenarios.

8.1 Tree growth under elevated CO_2 : experiments in Open Top Chambers (OTCs)

Teams 3 and 5 of the BELFOR programme developed multi-year experiments in open top chambers (OTCs). In these OTCs, young trees are subjected to increased levels of CO_2 as compared to normal atmospheric levels. Such type of investigations enables the assessment of particular physiological responses in temperate forests, to be expected when 21st century atmospheric CO_2 levels occur.

The experimental facilities of the teams 3 and 5 are extensively described in Vande Walle and Lemeur (2001). Team 3 used young Scots pine seedlings, which were planted in 4 OTCs. Two chambers had an ambient CO_2 concentration (ca. 350 µmol mol^{-1} or the current background level), while in the others an elevated CO_2 concentration was maintained (ambient + 350 µmol mol^{-1}). In Vielsalm (IV), 8 Open Top Chambers and 4 Unchambered Experimental Units (UEUs) were available. The complete experimental design is described in Laitat *et al.* (1994). In the OTCs, young Norway spruces were planted. Nominal CO_2 concentrations in the OTCs were about 700 ± 65, 583 ± 50, 467 ± 35 and 350 ± 21 µmol mol^{-1}.

8.1.1. Results for Scots pine in the OTCs at the UIA campus (Team 3)

Both during the first (1996) and second (1997) growing season of the experiment, spring bud phenology of the plants growing under elevated CO_2 conditions differed significantly from that of plants in the ambient CO_2 treatment (Jach and Ceulemans 1999). Budburst was significantly hastened by the elevated CO_2 treatment during both years, in 1996 with 6 days ($p = 0.05$) and in 1997 with 9 days ($p = 0.001$). Dry matter (DM) of litter fall in the elevated CO_2 treatment was significantly ($p = 0.01$) higher and averaged 53.0 (± 2.9) g DM per tree versus 33.3 (± 7.2) g DM per tree in the ambient CO_2 treatment. However, no difference between the CO_2 treatments was found when litter fall was expressed as a ratio of total DM of litter fall to total DM of one-year-old needles per tree.

The CO_2 enrichment significantly enhanced both stem height and diameter growth (Jach and Ceulemans 1999). The absolute difference in average stem height was 4.1 cm after one growing season, 21.8 cm after two growing seasons and 34.0 cm after three growing seasons. Relative difference in stem height between the elevated and the ambient CO_2 treatment, was + 6 % in 1996, + 20 % in 1997 and + 18 % in 1998. The absolute difference in average stem diameter was 4.0 mm after one growing season, 7.2 mm after two growing seasons and 7.0 mm after three growing seasons. Relative difference in stem diameter of elevated CO_2 grown trees as compared with ambient, was + 29 % in 1996, + 27 % in 1997 and + 20 % in 1998.

The elevated CO_2 treatment affected several aspects of branch and needle growth (Jach and Ceulemans 1999). During the first year, the main effect of CO_2 on branch characteristics was an increase in total shoot length through an increase of the length of individual shoots. The relative difference in total shoot length between ambient and elevated CO_2 grown trees was 28 %. Longer shoots together with a higher individual needle area in the elevated CO_2 treatment accounted for a 33 % increase in total needle area, as compared with ambient. Carbon dioxide had a significant effect on number of shoots, but not on needle density. During the second year LAI was estimated to be 3.66 (± 0.26) and 1.62 (± 0.24) in elevated and ambient CO_2, respectively. Dry mass (DM) of all needles was 114 % higher in the elevated CO_2 grown trees. During the third year, no significant difference between the treatments was found in total needle area per tree (+ 22 % in the elevated CO_2 treatment) and number of branches (+ 12 % in the elevated CO_2 treatment), however the length of branches was significantly higher (by +28 %) in CO_2 treated trees. The estimated LAI was 3.2 (± 0.5) and 2.6 (± 0.8), respectively in elevated and ambient CO_2 treatment.

Seedlings were harvested in October 1998, after three years of CO_2 treatment. The total biomass increased by 55 % under elevated CO_2 conditions. Shoot biomass increased by 75 %, stem biomass by 49 %, bud biomass by 5 %, and root biomass by 152 %.

Since LWR (leaf weight ratio) (Table 8.1) was lower under elevated CO_2, it can be concluded that the trees under elevated CO_2 conditions were more efficient in producing the same amount of biomass with a smaller amount of needles. Moreover, RWR (root weight ratio) was significantly higher in the elevated CO_2 treatment (Jach *et al.* 2000). Also R/S (root/shoot ratio) increased in the elevated CO_2, indicating a considerable biomass allocation below ground (Table 8.1). There was especially an increase in fine root (< 2 mm) mass.

Table 8.1. *Mean values of biomass allocation in Scots pine seedlings, from harvest in October 1998, after three years of growth in OTC under ambient or elevated CO_2 (i.e. 700 µmol mol $^{-1}$) in the atmosphere. Mean and standard error (within brackets) are shown, n = 12. D % = differences calculated as 100 ´ (elevated CO_2 - ambient CO_2)/ambient CO_2. Significant differences are shown as ***: p £ 0.001, **: p £ 0.01, *: p £ 0.05, n.s.: not significant.*

Parameter	Ambient	Elevated	Sign. diff.	D %
LWR (g g^{-1})	0.34 (0.01)	0.28 (0.01)	*	- 17
RWR (g g^{-1})	0.12 (0.01)	0.23 (0.01)	***	+ 92
R/S (g g^{-1})	0.22 (0.01)	0.36 (0.02)	***	+ 64

Foliar N concentration was significantly lower under elevated conditions, but there was no significant effect on N concentration in shoots and coarse roots. Stem wood N concentration was below the detection limit (Jach *et al.* 2000). In 1-2 mm fine roots the N concentration was lower in elevated CO_2 than in ambient conditions, while the opposite was true (not significant) for fine roots less than 1 mm in diameter.

After six months of exposure to elevated CO_2, root production measured by root in-growth bags, showed significant increases in mean total root length (+ 122 %) and biomass (+ 135 %), compared to the ambient treatment. This increased root length may have led to a more intensive soil exploration. Chemical analyses of the roots showed that roots in the elevated treatment accumulated more starch (2.6 *vs.* 4.9 % of DM) and had a lower C/N ratio (26.1 *vs.* 21.0). Specific root respiration rates were significantly higher in the elevated treatment (by + 45 %) and this was probably attributed to increased N concentrations (by + 29 %) in the roots, as compared to the ambient CO_2 treatment (Janssens *et al.* 1998). Rhizospheric respiration and soil CO_2 efflux were also enhanced in the elevated treatment and accounted for 66 to 71 % of total soil CO_2 efflux under elevated CO_2 and for 50 to 57 % under ambient CO_2. These results clearly indicated that under elevated atmospheric CO_2 root production and development of the seedlings were altered and respiratory carbon losses through the root system were increased (Janssens *et al*. 1998).

8.1.2. Results for Norway spruce in the OTCs of the FSAGx team (Team 5)

From 1994 to 1997, Norway spruces grew progressively higher in the increased CO_2 OTCs than in the control OTCs (350 µmol CO_2 mol^{-1}) (Table 8.2). Tree responses to increased CO_2 levels were similar in the 467 and 583 µmol mol^{-1} treatments. Tree height at 700 µmol mol^{-1} was lower than at 583 and 467 µmol mol^{-1}. These results suggest that maximum stem elongation was obtained at about 500 µmol mol^{-1}, while some inhibitory effects on stem elongation seemed to appear at 700 µmol mol^{-1}. The largest increase in height occurred during the 1996 growing season. The largest increase in biomass occurred in the 583 µmol mol^{-1} treatment, with total tree biomass being 134 % of that measured in the control (data not reported). At 700 µmol mol^{-1}, total biomass was only 14 % greater than that of the control treatment.

Table 8.2. *Relative increase in total height (H) due to increased CO_2 concentration for Norway spruce grown in OTCs during the 1994-97 period*

CO_2	**H 94 (%)**	**H 95 (%)**	**H 96 (%)**	**H 97 (%)**
700 vs. 350	**- 1.00**	+ 0.92	+ 7.72	+ 13.29
583 vs. 350	+ 2.84	+ 5.19	+ 21.39	+ 27.26
467 vs. 350	+ 4.09	+ 14.29	+ 29.37	+ 35.45

Table 8.3 shows the effects of elevated CO_2 on the allocation of biomass in the subplots. The 700/350 ratios reflect to a lesser extent the results discussed above. At 700 µmol mol^{-1}, aboveground biomass increased by about 14 %. Total fine root mass (< 5 mm) increased by 3%, while living fine root mass decreased by 8%. The increase in fine dead roots was much higher (+ 40 %), suggesting a higher root turnover under elevated CO_2. Root necromass represents 10 % of the total biomass at 350 µmol mol^{-1} and 17 % at 700 µmol mol^{-1}. The total biomass increased by 6 % when considering both above- and belowground contributions. When including dead roots, this increase reached 10 %. Aboveground allocation was strongly affected by CO_2 with an increase in branches (+ 38 %) and needles mass (+ 60 %) at the expenses of trunk (- 8 %). Similar effects of a doubling of CO_2 concentrations were reported by Lee *et al.* (1998).

8.1.3. Conclusions

Both experiments indicate that saplings of coniferous temperate trees respond to elevated CO_2 by an increase in stem height and biomass. Allocation patterns were not consistently modified at both experimental sites, which suggests that this response is species-specific. Scots pine allocated more resources to belowground organs when subjected to elevated CO_2, while this pattern was not observed for Norway spruce. The Scots pine experiment indicates that phenology is modified by elevated CO_2, which might help the trees take advantage of longer growing seasons as global warming progresses. The Norway spruce experiment indicates that tree growth enhancement in response to elevated CO_2 is maximum at about 500 µmol mol^{-1}.

Table 8.3. *Effect of doubled CO_2 concentration on Norway spruce grown in OTCs*

	Units	350 µmol mol^{-1} CO_2	Biomass 700/350 (%)
1. Aboveground Biomass	(kg DM m^{-2})	1.101	**+13.9 %**
1.1 Trunk	(kg DM m^{-2})	0.661	**-8.2 %**
1.2 Branches	(kg DM m^{-2})	0.270	**+38.4 %**
1.3 Needles	(kg DM m^{-2})	0.170	**+60.7 %**
2. Fine Root Mass	(kg DM m^{-2})	0.829	**+3.4 %**
2.1 Dry mass of living fine roots (< 5 mm)	(kg DM m^{-2})	0.630	**-8.3 %**
depth [0-15cm]	(kg DM m^{-2})	0.411	**-9.3 %**
depth [15-30cm]	(kg DM m^{-2})	0.137	**+12.5 %**
depth [30-45cm]	(kg DM m^{-2})	0.075	**-58.9 %**
depth [45-60cm]	(kg DM m^{-2})	0.008	**+206.1 %**
2.2 Length of living roots	(m ha^{-1})	9383	**+18.3 %**
2.3 Dry mass of dead fine roots (< 5 mm)	(kg DM m^{-2})	0.199	**+40.4 %**
3. Ratio aboveground/fine root biomass	-	1.75	**+24.2 %**
4. Root/shoot ratio	-	2.33	**-33.4 %**
5. Total Biomass	(kg DM m^{-2})	1.731	**+5.8 %**

8.2 Photosynthetic response curves to elevated CO_2

The response of photosynthetic rates to increased atmospheric CO_2 and temperature must be experimentally determined to predict forest responses to 21st century environmental conditions. Hence, forest models such as ASPECTS need an accurate description of photosynthetic processes and their response to increased atmospheric CO_2 and temperature. Nowadays, the Farquhar model, used in ASPECTS, is the most widespread photosynthesis model. This model is based on A-C_i curves, which represent the relation between the photosynthetic rate A (µmol CO_2 m^{-2} s^{-1}) and the internal CO_2 concentration C_i (µmol CO_2 mol^{-1} air), which can also be expressed as the partial pressure of CO_2, p_i (µbar) (Farquhar *et al.* 1980, Farquhar and Sharkey 1982). This C_i is directly related to the atmospheric CO_2 concentration Ca, which makes the model very useful in studying photosynthesis under 'global climate change'. Walcroft *et al.* (1997) give a clear summary of the theoretical background and the calculations related to this approach of the photosynthesis process. The two main parameters that have to be determined are Vc_{max} (µmol CO_2 m^{-2} s^{-1}), the maximal carboxylation rate, and J_{max} (µmol e^- m^{-2} s^{-1}), the maximum rate of electron transport. Both Vc_{max} and J_{max} are input parameters for vegetation models.

The studies summarised in this section aimed at determining the values of Vc_{max} and J_{max} for the young Scots pines grown in the OTCs at the UIA campus (Team 3) and for the main tree species of the mixed deciduous forest Aelmoeseneie at Gontrode (I), which are beech and ash, and for three shrub species : hazel (*Corylus avellana* L.), sycamore (*Acer pseudoplatanus* L.) and rowan tree (*Sorbus aucuparia* L.). A second objective was to study the relation between Vc_{max}, the specific leaf area and the N content of the leaves. This information can then be used as input for dynamic vegetation models.

8.2.1. Results for Scots pine grown in OTCs at the UIA campus (Team 3)

The research strategy used by Team 3 for the young Scots pine trees is clearly elucidated in Jach and Ceulemans (2000). The measuring techniques and sampling method used in Gontrode can be found in Vande Walle and Lemeur (2001).

Leaf photosynthetic CO_2 assimilation rates, when measured at the growth CO_2 concentration (A_{growth}), were significantly enhanced by the elevated CO_2 treatment during all measuring periods of the second growing season of the treatment. The yearly stimulation of photosynthesis at growth CO_2 (data pooled over the growing season) averaged 62 % for one-year-old needles and 65 % for current-year needles, *i.e*. a 63 % stimulation for both needle age classes combined. When measured at the same atmospheric CO_2 concentration (350 or 700 µmol mol^{-1}), light saturated photosynthesis was significantly lower over the growing season in foliage grown at elevated CO_2, than at ambient CO_2 concentration. When measured at 350 µmol mol^{-1}, photosynthesis (A_{350}) of one-year-old needles declined at the end of the season in both treatments, as a result of leaf senescence. However, this decline seemed to be faster in the elevated CO_2 treatment. Needle age also had a significant effect on photosynthesis with one-year-old needles showing lower rates than current-year needles. On an annual basis (all measuring periods pooled together), A_{350} of one-year-old needles and current-year needles was respectively 23 % and 18 % lower in elevated CO_2 as compared with ambient CO_2. When all measuring periods and needle age classes were pooled together, a 21 % reduction of photosynthesis at elevated CO_2 was observed during the second year of treatment. The ratio of intercellular CO_2 partial pressure to atmospheric CO_2 partial pressure (C_i/C_a) was not significantly affected by the CO_2 treatment during the course of the growing season. Downward adjustment of photosynthesis was apparent in both needle age classes and resulted in significant reductions in both Vc_{max} and J_{max} in the elevated CO_2 treatment (Jach and Ceulemans 2000).

There was a significant, overall effect of CO_2 treatment on Vc_{max}, although treatment differences were not significant in May (only a very slight reduction of photosynthesis by 4 % under elevated CO_2). In July and September a statistically significant reduction of the Rubisco capacity in the elevated CO_2 treatment as compared with the ambient treatment was observed in both needle age classes. The relative reduction of the Rubisco capacity between the elevated and ambient CO_2 treatments was about 54 % and 24 % in July and about 31 % and 30 % in September, for one-year-old and current-year needles, respectively. So, when all measuring periods and needle age classes were pooled together, an overall reduction of Rubisco capacity by 28 % was detected (Jach and Ceulemans 2000). A significant overall age effect was observed, indicating that current-year needles generally had a higher Rubisco capacity than one-year-old needles. There was no overall effect of CO_2 treatment on the electron transport capacity, J_{max}, over the course of the growing season. However, a significant decrease of J_{max} in the elevated CO_2 treatment was observed for both needle age classes, in July and September. When all measuring periods and needle age classes were pooled together, an overall reduction of J_{max} by 34 % was observed.

Except for one-year-old needles in ambient CO_2 the photosynthetic parameters Vc_{max} and J_{max} were significantly and positively correlated with needle N (Jach and Ceulemans 2000). The regression of J_{max} with N had steeper slopes than Vc_{max}, regardless of needle age. Growth under elevated CO_2 resulted in steeper slopes and lower intercepts of the regressions of Vc_{max} and J_{max} to needle N compared with the ambient CO_2 treatment, but this difference was most pronounced in one-year-old needles. A reduction of the intercept of the regression between Vc_{max} and leaf N in tree seedlings grown at elevated CO_2 compared with those in ambient CO_2 was found. In this experiment, the strong negative linear relationship between N and SLA indicated that N concentration on an area basis decreased with increasing mass per unit needle area. Consequently, negative relationships of Vc_{max} and J_{max} with SLA were found. So, lower SLA resulted generally in higher photosynthesis per unit leaf area. Differences in the relationships of Vc_{max}/N and J_{max}/N between the ambient and elevated CO_2 treatment might indicate differences in N use efficiency.

8.2.2. Results for the deciduous species grown in the Aelmoeseneie forest at Gontrode (I) (Team 1)

Table 8.4 presents values for Vc_{max} and J_{max} found for the main tree species growing in the Aelmoeseneie forest at Gontrode (I). From the measuring tower, branches were cut from the trees at different heights (7, 14 and 21 m). The branches were transported to the laboratory, were measurements were performed. Data were obtained for 4 consecutive periods of the 1999 growing season. From Table 8.4, it can be concluded that there was a variation in time for the Vc_{max} value, and that the lowest value was observed in October. The moment of the highest value was, however, not unambiguous : for the shrub species Vc_{max} was highest in July, for beech at 7 and 14 m height, the highest value was found in August and for beech at 21 m, the values remained almost equal during the summer period. For J_{max}, the pattern was even less clear.

For both Vc_{max} and J_{max}, an increasing trend towards the top of the canopy was observed. Vc_{max} and J_{max} values found in this study were in the lower range of results found in literature (Kellomäki and Wang 1997, Medlyn *et al.* 1999). Many studies however focussed on young trees or saplings which makes comparison of results difficult. The mean value (for all species and over the entire growing season) of J_{max}/Vc_{max} was 1.84 ± 0.52, which corresponds very well with results of Walcroft *et al*. (1997). A linear regression analysis gave following equation :

$$J_{max} = 1.50\, Vc_{max} + 7.56 \qquad (R^2 = 0.63) \qquad [8.1]$$

Table 8.4. *Values of Vc_{max} in µmol CO_2 m^{-2} s^{-1} (first line ± st. dev.) and J_{max} in µmol e^- m^{-2} s^{-1} (second line ± st. dev.), for the different species; different letters within a row indicate statistically different values ($p < 0.05$)*

1999	July	August	September	October
Ash	-	51.67 (9.71) a	42.25 (5.85) a	23.75 (9.03) b
	-	99.00 (17.58) a	69.50 (24.34) a,b	49.25 (19.99) b
Beech 21 m	38.67 (3.06) a	37.33 (1.53) a	39.25 (4.57) a	19.75 (0.96) b
	74.65 (11.59) a	66.00 (11.27) a	82.50 (9.68) a	62.25 (11.24) a
Beech 14 m	22.75 (4.19) a	41.00 (4.00) b	29.00 (2.45) a	22.00 (4.69) a
	43.25 (5.74) a	62.00 (5.57) b	36.25 (6.08) a	45.25 (9.57) a,b
Beech 7 m	26.67 (4.73) a	46.00 (6.25) b	27.50 (3.87) a	21.75 (3.20) a
	44.33 (4.16) a	46.67 (5.77) a	41.50 (3.70) a	40.75 (4.79) a
Hazel	32.25 (5.50) a	18.50 (3.32) b	24.50 (5.00) a,b	20.67 (3.06) b
	53.75 (11.30) a	28.25 (5.74) b	39.00 (10.89) a,b	29.67 (12.10) a,b
Rowan	28.50 (2.38) a	22.00 (1.00) b	13.00 (2.16) c	10.67 (3.79) c
	69.50 (3.42) a	30.00 (4.36) b	22.25 (3.77) b	24.00 (9.54) b
Maple	24.50 (2.12) a	8.50 (0.71) b,c	17.00 (4.08) a,b	2.67 (0.58) c
	31.5 (0.71) a	18.00 (1.41) b	45.25 (3.50) c	4.33 (1.53) d

The specific leaf area SLA was lowest in the upper part of the canopy (ash and beech at 21 m), which corresponds with the study of Walcroft *et al.* (1997). For these leaves, higher Vc_{max} values were measured. This negative relationship was translated into the following regression equation : Vc_{max} (µmol CO_2 m^{-2} s^{-1}) = 50.7 – 1108.5 * SLA (m^2 g^{-1}).

The N content of the leaves (determined by the Kjeldahl method) was expressed as µg N g^{-1} leaf and as g N m^{-2} leaf. In the first case, no relation could be found between the N content and Vc_{max} (Fig. 8.1.a). From Fig. 8.1.b, it can be concluded that the ash and the beech at 21 m have a higher N content than the other species, when expressed on a leaf area basis. This negative correlation between SLA and leaf N content was also observed by Walcroft *et al*. (1997). The regression equation established on base of data used in Fig. 8.1.b was : Vc_{max} (µmol CO_2 m^{-2} s^{-1}) = 4.9 + 18.1 * N (g N m^{-2} leaf).

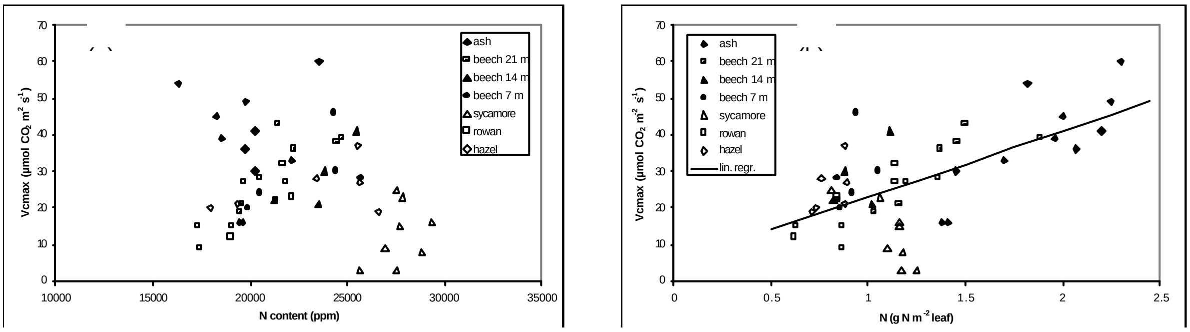

***Fig. 8.1**. Vc_{max} values in relation to (a) N (ppm) and (b) N (g m^{-2}); regression equation in (b) : Vcmax = 4.9 + 18.1 * N*

8.2.3. Conclusions

Studies conducted on Scots pine in OTCs and deciduous species at Gontrode (I) indicate that Vc_{max} and J_{max} are difficult to determine because these parameters display wide variations according to : (1) the time of measurement during the growing season, (2) the position of the leaves within the canopy, (3) the age of the leaves and the needles. These results underscore the difficulty to precisely determine species-specific values for the photosynthetic parameters, as previously reported by Peterson et al. (1999). In spite of the high variability of Vc_{max} and J_{max} values, three 'groups' of species could be distinguished in the Gontrode study : (1) the upper tree species / leaves (ash and beech at 21 m), which have the highest Vc_{max} and J_{max} values, the lowest SLA and the highest N content expressed on a leaf area basis; (2) the group of the shrub species (hazel, rowan and sycamore), with the lowest Vc_{max} and J_{max} values, the lowest N content and the highest SLA; and (3) the 'lower' tree species, which have intermediate characteristics. As such a distinction can be made between "sun" leaves with high photosynthetic capacity at the upper levels and the lower "shade" leaves with reduced capacity.

Relationships between Vc_{max} and leaf N content were obtained for Scots pines in OTC and deciduous species at Gontrode (I). Nevertheless, correlations between these two variables were fairly low because of the high variability of Vc_{max} measurements. This difficulty to precisely parametrise Vc_{max} and J_{max} relationships with leaf N content, together with the variability in space and time, severely limits our ability to accurately model canopy photosynthesis in a changing environment. Notwithstanding these limitations, crucial experimental results were obtained with respect to the characteristics of photosynthesis in a changing environment. Firstly, assimilation rates were increased under elevated CO_2; and secondly, the Vc_{max} and

J_{max} parameters were lower for leaves with long-time exposure to elevated CO_2 concentrations. This suggests an adaptation of the photosynthetic apparatus to the new environmental conditions. The benefit for an increased biomass accumulation under elevated CO_2 might more rely on an increased expansion of leaf area than an increased photosynthesis rate.

8.3 Reconstructed and predicted climatic and atmospheric CO_2 conditions for the 1900-2100 period

Site-specific synthetic weather data sets were developed on a sub-hourly basis for the 20th and 21st centuries from : (1) two to four years of measured meteorological data, depending on the site, and (2) outputs of a general circulation model (GCM) for the 1900-2100 period. These synthetic weather data are needed for simulating forest growth during the 20th century, as site-specific measurements on a sub-hourly basis were available only for 2 to 4 years in the late 1990's. In addition, these synthetic weather data need to incorporate climate change scenarios so that the ASPECTS model can be used to predict temperate forest growth under 21st century environmental conditions. Climate change scenarios are tightly coupled to the predicted increase in atmospheric CO_2 due to human activities. Therefore, ASPECTS predictions for the 21st century that will be presented in the next section are based on both climate change and atmospheric CO_2 rise scenarios. The site-specific synthetic weather data sets were generated for three of the BELFOR sites : Vielsalm (IV), Brasschaat (II) and Chimay (V).

Simulated weather data from the Canadian Global Coupled Model (CGCM1) (McFarlane et al. 1992, Flato et al. 2000) of the Canadian Center for Climate Modeling and Analysis (CCCMA) were used in the BELFOR programme. The CGCM1 model computes the atmospheric general circulation in response to an increase in the concentration of atmospheric CO_2 over the 20th and 21st centuries based on the IS92a (‘business as usual’) IPCC scenario. The radiative forcing of the climate system includes a warming by greenhouse gases and a cooling by sulphate aerosols (Reader and Boer 1998, Boer et al. 2000a, b). The equilibrium climate sensitivity of CGCM1, i.e. the global mean temperature response to a doubling of the effective CO_2 concentration, is about 2.5 °C. Monthly results are available in a database maintained by the Data Distribution Center of the Intergovernmental Panel on Climate Change (DDC-IPCC). The spatial resolution is 3.75° in longitude and about 3.7° in latitude.

Monthly averages of GCM-simulated weather data were extracted for the two grid cells corresponding to the Belgian territory. The Brasschaat (II) and Chimay (V) sites belong to the same grid cell, while Vielsalm (IV) belongs to the other. The downscaling procedure was conducted in a two-step approach. First, a spatial downscaling was conducted to ensure that GCM and measured site-specific monthly averages were identical over the period of measurement. This operation is necessary because grid-cell GCM outputs do not necessarily correspond to local measurements conducted in a specific set of altitudinal and latitudinal conditions within the grid cell. Second, time downscaling was conducted to add sub-hourly variability to the 200 years of locally-adjusted GCM simulations. More details about these two types of downscaling are given in Vande Walle and Lemeur (2001).

After the downscaling procedure, an atmospheric CO_2 forcing was built, similar to the forcing used in the GCM simulations. This is an increase based on historical records from 1900 to 1990 followed by a projection until 2100. The annual values of atmospheric CO_2 concentration were assumed to increase exponentially during both periods. As a consequence, annual atmospheric concentration $[CO_2(y)]$ at year y between y_1 and y_2 is given by :

$$[CO_2(y)] = [CO_2(y_1)] \cdot \exp(K_{12}.(y - y_1)) \qquad [8.2]$$

with

$$K_{12} = \frac{\ln\left(\frac{[CO_2(y_2)]}{[CO_2(y_1)]}\right)}{y_2 - y_1} \qquad [8.3]$$

The annual value of atmospheric CO_2 concentration was set to 300 µmol mol^{-1} in 1900, a mean value found in the air enclosed between 1883 and 1925 in the ice core of Siple Station, and to 355 µmol mol^{-1} in 1990, close to measurements at various sites in the Northern Hemisphere (Boden et al. 1994). The level of atmospheric CO_2 concentration reached in 2100 was estimated to 700 µmol mol^{-1}, as calculated by the scenario IS92a with the Bern model (Houghton et al. 1995). As a consequence, the values of K_{12} are 0.19 % y^{-1} and 0.62 % y^{-1} for the periods 1900-1990 and 1990-2100, respectively.

Annual averages of the six meteorological variables composing the site-specific synthetic weather data sets were not identical among sites during the 1900-2100 period. These differences originate from both the GCM scenarios, i.e. different GCM grid cells, and the measured data, i.e. site-specific conditions such as altitude. The most important climatic difference between the two sites appears to be temperature, with Brasschaat being consistently an approximate 3 ºC warmer than Vielsalm during the 1900-2100 period. Atmospheric pressure is also substantially higher at Brasschaat than at Vielsalm, as a direct result of the difference in altitude. Relative humidity remains on average 3 to 4 % higher at Vielsalm than at Brasschaat throughout the period. Consistent differences between the two sites in solar radiation, precipitation and wind speed are also predicted for the 1900-2100, although the magnitude of the difference is lower than the amplitude of the interannual variability. Because these two sites belong to two separate GCM grid cells, the interannual variability is not identical for the two sites, although quite similar.

According to CGCM1 simulations, temperature appears to be the only climatic variable which will be substantially modified in the course of the 21st century. Although the overall equilibrium climate sensitivity of CGCM1 is 2.5 ºC for the planet, predicted temperature increase for Belgium from 2000 to 2100 approximates 3 ºC. Predicted changes for the other five climatic variables appear minimal for the 21st century.

8.4 Predicted changes in the carbon, water and nitrogen cycles in response to Global Change

Predictive research objectives of the BELFOR network were designed to address two fundamental questions : 1) what is the potential of the Belgian forests for mitigating the increase in atmospheric CO_2 responsible for climate change, and 2) what will be the response of forest productivity in Belgium to changing environmental conditions in the course of the 21st century ? Answers to both of these questions are expressed in terms of carbon : 1) the net flux of carbon between the atmosphere and the forest ecosystem, and 2) the net accumulation of stem wood carbon within the forest ecosystem. Therefore, the carbon cycle is the primary cycle that holds the answers to climate change issues. Nevertheless, carbon, water and N form interdependent cycles that must be accurately modelled for predicting forest responses to 21st-century environmental conditions. In the next paragraph we will mainly present ASPECTS simulations for the carbon cycle, and interpret these in terms of CO_2 sequestration and forest productivity. The water and N cycles will be analysed for their interactions with the carbon cycle.

8.4.1. Materials and methods

The ASPECTS model, the description of the experimental sites and the climatic scenarios and site-specific weather data sets used for the simulations are all extensively described in the final report of the BELFOR programme (Vande Walle and Lemeur 2001).

Two types of long-term simulations were conducted with the site-specific weather data sets : (1) continuous tree growth from seedlings from 1900 to 1999 and from

2000 to 2099, and (2) steady state simulations with respect to tree growth from 1900 to 2099, and this for both the Brasschaat (II) and the Vielsalm (IV) forest. The first type of simulation allowed to compare the growth of temperate trees under 20th and 21st century environmental conditions. For realistic simulations and predictions, forest management was considered in these simulations. The forest management recorded at the specific sites, i.e. Brasschaat and Vielsalm, was used and applied at the corresponding stand age of the simulations. In other words, if a harvest had been conducted in 1970 in the 1929-planted Brasschaat stand, identical harvests were simulated in 1951 and 2051 for the 1900-planted and 2000-planted forests, respectively. The second type of simulation, used to test the water cycle, considered no woody tissue increment from one year to the next. Therefore the forest does not age, while the environmental conditions evolve over time. This type of simulation does not take management into account; no stem wood being produced, no stem wood should be harvested. This type of simulation allows to separate the temporal effects of an ageing forest from the effects of changing environmental conditions.

8.4.2. Results and discussion

a) The carbon cycle

The ASPECTS model predicts that the Gross Primary Productivity (GPP) of Scots pine growing at Brasschaat (II) and of beech trees growing at Vielsalm (IV) will be enhanced in the 21st century as compared to the 20th century (Fig. 8.2). The dip in the Scots pine GPP curves around stand age 60 is due to the heavy removal of trees, corresponding to the actual management of the Brasschaat plots. The ASPECTS model predicts that the difference in GPP between 20th and 21st century trees will increase as the stands mature, both for the Scots pine and for the beech trees. On average for 90- to 100-year-old trees, 21st century environmental conditions will increase GPP by 38 % and 43 % for Scots pines and beech trees respectively, as compared to 20th century environmental conditions (Table 8.5).

Table 8.5. *Average GPP, NPP, and NEE (g C m^{-2} y^{-1}) for 90- to 100-year-old stands growing at the end of the 20^{th} and 21^{st} centuries*

	Scots pine (Brasschaat, II)			Beech (Vielsalm, IV)		
(g C m^{-2} y^{-1})	**1990 - 1999**	**2090 - 2099**	**Increase (%)**	**1990 - 1999**	**2090 - 2099**	**Increase (%)**
GPP	1782	2455	38	1255	1791	43
NPP	587	662	13	615	787	28
NEE	256	282	10	241	304	26

The ASPECTS model predicts that the difference in NPP between 20^{th} and 21^{st} century temperate forests will be less substantial than that of the GPP (Fig. 8.2). This effect is predicted for both Scots pines at Brasschaat (II) and beech trees at Vielsalm (IV). The NPP represents the productivity of the forest, and therefore is directly linked to stem wood production. On average for 90- to 100-year-old trees, 21^{st} century environmental conditions will increase forest productivity by 13 % and 28 % for Scots pines and beech trees respectively, as compared to 20^{th} century environmental conditions (Table 8.5). Increased autotrophic respiration under 21^{st} century environmental conditions explains the reduced response of NPP as compared to GPP. Autotrophic respiration, and especially maintenance respiration is a function of live tissue biomass and temperature (Wang and Jarvis 1990, Running and Gower 1991).

Temperature is predicted to increase in the course of the 21^{st} century. Because the predicted NPP is greater for 21^{st} century Belgian forests, the biomass will be larger, which in turn increases the amount of respiring tissues. The end result is a dampening effect on the NPP response to 21^{st} century environmental conditions as compared to the GPP. The ASPECTS model predicts that the Scots pine at Brasschaat (II) will benefit less than the beech trees at Vielsalm (IV) from 21^{st} century environmental conditions. Maintenance respiration increases proportional to the N concentration of plant tissues (Ryan 1991, Ryan *et al*. 1996, Zogg *et al*. 1996). Measured N concentrations are higher for the Scots pines than the beech trees. In addition, Brasschaat is on average 3 ºC warmer than Vielsalm. Therefore, the Scots pines at Brasschaat, which have high maintenance respiration costs, will consume most of their resources by increased autotrophic respiration when exposed to 21^{st} century temperatures.

The NEE response to changing environmental conditions is predicted to be the most substantial for fairly young stands, mainly between age 20 and 40 (Fig. 8.2). This result agrees with other studies suggesting that maximum carbon sequestration is obtained with fairly young stands (Thornley and Cannell 2000). The effect is predicted for both Scots pines at Brasschaat (II) and beech trees at Vielsalm (IV). On average for 90- to 100-year-old stands, 21st century environmental conditions will increase forest NEE by 10 % and 26 % for Scots pines and beech trees respectively, as compared to 20th century environmental conditions (Table 8.5). So, on average, ASPECTS predicts that Belgian forests will sequester an additional 18 % of CO_2 by the end of the 21st century as compared to present levels.

b) Influence of the water cycle

The simulations presented in Fig. 8.2 were conducted with the water and N cycles fully coupled to the carbon cycle. The predicted increases in forest productivity and carbon fixation indicate that water stress will not impede tree growth in Belgian forests during the 21st century. This lack of response is explained by the fact that atmospheric CO_2 concentration and temperature, the two main variables susceptible to change during the 21st century, will have opposite effects on plant transpiration. To demonstrate this point we independently simulated the effects of (1) climate change, which has temperature increase as the predominant change, and (2) increasing atmospheric CO_2 concentrations, for the forests of Chimay (V) and of Brasschaat (II). On the one hand, climate modifications alone will slightly increase the transpiration rates, due to the effect of increased temperature, both at Chimay (V) and Brasschaat (II). On the other hand, increased CO_2 concentration will substantially reduce the transpiration rates at both sites. This effect is explained by reduced stomatal conductance under elevated CO_2 conditions, as suggested by Leuning (1995). When both temperature and CO_2 increases are considered into the simulation, ASPECTS predicts that transpiration rates of these Belgian forests will slightly decrease in the course of the 21st century, resulting in no negative effects of environmental changes on the water status of Belgian forests.

c) Influence of the nitrogen cycle

Simulations conducted for the Vielsalm forest (IV) during the 20th century indicate that atmospheric N depositions were larger than the demand of the forest stand and resulted in no limitation of tree growth by N deficiency. The literature value for atmospheric N deposition for the end of the 20th century in the Vielsalm region is 28 kg N ha^{-1} y^{-1} (Weissen *et al.* 1990). Simulations conducted with 21 kg N ha^{-1} y^{-1} yielded identical NPP and NEE values for the 20th century as to simulation results obtained with 28 kg N ha^{-1} y^{-1}. Simulations conducted with 14 kg N ha^{-1} y^{-1} yielded NPP and NEE values for the 20th century very similar to those obtained with 28 kg N ha^{-1} y^{-1}. Simulations conducted with 7 and 1 kg N ha^{-1} y^{-1} from atmospheric depositions indicated a decrease in the NPP by 17 % and 29 %, respectively, and a decrease in NEE by 28 % and 55 %, respectively, as compared to results obtained with 28 kg N ha^{-1} y^{-1}. ASPECTS predicted that substantial nitrate leaching took place during the 20th century under an atmospheric N deposition rate of 28 kg N ha^{-1} y^{-1}. The simulated nitrate leaching rate fell to about half of its value when considering an atmospheric N deposition rate of 21 kg N ha^{-1} y^{-1}. The simulated nitrate leaching rate was close to its minimum value when considering an atmospheric N deposition rate of 14 kg N ha^{-1} y^{-1}. Therefore, simulations of plant growth (NPP) and of nitrate leaching indicate that an atmospheric N deposition rate of 14 kg N ha^{-1} y^{-1} was optimal for the growth of a beech forest at Vielsalm during the 20th century. This N deposition rate is half of the value measured for this region.

When considering the 21st century, ASPECTS predictions conducted with 21 and 14 kg N ha^{-1} y^{-1} from atmospheric depositions indicated a decrease in the NPP by 3 % and 13 %, respectively, and a decrease in NEE by 6 % and 24 %, respectively, as compared to results obtained with 28 kg N ha^{-1} y^{-1} . ASPECTS simulations also indicated that nitrate leaching rates will approach their minimum value in the 21st century with atmospheric N deposition rate of 21 kg N ha^{-1} y^{-1}. In conclusion, ASPECTS predicts that enhanced growth of the Belgian forests in the course of the 21st century will not be limited by a shortage of N, given that atmospheric N deposition rates will remain higher than forest demand. Provided atmospheric N deposition rates remain equal to current values, nitrate leaching from Belgian forest ecosystems should decrease in the course of the 21st century due to enhanced plant uptake under elevated CO_2.

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10. APPENDIX : LIST OF PUBLICATIONS (UPDATED UNTIL 2001)

In this appendix, an overview is given of the publications in international journals, related to subjects studied during the BELFOR programme. In the extensive final report (Vande Walle and Lemeur 2001), an overview can be found of (chapters in) books or volumes with review boards, of papers in volumes, books or proceedings without review board and of abstracts.

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HYDROLOGICAL, SOIL CHEMICAL AND ECOLOGICAL EFFECTS OF CLIMATE CHANGE IN SPECIES RICH FENS

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1. INTRODUCTION

This *Global Change* study is oriented towards hydrological, soil chemical and ecological effects of *Climate Change* in wetlands, and more specifically in rich fens. These fens are base rich, have a low productive, herbaceous vegetation (*Caricion davallianae*) (because of the strong nutrient limitation, especially P) and are characterized by their quasi-permanent groundwater discharge, interrupted only during very dry summers. They are mostly situated in a river headwater basin or along a valley slope. The presence of the characteristic, rare vegetation types in these fens is determined by the special soil conditions that are created by the discharge of ground water. Among European herbaceous vegetation types, they rank at the highest levels of species richness and nature conservation value and they play an important role as a habitat for threatened plant species. Because of their species richness, these fens form a perfect model system to study interactions between biodiversity and *Global Change*.

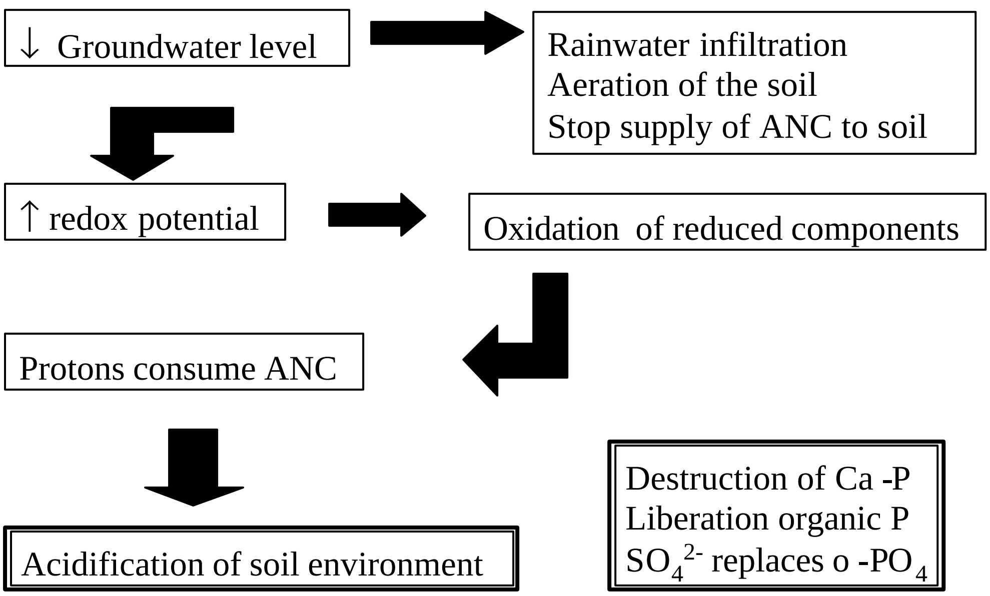

Figure 1.1 *Hypothetical rich fen response to a groundwater table decrease*

Earlier work has indicated that the soil chemistry of rich fens might be much more dynamic then previously thought (Van Haesebroeck et al. 1997). Lowering of the groundwater table during summer drought immediately initiates a series of soil chemical reactions. A hypothetical chain of these soil chemical processes occurring during drought periods in rich fens is given in figure 1.1. A drop of the groundwater level will result in more rainwater infiltrating into the fen soil and since no groundwater is supplied to the soil, no bicarbonate or base cations will be carried into it. Furthermore, a soil chemical response following immediately upon a decrease of the water table and increased oxygen diffusion is the augmentation of the redox potential (Giller and Wheeler 1988). Both, the increased soil aeration and the higher redox potential will result in proton producing chemical processes causing acidification of the soil environment: auto-oxidation of previously reduced substances (sulphide, iron), oxidation of iron and sulphide, increased nitrification and oxygen depended microbial processes. The acidity produced will now be buffered by the soils Acid Neutralising Capacity (ANC). It is obvious that the balance between rain and groundwater will strongly determine the power of the ANC and the actual acid-base status of the peat soil (Kenoyer and Anderson 1989, Webster 1990). Once all ANC present in the peat soil is consumed and no ANC is supplied to the soil due to low groundwater conditions, the soil solution will acidify and cations such as Ca and Mg will be leached out of the soil. At this moment, the soil solution composition will change drastically.

Besides this effect on the acid-base conditions of the soil, the temporary drought period may cause changes in the Soil Reactive Phosphorous (SRP) content present in the soil solution. Previous research in a Belgian rich fen revealed indications for an enhancement of the P-availability during periods of low groundwater table (Boeye et al. 1996). Also Kemmers and Jansen (1988) and Wassen (1990) have found changes in the P – availability during acidification. This increased mobilization of nutrients within the system is referred to as internal eutrophication (Roelofs 1991). Once the drought period ends, the groundwater supply to the peat soil increases and the influence of rainwater infiltration diminishes. To a certain extent, the whole cycle of soil chemical reactions is reversible, re-installing eventually the original rich fen situation.

Earlier, the importance of the hydrological conditions: quality (esp. base status, nutrient availability) and quantity (permanent high groundwater table), in determining the rich fen vegetation composition were mentioned. Reduction of the groundwater level might directly affect the fen vegetation through drought stress. Apart from this direct influence, the acidification, increased P – availability and possible presence of plant toxic metals, might also result in a vegetation response.

2. MAJOR TASKS OF THE STUDY

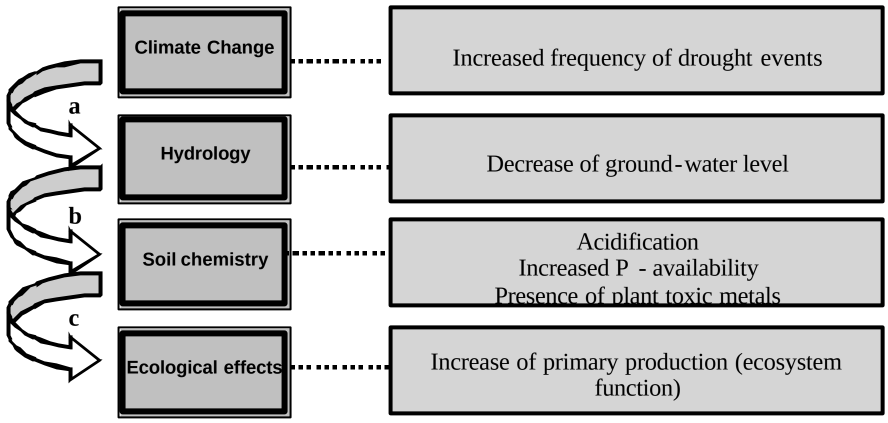

Figure 2.1. *Schematical representation of the objectives of this Climate Change study.*

In this project, the nature and extent of the previously mentioned hypothesis are further examined. The overall objective of the study is to understand and quantify the soil chemical and ecological responses of rich fen communities (e.g., changes in primary production and biodiversity) to drought induced acidification. This knowledge should in turn enable to forecast rich fen responses to summer drought frequencies in Climate Change scenarios.

Three major tasks can be distinguished in the project (figure 2.1.). The first task (a) deals with the relation between climate and rich fen hydrology. More specific it studies the influence of the climate on the level of the fen water resource situation. A second task (b) concentrates on the characterisation of the relation between fen ground water level and acidification. This is studied in the second part of task b. The reaction of the vegetation both on temporary acidification and on an increased P – availability, occurring immediately after lowering of the groundwater table, was dealed with in task (c) of the project.

3. CLIMATE CHANGE AND RICH FEN HYDROLOGY (TASK A)

3.1 Introduction and methodology

Hydrology plays a central role in the functioning of wetlands: base saturation, a permanently high groundwater level, and low primary production are characteristic system properties, directly influenced by the hydrologic relations between the system and its surroundings. Previous research revealed the system's soil chemistry to be much more dynamic then previously thought. Groundwater level drops during dry summer periods, immediately introduce acidification of the peat soil, possibly associated with increased phosphorus (P) availability (Van Haesebroeck et al., 1997). It is believed that this process is of key importance when evaluating Climate Change effects on fen ecosystems. As such, the vulnerability of three fen sites (Belgium: Torfbroek (province of Brabant) and Marais de Vance (province of Luxemburg); Great Britain: Buxton Heath (Norfolk)) for changing groundwater levels because of varying climatologically parameters is discussed here.

In all three study sites, two piezometers (ranging from 1 - 1.5 m and from 3 - 5 m) were installed within a distance of 50 cm from each other. Groundwater levels were recorded automatically at two hourly intervals by means of a compact “Diver” pressure sonde (Eijkelkamp). Daily climatical data for the study period were obtained from the nearby climatic stations (The MET office (English data), Royal Meteorological Institute (Belgian data)). For the period of groundwater level measuring, hourly discharge data of the nearest limnographic station within the catchments were collected (Buxton Heath: River Bure (Environment Agency – Anglian Region); Torfbroek and Marais de Vance: respectively Voer (Aminal) and Semois (Ministère de la Région Wallone – Division de l’Eau)).

3.2 Groundwater level modelling

In the absence of surface water supply (apart from rainfall, groundwater discharge is the only water supply in these areas), the hydrological balance of a rich fen can be written as follows:

ht = a ht-1 + b Peff – c E + d ?G + m (1)

with Peff = (1 – r) P

and P Precipitation
r Runoff coefficient
E Evapotranspiration
ht Water level at time t
ht-1 Water level at time t-1
?G Net groundwater supply

The runoff coefficient was assumed to be 1 if the groundwater level in the piezometer was equal or higher then the soil surface. Under these circumstances, rainfall will be directly transferred out of the system as runoff without causing a rise of the groundwater table. When the groundwater height in the piezometer was lower than the soil surface level, the runoff coefficient was considered to be 0. From the variables on the right hand side of the equation, some variables were measured directly (ht-1), some were obtained from the climatical stations (P) and others were estimated using multiple regression (evapotranspiration (E), net groundwater supply (?G). Once each variable was related to a proportional quantity, the equation can be calibrated by multiple regression.

A common method of estimating E is to take E0 measurements and to multiply these with an "appropriate" correction factor (crop factor) as given in the literature. For fens characterized by a high water level, Koerselman (1988) found the following equation which was used here:

$$E = 0.75\ E0 + 0.25 \qquad (2)$$

Since river base flow provides a good estimate of the groundwater supply to the river, it gives also a good idea of the groundwater supply to the saturated zones bordering the river. The groundwater discharge in each area was therefore related to base flow measurements from limnographic stations nearest to the rich fens under study. In this way a relation between the rivers dry weather flow and the groundwater supply was established, which was used in the hydrological balanc (equation 1) of the sites.

The results of this regression equation are shown in table 3.1. The significance of the overall regression from Torfbroek was slightly higher than for both other areas. Also the individual parameters were only slightly varying between all sites.

Table 3.1. Values of parameters and multiple correlation coefficient and their significance in the regression equation 1, for the 3 study sites

Parameter	Marais de Vance	Torfbroek	Buxton Heath
m	0.86	0.432	0.668
SE	0.1730	0.104	0.082
p	0.0000	0.0000	0.0000
a	0.9070	0.948	0.892
SE	0.0190	0.013	0.013
p	0.0000	0.0000	0.0000
b	0.7320	0.745	0.441
SE	0.1130	0.155	0.084
p	0.0000	0.0000	0.0000
c	-1.381	-2.974	-2.945
SE	0.725	0.586	0.41
p	0.0580	0.0000	0.0000
d	0.007	0.018	0.017
SE	0.001	0.009	0.002
p	0.0000	0.038	0.0000
R	0.948	0.985	0.956
SE	0.014	0.011	0.009
p	0.0000	0.0000	0.0000

SE: standard error; p: probability

3.3 Model validation and conclusion

After developing this model, it was used to predict groundwater levels in all study sites during calibration and validation periods for Buxton Heath and during calibration period for both Belgian fens. Figure 3.1. shows the difference between the calculated and the measured groundwater levels. During both validation periods, the residuals are somewhat higher and better calibration of the model is still needed.

However this “simple” model obtained here gives a clear view on the relation between the local climate and the groundwater fluctuations in these rich fens. In this way, future effects of groundwater level lowerings due to Climate Change or human activities can be predicted in a better way.

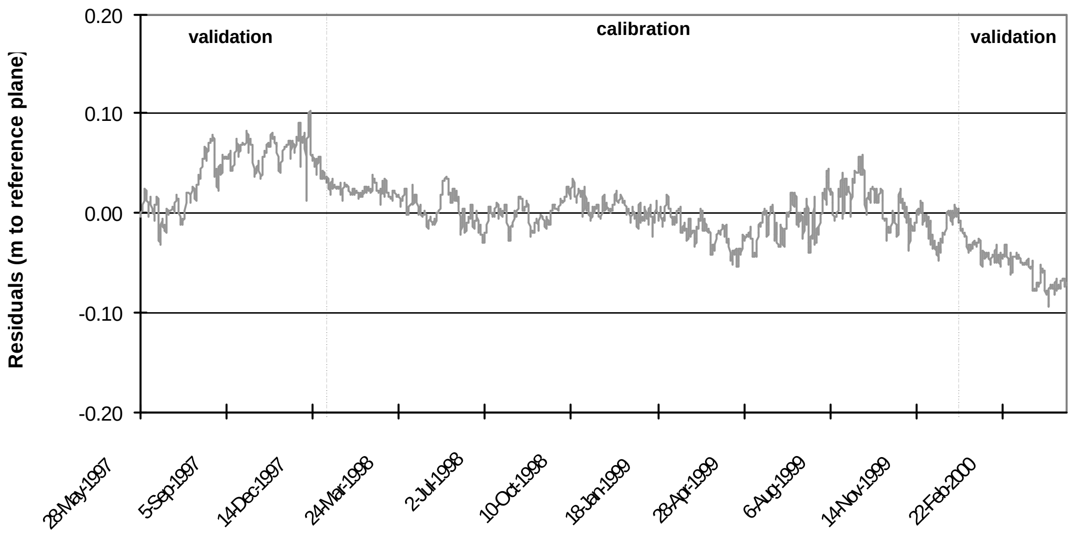

Figure 3.1. *Residuals from Buxton Heath groundwater level for validation and calibration period.*

4. SENSITIVITY FOR DROUGHT INDUCED ACIDIFICATION (TASK B)

4.1 A comparison between three European rich fens

4.1.1 Introduction and methodology

During a previous study, drought induced acidification was observed and experimentally detected in a Belgian rich fen (Buitengoor, province of Antwerp) (Van Haesebroeck et al. 1997). In the present research, a similar approach was used to examine the differences in occurrence of this acidifying process between the

Buitengoor and two other rich fens (Marais de Vance, Arlon – Belgium; Buxton Heath, Norfolk – UK).

Analysis of the most important soil parameters took place on control soils. In order to characterize the acidification process, a soil column technique, developed during the previous study, was used. For all sites, 5 cores were treated as blanks and were maintained with their groundwater table near the surface. In the remaining monolith (experimental), the water level was gradually reduced to a depth of 20 cm below the soil surface from the 2 ½ week on. Soil solution samples for analysis were gathered regularly during the experiment (pH, EC25, redox potential, HCO3-, Cl-, NH4+, NO3- and SO42- concentration and amount of major cations).

4.1.2 Results

The soil-water analyses (5 cm depth samples) of the experimental soils from the Buitengoor were compared with those from Marais de Vance and Buxton Heath. Onset of low water levels induced in the soils of the different sites a similar reaction. Drought treatment induced in the Buitengoor and the Buxton Heath columns a decrease in pH and HCO3-. In Marais de Vance, pH remained stable and HCO3- decreased. Drought also caused a significant increase of the redox potential and of the SO42- content in the soil solution of all experimental soils. Data on the Ca2+ and Mg2+ concentration in the experimental soils, illustrate in all three soil series an increase of the concentration. In all 3 study terrains, the Fe and Mn2+ content decreased immediately after lowering the groundwater table. Both concentrations almost reached zero levels within one week after drainage.

Between the 3 study areas, there was a notable difference in intensity and occurrence of the drought response (figure 4.1.). In all sites, HCO3- and Fe reacted immediately upon onset of drought. Ca2+ and Mg2+ also showed a direct response to drought but the expected concentration increase seemed to be postponed in Buxton Heath and Buitengoor. At first concentrations decreased upon drought and afterwards they increased. In Marais de Vance on the other hand, a direct Ca2+ response was found. In Buxton Heath, other parameters seemed to react only after a second more severe lowering of the water table (redox potential, pH). Also the SO42- content showed a slight effect after the first decrease of the groundwater table and increased strongly after the second groundwater level lowering. In Marais de Vance, almost immediately a response is followed after onset of low groundwater levels, while in the Buitengoor SO42- concentrations first decreased slightly to afterwards increase strong.

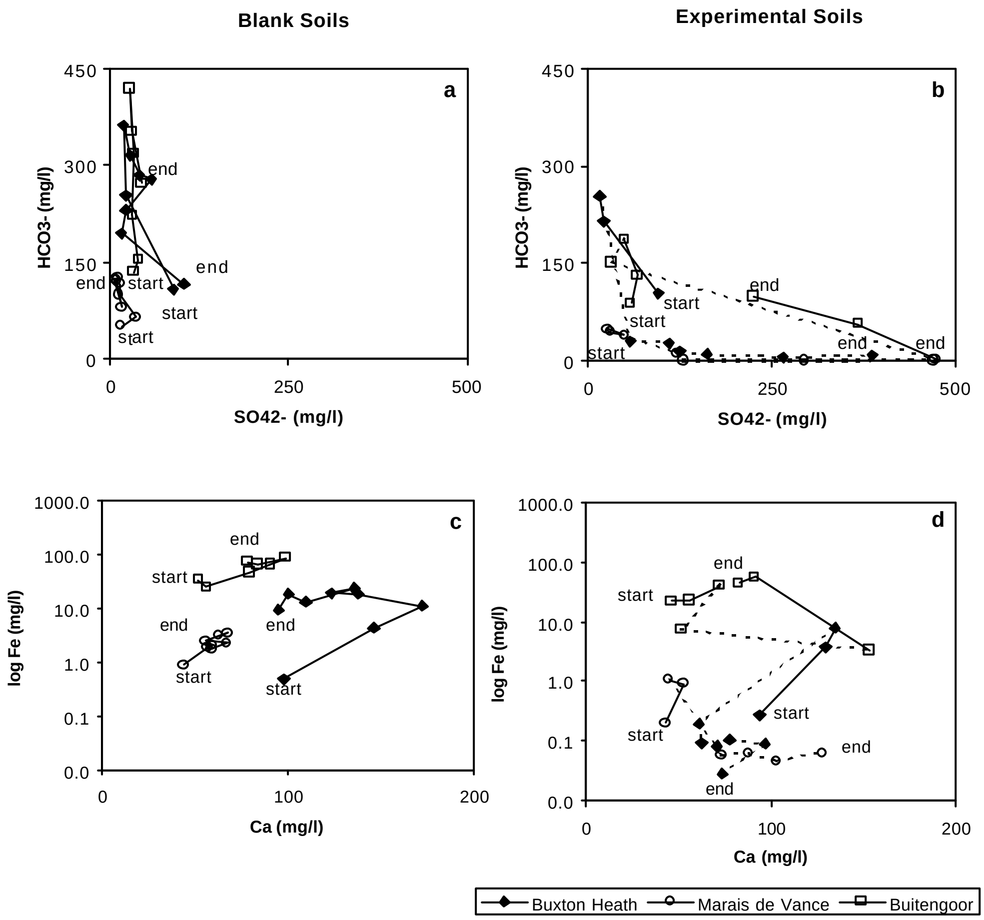

Figure 4.1. *HCO3-, SO42-, Fe and Ca concentration in soil solution from blank and experimental soil columns from Buxton Heath, Marais de Vance and Buitengoor (---- period of low groundwater level; ___ period of high groundwater level)*

4.2 A survey across Western European rich fens

4.2.1 Introduction and methodology

In the previous research, we experimentally detected drought-induced acidification during short drought events. The intensity of the processes seemed to depend on physical and chemical soil characteristics (e.g. moisture retention capacity, acid neutralizing capacity etc.). In this Global Change study, which deviates from the classical approach (impact from atmospheric drivers on individuals or monocultures), the relation between drought induced acidification and different soil physical and chemical parameters was determined in different fen sites all over Belgium, The Netherlands, and Great Britain. In all study sites vegetation description and sampling took place. Afterwards, the vegetation samples were analysed (N, P, major cations). With regard to the soil chemistry, the ANC and the amount of organic material were quantified upon fresh soil material. Soil physical factors important to detect on the fresh soil cores were the moisture retention capacity and the texture. Acidification of the different soils was induced in a small column experiment. The soil column technique, developed to experimentally study drought-induced acidification in peat soils (Van Haesebroeck et al., 1997), was used in a more simple design. Soil monoliths from each study site were kept in PVC tubes and were placed into a PVC box. Between the soil cores and the box wall and bottom, a layer of fine chemically inert sand was introduced. After a 10-week drought period, similar soil analysis as took place on the fresh soil material were conducted.

4.2.2 Results

Based on the vegetation, 4 groups could be recognized within the different sites. Some sites formed a transition towards intermediate fens, while others were characterised by the presence of rich fen species and some species (Carex hostiana) that indicate the presence of a calcareous substrate or the supply of calcareous groundwater. The fen sites gathered in group 3 contained many poor fen species. The fourth group contained many species revealing the character of a wet meadow.

All soil samples were characterized by a peat layer (10-20 cm) on top of a sandy, clayey/loamy sand or loam substrate. Their pH ranges between 4.5 and 8. Considering the SO42- concentration, two groups could be separated. A first group having an SO42- concentration around 1 mg /g dry weight and a second group with a concentration around 0.1 mg /g dry weight. Also when looking to the Ca concentration, 3 sites showed a much higher concentration compared to the other sites. The Cation Exchange Capacity (CEC) of the different soils showed a clear relation with the soil pH (n 158, r 0.35/ p <0.001) and the amount of organic matter (n 136, r -0.19/ p 0.025).

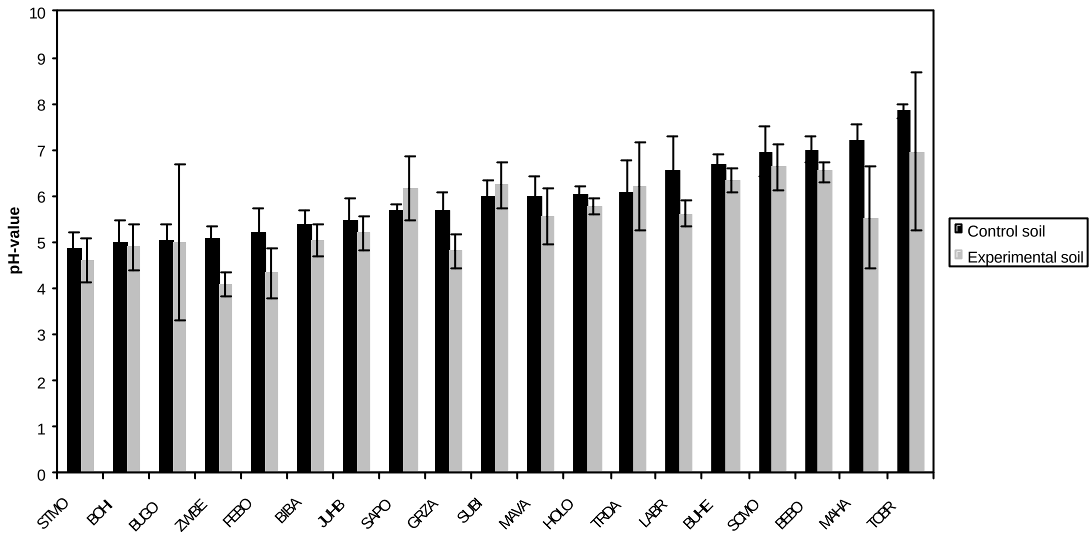

Figure 4.2. *Soil pH in control and experimental (drought) soil from different rich fen sites. Values are means from 5 replicates.*

Temporary drought had a significant effect on different soil parameters. In nearly all study sites, acidification of the soil environment occurs after a period of drought (figure 4.2.). For the amount of SO42-, a clear incensement between initial and end concentration was measured. Temporary lowering of the groundwater table did not seem to influence the Fe and Al concentration nor the amount of Cl measured. The latter indicates that differences measured for the other chemical parameters cannot be explained by a dilution effect.

Table 4.1. Pearsons correlation coefficient between soil variables and degree of acidification expressed as difference in pH and SO_4^{2-} concentration.
Only significant correlations are shown. Number of cases indicated between brackets.

	Degree of Acidification	
	pH	**SO42-concentration**
Bulk density	0.22 (180)	
% water	-0.20 (180)	
% Organic Matter		0.16 (178)
initial pH	-0.30 (180)	0.16(178)
SO4 (mg /g dry weight)		-0.32 (179)
Ca (Amac) (mg/g dry weight)	-0.29 (170)	0.19 (170)
Fe (Amac) (mg/g dry weight)	-0.22 (169)	
Mg (Amac) (mg/g dry weight)	-0.25 (170)	
P (Amac) (mg/g dry weight)	-0.16 (169)	0.16 (169)
Mg (Oxac) (mg/g dry weight)	-0.21 (179)	
CEC (meq/100cm3)	0.28 (152)	
S (meq/100g wet soil)	0.22 (160)	

Table 4.1. shows the Pearson coefficient for the correlations between different soil parameters and the severeness of acidification. Latter is expressed by the difference between the end and initial soil pH and the SO42- concentration. Increasing negative pH difference and increasing SO42- concentration indicates an increasing acidification. For both, pH difference and difference in SO42- concentration, a negative correlation with the original soil pH was found while a positive interaction with the initial SO42- concentration was observed. Stricking is the negative correlation for both with the Ca2+ concentration measured after an Ammonium acetate (Amac) extraction. The pH difference shows also a negative correlation with Fe, Mg and P after the Amac extraction. At least, important to mention is the positive correlation of the pH difference with the CEC and the sum of bases (S).

4.3 Conclusion

Following the results of both experiments, we may say that in all sites a drought response similar to the one found for the Buitengoor took place. In all of them, drought caused acidification of the soil environment and induced an increase of solubility of cations (Ca2+, Mg2+) and of insolubility of Fe and Mn. However variation in time and depth of the effect occured between the different rich fens. The extent, to which drought sensitivity appeared, depended on the soils physical and chemical characteristics (texture, CEC and Base Saturation). It became clear that areas with low “Acid Neutralising Capacity” were particularly vulnerable for drought-induced acidification. Since different soil parameters participate in determining the peat soils “Acid Neutralizing Capacity” (Lamers 2001), or in its power to temper acidification and to reduce concomitant soil chemical processes, in order to predict the effect of a groundwater level lowering in a certain area, it is of importance to determine these parameters.

5. A MICROCOSM STUDY OF THE ECOLOGICAL EFFECTS OF CLIMATE CHANGE IN A BELGIAN RICH FEN (TASK C)

5.1 Introduction and methodology

In order to reduce some of the uncertainties in predicting the responses of these vegetations and to take valuable conservation measures, a microcosm experiment with intact sods from a Belgian rich fen (Buitengoor at Mol, province of Antwerp) was conducted. Three water levels were established: permanent wet (groundwater table at soil surface), fluctuating (groundwater table temporary at soil surface and 20 cm below soil surface), permanent dry (groundwater table permanent 20 cm below soil surface). Regularly soil solution samples were taken (analysed for pH, EC25, redox potential, major ions, and Cl-, SO42+, NH4+, NO3-, NO2 and P). The fen vegetation reaction on temporary drought induced acidification and increased P-availability, was observed closely. Changes in growth and distribution of different plant species was followed and small vegetation fractions were harvested to determine the plant nutrient content. At the end of the experiment, soil and total vegetation were analysed in detail.

5.2 Results

The results showed that drought caused immediate acidification of the soil environment and induced changes in solubility of Ca and Mg (increased) and of Fe and Mn (decreased).

The groundwater manipulation effect on the total number of plants in each

Table 6.1. Values of F and p of a Repeated Measures Anova of the effect of treatment on the amount of N and P in the plantmaterial from the microcosms. p values < 0.05 are considered statistically significant.

	df	#mg N/g dry plant weight	#mg P/g dry plant weight
Carex demissa	2	**4.67/0.045**	0.89/0.449
Carex dioica	2	0.98/0.418	1.00/0.411
Carex panicea	2	1.86/0.218	1.72/0.24
Eleocharis quinqueflora	2	0.92/0.436	0.99/0.413
Juncus articulatus	2	1.05/0.395	1.01/0.405
Molinia caerulea	2	**8.79/0.010**	2.55/0.139
Young germinating plants	2	**376.33/<0.001**	**16525.08/<0.001**

microcosm was most clearly for Molinia caerulea, where a decrease was found in the permanent wet soils compared with the permanent dry and fluctuating soils. Also for the number of Juncus articulatus individuals the groundwater treatment had a significant effect. An increased amount of Juncus articulatus individuals in the wet microcosms towards the permanent dry was noted. Figure 6.1. shows the mean total aboveground biomass over all species. Biomass production in the permanent dry soils is significantly lower then biomass production in permanent wet and fluctuating soils. Striking when looking to the biomass production per species is the contrasting response of Molinia caerulea (lower biomass in wet microcosms), against the other species.

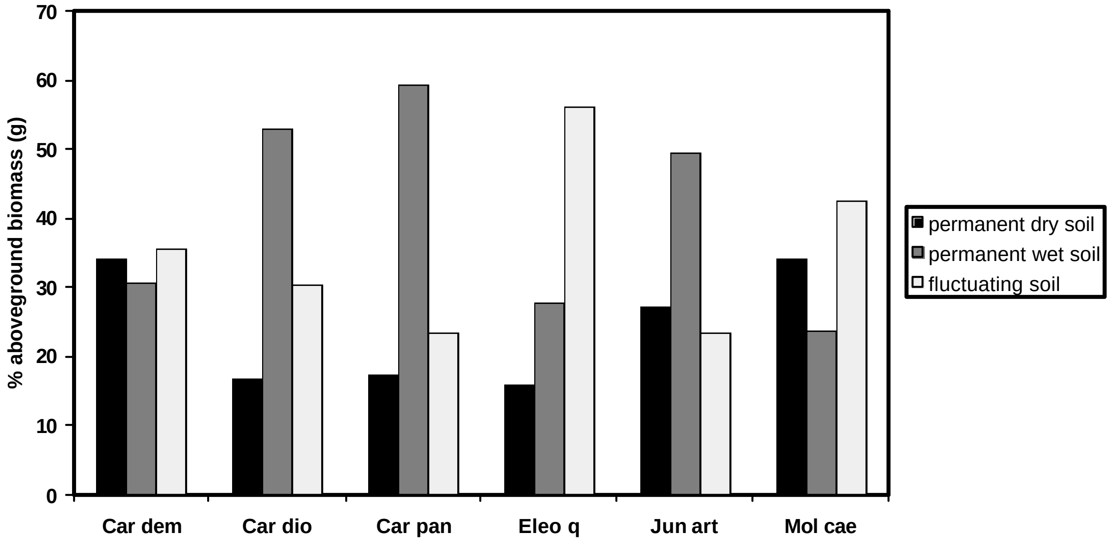

Figure 6.1. *Percentage of aboveground biomass of the most dominant species present in the microcosms.*

When comparing the mean N concentrations in the total vegetation at the end of the experiment, the groundwater treatment did not have a significant influence (df 2, F 3.241 / p 0.093). If we looked more into detail to the N concentration per species (table 6.1.), a significant effect of treatment was found for Carex demissa and for young germinating plants. Also for Molinia caerulea a significant effect was found. The N concentration in Molinia caerulea from the permanent dry soils was higher then the one measured in the fluctuating (df 1, F 17.05 / p 0.014) and permanent wet (df 1, F 9.45 / p 0.037) microcosms. This difference cannot be explained by a dilution effect since the highest growth coincides with the highest concentration. For the P concentration a significant influence of the groundwater level was found (df 2, F 5.689 / p 0.029). In the vegetation at the end of the experiment the P concentration in the fluctuating soil monoliths was higher compared to the permanent dry soils (df 1, F 16.59/ p 0.015). Also for P Molinia caerulea shows a different response to the treatment compared to the 5 other species (table 6.1.).

5.3 Conclusion

After two growing seasons, acid tolerant species (e.g. Molinia caerulea) clearly were beneficiated by dry and fluctuating groundwater conditions and had expanded their growth. Acid intolerant species such as Eleocharis quinqueflora on the cotrary became much less abundant.

6. CONCLUSION

This study focussed on rich fens, a special class of peat-forming wetlands. Rich fens are considered as one of the most species rich herbaceous vegetation type of Western Europe. They harbor a species rich vegetation with many typical rich fen species (Boeye & Verheyen 1994). As water is the primary driving force influencing rich fen structure and function, its hydrology forms the basis in understanding, quantifying and evaluating its function and processes.

The ground water - surface water interaction and the discharge - recharge relationship have been found to affect the wetland water quality and nutrient budgets as well as the vegetation composition. We have illustrated that water level fluctuations result strong dynamics of the soil hydrochemical system of a weakly buffered fen with acidification and increased nutrient availability as a consequence. The study of the tolerance limits of rich fen species for temporal acidification and of their potential to use the available nutrients under these conditions provided more insight in the biological effects. Acid tolerant species as Molinia caerulea seemed to be beneficiated by these drought induced chemical soil changes. The rare rich fen species however were found to receive a negative effect from these processes.

Clearly of primary importance for the conservation of these rich fens is a good regional water management, which prevents strong increases of drainage. Based upon the hydrological models produced here, we obtained a clear view on the relation between climate and groundwater fluctuations in these areas. In view of predicted Climate Changes, for rich fen management, especially the indirect effects on local biodiversity deserve much attention. Management therefore should in such areas pay much attention to the preservation or restoration of the original hydrologic status in order to prevent decreases of the groundwater table. In this way, the possibility that the here studied chain of chemical and biological processes take place in rich fens will be smaller.

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PARAMETERISATION AND INVENTARISATION OF GASEOUS NITROGEN COMPOUNDS FROM AGRICULTURAL SOURCES

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1. PROJECT SUMMARY

The changing composition of the atmosphere influences the global and regional climate. It is well known that natural and agricultural ecosystems can be important sources and sinks for atmospheric trace gases such as nitrous oxide (N_2O), nitric oxide (NO) and methane (CH_4), but they are poorly quantified and therefore, no reliable budgets exist. In addition, the impact of changes in land-use, agricultural practice or climate cannot be predicted. So, on the one hand, there is a clear need for long-term field campaigns to obtain a more precise knowledge of source strengths. On the other hand, process studies are required to increase our fundamental understanding of trace gas generating processes.

Therefore the main goals of the present project were:

- to generate an accurate and scientifically based inventory of :
  - the emission of nitric oxide and nitrous oxide from natural and agricultural sources in Belgium
  - the methane oxidation capacity of several natural and agricultural ecosystems in Belgium
- to gain a better understanding in the processes leading to such emissions and the factors determining the emission rates.

This should lead to the formulation of strategies to reduce trace gas emissions from agricultural land.

2. SCIENTIFIC ACTIVITIES

2.1 Inventory on nitrous oxide and methane emissions

Nitrous oxide and methane are important greenhouse gases and contribute significantly to the greenhouse effect. Agricultural soils are a known source of nitrous oxide. Comparison of the annual nitrous oxide flux measured at 11 different field-sites indicated that fertilization, climate and land use where the main factors influencing the magnitude of the emission. In general, the nitrous oxide emission was larger from managed grassland and pastures than from arable land. Increasing fertilization rates also led to an increased nitrous oxide emission. A fertilizer-induced nitrous oxide emission of 5.3% of the applied N could be derived; a factor that could be considered specific for the intensively managed Belgian agricultural soils. At a forest site where we measured, a net uptake of nitrous oxide was recorded, indicating that soils might also act as a sink for nitrous oxide.

Methane uptake by soils is a positive effect in terms of environmental concern. At most field-sites, however, a rather low methane uptake was recorded, probably due to intensive use of fertilizers. The measured methane uptake was in general higher for the grasslands and pastures than for the arable lands. During periods of heavy rainfall, however, when the soil becomes saturated with water, they can start to emit considerable amounts of methane.

2.2 Process studies on nitric oxide and nitrous oxide emissions

Soil biological processes such as nitrification and denitrification are important sources of nitrous oxide emissions. The most important factors influencing the denitrification process are the nitrate concentration, the moisture content of the soil and the amount of available carbon.

2.2.1 Impact of compost amendments on denitrification

More and more organic amendments such as compost will have to be added to arable land in the future and they are assumed to increase the amount of available carbon in the soil. Therefore, the impact of compost on the denitrification process and the dynamics of the process were studied. In a series of laboratory experiments, a loamy soil and a loamy sand were mixed with compost and the production of the denitrification products nitrous oxide and nitrogen gas was measured frequently over a long period of time. For the loamy soil, addition of compost lead to a temporarily increased production of nitrous oxide compared to the case where no organic material was added. Simultaneous addition of compost and nitrate resulted in even stronger nitrous oxide emissions. In the loamy sand, a long period of high nitrous oxide emissions was always observed, followed by nitrous oxide consumption. The addition of compost increased the rate at which nitrous oxide was produced, but not the total emission. In all test conditions, emissions from the loamy sand were higher than those from the loamy soil. Total denitrification losses and nitrous oxide emissions were minimal for both soils when the ratio of the initial soluble carbon (measured as Total Organic Carbon) to the initial nitrate concentration of the soil exceeded 4.

From the results obtained, it seemed that compost addition had much less impact on nitrous oxide production rates than nitrate amendments. The use of compost as organic fertilizer is therefore not expected to have a large effect on nitrous oxide emissions. However, because the compost-nitrate combination lead to high nitrous oxide emissions in the loam, it might be preferable to avoid the simultaneous addition of compost and nitrate to this type of soil.

2.2.2 Development of a soil incubation system capable of measuring gaseous emissions in response to changes in soil moisture content

Since it is impossible to measure nitrous oxide emissions for all types of soil with all kinds of organic amendments and at different moisture contents, another approach was chosen to gain a more fundamental insight in the distribution of available carbon in the soil and how the addition of organic amendments such as compost or straw would affect this.

To this end, a new advanced laboratory set-up was developed. On the one hand, it enabled accurate and frequent measurements of several greenhouse gases such as nitric oxide and nitrous oxide in up to nine soil columns. On the other hand, the matric potential of the soil columns, which is a well-defined measure of the soil water content, could easily and accurately be established and altered. The system was used to perform the experiments described below.

2.2.3 Influence of soil matric potential on nitrous oxide emissions

While nitrification only takes place at high oxygen concentrations, denitrification will only occur at low oxygen levels. As a consequence, when soil water content is gradually increased and oxygen supply becomes limiting, denitrification will become the main source of nitrous oxide production.

When we measured nitrous oxide production at increasing moisture contents for different types of soil, the response could be described with exponential relationships. From the latter, matric potential threshold values were calculated, at which the nitrous oxide emissions amounted to 2.5 µg N_2O-N/kg dry soil/h (TH2.5). These varied between –10 kPa and –1.9 kPa for the different soils. Moreover, a strong correlation existed between the threshold values and the percentage of aggregates in the soil, larger than 2000 µm. In other words, the more large aggregates a soil has, the wetter it has to be to produce the same amount of nitrous oxide.

Finally, a statistically significant equation was found relating the percentage of aggregates larger than 2000 µm to the threshold value:

$$\text{TH2.5} = -8.45 + 13.5 \times (\%\ \text{aggregates} > 2000\ \mu\text{m})$$

For soils with different degree of aggregation, the matric potential can thus be determined at which 2.5 µg N_2O-N/kg dry soil/h is produced, provided that the percentage of large aggregates in the soil is known.

2.2.4 Influence of carbon availability on denitrification

In this project the concept of carbon availability was defined and its effect on N gas emissions was studied in a novel way. We obtained strong indications that there exists a non-uniform distribution of carbon in the soil pore network and that this has implications for nitric oxide and nitrous oxide emissions through denitrification.

Our studies showed that microbial activity in relatively dry soils is mostly situated in the smaller water-filled soil pores. In the larger air-filled pores, the activity was much lower and carbon could accumulate. When the soil moisture content was subsequently increased, also the larger pores were water-filled and the undegraded carbon could serve as substrate for the denitrifying organisms. Different soil pore classes were characterized by different rates of carbon decomposition and this had a direct effect on the dynamics of the denitrification process. The data showed that the proportion of nitric oxide and nitrous oxide in the total N gas production decreased, when the soil matric potential increased, in other words, when the soil became wetter. Under the experimental conditions this could only have been due to a difference in available carbon.

2.3 Laboratory and field study on factors influencing nitric oxide emissions

Nitric oxide plays an important role in the formation of tropospheric ozone and in the acidification of precipitation. The nitric oxide emission from intensively managed agricultural soils can be of the same order of magnitude than the nitrous oxide emission. As for nitrous oxide, the use of increasing amount of fertilizer leads to an increased nitric oxide emission. There is, however, not yet enough long-term data from field experiments to establish a nitric oxide emission factor. There are some indications that the type of fertilizer that is added to the soil affects the nitric oxide emission. Ammonium-nitrate based fertilizers and pig-slurry cause lower nitric oxide emissions than the use of ammonium or nitrate fertilizers.

2.4 Process studies and modeling of methane uptake

The decomposition of organic waste in a landfill leads to high methane emissions. Covering the landfill with a layer of soil might reduce these emissions. Preliminary modeling results indicate that landfill cover soils could oxidize 10-30% of the methane entering it.

There is also a possibility to optimize the methane oxidation by landfill cover soils by choosing a proper organic residue to add to the soil. Two approaches might be adopted. If one aims at a brief and vigorous methane oxidation, e.g. in a temporary landfill cover shortly before the onset of landfill gas extraction, an nitrogen-rich residue might be added to the cover soil. If a more stable mode of methane oxidation is required, like in a landfill cap, an nitrogen-poor residue might be preferred.

3. VALORISATION POTENTIAL AND RECOMMENDATIONS

Three newsletters were published which on the one hand contained general information on climate change and on the trace gases nitrous oxide and methane and on the other hand discussed the activities of the different teams in the project. In addition, a workshop was organized, in which the scientific results were presented to an audience of academics and policy makers.

From the experimental results the following recommendations can be formulated:

1. A fertilizer induced nitrous oxide emission factor of 5.3 ± 1.7% of the applied nitrogen was derived from long-term field experiments. This emission factor could be considered specific for intensively managed Belgian soils.

2. Net nitrous oxide uptake was recorded at a forest site during 2 consecutive years. The role of soils as a sink for greenhouse gases should maybe be reconsidered.

3. Compost addition has a minor influence on nitrous oxide emissions through denitrification. In certain cases, a simultaneous addition of compost and nitrate to soil should however be avoided.

4. A chosen threshold value in nitrous oxide emission can be predicted using a simple regression equation provided that the amount of large aggregates in the soi

5. l is known.

6. Emission of nitric oxide from agricultural soils can be substantial. There is some indication that the type of fertilizer influences the magnitude of the nitric oxide flux.

7. Two approaches can be adopted to optimize methane oxidation by landfill cover soils: addition of N-rich organic residues for a brief and vigorous activity, addition of N-poor organic residues for a more stable mode of activity.

8. Modeling results have indicated that landfill cover soils can oxidize 10-30% of the methane entering it. If further testing supports this finding, methane oxidation by landfill cover soils should be accounted for in the greenhouse gas inventory.

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INTEGRATED MODELLING OF THE HYDROLOGICAL CYCLE IN RELATION TO GLOBAL CLIMATE CHANGE

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1. INTRODUCTION

The main objectives of the project are :

- to gain knowledge in the understanding of the hydrological system at different time and space scales;
- to develop and test an integrated holistic approach that is able to assess the effects of climate change on the terrestrial hydrologic cycle and on the water resources systems.

The project is focused on two main aspects :

1) The comparison of models :

3 different hydrological models are used and compared :

- the HA-FUSAG, HG-KUL, LGIH-ULG and CE-ULG teams develop and use a spatially-discretized integrated model, the MOHISE Model. This model is composed of existing sub-models of land surface (soils), groundwater and surface water.
- the ILWM-KUL uses an existing spatially discretized integrated model, the MIKE-SHE model;
- the IRM/KMI uses a spatially non-discretized model (the IRMB model) and develops a spatially semi-discretized model (the SCHEME model);

These models models are tested, calibrated and validated on a few representative Belgian basins. The selected test-basins are the Gette basin (at Budingen : 600 km²), the Geer basin (at Kanne : 465 km²) and the Ourthe Orientale basin (at Mabompré : 319 km²). The models are tested and compared using the same data set, to assess their capabilities to represent the different phases of the terrestrial hydrological cycle (soil, groundwater, surface water) under present (historic) climate situation.

2) The simulation of the impacts of climate changes on the terrestrial hydrological cycle

Climate change scenarios (monthly changes of meteorological variables) are elaborated on the basis of the results of three GCM (Global Climate Models) experiments provided by the IPCC (International Panel on Climate Change). These climate change scenarios are then tested using the three hydrological models on the same test-basins, in order to asses the impacts of potential climate changes on the terrestrial hydrological cycle. Indirect effects on agricultural soils and crop production are also assessed.

2. DESCRIPTION OF THE MODELS

2.1 The MOHISE model (HA-FUSAG, LGIH-ULG, HG-KUL, CEME-ULG)

The MOHISE model (an acronym for 'Modèle Hydrologique Intégré pour la Simulation du cycle de l'Eau') is developed jointly by HA-FUSAG, LGIH-ULG, HG-KUL and CEME-ULG. It is an integrated, deterministic, spatially discretized, physically-based model, composed of sub-models of the 3 main compartments of the hydrological cycle : soil, groundwater, surface water. These 3 sub-models are linked in an integrated operational model which involve parallel and synchronised execution of each sub-model.

2.1.1 The soil sub-model : EPIC-GRID (HA-FUSAG)

The ‘soil’ sub-model EPIC-GRID computes, for each basin grid square :

- the evapotranspiration;

- the water stock variations into the non-saturated zone;

- the fluxes of superficial runoff, fast and slow subsurface flows and percolation;

- the transfer of the percolation to the groundwater table.

The EPIC-GRID sub-model was developed at basin scale, on the basis of the EPIC model (Water-Soil-Plants) model at field scale with a daily time step; the time step is daily. The EPIC-GRID model is composed of several modules dealing with climate, hydrology, crop growth, tillage, erosion, nutrient cycle, soil temperature, crop management and economical aspects. The main hydrological processes simulated are : superficial runoff, subsurface flows, percolation to groundwater, soil moisture, soil evaporation, crop transpiration, snow melt, crop cover type and development, crop practices (forty different speculations).

2.1.2 The groundwater sub-model : SUFT3D / MODFLOW (LGIH-ULG and HG-KUL)

Two codes are considered for groundwater modelling in the scope of this part of the project, i.e. the SUFT3D and the MODFLOW codes :

- the SUFT3D (Saturated Unsaturated Flow and Transport in 3D) program, developed at the LGIH-ULG, is a finite-element code, which allows the modelling of the unsaturated and saturated zones and allows local mesh refinements depending on local geological characteristics;

- the MODFLOW program is a finite-difference code. It resolves the flow equation strictly in fully saturated conditions. This model does not allow local mesh refinements without increasing drastically the number of finite difference cells in the whole domain (and thus also the memory and CPU requirements).

The choice of the code which is used to simulate a specific hydrogeological basin depends on the chosen conceptual model for the basin. This conceptual model (where decisions are made in terms of dimensions, boundary conditions, stress scenarios, coupled processes,...) is chosen on basis of the synthesis and the hydrogeological interpretation of all the existing data.

2.1.3 The surface water model : RIVER (CEME-ULG)

The surface water sub-model (RIVER) simulates the dynamics of the water movement in the river network. Input of water are the fluxes from the soil surface and the fluxes from/to the groundwater. The model is based on the Saint-Venant equations (mass and momentum balances) in (one-dimensional) network channels. The momentum balance is simplified to the kinematic wave description. This representation is consistent with the long time simulation periods (decades to centuries) and with the characteristic time step (daily) of the input fluxes.

The surface water sub-model calculates river flow, mean cross-section velocities and depths, at each node of the spatial discretization of the river network.

2.1.4 The supervisor of the integrated structure : MASTER

The construction of the global structure of the integrated model MOHISE requires the elaboration of :

- an adapted version of the different sub-models;

- a meta-structure, the "MASTER" code (developed by CEME-ULG in collaboration with the other teams) which links and synchronise the parallel execution of the 3 sub-models;

- interfaces between the sub-models and the meta-structure, in order to control the transfer of information (water fluxes) between the 3 sub-models.

The meta-structure and interfaces are designed to handle the fluxes of water between the soil and surface water compartments (one-directional), between the soil and the groundwater compartments (one-directional), and between the groundwater and the surface water compartments (bi-directional fluxes).

The state variables calculated by the surface water sub-model RIVER and the groundwater sub-model (MODFLOW or SUFT3D) are used by the MASTER to establish the connection between the two sub-models, so that the flow rate of water exchanged between the river and the groundwater (in both directions) can be computed.

The main characteristics of the MOHISE model are the representation of each compartment by a specific sub-model and thus the use of specific appropriate time and length grid scales for each compartment.

The integrated MOHISE model runs on single- or multi-processors workstations thanks to the development of an innovative IT (Information Technology) which allows to dedicate one processor to each sub-model. The sub-models are coupled using MPI (Message Passing Interface) dedicated libraries. This method leads to intensive parallel calculation.

2.2 The MIKE-SHE model (ILWM-KUL)

The MIKE SHE model covers the entire hydrological system on a basin scale. The model can be classified as deterministic (but can be integrated in a joint stochastic-deterministic approach), physically-based, continuous in time, fully spatially distributed, and using a finite difference numerical scheme for energy and mass differential equations. This model was selected for different reasons, ranging from pragmatic (the model was readily available) to scientific (no other similar models was existing when the research started and the model reflected the basin distributed modelling state of the art). In addition to modelling the water flow in the different compartments of the hydrological cycle, the model is also able to simulate solute transport and transformations. The model offers different descriptions, going from simple to more complex, in order to allow the user to select the approach with regards with the availability of data.

In this study only the water module of MIKE SHE has been used and tested. The processes described are:

- interception and evapotranspiration (potential evapotranspiration is reduced to the actual evapotranspiration using the Kristensen and Jensen model);
- overland flow and channel flow (Saint Venant equations);

- transport of water in the unsaturated (Richards equation) and the saturated (Boussinesq equations) zones;
- exchange between the aquifer system and the rivers.

The processes are modelled in a network of grid squares, with the river network located on the borders of the grids. A column of horizontal (soil and geological) layers makes up the vertical dimension within each grid square. All process descriptions operate at individual appropriate time step, according to the needs of the process that is simulated. These time steps are dynamic, and are typically decreasing when transient phenomena, such as precipitation, occur. Bordering processes synchronise at specific points in time where their timing coincides.

The frame component in the model co-ordinates the simultaneous execution of the process components by selecting their different time scales and organising their data exchanges. Data requirement of the model is quite high due to the fact that processes are described using mainly physical-based process descriptions.

A trial and error optimisation process is applied, following a sensitivity analysis, to derive the most optimal model parameter set. In a series of steps the model is calibrated successively against the overall discharge of the catchment and the piezometric levels. For the model validation a split-sample procedure is performed, followed by a multi-site validation.

2.3 The IRMB and SCHEME models (IRM-KMI)

The IRMB (Integrated Runoff Model Franz Bultot) conceptual model has been developed in order to study the hydrological cycle of medium-sized catchments. It has been applied in impact studies of climate change on river basins in Belgium. The IRMB model is characterised by a daily time step, eight land covers and a set of reservoirs that simulate different hydrological processes lumped at the scale of the catchment.

The SCHEME model is the distributed version of the IRMB conceptual model and is designed to simulate the water balance of basins as large as the basins of the rivers Scheldt and Meuse and to allow repeated long runs - typically 30 years for impact studies of climate change. The main difference between the IRMB and the SCHEME models is that the latter is intended to cover area of about 20,000 km^2. In the SCHEME model, the hydrological processes are lumped within grid cells of about 50 km^2. This size is compatible with the use of a conceptual approach whereas it allows the heterogeneity of hydrologic conditions and of hydrometeorologic input data to be properly described. The targeted scale implies that the routing of the streamflow in the river network must be approached with more details than being implicitly included in an empirical unit hydrograph. This scale implies also to cover ungauged areas.

For the purpose of the parameter regionalisation, it has been chosen to first optimise the values of the model parameters on a sufficient number of representative gauged catchments using an automatic optimisation procedure; then, to find rules relating the obtained values to the available information about these catchments. Finally, these rules have to be applied to the whole basin.

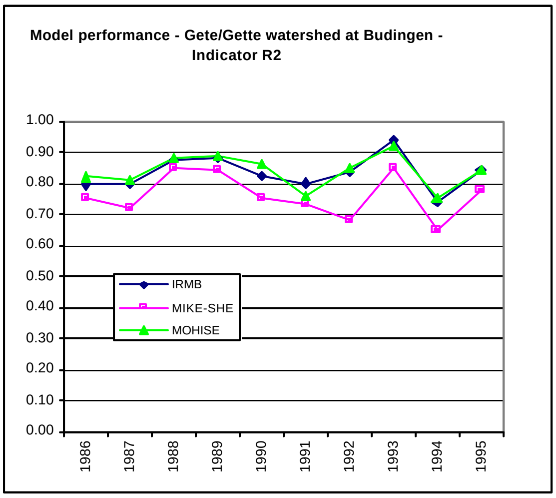
3. RESULTS AND INTERCOMPARISON OF THE MODELS UNDER PRESENT CLIMATE

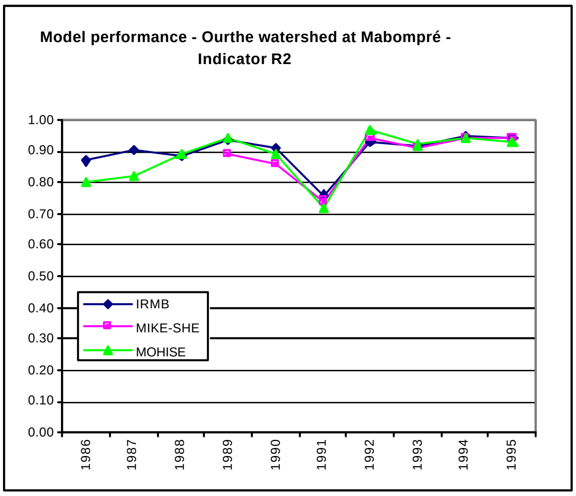
Validation simulations were made on the Geer, Gette and Ourthe basins using 'historical scenarios' over the period 1969-1995.

Simulation outputs of the models that can be compared to observations are the daily discharge at measurement stations of the test basins (MOHISE, Mike-SHE and IRMB models) and the piezometric level of the groundwater (MOHISE and Mike SHE models only).

The simulation results obtained for the three models on the three basins were compared to observed values and presented in tables and graphs. Statistical criteria were also calculated in order to characterise the performance of the models : the root mean square error (RMSE), the correlation coefficient (R^2), the model efficiency (EF), the mean absolute error (ABSERR), and the bias criteria (BIAS).

The figure 1 and 2 present, for the three models, the correlation coefficient calculated on the Gette and Ourthe basins.





***Figures 1 and 2** : Model performance (correlation coefficient R^2) for the Gette and the Ourthe basins*

The analysis of results shows that the three models are able to simulate the hydrological cycle and that the reliability of the simulations is high (the model performance indicators rise above 0.80 and 0.90). The analysis of the results also shows that the remaining uncertainty can be associated partly to the structure and parametrizations of the models, but also to the quality and/or availability of the data (e.g. hydro-geological characteristics of the ground, piezometric level measurements, water abstraction and pumping rate information, precipitation data, …).

4. CLIMATE CHANGE SCENARIOS

The results of experiments conducted with seven GCMs (General Circulation Models) have been made available to the scientific community through the Intergovernmental Panel on Climate Change. They respond to the criteria selected by the IPCC Task Group on Climate Scenarios for Impact Assessment .

Different sets of meteorological variables are available for the different experiments. The lack of some variables needed to assess evapotranspiration (windspeed, …) introduces some difficulties in applying some of these scenarios.

In order to reduce the amount of runs to be performed (and thus the total computation time), a subset of 3 GCMs has been selected. Preference was given to the models offering the highest resolution and the most contrasted changes : the ECHAM4 (German Climate Research Centre), the HadCM2 (UK Hadley Centre for Climate Prediction and Research) and the CGCM1 (Canadian Centre for Climate

Modelling and Analysis) models. The local climate change values are constructed by combining the appropriate monthly change rates with the daily values of a baseline period (1961-1990), corresponding to the 30 year simulation period of the GCM. For the precipitation, relative changes have been applied to the observed values. Coefficients have been calculated on observed data to convert changes in cloudiness to changes in global radiation and vice versa.

Monthly changes of meteorological variables have been interpolated on a 0.5×0.5 ° grid using the Cressman algorithm. Results of expected temperature and precipitation changes for the 21st century are presented in **figure 3.** Three periods of time are selected : 2010 – 2039, 2040 – 2069, 2070-2099.

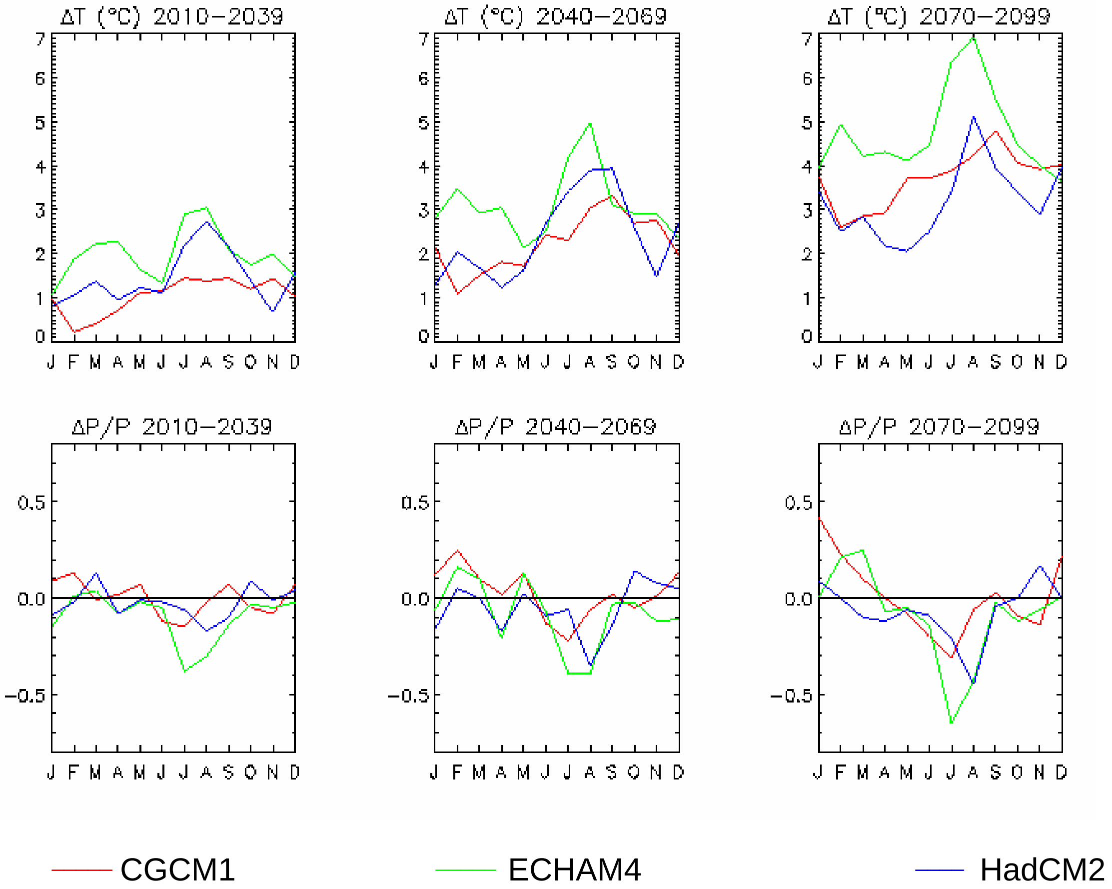


***Figure 3** Calculated changes in temperature and precipitation in Belgium from IPCC scenarios*

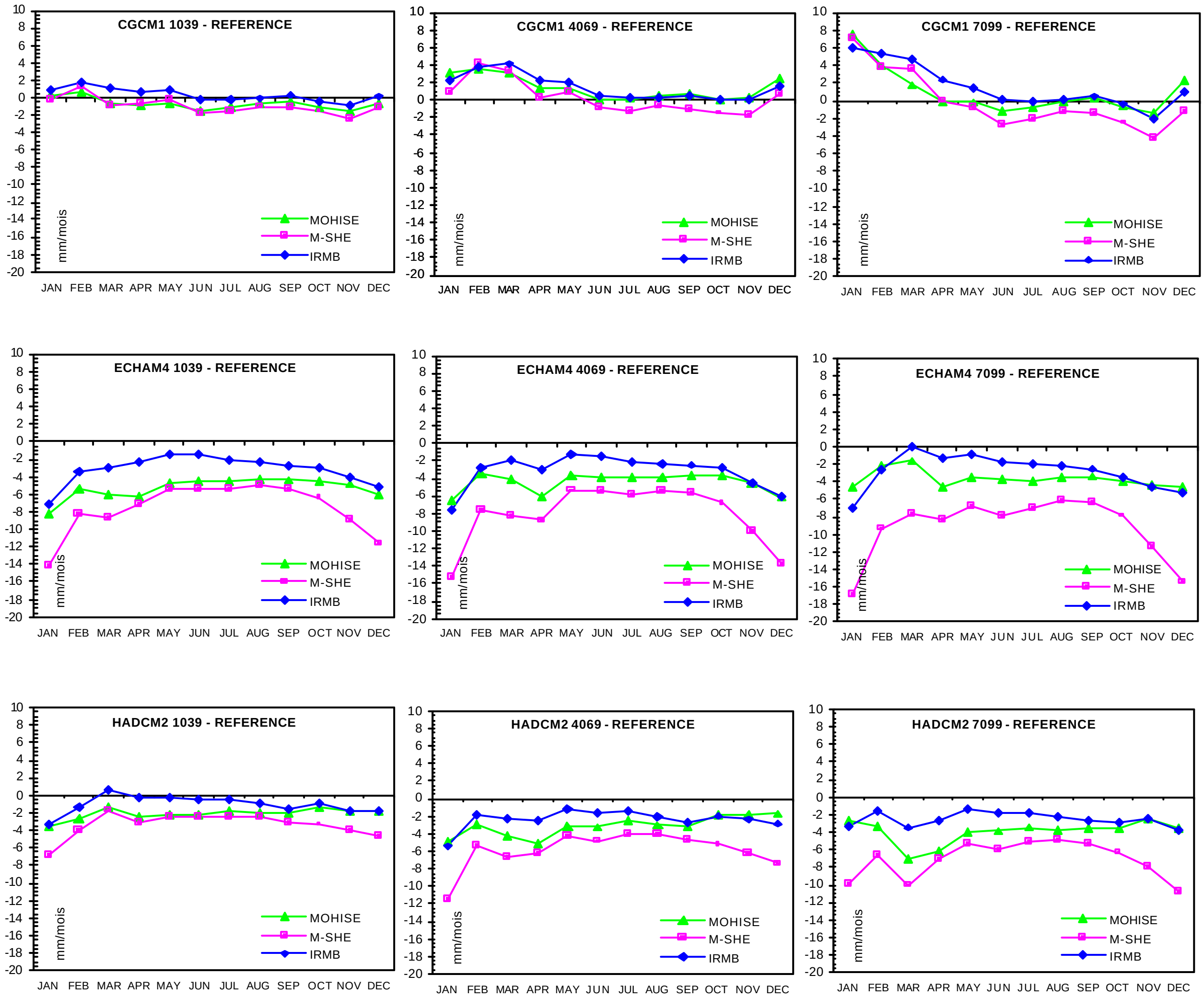
5. IMPACTS OF CLIMATE CHANGE SCENARIOS

5.1 Impacts on 3 Belgian test-basins

The impact of the CGCM1, ECHAM4 and HadCM2 scenarios on the Gette, Geer and Ourthe basins are calculated for the three 30 years periods 2010-2039, 2040-2069 and 2070-2099. The results of the 3 models are compared to the reference scenario obtained under present (historical) simulations.

Figure 4 shows as an example the changes in the total discharge at the outlet (monthly values) simulated by the three models (MOHISE, MIKE-SHE, IRMB) for the Gette basin.

Figure 4 : Comparison of the 3 Models on the Gette Basin
Mean monthly changes in the total discharge (mm/month)
(Difference between the scenario and the reference)



From top to bottom : the figures present successively the results of the CGCM1, ECHAM4 and HADCM2 scenarios. From left to right : the figures present the situation expected for the years 2010-2039, 2040-2069 and 2070-2099 periods respectively.These results show that :

- the three models (MOHISE, Mike-SHE, IRMB) give a 'similar' response to the scenarios; however, some differences appear;

- the climate scenario CGCM1 has little effect on the annual value of rainfall, evapotranspiration, discharge and groundwater level. The summer periods are calculated to become somewhat drier (less rainfall, higher evapotranspiration), the winter periods to become more wet. The detailed results show that the number of days with low flow in summer and autumn increases slightly, and that the number of days of high flows in winter and spring increases also slightly.

- the climate scenario ECHAM4 presents the strongest hydrological impact : rainfall rates decrease and evapotranspiration rates increase during the summer/autumn periods. The impact on the hydrological cycle shows a significant lowering of the water content in the upper horizon of the soil, in the unsaturated and saturated zones, and a significant decrease of the river flow during low flow periods.

- the impact of the climate scenario HadCM2 lies between the impacts of the CGCM1 and the ECHAM4 scenarios.

5.2 Impacts on agricultural soils

The use of the EPIC-GRID sub-model (HA-FUSAGx), part of the MOHISE model, makes it possible to assess the impact of the climate change scenarios on the soils and on crop productions.

In the scope of the present study, the following impacts are calculated for the agricultural soils of the Gette basin :

- the effect of the increase of the atmospheric CO2 concentration and of vapour pressure deficits on plants and crops;
- the crops water deficiencies and the agricultural yields;
- the problems of field accessibility, soil compaction and root extraction;
- the irrigation needs.

The results show that the water deficiency periods and their frequency are accented; the water deficiency periods increase with the temporal horizon within the 21st century.

Under the hypothesis of crop variety, diseases and insect damages, as well as fertilisation rates identical to the present situation, the simulation of the climate change scenarios indicates a small increase of the sugar beet and of the winter wheat yields. This increase, small on a long term averaged value, presents a great variability in relation to the annual climatic conditions, including possible yearly reductions.

The results show also that the periods of field inaccessibility are shorter, especially in spring. The periods with risks of compaction and problems of roots an tubers extraction are more important, especially in spring and summer.

The results about irrigation needs show an appreciable increase of the water deficiencies during the vegetation period and thus an increase of the irrigation needs. The increase of the critical ten days deficiency (between July 10th and August 10th) is general and bring to the fore an accented drought that implies an increase of the irrigation volumes which are necessary to satisfy the needs. These conclusions can be drawn for all the climate change scenarios and simulation periods.

6. GENERAL CONCLUSIONS

In this research, three different models (MOHISE, Mike-SHE, IRMB models) have been used to assess the effects of climate change on the terrestrial hydrologic cycle and on the water resources system.

The results of this research demonstrate the ability of the models to take into account the major hydrological processes that occur in the soils, groundwater and surface water compartments and the ability of the models to simulate the behaviour of the terrestrial hydrological cycle under the present climate conditions.

The models are then used to assess <u>the effects of potential climate changes scenarios</u> on the terrestrial hydrological cycle.

The results of the simulations clearly demonstrate that the potential climate changes can have significant impacts on the hydrological cycle of Belgian basins at the horizon of the mid-21st century.

However, for some variables, the magnitude and direction of the calculated impacts still present an important variability. The main reasons of this variability are :

the fairly large variability which remains in the different climate change scenarios generated at the international level (IPCC scenarios) by the different global climate change models;

the variability introduced by the hydrological modelling process itself, mainly related to the structure of the models and to the quality or availability of observation data on the test-basins.

For almost all the climate scenarios provided by the global climate models (GCMs), the simulations of the impacts of potential climate changes on the Belgian test-basins show:

- a decrease of moisture rates in the soils during the summertime,
- a decrease of piezometric levels of groundwater,

and a decrease of low river flow rates.

Simulated effects of climate change on high flows are however more contrasted : depending on the climate scenario, increase as well as decrease of mean monthly flow values during the winter period are calculated. For some scenarios, an increase of the river flow during some days can occur while the mean monthly flow is decreasing, so that no definitive conclusions can be drawn until now as regards the influence of potential climate changes on high flows events.

Significant effects of climate change scenarios on the agricultural soils, on crop production and agricultural practices are also emphasised (crop water deficiencies, irrigation needs, yield modifications, field accessibility, …).

New climate change scenarios, more precise and reliable, are expected in a near future. The models developed and used in the scope of the present study can be used in the future to simulate the effects of these improved climate change scenarios, in order to progressively reduce the uncertainties of the predictions.

7. SCIENTISTS INVOLVED IN THE NETWORK PROJECTS

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PART 1: REDUCING UNCERTAINTIES

Related supporting actions

AS/00/10

BELEUROS: IMPLEMENTATION AND EXTENSION OF THE EUROS MODEL FOR POLICY SUPPORT IN BELGIUM

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1. SUMMARY

The EUROS model is an atmospheric model that simulates tropospheric ozone over Europe on a long term basis. The model was originally developed at RIVM (The Netherlands). In the framework of the BelEUROS project, a new version of the EUROS model coupled with a state-of-the-art user interface has been installed at IRCEL/CELINE as a tool for policy support with respect to tropospheric ozone. This tool allows evaluating the impact of potential emission reduction strategies on ozone concentrations.

2. GENERAL CONTEXT

During summertime, high ground-level ozone concentrations are often observed in Belgium and the surrounding countries. Ozone is chemically formed from nitrogen oxides ($NO_x = NO + NO_2$) and volatile organic compounds (VOCs). These precursors of ozone are mainly emitted by road traffic and industrial activities. Ozone formation is driven by photochemically initiated reactions and is correlated to air temperature, so that elevated ozone levels are typically found in meteorological situations with clear skies and high temperatures.

Ozone has significant effects on human health and vegetation. Through its oxidation capacity, ozone affects lung functions, particularly in children and asthmatics. Exposure to ozone also induces damage to agricultural crops, forests and ecosystems, as well as to materials such as rubber and paints. For the protection of human health, a warning threshold of 180 $\mu g/m^3$ has been defined. In Belgium, the threshold value is frequently exceeded. In 1995, a very hot summer, 32 days with exceedance in at least one of the Belgian monitoring stations have been reported (IRCEL/CELINE, http://www.irceline.be).

The concern about the damaging effect of ozone is shared at various policy levels. At the European level, long-term objectives for the reduction of ozone concentrations have been defined in the framework of the Directive 96/62/EC. According to the daughter directive in preparation, the target values should be attained by the member states by the year 2010. In order to reach these objectives, most of the member states will have to reduce drastically the emission of pollutants responsible for ozone formation, i.e. nitrogen oxides (NOx) and non-methane volatile organic compounds (VOC). The emission reductions are prescribed for each of the EU member states in the form of national emission ceilings under the Gothenburg Protocol (1999) en in de NEC (National Emission Ceilings) directive in preparation.

In this perspective, it is essential to provide the policy makers with adequate tools for evaluating the impact of possible emission reduction strategies on the ozone concentrations. Numerical atmospheric models are well suited for this task. These models represent the various atmospheric processes responsible for ozone formation and destruction: pollutant emission, atmospheric dispersion and transport, chemical transformations and deposition. Model simulations allow estimating the effect of specific emission reduction measures on ozone concentrations.

3. THE BELEUROS PROJECT

The aim of the BelEUROS project was to provide the Belgian authorities with such a modelling tool for policy support with respect to tropospheric ozone. The EUROS model (EURopean Operational Smog model) was selected for this purpose. A schematic view of EUROS is given in Figure 1. It is a regional chemistry-transport model which has been developed at the RIVM (Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven, The Netherlands). It simulates the hourly variations of ozone over Europe over long time scales (typically a few months) with a standard resolution of 60 km. A grid refinement procedure allows refining the spatial resolution in certain areas of the model domain, for example Belgium. A detailed emission module describes the emission of three pollutant categories (NO_x, VOC, SO_2) and for 6 different emission sectors (traffic, space heating, refinery, solvents use, combustion, industry). The implementation of EUROS in Belgium required the adaptation of some input data (emission and meteorology) and of some intrinsic features of the model as well. These developments on the EUROS were realised in close collaboration with the RIVM and mainly concern a better representation of the transport and dispersion of pollutants in the lower layers of the atmosphere.

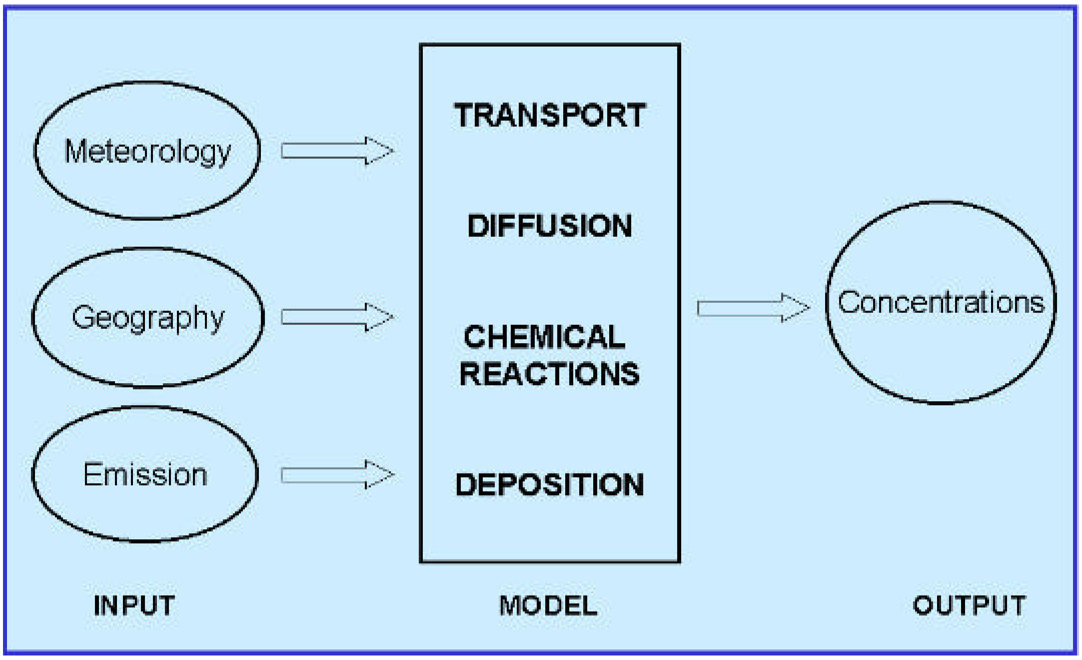

Figure 1: *A schematic view of the EUROS model*

The new version of the model has been installed at the Interregional Cell for the Environment (IRCEL/CELINE) in Brussels and made available to user groups in the three Belgian Regions (http://www.beleuros.be). A complex model as EUROS can not be used efficiently by policy makers if it is not provided with a user friendly interface allowing the user to define the general characteristics of his simulation, to specify the emission scenarios and to visualise and analyse the output results. Therefore, an important task of this project was the development of an effective Windows user interface. This interface must also control the Internet exchanges between the local computer of the user and the central computer at IRCEL where the model runs. This allows the user to start a simulation from a remote location through Internet connection.

The distribution of the tasks between the various partners was organised as follows. VITO (Mol) was in charge for the development of a new emission inventory. The new developments on the EUROS model itself were realised by VITO in collaboration with UCL (Louvain-la-Neuve) for the meteorological aspects. FPMs (Mons) was in charge for the development of the user interface and for the installation at IRCEL in collaboration with the VITO and IRCEL. The task of RMI (Brussels) was to provide the meteorological data. VITO was also in charge of a study concerning the impact modelling of ozone on human health and vegetation. As user and associate partner, IRCEL has played an important role as adviser throughout the whole project. The co-ordination of these tasks was ensured by the VITO.

4. MAIN RESULTS

4.1 Generation of new input data for EUROS

A dynamic emission inventory has been compiled for the European countries that are covered by the EUROS domain. The inventory provides the spatial and temporal variations in anthropogenic emissions for six economical sectors and the distribution of biogenic emissions varying with temperature. This inventory was implemented in a Geographical Information System (Arcview) which proved to be very helpful in this context.

As far as the meteorology is concerned, a new three-dimensional input data set for EUROS has been generated from the ECMWF meteorological data (European Centre for Medium-Range Weather Forecasts, Reading, UK). Moreover, an important atmospheric parameter in EUROS is the mixing height, i.e. the height of the atmospheric layer adjacent to the ground, where the pollutants are well mixed through the action of turbulence and convection processes. Several methods have been explored to estimate the mixing height from the meteorological data set. The results have been compared with observational data and with the results of detailed model simulations. Based on these results, a new method has been proposed for the determination of the mixing height in air quality models.

4.2 Development of a new version of EUROS

The EUROS model has been further developed in close collaboration with the RIVM (Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven , The Netherlands). A new version has been set up. It includes a spatially variable mixing height and a multi-layer representation of the horizontal transport. This allows a much more realistic representation of the atmospheric processes responsible for the transport and dispersion of pollutants. The model is now provided with a three-dimensional grid structure, which constitutes a first step towards a fully three-dimensional representation of the transport and dispersion processes. The new version has been tested by comparing the simulated ozone concentrations with observational data.

4.3 Development of a user interface

A user-friendly interface has been developed. It consists of a Windows platform written in VISUAL-C++. The interface allows the user to define his emission scenario, to start the simulation from his computer and to visualise the output results. The user has the possibility to modify the emission rates of a given pollutant (NOx or VOC) for a given emission sector (traffic, space heating, refinery, solvents use, combustion, industry) and for a given geographical area. Monthly, daily and hourly emission factors can also be modified for each sector. These factors account for the influence of the month in the year, the day in the week, and the hour of the day. As far as the output results are concerned, the user interface allows an easy visualisation of the geographical distribution of the pollutants over Europe with the possibility to zoom on Belgium (Figure 2). The visualisation of long term indicators like AOTs (Accumulated Exposure over a Threshold) is also possible. In addition, the time evolution of pollutant concentrations on a specific location can be displayed.

4.4 Installation at IRCEL/CELINE

The new version of the EUROS coupled with the user interface is now installed at IRCEL/CELINE and can be used by policy makers and researchers for evaluating the impact of possible emission reduction strategies on ozone concentrations. The output results of EUROS allow an evaluation of the indicators currently used for estimating the impact of ozone on vegetation and human health. Some of these indicators are also used in the current European legislation related to ozone in ambient air.

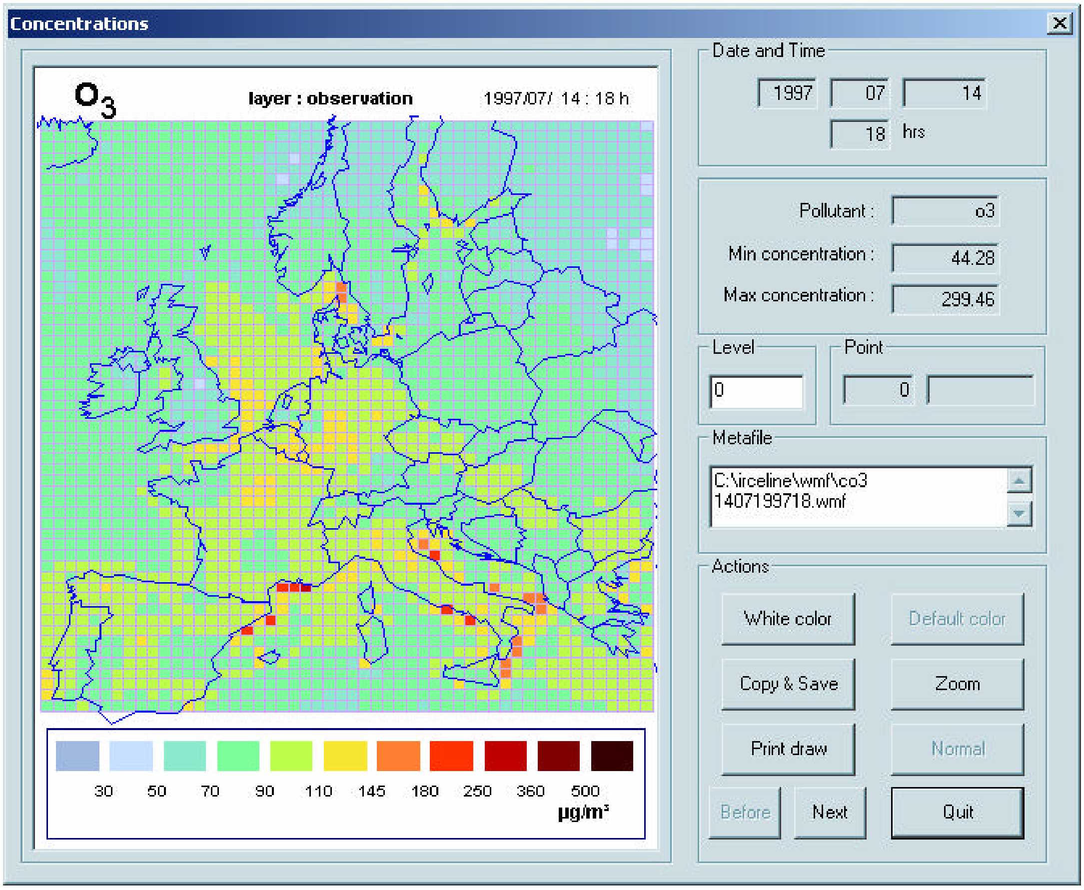

Figure 2: *Visualisation of ozone concentrations over Europe*

AS/DD/09

DEVELOPMENT OF A SPECIFIC INTERPOLATION METHOD FOR AIR POLLUTANTS MEASURED IN AUTOMATIC NETWORKS (SMOGSTOP)

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The final report makes the synthesis of a search for methods of interpolation necessary to the exploitation of data of concentration of pollutant which are generally dispersed on a given space field. Four great methods were adopted and applied to concrete data of pollution and visualized in a very convivial data-processing environment. It appears that a great rigour in measurements, prudence in the interpretation and the choice of methods are necessary so that the adopted methods of interpolation have objective results. It often happens that measurements concerning pollution force the majority of the methods of interpolation to force some their theoretical limits. Spatial distribution of the measuring sites is often far from the assumptions of a homogeneous distribution. The critical zones characterized by a superabundance or a poverty of information must be treated carefully. It is necessary to emphasize there just the useful one when they are located in an environment either too overloaded in information or too low in measurements like are often the frontier zones of the field of study. It should not be forgotten that measurements of pollution record the internal and external contributions without distinguishing them.

The object of the study consist in developing a data-processing module fast and easy to use making it possible to build, starting from measurements with the receivers (immissions), a continuous space representation of pollution present on the studied area. It must allow cross analyses and cartographic visualizations, both necessary to the exploitation as well of the bank of data as of models (such as model SMOGSTOP of forecast of the ozone peaks).

The examined methods of interpolation and reserves in this study for a scalar size turn around four great classes:

- **Method of weighting compared to the distances.** This analytical formulation exploits the idea individually that each measured value contains information which is degraded while moving away from the point of measurement. The effect additive or linear of these various "sources" of information led, by a weighted average, with an estimate of the size measured in each point of the studied geographical area. For a choice of a function defining the decrease of information an alternative of this type of method of interpolation corresponds (Model in the reverse of a power of the distance, models of Cressman, Thiébaux-Pedder and Sasaki-Barnes).

- **Methods based on the triangulation of Delaunay.** These methods are of type "patchwork" i.e. that they build, starting from inter-connected elementary surfaces, a total surface passing by all the points of measurement. As it is not possible to build a rectangular grid, elementary surfaces are triangles, with for tops three sites measuring, having good properties: their interiors must be disjoined two to two and each one cannot contain stations. The triangulation of Delaunay makes it possible to build a single network of triangles having these properties. This parcelling out carried out, the quality of connectivity (continuity) defines the type of method: the interpolation on this network can be realized by ensuring either a simple continuity in the method of interpolation linear, or a continuity until the derivative first in the method of interpolation quadratic or method of Cendes-Wong, or a continuity until the second derivative in the method of cubic interpolation known as method of Akima.

- **Method of the splines functions of thin plate type**. This method contrary to the preceding one does not require any more one cutting in triangles of the studied zone. It directly seeks a function which always passes by the points of measurement (condition which can be softened) and which is subjected to a general constraint instead of satisfying local conditions of continuity. Total surface obtained resembles that given by a material low thickness (thin section) subjected to a whole of local forces (points of measurement) with boundary conditions particular.

- **Krieger method** . The individual character which is used as a basis for the first method owes, in the facts, being limited by the taking into account of the interactions existing between the measured values if one wishes to obtain a good interpolation. Certain parameters of this method are defined by revealing these structuring interactions. The first method returns thus to a whole of separate actions which try to correct the individual nature of this method. On the contrary, the Krieger method is based on nature correlated spatially measured information of which she does not know *a priori* the structure. A significant part of the method consists in explicitly defining this structure while being useful of the concept of “variogramme”. Once this space structurality modelled, the Krieger method itself consists in seeking the minimum of the variance of the error existing in each point of estimate. The various stages intervening in the Krieger method make this method more technical and thus less usable "the closed eyes" as allows it the three other methods of interpolation.

For three of the four adopted methods, the results of the interpolation established on a rectangular grid covering the studied area can undergo a smoothing (face lift) using functions N. U. R. B. S. If this method makes it possible, in certain case, to free itself from a too small mesh to avoid of long computing time, it has the advantage of building an interpolation having of very good conditions of continuity. All the methods of interpolation were developed in a data-processing application written in Visual C++.

The interpolations were applied to two pollutants having contrary behaviours to know ozone O_3 and the sulphur dioxide SO_2. This primary education pollutant is emitted mainly in the cities and their crowns. Ozone, secondary pollutant, is the result, under the action of solar energy, of chemical reactions utilizing mainly the oxides of nitrogen and the volatile organic compounds (COV). If the SO_2 finds itself mainly to the crowns zone, ozone really starts beyond this zone.

With these data files the applications at the Belgian level highlight the following principal fact: the interpolation has effectiveness only inside the envelope containing the measuring sites. In outside of this envelope, the interpolation becomes an extrapolation which it is difficult to control as long as information external to Belgium is not known. Into waiting of data exchanges at the European level, fictitious points were introduced and responsible for values in concentration starting from a method of interpolation based on values of "bottom". This behaviour out of the triangular network appears clearly with the Krieger method which is the only one to determine the error related to the estimate. It is always significant in the vicinity of the Belgian borders (except triangular network) in the absence of the fictitious points when all the stations are considered. For the other methods of interpolation, that is marked by abnormal behaviours in extreme cases of Belgium.

A second interesting result arises when one considers not only all the stations but when one gathers the stations in a class of national station and a class of regional station (city). This dichotomy was made possible thanks to the classification of the stations. Each name of station carries information making it possible to know if this station is urban (letter R) or not-urban (letter N) to take account of the influence or not multi-transmitters (transport, heating, industry). The results based on the national stations are, for all the methods, practically similar both for ozone and SO_2. This behaviour tends to confirm the objective of these stations which is to follow the air pollution known as of "bottom". It does not matter the method, the structure of the field of pollution seems returned well. Differences appear if the regional stations are only considered. The coherence of the interpolations obtained with these stations is difficult to show both for ozone and the SO_2. The reasons can be multiple, for example, a low number of regional stations for ozone or the groupings very centred for the SO_2. If all the stations are considered, the results are also similar with all the methods. However, for the SO_2 the Krieger method clearly limits the extensions of certain stations with strong values of concentration.

For a complete analysis, the Krieger method is a method which must be considered in first analysis since it makes it possible on the one hand to decode the structures or space correlations of the analysed phenomenon and on the other hand to establish the values estimated as well as the errors related to the estimate. The results, if they lead to a coherence interns near to a reality in conformity with the practice, must be subjected to a confrontation with the results obtained by at least another method of interpolation. This one is to be sought among the total methods of type "patchwork" or thin section type. For these methods, negative values can appear. A procedure was installation to avoid the presence of significant gradients non existing in reality.

If, a new problem is to be treated, a first fast and effective analysis is to be made using a method of interpolation based on the triangles of Delaunay (straight-line method with NURBS, the method of Cendes-Wong, method of Akima) or the method of the splines of thin plate type. The particular choice of one of these methods will result from the properties of continuity required by the secondary treatments applied to the data of the interpolation.

AS/DD/01B

VULNERABILITY ASSESSMENT, CLIMATE CHANGE IMPACTS AND ADAPTATION MEASURES

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1. INTRODUCTION

Under the UNFCCC which entered in effect on 21 December, 1993, Belgium is compelled to report in the form a National Statement to the secretary of the Treaty of Bonn at set times. Early 1997, Belgium submitted its first National Statement, with an update in August 1997.

Vulnerability depends on the sensitivity of a system and on its ability to cope with change; this is the reaction level of this system to a specific climate change (positive as well as negative effects) and the adaptation possibility of the system to climate changes. Due to the fact that the available studies do not use similar climate scenario's and methods and due to uncertainties with regard to sensitivity and adaptation ability of natural and social systems, the vulnerability assessment of the different sectors in Belgium is of a qualitative nature.

The priority themes such as soil, agriculture, horticulture and forestry, freshwater systems, coastal zones and sea level have been elaborated according to the guidelines of the Intergovernmental Panel on Climate Change (IPCC). The other themes such as fauna and flora, landscape, energy sector, industry, transport, financial sector, health, leisure and tourism are described in a synthesis of the most important data for the assessment of effects of climate change in Belgium.

The scenario chosen for Belgium is based on international data. The basic assumption is that without further policy measures, this scenario projects the climate of 2100. In addition to the description of the effects and the adaptation strategies, recommendations for future research and for strategic approaches are given.

1.1 Evaluation methods

Contrary to NC-1 and NC-2 that were based in essence on one or a few experiments, this statement applies a combination of methods. The methods applied in the preparation of this statement include the following elements:

- an inventory and in-depth analysis of all experimental data of relevant research projects for effects reporting of climate changes and this for:
  - all Belgian research programmes;
  - other research activities in Belgium within the framework of international programmes;
  - international research programmes and programmes in countries with relevant results for Belgium (regional and empirical analogies);

- research on the models and scenarios applied and used in Belgium;
- discussion with foreign experts;
- discussion and follow-up by Belgian experts

1.2 Scenario for Belgium

The scenario for Belgium is based upon the scenarios of the IPPC (1997, 2001), the UK Climate Change Impact Review Group (1996). This scenario assumes a status quo concerning greenhouse gas emissions. This is based on the fact that there are a lot of uncertainties concerning the future policy and it is impossible at this point to estimate the effectiveness of policy measures in achieving the Kyoto Protocol greenhouse gas emission reduction objectives of 7.5% by 2008-2012. However, the need for reaching these objectives is supported.

The climate scenario used here is based on the following assumptions:

- the present "equivalent CO_2" concentration will double to reach 700 ppmv by 2100;
- a CO_2 concentration of 700 ppmv will result in an average temperature increase of 2°C by 2100;
- the period 1990 up till 2100 is considered;
- the temperature changes will be uniform for the whole of Belgium.

It should be emphasized however that a range of scenarios has been taken into consideration for the further assessment of the effects. The above scenario has been selected for Belgium in concertation with both a resource team of scientific experts and a guidance committee representing the Federal and Regional Departments involved.

1.3 Description of the climate and hydrology in 2100 in Belgium, based on the adopted scenario. Reference year is 1990.

Temperature

- average air temperature increase (winter and summer) of 2°C;
- increase of extreme weather conditions (not only changes in the average temperatures but also in extremes and variability), sudden unusually cold conditions

Precipitation

- slight decrease (approx. 3%) in precipitation, or stabilised precipitation during summer but increase during winter (approx. 10%);
- changes to precipitation distribution will have a major impact.
- storm frequency will increase by 30% towards 2050. The exact frequency or the frequency changes of the occurrence of storms cannot yet be predicted.

Relative humidity

- relative humidity decrease by approx. 6%;

Potential evapotranspiration

- increase by 10-15%.

Drainage of rivers

- changed annual drainage of between 5% increase to 30% decrease;
- increase in flood frequency during winter and spring, increased low flows in summer and autumn

Sea level

- sea level rise for Belgium of between 40 and 70 cm.

Uncertainties

- there will be much more natural variation in local climate than the continental-scale climate variables can show;
- when determining the future effect, the strong regional variations with variables such as precipitation, clouds and the frequency of extreme weather conditions (extreme precipitation, extreme drought, storms etc.) must be taken into account.

2. IMPACTS AND ADAPTATION

2.1 Sector I: Freshwater systems

2.1.1 Impacts assessment

The major effects of climate change as predicted by the models that have been adopted on freshwater systems are summarised in Table I.

__Table I.__ Climate change effects on freshwater systems.

Effects	Remarks
The recharge and content of groundwater and surface water reservoirs decreases during summer	Possible problems for drinking-water provision and irrigation water; possible reduction of wetlands
Probably rise of water level of rivers during winter	Increased risk of floods
Groundwater quality deteriorates following: - salt intrusion caused by higher seawater levels - alterations in soil properties due to changed groundwater levels	Groundwater quality is predominantly affected by factors other than climate change
Demand for water for consumption increases	
Increasing frequency of extreme conditions leads to more frequent and more extensive floods and low flows	The effect is difficult to predict and depends on the river basin
River morphology changes brought about by increased erosion	There is a possible impact notably on floods and navigation
Lower flows in summer and autumn	Possible problems for river biota and aquaculture

2.1.2 Adaptation strategies and measures

Water management is a process of constant adaptation, anticipating demands, new technologies, new information, new legislation and new expectations. To prevent water shortages and floods, management and use measures are taken, irrespective of the direct causes such as climate change.

Adaptation strategies include:

- adequate management of returning of land to rivers to prevent floods (as already applied in Belgium);
- introduction of technological measures for the management of water reserves; these include water-saving measures, development of criteria for land use, erosion control; possible construction of additional basins and pipelines to assure the availability of freshwater must be further foreseen, in an integrated and global watershed management approach;
- direct measures for more efficient water use to limit the use of water and land (including promotion of sky water use);
- incentives and penalties for more efficient water use.

2.1.3 Conclusion

As with the other sectors, there are still many uncertainties about the prediction of effects on freshwater systems. The most important factor is the driving force of the hydrological system, i.e., precipitation. Certainly when modelled at a regional scale (watershed scale), very diverse predictions are obtained. It is of major importance that further research is done to improve the understanding of the hydrological cycle, which will result in great overall improvements of the predictions of the impact of climate change. The predictions of the frequency of extreme conditions are in particular subject to great uncertainties. The overall trend, however, with regard to Belgian river basins is that there will be a likely increase in flood and low flow frequency and extent. Given the fact that water management activities can minimise the effects of climate change on freshwater systems, they play an important role in policy decisions.

2.2 Sector II: Coastal zone and sea levels

2.2.1 Impacts assessment

The possible effects of climate change following the scenario that was adopted are described in Table II.

Table II. *Qualitative description of the possible effects of climate change on the Belgian coast*

Factor	Intermediate effects		Final effects
	Primary	Secondary	
Sea level rise Storm frequency increase	Biota change		impact on fisheries
	River tide alterations	Increase of inland floods	increased risk for victims and damage
	River tide alterations		impact on navigation / shipping
	Salt intrusion in surface waters	Biota changes	nature value damage
	Sedimentation patterns change		impact on fisheries
			increased risk for victims and damage
			impact on navigation / shipping
	Coastal erosion	Biota changes	nature value damage
			infrastructure damage
			increased risk for victims and damage
			tourism decline
	Floods increase		increased risk for victims and damage
			impact on agriculture
		Soil quality damage	impact on agriculture
	Coastal pollution increase		tourism decline
			increased health risks
			increased health risks
			impact on fisheries
			impact on navigation / shipping

Storm frequency increase			impact on fisheries
			impact on navigation / shipping

2.2.2 Adaptation strategies and measures

The following adaptation strategies in the light of the impacts of climate change are considered:

- a prevention strategy focussed on coastal defence;
- intensifying preventive measures against coastal erosion caused by waves and tides, particularly soft measures such as beach profiling, sand accumulation, sand suppletion, planting of beach grass);
- provision of funds sufficient for effective coastal defence in the light of climate change.

2.2.3 Conclusion

The major effects of a sea level rise are considered to be the risks to coastal residents, the damage to nature values, a decrease in tourism and an impact on agriculture. An increase in storm frequency will affect adversely fisheries and navigation/shipping. Intensification of coastal erosion prevention measures will limit the effect of a sea level rise in Belgium to a loss of nature values.

Policy measures in this context have to be part of Integrated Coastal Zone Management (ICZM). The different sectors involved, however, often have different priorities, complicating the introduction of ICZM. An integrated coastal zone policy should be process-oriented rather than goal-oriented. It is crucial in this context to improve co-operation between coastal planning (possible future effects) and coastal defence (preservation of the actual situation).

2.3 Sector III: Soil

2.3.1 Impacts assessment

The major effects of climate change as predicted by the models that have been used for effect assessment on soils are summarised in Table III.

Table III. *Climate change effects on soils.*

Effects on soil	Remarks
Slight enrichment with salts	
Increased erosion caused by increased precipitation and wind action	- taking into account the erosion increase through changes in land use - partial prevention through afforestation and land management programmes
Modification of soil moisture evolution (more frequent moisture deficit).	Consequences for soil biota
Lower organic material content following the temperature increase resulting in higher rates of mineralisation	Limited importance in relation to impact of agriculture
Soil shrinking: peat by up to 45 cm, clay by 10-45 cm; increased shrinking and expansion action	Affected areas include polder, river depositions, Rupel area, large parts of East and West Flanders, the Fens; repercussions mainly for the construction industry
Sea level rise will result in increased salinity in polder	

2.3.2 Adaptation strategies and measures

The following adaptation strategies in the light of the impacts of climate change are considered:

- current land use is a major contributor to soil erosion. At present, a number of erosion prevention measures are being elaborated, including slope reduction, specific agricultural interventions and land management;
- improved management of underground / soil water is necessary;
- use of exogenous humus;
- guidelines development for construction works stability.

2.3.3 Conclusion

There is still a lot of uncertainty about the effects of climate change on soils because most effects depend on the future precipitation patterns, which are hard to predict. Furthermore, there is uncertainty about the effect of an increased CO_2 concentration on vegetation. This will influence organic material content, degradation speed, nutrient balance, etc. of the soils (secondary effect). Despite of the available data concerning changes in humidity, erosion and organic material, it remains impossible to clearly quantify the effects of climate change on soils in natural and semi-natural habitats.

In the foreseeable future, land use will still have a much larger impact on soils in Belgium than the possible effects of climate change. On its turn climate change may be a driving force for land use change in the future (e.g. flooding, erosion,…) It is therefore necessary to link these two elements in further research.

The data available at present allow to conclude that climate change in Belgium will have little or no significant direct effect on soils. Indirect effect as a result from moisture deficits and erosion may however occur.

2.4 Sector IV: Agriculture, horticulture and forestry

2.4.1 Impacts assessment

The effects of climate change on agriculture, horticulture and forestry are diverse and wide-ranging. Table IV presents the effects that in general are the most important ones.

Table IV. *Most important effects of climate change on agriculture, horticulture and forestry*

EFFECTS ON AGRICULTURE, HORTICULTURE AND FORESTRY	REMARKS
Increased rates of photosynthesis will result in increased rates of crop development	- production and productivity increases for most crops, especially for sugar beet and carrot. - production decrease for cauliflower and fruit trees
Improved water use efficiency	In case of elevated CO_2 levels
Hydric stress for grasslands and vegetable crops	In relation to increasing soil moisture deficits
Decreased protein level in crops	Unknown effect on crop quality
Increased migration and distribution of pests	New pest control techniques will be required
Change in species composition	Effect on biodiversity
Sea level rise will result in increased salinity in polder	Decrease in agriculture area, possible damage to crops
Increased temperature will benefit horticulture	Less energy (heating) use, possibility to cultivate more species
Decreased forests diversity but higher overall productivity	Strongly influenced by management

2.4.2 Adaptation strategies and measures

The following adaptation strategies in the light of the impacts of climate change are considered:

- formulation of adjusted pesticides and pest management policies if and when new pests occur;
- technology improvement to overcome biophysical limitations such as water availability, soil characteristics, genetic diversity for crop cultivation and topography;
- intensification of afforestation programmes (CO_2 sinks and erosion prevention);
- further global analysis of consequences for vegetable crops and husbandry.

2.4.3 Conclusion

The vulnerability to the effects of climate change depends not only on physical and biological but also on socio-economical characteristics. In case of a good socio-economical situation (such as in Belgium), vulnerability of agriculture, horticulture and forestry is generally rather low. This is due to the fact that only a minor part of the GDP originates from primary agriculture. Furthermore, only a small part of the population is active in agriculture and there is a capacity for adaptation.

An increase in CO_2 concentration and temperature will result for most crops in Belgium in an increased production; however, this increase is crop-specific and will compensate for a possible water shortage (notably grassland and vegetable crops). In horticulture, climate change in Belgium is expected to have a positive effect partly due to the opportunity to grow new species and partly due to reduced energy needs. Fruit cultivation, however, would be threatened, although only to a small extent.

Recent trends of more natural approaches to forest management make it hard to determine the cause of changes: climate change or change in management. Climate change effects on forests in Belgium are considered to be minimal when compared to the impacts of land use and of socio-economic factors.

2.5 The other sectors: overview

2.5.1 Impacts assessment and adaptation strategies

The most relevant available information for the other sectors are given below:

Fauna and flora	
Important effects	- change in species composition - species diversity (particularly for plants) is expected to decrease - increase in insects populations - invasion of new species
Possible adaptation strategies	- transfer static approach to nature conservation and management to a dynamic approach - creation and conservation of corridors and/or stepping stones

Landscape

No important effects or adaptation strategies to mention, except those that may originate from coastal and river defence structures on the one hand and from watershed management on the other hand.

Public Health

Important effects	- effects will mainly occur in summer (less in winter) as a consequence of: ▪ heat waves resulting in increased mortality; ▪ increased air pollution caused by heat (more asthma and allergies to pollen and spores) ▪ thinning of the ozone layer resulting in increased harmful ultraviolet light exposure - contamination of water reserves by increased floods
Possible adaptation strategies	- further extension of present public health system - improved control of climate change effects

Energy

Important effects	- changes in energy consumption for heating and cooling of residential and commercial buildings - restricted availability of cooling water
Possible adaptation strategies	- in case of gradual climate change, there is a high possibility for autonomous adaptation through new techniques and industrial processes - research on renewable energy sources

Industry

Important effects	- the production sector is often directly or indirectly related to freshwater systems (extraction, transport, cooling, water quality) - more demand for light clothing - more light food and increased consumption of (soft) drinks

Possible adaptation strategies	-	taking possible effects of climate change (stability issue) into account in the development of new technologies in the construction industry
	-	preparation to demand changes by means of market studies

Financial sector

Insufficient data available to make an impacts assessment.

Tourism

Important effects	-	coastal tourism will increase (if the sea level rise is under control)
	-	winter sports and river sports industry will decrease
	-	indirect effects depend on the effects on freshwater systems, fauna and flora and sea level
Possible adaptation strategies	-	already constant adaptation depending on demographic, ecological and economic processes

Transport

Important effects	-	indirect effects through changes in flows of goods (e.g., following changes in agricultural production patterns) and passengers
	-	changes in river flows may affect inland shipping
Possible adaptation strategies	-	for this sector, a strong autonomous adaptation is expected in the coming 50 years

2.5.2 Conclusions for the other sectors

Little information is available on the effects in Belgium of climate change on **fauna and flora**, and most of it is mere expert opinion. Changes in species distribution, loss of biodiversity and/or invasion of new species are probably the most important effects of climate change. Policy in this sector in the light of climate change needs to give due consideration to other factors that have an impact. It is thus expected that e.g. changes in agriculture policy, possible fiscal advantages for forestry, changes in land use or changes in water extraction in the near future (next 50 years), will have a much larger impact on fauna and flora in Belgium than the effects of climate change.

Future changes in **landscape**, in species composition and distribution of plants and animals in the landscape are likely to be equally or yet more influenced by land use policy measures than by climate change. Significant policy decisions which entail changes in the agriculture policy, fiscal stimulants for forestry or changes in water use are likely to have more impact on the landscape than climate change. These policy decisions, however, could be (in part) motivated by climate change.

Climate change, together with its ecological and economic consequences, poses an increased risk to **public health** in the long term. Monitoring of possible effects of climate change on human populations is indicated. Overall, vulnerability in Belgium to the different effects of climate change on public health is limited due to the existence of adequate public health infrastructure and systems. The effects of heat waves and extreme weather conditions, however, can not be excluded.

The **energy** sector in relation to climate changes is shown to be the main cause of climate change. After all, the energy sector is the major source of antropogenous CO_2 emissions, the most important greenhouse gas. Direct impacts of climate change on the energy sector will, however, be much smaller than those caused by economic developments, technological changes or mitigating measures which will be imposed to reduce the greenhouse gas emissions. The kind of energy use that is most susceptible to climate change effects is heating and cooling of residential and commercial buildings, which will entail a net reduction in energy use.

The **industries** that are thought to be most vulnerable to climate change are those depending on agriculture, horticulture or forestry for the supply of raw materials. The relation between industrial processes and their impact on freshwater systems and the energy sector is an important element for the evolution in these sectors. The development of new technologies for the construction sector should take possible effects of climate change into account. By means of market studies, the industry, retail trade and tertiary sector are able to prepare themselves for changes in demand for certain products.

At present, little information is available about the possible effects of climate change on the **financial sector**.

Under the present predictions there are mostly positive effects of climate change on **tourism.** Precaution and adaptation measures are required for sectors that indirectly influence tourism. Major negative impact is anticipated for the winter sports and river sports in the Ardennes. Coastal tourism will enjoy a mainly positive impact, provided that the possible adverse effects of sea level rise are controlled. Belgian tourism will always be linked with possible climate change in the future. The predictions, however, are all based on the assumption that the present economic, ecological and demographic conditions persist. Any change in these conditions (which is very likely) will influence the present findings.

Like the energy sector, the subject of **transport** in relation to climate change is also seen in most studies as a cause of climate change. The direct impacts of a climate change on the transport sector will therefore be much smaller than those caused by economic developments, technological changes or mitigating measures imposed to reduce greenhouse gas emissions and to meet the growing demand for transport.

3. OVERALL CONCLUSION

Based on the present information, it can be put forward that there are rather limited effects to be expected with regard to a climate change in Belgium. This is the result of the stable socio-economic situation in Belgium and the specificity and resilience of the different sectors that are affected. Nevertheless caution is always needed when little information is available. In a scenario of large climate change, effects may become more significant. The sectors that will experience the most direct impacts are the freshwater systems (change in flow rates and water reserves) and the coastal zone. For the coastal zone, the impact will be minimal with proper adaptation measures. Next to these, the industry, and the construction industry in particular, agriculture, public health and tourism are important issues. Apart from the effects of climate change, important evolutions are expected in sectors such as industry, transport and energy which will enable an autonomous adaptation with regard to climate changes.

The major effects, which are very hard to predict with the current understanding of the climate, will occur under extreme conditions. Due to an increase in the frequency of storms, floods, heavy precipitation, extreme heat, soil moisture stress, etc, effects will emerge that were not taken into account. It is of major importance for relevant policies to take these effects into consideration and to further investigate them in order to elaborate contingency plans.

It is unlikely that efforts to reduce the emission of greenhouse gasses will be sufficient to exclude the possibility of climate change. Thus, policy makers will also have to pay attention to possible adaptations to the effects of climate change. Based upon these uncertainties with regard to the effects of climate change, one could suppose that it is better to postpone the measures for adaptation until after major climate change. However, this is not recommended for the effects that entail significant risks, that are irrevocable or catastrophic. Furthermore the precautionary principle may not be abandoned. But attention must be given to the fact that anticipating measures must be flexible and economically efficient (their benefit must balance their cost).

Adaptation is seldom a response to only one environmental variable. It is more likely that the adaptation will take place through a combination of alternative management, changed patterns of land use, exploitation of new possibilities and new markets. The challenge remains connecting short term adaptations of specific systems with their sustainability in the long run. It is exactly this sustainability that determines the ability to long term adaptation.

PART 2: TO PROVIDE SCIENTIFIC SUPPORT FOR BELGIAN POLITICS

Reduction of greenhouse gas emissions

CG/DD/211
CG/DD/212

A SIMULATION MODEL TO EVALUATE THE CO_2 – EMISSION REDUCTION POSSIBILITIES OF COMBINATIONS OF ENERGY SAVING MEASURES

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The study of the energy saving potential in the residential sector starts, at least in the 'bottom-up' approach we have decided to follow, from an estimate of the technically feasible saving. This estimate in turn depends on an accurate estimation of the 'thermal quality' of the existing housing stock. Until now, this estimation was based on a rather rudimentary approximation of the distribution of K-values over the housing stock. The first contribution of the current research project therefore consisted in improving this approximation. To achieve this, a statistical relationship, based on the available data, was estimated between housing characteristics and their measured K-value. This relationship was subsequently used to calculate the average K-value for houses of a specified type and age category, using a representative sample of Flemish houses. The obtained K-value distribution then served as an input to compute the average energy demand for each housing category, by means of the stationary heat balance model. Finally, the technical saving potential could be estimated by calculating the effect of a maximal saving effort (maximum insulation and maximum boiler efficiency) on the average energy use.

The technical saving potential is the upper limit of the technico-economic potential. The latter is defined as the amount of energy saved as a result of the implementation of all measures with a unit annual conservation life-cycle cost below the prevailing energy price. The saving potential of a set of conservation measures is traditionally determined by using 'energy conservation supply curves', representing the cumulated amount of conserved energy as a function of their unit costs, ordered from least to highest cost. While the resulting step-functions provide a relatively easy way to estimate the technico-economic potential, they have a number of well-known disadvantages. The most important ones are the presumed sequential implementation of the measures, and the assumption of 'single point' average unit costs. In real world situations, it is rather more probable that energy saving measures will be implemented, at least partially, simultaneously, as a result of the fact that unit conservation costs will be distributed over a range of values. This observation implies that due consideration ought to be given to possible interaction effects between measures, another aspect of real-world situations that is hard to incorporate in the classical model. The second contribution of the current project has been to replace the traditional step-functions by a model allowing to introduce saving measures simultaneously, and in which interaction can be taken into account. The model is based on the logistic distribution, and the resulting cumulative energy savings function is called the 'Logistic Conservation Supply Curve' (LCSC).

Using this LCSC model, the CO_2 emission reduction potential in 2000 was estimated to be close to 2200 kTon per year, or approximately 16% of the annual residential emission for space heating. This reduction potential was computed in a ‘business as usual’ scenario, assuming no additional government intervention takes place. It respresents the economically feasible energy saving in the existing housing stock and the newly built houses. It should be stressed however, that this figure is a savings potential, which may not correspond to actual energy saving behaviour.

The model has been used to estimate the additional savings that could (potentially) be achieved when additional stimuli are provided by government policy measures. A distinction was made between measures pertaining to the existing dwellings, and those for newly built houses. For the existing housing stock, the effect of the following measures was calculated: a 10% energy tax, a 10% insulation subsidy, and a budget-neutral combination of both measures. The latter appears to be a promising policy: our simulation results indicate that a moderate energy tax (5%) could generate substantial energy savings, provided that the extra tax income is used to stimulate energy saving behaviour through investment subsidies (a 20% subsidy on efficient boilers and wall insulation). These measures do not seem to be equally effective for new houses, where they should be supplemented by measures in the domain of urban planning (a reduction of the share of ‘open space’ single-family dwellings). This combination has a reduction potential comparable to a strict (and enforceable) K50 insulation norm.

The essential conclusion of our research is that a policy of combined and mutually reinforcing financial stimuli is probably the most succesful strategy to achieve the desired control of CO_2 emission. Moreover, this policy should focus on improving the quality of the older houses, which are a substantial part of the total stock, and whose energy efficiency is well below the efficiency of their more recent counterparts.

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CG/DD/222

MARKAL, A MODEL TO SUPPORT GREENHOUSE GAS REDUCTION POLICIES

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1. OBJECTIVE AND RESEARCH STRATEGY

1.1 Objective

In view of the Kyoto protocol signed by the EU, climate change and its policy implications both at national and international level will remain a priority for the policymakers. A correct evaluation of the potential for emission reduction in Belgium, their allocation between economic sectors and their cost is therefore essential. It is the main goal of this project to support the policy in Belgium regarding climate change with the MARKAL model. More concrete, it can contribute to the following objectives:

- evaluation of the greenhouse emission targets, which Belgium can achieve in the long term
- determine which sectors or technologies have to be considered in priority

1.2 Research Strategy

To achieve the goal of this project, the objective is to make the MARKAL model available in Belgium to contribute to the definition of policies regarding climate change, at national and international level.

MARKAL is a generic model that represents all energy demand and supply activities and technologies for a country with a horizon of up to 40 years. It is a technico-economic model which assembles in a simple but economically consistent way technological information (conversion-efficiency, investment- and variable costs, etc.). As the model is formulated as a dynamic optimisation model, it can produce alternative developments for energy supply and demand that achieve CO2 emission reduction goals at least cost. Simultaneously, the model makes prospective energy and emission balances, tests the potential of new energy technologies and contributes to R&D policy formulation. Finally the model is well suited to approach the burden sharing issue between sectors of the same country in a transparent and scientific way. Compared to ad-hoc models which are more specific to a country or a sector and which use another modelling technique, it presents three important advantages:

- due to its transparency it promotes the communication between experts with different sectoral or technological background (it is the place where engineers and economists understand each other),

- it is easily verifiable: its results can be related to assumptions regarding technological data and economic parameters,

- it is comparable at an international level: as many countries use the same model, its results can be immediately compared with results from other countries.

The first Belgian version has been developed by CES-KULeuven and VITO in the first GLOBAL CHANGE program of the DWTC-SSTC and has already been used intensively for policy support.

At present the model is used in 30 countries for policy analysis purposes. It is a collaborative effort coordinated by the ETSAP (IEA) network. The ETSAP-network (Energy Technology Systems Analysis Programme) is an agreement within the International Energy Agency which concentrates its work on “Energy Options for sustainable Development”. The ETSAP-network is in charge of the maintenance of most of MARKAL model software (database-management system and model specification) and organises two workshops per year where the experience with case-studies of some 20 countries are compared. Results from common case-studies are presented in international forums, organised ea. by IEA and can contribute to the negotiations within the United Nations Framework Convention on Climate Change (FCCC). This international network contributes particularly to a continuous development of the model in many directions and the network is currently involved in the development of a new Markal, called TIMES.

Markal is a partial equilibrium model, which is complementary to other models. The complementarity is mainly related to the following three types of models:

- detailed sectoral models: a model for one sector can be more detailed for the technologies or the type of behaviour of the economic agents (e.g. microsimulation models which represent the behaviour of a representative sample of approximately a hundred households); this type of model allows to evaluate more correctly other instruments with a more short term impact (information, specific norms, ...); these results can be used as an input to energy models as MARKAL.

- national general equilibrium models: these are economic models which allow to evaluate the macroeconomic impact of a CO2 policy (e.g. GEM-E3 model of the EU). These models can study such questions as the use of the revenue from a CO2 tax, the double-dividend discussion, the total impact on employment, etc. and deliver a basic forecast for the demand for energy services (an input for MARKAL).

- international energy-economy models: these models evaluate the world impact of CO2 emission reduction options in terms of burden sharing, climate damage, exhaustion of resources, etc. (e.g. DICE model of Nordhaus, MERGE model of Manne & Richels and GEM-E3 for the EU) - Markal can deliver inputs to such models and can make use of some of their results (e.g. feedback on the price of resources).

The MARKAL model can contribute to the following problems:

- propose minimum cost solutions for CO2 reductions and in this way contribute to the burden-sharing within a country,

- compute prospective energy and emission balances,

- evaluate the role of new technologies for CO2 reductions and contribute to the setting of R & D priorities,

- evaluate the impact on the costs and on emissions of different types of regulations, standards and taxes

The research has focused on three components to achieve its objective:

- the maintenance of the Markal model

- the development of the model

- the development of scenarios and policy analysis with Markal

and the results obtained regarding these different aspects are described hereafter.

2. THE RESULTS

2.1 Extension, maintenance and quality control of the database

To have a basic version of Markal directly available for policy analysis, it needs to be maintained and it has been an important activity in the overall project, as the technology database is the basic element of MARKAL and as it is essential to be able to take the potential development of technologies into account in the long term studies. In the Belgian database approximately two hundred technologies are described. This includes existing technologies and technologies still under development and covers both technological and economical data. VITO was mainly in charge of this activity.

A first task consists in a continuous update of the parameters of the technologies already included and in a transformation of the data for technologies under development into suitable data for the model formulation. Secondly, as industry is an important user of energy and an important emitter of CO2, its modelling has been extended: a further decomposition of the industrial sectors into subsectors and revision of the data for existing subsectors with a special attention for the evaluation of the potential and the associated investment- and variable cost of energy saving technologies.

2.1.1 The electricity sector

The data concerning the electricity sector were updated based on data collected within the Ampere Commission. A complete database with the cost and technical data on potential electricity generation technologies in Belgium until 2030 was established with the help of the Ampere reports on each technology, and through consultations with experts from the sector and members from the Commission. The engineering department of KULeuven also contributed. Significant changes were made in the fields of nuclear energy, fuel cells, wind turbines, STAGs, coal power plants and cogeneration.

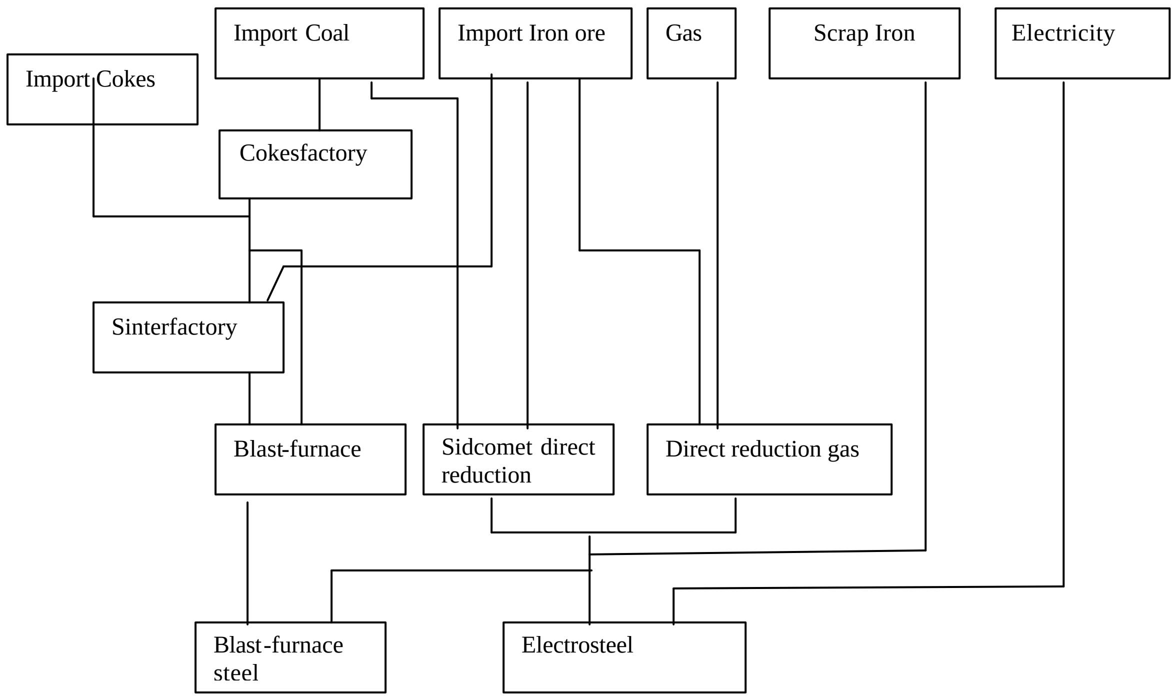
2.1.2 The industrial sector

A decomposition of the most energy intensive sectors was done with a complete revision of the technological and economic data associated with these sectors. A short description for the steel industry is given below as an illustration of the work done. Steel production represents more than 40% of the industrial CO2 emissions in

Belgium. The flowchart gives a first impression of the database structure for this sector.

The model has three reduction processes. Blast furnace reduction is the common used technology. Main inputs are sintered iron (and pellets can be used as well) and cokes. High quality steel requires high quality cokes, which is produced locally or is imported (not on the flowchart). A second technology is direct reduction on gas. This technology is actually not used in Belgium (it exists in Germany) but should be looked at as a theoretical solution. The third technology, Sidcomet is a direct reduction technology based on coal, which will be implemented in Belgian steel production.

Steel production in the Belgian Markal database



Another alternative for steel production is the use of scrap iron. Depending on quality requirements it can be mixed with blast furnace steel or it can be used in electro-steel

Some secondary flows have not been indicated on the flowchart. At the blast furnace reduction process, blast furnace gas is produced. This low-caloric waste gas is used in electricity production. In the cokes factory, high caloric cokes-oven gas is produced as by-product. This gas can have different applications in steel industry (heating cowpers) as well as in electricity production. Also a small amount of coal is directly injected in blast furnace. Not all energy requirements are indicated on the flowchart. For instance small amounts of electricity are used is almost all processes. In the database these flows are considered.

2.1.3 The residential sector

The data for the evaluation of the useful energy demand in the residential sector have been completely reviewed and updated on the basis of a specific study on heat demand per type of building by Prof. Hens of the Laboratory of Construction Physics of the KULeuven and of the population survey of 1991. This has led to a completely revised procedure to compute the total heat demand: it is based on assumptions regarding the evolution of the housing stock, the population and the size of households, starting from the heat demand per type of building and the allocation of the housing stock over the types in the base-year. The types of insulation measures in buildings and their cost were also revised.

2.1.4 The transport sector

Road transport has been modelled in detail, as it is in Belgium the primary energy consuming transport mode. Classical fuels (petrol-, diesel and LPG cars) as well as more advanced technologies (electrical cars, hybrid cars, natural gas, ethanol and methanol and fuel cell technologies) are introduced in the database. For classical cars, the European emission standards for different pollutants are explicit in the database through the introduction of distinctive car technologies according to their emission standards (Euro 0 cars, Euro 1, Euro 2, Euro 3 and Euro 4). The fuel-efficient cars, as specified in the voluntary agreement of the car-manufactures with the European Commission, were also introduced. For busses and trucks, a wide variety of technologies, using different types of energy and with the different European emission standards have been implemented.

Summary statistics of the transport sector in Markal

Demand category	Unit of measure	Number of demand technologies
Cars for short distance (14400km/year)	Billion km	17
Cars for long distance (22400 km/year)	Billion km	19
Busses	Billion km	13
Trucks	Billion km	11
Passenger train	Million km	2
Goods train	Million km	2
Inland transport by boat	Million km	1

2.1.5 Quality control

To maintain a consistent national database it is necessary to involve national and international reference- and review groups to make an analysis and quality control of the database. Within ETSAP it is for instance possible to link in this way technological and non-technological factors. This control is required to use of the database in the long-term policy studies.

2.2 The development of the model

2.2.1 Development of MARKAL-STOCHASTIC

This version of MARKAL can compute optimal hedging strategies when the information on the necessity of CO2 emission reductions or the availability of cheap carbon free technologies becomes only available in later periods. It was decided to implement this version, as there are no other models in Belgium that take this uncertainty element into account. Deterministic scenario analysis and sensibility analysis, the approach followed until now in the Belgian studies with MARKAL, can give some insights, but their results are not always useful for policymakers when the outcomes are very diverging and only one set of actions can be taken.

The experimental version of MARKAL-STOCHASTIC was developed, within the ETSAP network, in the Netherlands and Canada, based on “multi-stage stochastic programming”. This version has been adapted to the Belgian case. Its implementation started with an overview of the literature on uncertainty and the GHG effect. Scenarios have been built for climate change, each with its associated probabilities and they have been translated into operational terms for MARKAL. The model has been applied to the Kyoto scenario. Four possible states of nature are considered for the cumulative CO2 constraints to be imposed in 2030. It is assumed that it will only become clear which cumulative constraint is relevant after 2010.

Thus, one path is followed until 2010 and starting from 2011, four different paths are possible, one for each alternative emission constraint. The path to 2010 contains the optimal hedging strategy. This strategy was then compared with the results from deterministic scenarios.

2.2.2 Representation of secondary benefits

The model is reformulated to take better into account the secondary benefits of CO2 emission reduction, as a reduction in greenhouse-gas emissions is often justified by the secondary benefits it would bring. By secondary benefits one understands the saving of other external costs e.g. by the decrease in emissions of other pollutants or the macroeconomic impact (e.g. the employment effect). Those secondary benefits accrue to the country making the reduction contrary to the climate change reduction that has more diffuse and long term benefits.

The local environmental problems considered are: (i) problems related to the deposition of acidifying emissions and (ii) ambient air quality linked to acidifying emissions and ozone concentration. We consider the energy-related emissions of NO_x, SO_2, VOC and particulates, which are the main source of air pollution. NO_x is almost exclusively generated by combustion process, whereas VOC's are only partly generated by energy using activities (refineries, combustion of motor fuels); other important sources of VOC's are the use of solvents in the metal industry and in different chemical products.

The approach followed for the evaluation of the benefits from the reduction of local pollutants is based on the bottom up damage function approach as developed by the ExternE project, an EU research project on the evaluation of the cost of pollution. This approach can be illustrated by the following figure taken from ExternE

EMISSIONS

↓

DISPERSION

↓

IMPACT

↓

DAMAGE VALUATION

The Markal database has been extended into three directions:

- emission coefficients for pollutants such as NOx, SO2, VOC and PM,
- transfer coefficients for those pollutants, i.e. coefficient for the translation of emissions into deposition and concentration, inclusive the transportation mechanism
- impact of deposition/concentrations and their monetary valuation.

The last two parameters are derived from the ExternE study and are used to compute a damage value per unit of incremental emission in Belgium.

The Markal model was adapted to take into account in the analysis of policy options the benefits/costs coming from local pollutants, following two approaches:

- the environmental damages are computed ex-post, without feedback into the optimisation process

- the environmental damages are part of the objective function and are therefore taken into account in the optimisation process.

In the first approach this function is used to compute ex-post the damage associated with the model solution. In the second approach, which is more global, a term is added to the objective function, which contains the sum of the damage-functions per pollutant. This allows, when evaluating long term options, to make a more complete assessment of different policies.

The new model specification has been used to evaluate a GHG policy associated with a local air pollutant policy. Taking into account the environmental damage of local pollutants in the optimisation process, i.e. implementing a local air pollution policy, reduces the damage from these pollutants with only a slight increase in total cost (investment, fixed and variable costs) and reduces also the CO2 emissions. Moreover, combining a CO2 policy and a local policy allows to benefit at the local level without increasing the cost of the CO2 policy. This shows that secondary benefits are not negligible and this affects also the structure of the optimal greenhouse policy.

Both development of Markal were undertaken by the CES.

2.3 The development of scenarios and policy analysis with Markal

Regarding policy analysis, the focus has been on the identification of the options to reach the Kyoto target for GHG emissions, both in terms of technological choices and in terms of policy instruments. Such studies imply the following steps:

- the elaboration of long term perspectives (30 to 40 years) which have to be consistent with other medium term forecasts (Planning Office, EC)

- the transposition into MARKAL of the already taken measures

- the analysis of the policy questions and their translation into MARKAL

- reporting to the policymakers

Different studies were made for the Federal government during 1999 and 2000. The results are briefly described hereafter, starting with the baseline scenario which is the reference for the different policy studies.

2.3.1 The baseline scenario

A baseline scenario was built with the Markal model in preparation of the case studies. It gives a path for the demand of energy and of the GHG emissions in Belgium until 2030, given assumptions regarding energy prices and economic growth. The assumptions regarding these exogenous variables are based on the 1999 study by the EU DG Research with the energy world model POLES[1]. An average GDP growth of 2.5% is assumed till 2005, 2.1% between 2005-2020 and thereafter 1.6% for the OECD countries. The oil prices are increasing till 2010 given an assumption of relatively low oil reserves and the assumption on economic growth. Oil and gas prices are evolving in parallel. All this gives an average growth for Belgium of 2.1% till 2010 and 1.8% thereafter.

The final energy demand increases with 1.1% till 2010 and with 0.9% thereafter. The growth is highest in the transport sector. The electricity demand increases more than the fuel demand and there is a shift to heat produced in cogeneration plants from 2000 on. In terms of primary energy, the average growth is 0.8%. There is a shift from solids to gas till 2010, principally due to the replacement of coal power plants with gas power plants. This tendency is reversed afterwards when coal powerplants replace the nuclear power plants. Oil products keep a relatively high share because they remain the dominant fuel in the transport sector. Renewable energy do not break through given the energy price assumptions

This induces an increase in the GHG emissions linked to energy. They are in 2010 16% above the level of 1990 and continue to increase thereafter, especially after 2025 if coal power plants should replace the nuclear power plants. Belgium would therefore have to reduce its GHG emissions with 22% in 2010 compared to the baseline to reach its Kyoto target.

2.3.2 Policy Studies

a) The Kyoto target

The objective of this study was to evaluate measures and policy instruments to reduce the greenhouse gas (GHG) emissions in Belgium to the level agreed upon in the Kyoto protocol (-7.5% compared to the 1990 level). The policy evaluation had to take into account three constraints: the reduction target should be reached by

[1] Energy Technology Dynamics and Advanced Energy System Modelling, Final Technical Report, July 1999, Chapter 5: World Energy Projections to 2030, P. Criqui (IEPE) and N. Kouvaritakis (ECOSIM)

measures that can be taken by policy makers in Belgium, the reduction of GHG should continue after 2010 at the same rate as the one decided for 1990-2010, no new nuclear power investments are allowed in the period 1990-2030.

Given the baseline assumptions (as described in the previous section), Belgium has to reduce its GHG emissions in 2010 by 20% compared to the reference level to reach the Belgian Kyoto target. The policy measures already taken or planned since 1990 to reduce the GHG emissions, will only contribute to a reduction of 1.8% in 2010.

Using a GHG emission tax as policy instrument, which is the least cost instrument for meeting an emission target, the cost per ton of GHG reduced reaches approximately 1000BF in 2010 and increases sharply in 2030. This sharp increase is due to the investment in coal power plants at the end of the horizon in the reference scenario and the ban on new nuclear capacity. The total discounted cost of reaching the target for 2010 and 2030, in terms of loss in consumer/producer surplus, is approximately 4% of the 1990 GDP. The macroeconomic impact of the Kyoto target in 2010 remains very small.

In 2010 the greatest reductions are in the energy sector, -41%, followed by the industrial sector, -25.9% and the residential and service sector, -18.3%; the reduction in the transport sector remains more limited, -2.6%. The Kyoto target is reached through a least-cost mix of energy services reductions, changes in technologies and fuel switching that are triggered by the GHG emission tax. The demand for energy services is reduced by 8.5% in the industry and the residential & service sector, but only by 2.9% in the transport sector. There is a switch away from solid fuels and oil products towards natural gas and, in a more limited way, towards renewables. More efficient and energy saving technologies are used in the different sectors. Cogeneration is penetrating further in the industry and in the residential & service sector.

Using alternative instruments such as an energy tax or standards increases the cost of reaching the Kyoto target. An energy tax leaves out one option for emission reduction, as it does not give an incentive towards fuel switching. The loss in welfare is increased with 4.2% over the entire horizon 1990-2030 compared to the GHG tax. The use of standards will approximately double the loss in welfare: the reduction in the level of energy services is smaller, because the remaining emissions are not taxed and therefore stronger efficiency standards have to be imposed to reach the reduction target.

If the nuclear option is available, the total loss is reduced with 23%. The impact is rather limited until 2010 but becomes significant from 2025 onwards when the existing nuclear power plants are scrapped. The reduction effort is shifted towards the energy sector, allowing the other sectors to reduce their emissions far less.

b) Excise tax policies

In 2000, some specific policies were evaluated by CES with Markal for the Federal Minister of the Environment: the harmonisation of excise taxes in the EU and the increase of Belgian excise taxes to the levels in the neighbouring countries. These policies contribute to a reduction of the CO2 emissions in Belgium, but are not sufficient to reach the Kyoto target. Moreover the results show that the use of such policy instruments (an energy tax) increases the cost of the CO2 reduction compared to a CO2 tax, as observed in the previous study.

c) Reduction potential for technological and policy measures

For the Federal Ministry of Economic Affairs an estimation of the CO2 emission reduction potential for a number of exogenous defined measures has been made by VITO. The type of measures is summarised in the following table. The simulation period is 2000-2030. In this study, the Markal model has been used to evaluate the reduction potential, without any cost consideration.

Different types of measures with their cumulative CO_2 emission reduction potential.

	Description of the measure	Cumulative CO_2 reduction (Mton)
Centralised electricity production	1000 MW additional nuclear power plant	85
	New coal fired plant replaced by STEG	142.5
	Limiting coal fired plant at 1200 MW	62.4
CHP	CHP as foreseen in the national equipment plan of the electricity sector	57
	CHP – additional 1200 MW in period 1995-2005	117.5
	Reduced delivery price gas for CHP modest reduction	270
	Reduced delivery price gas for CHP high reduction	211
Renewable	Additional wind energy	10.5
	35.000 ha biomass	4.5
	70.000 ha biomass	27
Taxes	EU proposal harmonising taxes	122
	Higher tax levels	355
	Tax on low voltage electricity consumption (1Bef/Kwh)	55.5
	Tax on low voltage (1 Bef/Kwh) and high voltage (0.1 Bef/Kwh)	207.5
Transport Sector	Increased road taxation	29.5
	Increased tax on motor fuels (petrol & diesel)	160
	Efficiency improvement cars (ACEA)	122.5
	Hybrid traction	76.5
Other	Efficiency improvement industry	27.3
	Improvement electrical appliances	27.5
	Combined action	**363**

2.3.3 Study for the Ampere Commission

This study focused on the electricity sector, it was made by CES. Besides the full update of the MARKAL database concerning this sector, it evaluates the choice of technologies in this sector for the period 2005/2010, under different constraints, as the Kyoto target and the nuclear phase-out.

The case studies activity were either undertaken jointly by the partners either done individually, however in both cases this activity benefits from the development by all partners.

2.4 Participation in ETSAP network

This activity concerns on the one hand the participation to the ETSAP workshops, the presentation of the Belgian research results and the integration of the results for Belgium in common studies within ETSAP. On the other hand it concerns the continuous development of the Markal model. This participation is very important at this stage, as the ETSAP participants, including CES-KULeuven and VITO, are currently engaged in the development of a new Markal model, TIMES. The general model specification is still using the Markal paradigm (perfect foresight optimisation), but allows more flexibility and a further development of the model. It includes also an update of the database software. The new model is being tested out now.

3. ASSESSMENT AND PERSPECTIVES

3.1 Assessment

The principal goal of the MARKAL research consortium was to maintain the Markal expertise in Belgium and to make it available for policy studies. This goal has been achieved in the sense that Markal has been used as the principal policy tool in the study of greenhouse gas policies in Belgium and is the reference for energy policy studies.

The second goal has been to improve the Markal modelling tool itself. This goal has been achieved too. The stochastic model is probably the most complex but it proved to be relatively difficult to use for policy studies. The extension to Markal-Micro (inclusion of demand function) was very successful and proved to be an important addition to the Markal model. The same holds for the inclusion of the secondary benefits in the objective function. Both are now included in the standard MARKAL model distributed to ETSAP members.

In order to achieve this goal it proved important to function in the international ETSAP consortium and to have a sufficiently stable research staff. Long term research contracts proved to be important in this respect.

3.2 Project perspectives

Both CES and VITO are considering the possibility to develop further the model to improve its capacity to evaluate climate change and energy policies. One is certainly the continuation of the contribution to the development of TIMES, the new Markal model. Further the model has to be extended to include the GHG emissions not linked to energy to allow for a consistent policy evaluation covering the GHG emissions from all sources. Because of the importance of international negotiations in climate change policy, there is a need to develop the international dimension of the model, e.g. to evaluate the possible contribution of the Kyoto flexibility mechanism to a national climate change policy. Moreover the opening of the EU energy market reinforce the need for the international dimension.

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CLIMNEG
CLIMATE CHANGE, INTERNATIONAL NEGOTIATIONS AND BELGIAN STRATEGIES

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1. OBJECTIVES AND RESEARCH STRATEGY

Conceived of in the early months of 1996 and created at the end of that year, the network has been devoted to the *interdisciplinary* study of decision making in matters relating to climate change.

The overall overall objective was to integrate what can be obtained from economic theory (CORE), climate sciences (ASTR), econometric simulation (CES), administrative and diplomatic experience (FPB) in the area, using simulation models as main research tool and common language.

The strategy was to structure the work into four parts, corresponding to four implemented projects:

Project CLIMNEG I : On the basis of existing economic-climatic models, the first purpose was to develop their economic components by searching for a characterization of the policies (scenarios) of greenhouse gases abatement in a multi-region world model, in terms of three alternative criteria (optimality, equity, strategic stability), by analyzing the ways to share the burden of those policies, and by examining the possibility of activities to be implemented jointly by different groups of countries.

Project CLIMNEG II had as purpose to look for enrichments of the climatic components of the basic models by integrating transfer functions that reflect the most recent state of the art, and thereby evaluating the effects on the global climate of the different scenarios studied in the economic component.

Project CLIMNEG III had as purpose to include, in an econometric component added to the basic models, the effects of these policies on economic equilibria at the world, European and Belgian levels.

Project CLIMNEG IV was to confront research activities with practice, by studying two fundamental aspects of the institutional implementation of policies, namely the international implementation of the instruments, and the coordination mechanisms between the decisions made by the concerned countries.

Using the methods of each of these disciplines involved in the network (physics, economics, econometrics), the purpose was to define, characterise and calculate policies of greenhouse gases abatement at the world, European and Belgian levels. The role of the simulation results was to serve as a reference for those who are in charge of participating, for our country, to the international negotiations.

2. RESULTS

Although the results are presented below under four headings that approximately correspond to the four projects outlined above, it must be stressed that the interactions between the researchers has been so strong that all results must be considered common to the entire research group. A companion research project called CLIMBEL, started in 1998, on which it is reported separately, produced further joint results. Those of both CLIMNEG and CLIMBEL are collected together in the series *CLIMNEG-CLIMBEL Working Papers* whose titles are listed at the end of this report. It is referred to them by the acronym **CWP** followed by the number in the series.

Space constraints for this executive summary compels one to make a selection among the contributions made, a selection guided more by the necessity of homogeneity than by the intrinsic importance of some of the papers. The summary is therefore quite incomplete. A fuller appreciation of the contributions can be obtained by reading the final report or, better, the papers themselves.

I. At the ***economic theoretical*** level, the project has yielded the main following insights:

- Extending to *stock* externalities — an extension required by the nature of the climatic change problem — results that were available in the literature *on the strategic stability of cooperative agreements* in transfrontier (flow) pollution problems. The essence of the result obtained here (**CWP n° 1, 2, 6**) consists of an explicit formula to compute international resource transfers that induce the strategic stability property. The fact that this extension was successful opened the way to the numerical simulations reported on under **II** and **III** below.

- Combining *equity considerations* with efficiency and strategic acceptability conditions in the design of abatement scenarios. The tool is again the one of international resource transfers, inspired by those reported on above, but corrected for equity purposes, and derived from alternative initial allocations of tradable emission permits. (**CWP n° 39**)

- An economic and game theoretic *interpretation of the Kyoto Protocol* (**CWP n° 12**). Based upon explicit modeling derived from the economic theory of competitive markets as well as from the theory of cooperative games the three following conclusions are established:

(i) the quotas adopted in the Kyoto protocol are a step in the right direction, as far as overall international economic and environmental optimality is concerned;

(ii) trading mechanisms for emission permits allow for an efficient and strategically stable allocation across countries of the overall abatement effort just mentioned;

(iii) as far as future commitment periods are concerned, the "Kyoto scheme" of quotas — properly assigned — together with tradable permits constitutes an appropriate instrument for eventually reaching an international optimum, characterised by strategic stability.

II. At the ***climate modeling*** level, the project's main results are as follows:

- An improved climate module has been developed, from a starting model by Kverndokk, and validated on the basis of other two-dimensional models (**CWP n°21**).
- Extension of this improved model, whereby emission trajectories are translated into *regional* temperature changes, aimed at being fed back into the economic model through climate change damage functions.
- Introduction of *sulphate aerosols*: sulphate aerosols represent one of the main reasons for which regionalisation of impacts is important in economic studies. A simplified way to represent the regional effect of aerosols was needed, however. A first attempt was made using results from the ASTR-UCL two-dimensional model, which includes the effect of aerosols (**CWP n°7**). Additional geographical information came from existing three-dimensional simulations made with coupled atmosphere-ocean general circulation models forced with both greenhouse gases and aerosols.

These improvements to the climate module (regionalisation and treatment of sulphate aerosols) allow the coupled climate-economy models mentioned in **I** above and **III** below to be one step ahead of the models existing in the literature. The first simulations using this improved climate module are described in **CWP n°32** and in **CWP n°44.**

III. As far as ***economic modeling and econometric simulations*** are concerned, the project's main results are the following:

- at the *world* level:

- A six regions integrated assessment model called *"Climneg World Simulation" (CWS)* has been constructed, derived from the Nordhaus and Yang model published in 1996. For this CWS model, the stability inducing transfers identified in **I** above have been computed and efficient stable cooperative emission trajectories determined. These appear to be quite more demanding than Nash equilibrium ones, although the economic gain they induce is only moderate. This sheds some light on the issue of the relative importance of national *vs.* global policies. Another remarkable finding from these simulations is that while world consumption is steadily increasing in the long run under the efficient (and stable) emissions scenarios, world consumption is not sustainable under Nash as well as business as usual scenarios in the sense that it is bound to decrease from the middle of the next century on (**CWP n° 18** and **19**).

- An extension of the CWS model has been subsequently formulated (**CWP n° 32**) to account for *sulphate aerosols*, which dampen the effects of CO2 concentrations on temperature. While this appears to be indeed the case in the early periods, later periods (beyond 2100) exhibit an overwhelming domination of the CO2 effects, rendering irrational sulphur emissions reduction.

- Finally, the *stability* of alternative forms of *international cooperation* has been tested using the CWS model in **CWP n° 40**, based on the theory of endogenous formation of coalitions. The analysis concludes with a strong stability of the "Kyoto coalition", in spite of credible possible deviations on the part of the countries that formerly belonged to the Soviet Union

• at the *European* level:

- the EU "bubble" Burden sharing agreement on the distribution of the Kyoto emission reduction target over the EU member states was investigated using an "inverse opptimum" approach and marginal abatement cost curves. The simulations reveal that the EU bubble improves in terms of cost efficiency upon a uniform reduction assignment, but that substantial differences in marginal costs persist. (**CWP n°33**).

- using the (pre-existing) GEM-E3 medium term general equilibrium model, marginal abatement cost functions have been estimated for the European countries as well as for 6 to 8 other regions of the world. This was done in order to compare the global costs of emissions reduction under alternative settings, an efficient one and a uniform one across countries. For the EU countries, the difference shows as follows: for a same tax of $100/ton of CO2, efficient allocation of the effort reaches 31% whereas uniformity of effort (that is, if no account is taken of cost differences between countries) allows only for 17%.

- at the *Belgian* level

  - using the (pre-existing) MARKAL partial equilibrium model of the energy system in Belgium, *marginal abatement costs* of greenhouse gases emissions abatement in 2010 for the country have been estimated. A figure of about BEF 2000/ton is obtained for reductions corresponding to Belgium's commitment under the Kyoto Protocol (**CWP n° 41**).

  - *Macroeconomic impacts for Belgium* of alternative domestic policies to meet the Kyoto targets are also reported on in **CWP n° 41**.

IV. At the ***interface between research and policy design***, an essential part of the CLIMNEG project (one fourth of the resources were devoted to it) was the inclusion in the researchers' team of members of the federal administration of the Belgian government, who are involved in the preparation, the attendance and the follow up of the international climate negotiations.

The specific tasks assigned to these persons and their activities in the network resulted in four categories of contributions:

- The preparation of *pedagogical documents* destined to political decision makers and high administration officials not directly involved as well as to the public at large, on various aspects of climate change issues, namely: the history and evaluation of international collaboration on climate change over the last ten years (**CWP n°28**); the theory and evaluation of tradable emission permits (**CWP n°29**); the fiscal instruments of climate policies (**CWP n°30**); the regulatory instruments of climate policies (**CWP n°31**); the communication instruments in national and international climate policies (**CWP n°38**); the voluntary agreements on emission abatement (types, characteristics, implementation, examples) (**CWP n°37**). All six documents have been re-issued in French as **CWP n°47.**

- Through the CLIMNEG coordination meetings, continuous *exchanges of information* and ideas between academics and practitioners, which led the former to be regularly briefed by the latter on the most recent developments (*e.g.* after the Kyoto, Berlin, Buenos Ayres, The Hague Conferences of the Parties and other meetings in Bonn). Reciprocally, practitioners have been offered ample exposure to conceptual and methodological results as they were developing, both in climate science and in economics (*e.g.* on alternative climatic models, on tradable permits, on cooperation issues, on simulation techniques, etc.)

- Increased motivation for academic members of the network to take part, when invited to, in several of the key events that occurred over the years in climatic change affairs, both internationally and in Belgian circles.
- Finally, diffusion of knowledge for the public at large, through public seminars, lectures, publishing of vulgarisation articles, and interviews given to the printed and audio-visual press.

3. ASSESSMENT

With the financial means set at the disposal of the research team, not only pre-existing research on climate affairs was allowed to be pursued in Belgium, but new research has been developed.

Interdisciplinarity is probably the most prominent characteristic of this new stage; it may also be considered as the most important as it was non existant beforehand. Obvious results of that are the greater attention attached by scientists in Belgium to the socio-economic implications of climate change policies, as well as the greater concern by Belgian social and economic scientists for the climate change problem.

A further result, specific to the CLIMNEG project, is that a team of increasingly competent persons has been formed, many of which are outside of CLIMNEG today but exert usefully their competence in a variety of institutions. Building this kind of capacity is probably a major and long lasting benefit of the project, for the community at large.

Last but not least, the scientific contributions themselves should have lasting effects. Those, to be judged by the publication record, cannot be seriously ascertained at this stage, given the long delays prevailing.

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CLIMBEL
CLIMATE CHANGE AND INSTRUMENTS FOR EMISSIONS ABATEMENT IN BELGIUM: AN INTERDISCIPLINARY ANALYSIS

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1. PROJECT SUMMARY

Launched in 1999 for two years, and designed to accompany the CLIMNEG project (on which it is reported separately), the research network CLIMBEL bears upon the evaluation of the instruments and measures allowing to reduce the emissions of greenhouse gases in Belgium. Also conceived of as an interdisciplinary scientific endeavour, it contained three projects.

(i) Project CLIMBEL I, devoted to analysing the *macroeconomic framework* within which the envisaged instruments will be adopted. This study was to put the reduction obligations of Belgium in perspective *vis-à-vis* those of the other European countries; to examine the potential of the "joint implementation" instrument and to assess the sectoral impacts of the Belgian policies.

(ii) Project CLIMBEL II, focusing on one particularly important instrument: tradable permits. It included two approaches.

Firstly, a *microeconomic* study of permits, bearing upon the concerned actors, the forms and characteristics of the instrument, the procedures of initial allocation and of functioning of the market after permits have been emitted, and finally the "domestic burden sharing" implied by the various initial distributions.

Secondly, a *juridical* study following a *de lege ferenda* reflection, directly inspired by the foregoing microeconomic study. It was to cover private and economic law aspects, public law, administrative law as well as aspects of private and penal responsibility.

(iii) Project CLIMBEL III consisted in a reflection conducted within the Administration of the Belgian State, bearing upon the *implementation of permits and of other instruments* by the competent authorities.

2. RESULTS

Results are presented below under headings that approximately correspond to the projects outlined above. However, interactions among the CLIMBEL researchers, as well as between them and those of the companion project CLIMNEG have been strong enough for it being difficult to allocate papers to projects in an exclusive way. All results are therefore better considered as common to the entire research group, and those of both CLIMNEG and CLIMBEL are collected together in the series *CLIMNEG-CLIMBEL Working Papers* whose titles are listed at the end of this report.

It is referred to them by the acronym **CWP** followed by the number in the series. We also provide the complete list of the persons associated with the CLIMNEG and/or CLIMBEL projects over the years.

Space constraints for this executive summary compels one to make a selection among the many contributions made, a selection guided more by the necessity of homogeneity than by the intrinsic importance of some of the papers. The summary is therefore quite incomplete. A fuller appreciation of the contributions can be obtained by reading the final report or, better, the papers themselves.

2.1 Emission reduction constraints for Belgium after Kyoto, macro-economic and sectoral dimensions

2.1.1 International burden sharing and the efforts of Belgium(CWP n°33)

The European GHG emission reduction target of minus 8% has been reallocated among the EU member states taking into account considerations of both efficiency and equity. **CWP n°33** investigates this European burden sharing agreement using an inverse welfare optimum approach. Implicit welfare weights are computed that were used by the EU negotiators to fix the Burden Sharing Agreement in order to visualize the efficiency-equity trade off.

The following conclusions can be drawn:

(i) the EU renogotiation of the abatement burden does indeed much better in terms of cost efficiency than a uniform allocation of 8% for every EU member.

(ii) Portugal and Greece should have been allowed a higher increase on the basis of cost efficiency considerations

(iii) Germany and the UK should have been assigned an higher reduction on the basis of cost efficiency considerations

(iv) introducing inequality aversion (income distribution concern) reinforces the last two conclusions

(v) the Netherlands and Belgium have assumed relatively ambitious emission abatement targets compared to the other EU member states

Recently, this analysis has been extended to account for market power and to evaluate emission trading ceilings within a EU permit market. The general conclusion is that also in the EU permit market, the discussion on permit import/export ceilings is probably motivated by market power arguments. Similarly as in a paper by Ellerman and Wing (2000) for the world carbon market, strong monopoly effects are found in the European carbon market if market supply of permits is restricted by means of an export trading cap.

2.1.2 Potential of Joint Implementation

From a survey of the literature, it is concluded that

- By its nature, ET (Emissions Trading) would be environmentally more efficient than JI (Joint Implementation) and CDM (Clean Developmenet Mechanism). Regarded in general as a step *before* ET, JI and CDM substitute for ET when the emission trading mechanism is not yet available and they will become unnecessary as soon as ET can be implemented. ET covers all sectors, can execute whatever measures to curb domestic emissions, and therefore is able to reduce economy-wide emissions, whereas JI/CDM are project-linked and therefore less flexible.

- Most researches consider that ET will be economically more efficient than JI/CDM.

- CDM in general has greater potential for cost efficiency than JI. Many researches have reported that non-Annex I countries have very low abatement costs compared with Annex I region. However, CDM may not easily achieve cost efficiency. There are a number of adverse factors likely to erode the potential for cost efficiency.

- Finally, considering transaction costs as an additional cost to emission trading, simulations show that transaction costs will cause cost inefficiency unevenly to all parties of emission trading, depending on their marginal abatement cost and being seller or buyer of permits. Based on the idea that pre-action could contribute to reduce transaction costs, we analyse the costs and benefits of pre-action, using hypothetical values on the efficiency of the “learning by doing” process. We find that the pre-action could effectively offset transaction costs. The extent of net gain from pre-action however depends crucially on the speed of the “learning by doing” process, which is represented in the model by the elasticity of the reduction in transaction costs in response to pre-action effort

2.1.3 Macroeconomic and sectoral effects of Belgian policy initiatives to implement the Kyoto agreement (CWP n°41)

The GEM-E3 European model was used to evaluate the macroeconomic and sectoral impact of policies in Belgium allowing to reach the Kyoto target in 2010.

- The first policy measure evaluated was the impact of the implementation of a GHG emission tax in Belgium. The revenue of the GHG tax is assumed to be recycled through a reduction of the employers' social security contributions, while maintaining the public budget constant in terms of GDP. It is also assumed that the other EU countries are following the same type of policy to reach their own Kyoto target.

  The macroeconomic impact of this scenario in 2010 is very small: the private consumption is increased by 0.5% compared to the reference scenario, while employment is increasing with 1.2%. Regarding the sectoral evolution, the impact is the highest for the energy sector and for the energy intensive sectors, especially the exporting ones.

- Imposing an energy tax instead of a GHG tax will increase the cost of reaching the Kyoto target.

- Tradable permits, in as far as they are auctioned, will in first approximation, produce the same results as a GHG emission tax. In closed economies, grandfathered tradable permits increases the cost compared to an emission tax as there are no carbon tax revenues to reduce other distortion in the economy. However in an open economy such as Belgium, grandfathered tradable permits may have the same macroeconomic effect.

3. DESIGN AND ORGANISATION OF A TRADABLE PERMITS MARKET IN BELGIUM: MICROECONOMIC AND JURIDICAL ANALYSES

3.1 Economic aspects of the design of the permits market

3.1.1 Alternative ways of designing a domestic market of CO_2 emission permits. (CWP n°20)

- The research began with an extended and careful perusal of the literature on emission permits in general and on the US experience with SO_2 in particular. The paper reports lengthily on this inquiry, including private initiatives in the field.

- On the basic issue of the choice between auctioning *vs* grandfathering initial permits, the paper makes the point that auctioning yields revenues to the public authorities, revenues that can be used for other purposes in the economy (*double dividend* argument); grandfathering does not provide this double advantage. The respective effects of the two methods are essentially distributional.

- Once initial permits have been issued (irrespective of whether this occurs by auction or by grandfathering), the *competitiveness* of the secondary market is the key factor as far as the allocative efficiency of the system (in terms of cost minimisation) is concerned.

3.1.2 Modeling the microstructure of an emission permits market and analysis of its impact on environmental policy (CWP n°24)

With the collaboration of a financial market specialist, the role of intermediaries (brokers) is analysed in permits markets treated as "quote driven markets". Monopolistic and oligopolistic structures are considered as well as the influence of uncertainty, and compared with walrasian perfectly competitive structures.

3.1.3 Should banking of permits be allowed ? (CWP n°43)

The research concludes that in the presence of uncertainty, allowing for banking of permits increases welfare in the economy and should therefore be recommended.

3.1.4 "Burden sharing": An analysis of rules for allocating emission quotas between countries (CWP n°39)

Equity considerations are combined here with acceptability conditions for the initial allocations of permits to countries, in the framework of the CWS model developed in the CLIMNEG project. Purely equitable allocations (*e.g.* per capita) appear to be unacceptable for most countries, *i.e.* the outcome would be less beneficial to them than if they declined to cooperate in a worldwide agreement. Acceptability constraints are therefore introduced and their effect on the final allocation is determined, benefiting some countries and being less favourable to other ones.

3.2 Juridical aspects of the organisation of the market for tradable permits

3.2.1 Functions and limits of contractual relations involved in transactions on permits (CWP n°23)

While the Kyoto Protocol provisions on permits trading only deals with States, firms are bound to be involved in the actual operations of the markets. Private law issues arise such as the types of contracts that will be used as well as the nature of the prerogatives that holders of permits can claim.

The paper makes the point that not only contractual but also statutory and institutional apparatuses will be needed. Prerogatives of permit holders are essentially of personal nature (as opposed to "real"). As far as property rights are concerned, their rights bear on the permits, not on the environment.

3.2.2 Emerging permits markets and competition policy problems (CWP n°34)

International trade liberalisation, as organised by the WTO and the EU treaties, should also apply to emission permits, to their derivatives, as well as to energy markets whose products require permits. Such liberalisation might be jeopardized by lack of coordination in the legislations adopted by countries. Harmonisation will be necessary, many aspects of which can already be borrowed from harmonisations taking place within the WTO and the EU.

3.2.3 Banking and financial law developments (CWP n°35)

Markets for emission permits will have much in common with existing financial stock markets. The paper explores the potential for centralised permits exchange and the financial law implications of such a setting. The US experience with SO_2 is referred to.

3.2.4 Institutional aspects of the use of flexible mechanisms in Belgium and of the complementarity between instruments (CWP n°45 & 46)

- Information exchanges between the administration and the scientific community on emissions trading.

  These have been exceptionally numerous, from participation and work done for COP6 and other international meetings to taking an active part in the preparation of domestic policy.

- Writing of reports for the general public

  - on climate change problems and their solutions in general (**CWP n°45**), and

  - on emissions trading in Belgium in particular (**CWP n°46**). This last document also discusses the Belgian "National Climate Plan" and provides a list of main fixed emission sources in the country.

- Periodic information and briefing of CLIMNEG-CLIMBEL team members on the major developments in the international negotiation process.

ASSESSMENT

CLIMBEL has usefully supplemented CLIMNEG essentially in three ways:

(i) in widening the interdisciplinary character of the combined projects by adding the legal dimension, which neither climate scientists nor economists should ignore or neglect. Admittedly only a limited step has been taken in that direction, but it is substantial; it is also comforting to note that it has already been relayed in other instances.

(ii) in concentrating attention on Belgian aspects of the problem and coming up with numerical estimates of the issues.

(iii) in allowing to pursue the continuous contacts and exchanges between academic climate scientists, economists and lawyers on the one hand and the government's administration involved in the negotiations on the other hand. In spite of the risk of being repetitive, the coordinator whishes to express his very strong conviction that a research team having such a structure is a major advantage for all, yielding motivation and widening of perspectives.

Other assessment statements, presented in the CLIMNEG report, apply equally to CLIMBEL.

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EVALUATION OF COAL-BASED POWER GENERATION IN AN UNCERTAIN CONTEXT

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ABBREVIATIONS

STAG	STeam And Gas combined cycle
CCGT	Combined Cycle Gas Turbine
NGCC	Natural Gas Combined Cycle
IGCC	Integrated coal Gasification Combined Cycle
PC-USC	Pulverised-Coal fired plants with (Ultra) Supercritical steam Cycle
GBM	Geometric Brownian Motion

SYMBOLS

t, y	time, year
t_0	commissioning year of the plant
t_R	repowering year
n	lifetime, year
I	specific investment cost, EUR/kW
CP(t)	coal price at time t, EUR/GJ
P(t)	natural gas price at time t, EUR/GJ
P'(t)	natural gas price at time t, EUR/kWhe
$f_y[P(t)]$	probability density function of natural gas price at time t based on price given at time y
E_y [P(t)]	mean expected value of natural gas price at time t based on price given at time y, EUR/GJ
μ	mean expected growth, s^{-1}
σ	volatility, $s^{-1/2}$
α	trend, s^{-1}
I	discount rate
U_t	annual utilisation for year t, hours/year
FOM(t)	fixed O&M costs for year t, EUR/kW.year
VOM(t)	variable O&M costs for year t, EUR/kWh
EGC	electricity generating cost, EUR/kWh
NPV_t	net present value based on natural gas price information given at time t, EUR/kW
ROVt	real options value based on natural gas price information given at time t, EUR/kW
FV	flexibility value, EUR/kW
OC	option cost, EUR/kW

1. OBJECTIVES

1.1 Global issue

Consequences of the new competitive European electricity market on power plant investment decisions.

Towards a better treatment of uncertainty.

Uncertainty has reached an unprecedented level in the European electricity market: impacts of the liberalisation on power companies and on electricity prices, evolution of long-run natural gas prices, evolution of the greenhouse gases reduction commitments, evolution of emissions standards (SO_2, NOx, dust,…), performances of newly emerging technologies.

It has been recognised in the last ten years by major lenders that investments in the energy sector in general, and in the electricity sector in particular should not be driven by the simple net present value criterion. The reason is the uncertainty that normally surrounds the energy field. Interestingly enough it has long been recognised in other energy areas, and in particular in energy consuming industries that investment choices are effectively not always dictated by this criterion. Future uncertainty is in those cases too often mentioned as the reason to depart from the pure application of net present value computation. While regulated companies like power companies have, in the past, been able to pass uncertainty to their customers, this will no longer be possible in the future.

Opportunities for emerging power plant technologies?

Serious mistakes on the assessment of the possibilities of technologies can be made if the methodology does not take into account their capability to adapt to uncertainty ("flexibility"). Therefore, flexibility need to be taken into account when assessing the economic potential of alternative technologies with respect to their main competitors.

Which impact on CO_2 emissions?

Extensive use of such new investment decision methods in the power industry will probably modify the generation capacity mix and thus have an impact on CO_2 emissions dedicated to electricity generation.

Moreover, instruments introduced by public authorities mainly modify the economic and technological parameters of the relevant technologies. Their effectiveness is thus also affected by the prevailing uncertainty. The same shortcomings will thus also be found in the evaluation of their effectiveness if one restricts oneself to standard techniques that do not account for the ability of technologies to adapt to uncertainty.

1.2 Goal

Analysis of competition between fossil fuel power plants by means of the theory of real options

Limitations of greenhouse gas emission from large-scale fossil fuel-based power plants are probably a key element of a strategy towards sustainable development. The power sector is currently driven by a dash for gas that, at least partially, contributes to the desired result when substituting for less efficient coal power plants. Major characteristics of the natural gas-fired combined cycle plant are high efficiency, low investment costs, low environmental impact, short installation time and good operating flexibility. Many expect that for reasons of resource availability and/or production and transportation cost of the natural gas, this evolution will be limited in time.

In this case, whatever attitude towards nuclear energy and renewables, new investments in coal power plants will probably be considered. In comparison to other fuels, coal is characterised by important reserves and lower prices but also by much higher emissions of pollutants. Newly emerging coal-based technologies with more efficient conversion of coal and improved environmental performances appear then as a main option to limit greenhouse gas emission with respect to conventional coal power plants: they will thus have to be considered in any strategy of the power sector to contribute to sustainable development.

In an uncertain context, are these new, less polluting but more expensive innovative coal power plants competitive in comparison to gas-fired STAG units and more conventional coal power plants? What are the capabilities to adapt to uncertainty ("flexibility") of these power plants? What are their economic values?

The theory of real options applies to power plant valuation and optimal investment decision modelling allows a more adequate treatment of uncertainty than methods based on a net present value computed over a set of scenarios. The idea of the theory is that a less flexible equipment is at a disadvantage that is not included in the standard net present value calculation. Then, this theory gives an economic value to power plants flexibility's such as fuel switching, repowering opportunities, capability to adapt to the standards of emission and operational flexibility.

This approach directly draws on the theory of financial options initiated in the celebrated work of Black-Scholes (1973). It culminated in the book of *Pindyck and*

Dixit (1994). The idea was well publicised by the World Bank which first pointed out the drawbacks of using net present value calculation for assessing the relative competitiveness of equipment that have quite different characteristics of flexibility. The relevance of the theory of both financial options and real options is illustrated by the importance taken by this subject in several energy companies in the world. It is noticeable that this work has also found its way into issue of sustainable development.

1.3 Research strategy

Development of a tool taking into account uncertain facfors for the analysis of competition between coal-fired and gas-fired power plants in the mid- and long run.

TERM

Technological characteristics (technical, environmental, economic and flexibility) and potential for innovation (in the mid- and long-run) of coal and gas-based power plants

Specific objectives are:

1. Identification and characterisation of main coal-based and gas-based technologies
2. Performances of current power plants
3. Scenarios of evolution of these performances in future
4. Flexibility characteristics of these power plants
5. Scenarios of evolution of these performances in future
6. Case studies by integration of the data generated by TERM in the model developed by CORE

These objectives have been achieved by data collection from scientific publications, trade journals and manufacturer communications and by the development of physico-chemical / thermodynamic / techno-economic power plant models.

CORE

Application of the real options theory

Specific objectives are:

1. Risk factors modelling : stochastic processes selection and calibration for fuel prices, electricity prices and CO2 emission permits
2. Development of a power plant valuation model
3. Development of power plant investment decision model

2. RESULTS

Main results provided by this project are:

1. A method for techno-economic optimisation of electric power plants that make it possible to estimate the potential of innovation. This method will be transposable to other types of thermal power plants (combined heat and power systems, biomass gasification systems,…). Results consist of database and models.
2. Standard performance curves and scenarios for each technological options considered.
3. Calibration of stochastic processes (fuel prices, electricity prices and emission permits).
4. A methodology for power plants valuation and investment decision in a competitive organisation of the industry, considering a financial value for power plants flexibility's.

Unfortunately, due to a lack of human resources it has not been possible to integrate these flexibility options in the model. Only limited case studies based on a simplified approach have been performed simulating competition between gas-fired and coal-fired power plants or between state-of-the-art power plants and innovative concepts.

2.1 Gas-fired and coal-fired power plants performances

Power plants considered are limited to gas-fired STAG units (STeam And Gas turbines combined cycles) and coal-fired IGCC (Integrated Gasification Combined Cycle) and PC-SC units (Puliverised Coal SuperCritical steam cycle).

2.1.1 Technical options

For each technology considered (STAG, PC-USC, IGCC), several technical options have been selected and standardised according to the following classification:

Physico-chemical data

- fuel conditioning and feeding
- nature of the oxidant or the gasifying agent
- combustion / gasification conditions

Thermodynamic data

- gas turbine cycle conditions (pressure and temperature)
- steam cycle conditions (pressure and temperature)

Environmental data

- fuel gas treatment (IGCC)
- flue gas treatment (dust, NOx, SO2)
- solid and liquid residues

2.1.2 Current power plants performances

We have only considered commercial plants or demonstration plants at commercial scale (e.g. Buggenum IGCC power plants in The Netherlands). For each identified power plant, the following data have been collected and standardised (fuel composition, air and cold-end conditions,…) :

Techno-economic performances

1. Installed capacity
2. Full load and part load efficiency
3. Investment cost
4. O&M costs

On this basis, two types of **standard curves** have been achieved:

1. Effect of size for efficiency, investment cost, O&M costs (see Figure 2-1)

2. Part load efficiency

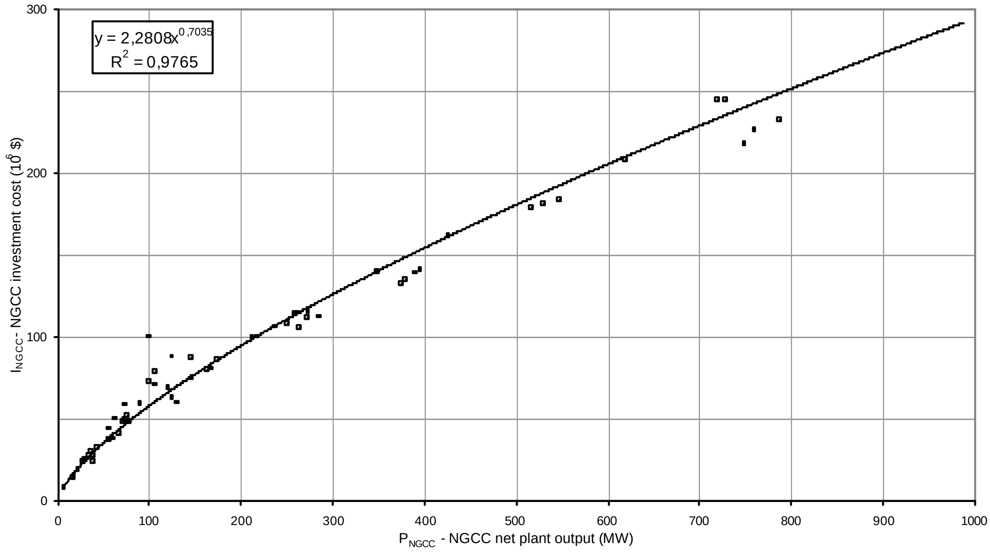

***Figure 2-1** : NGCC investment cost : effect of size (GTW, 1996-2001)*

Environmental performances

We have only considered emission related to power plant operation. Emissions from fuel extraction, transport, power plant building and dismantling are therefore not considered, as it's the case with the LCA approach.

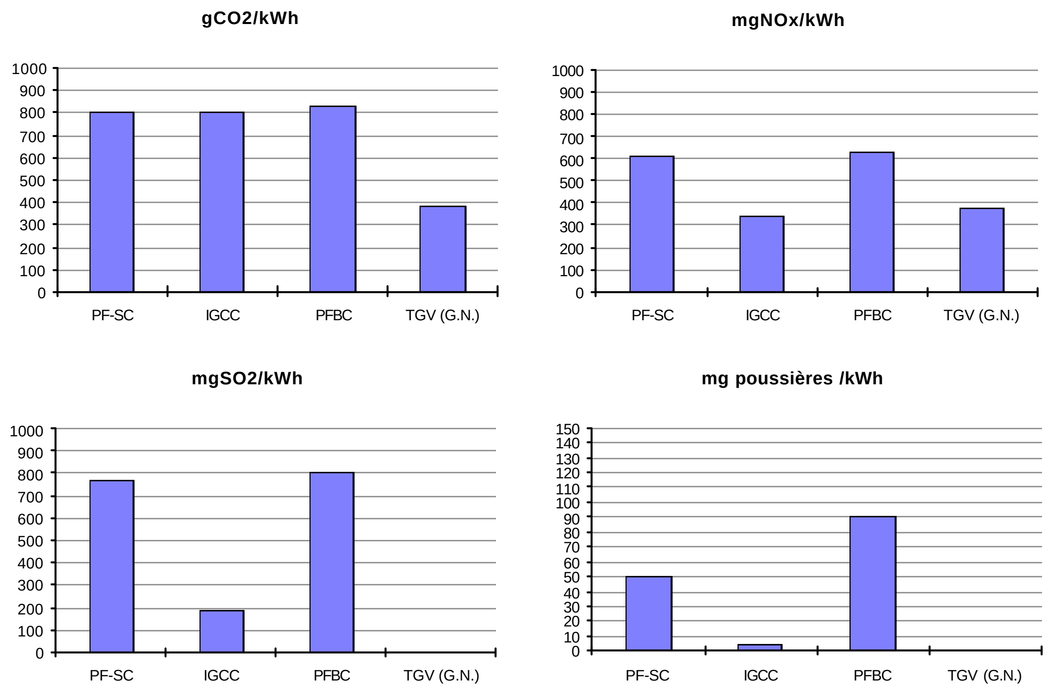

***Figure 2-2 :** Specific CO2, NOx, SO2 and dust emissions of STAG, IGCC, PFBC and USC*

In this study, CO_2 capture technologies in flue and fuel gases are not considered. Then, CO_2 emissions are simply derived from power plant efficiency and fuel composition. In addition of these parameters, combustion/gasification conditions and flue gas treatment are used to assess NOx, SO_2 and dust specific emissions. On this basis, standard curves have been obtained (effect of size for specific emission and specific emission at part load).

2.1.3 Potential for innovation

Evolution of power plants performances has been obtained by the following way:

1. Evolution of major technological parameters:

   The selected parameters are only those related to the thermodynamic cycle (maximal firing temperature of the gas turbine cycle and steam pressures and temperatures of the steam cycle).

2. Performance calculation by means of these technological parameters:

   Efficiency and specific emissions are obtained from physico-chemical and thermodynamics models of the various power plants considered. Some of the thermodynamic parameters are optimised according to a techno-economic criteria (e.g. steam pressures of the steam cycle in a STAG power plant).

   Concerning the investment costs, correlations from cost engineering databases and thermoeconomics developments are used to express the cost in function of thermodynamics parameters, material used and design of the components.

3. Combining step 1 and 2 gives us various scenarios describing the time-evolution of the performance (efficiency, specific emissions, investment costs) for gas-fired and coal-fired power plants.

4. Above-mentioned thermodynamic parameters are not the only driving force for improvement of power plants performances. Scenarios also include potential technological jumps identified in the frame of this project (hot gas filtration for IGCC, sequential combustion for gas turbine,…)

5. These scenarios are compared and completed by those obtained with the *experience curve* methodology *(Wene, 2000)*. In this case, a power function between price / cost or efficiency and experience over time, i.e. cumulative production of units, installed capacity, is derived from historical data. The time-

evolution of power plants performance is then obtained from market development scenario (e.g. period for doubling the cumulative production) .

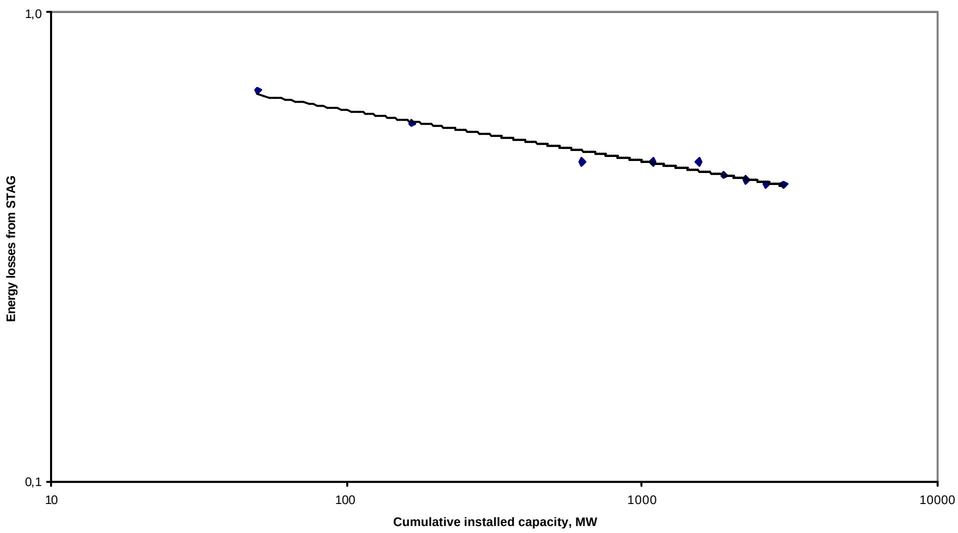

Figure 2-3 : *Experience curve for STAG power plants (progress ratio observed is 93%).*

These scenarios are only valid for an installed capacity range. They can be adapted by means of the standard scale laws in the case of other capacity range. These scenarios are dedicated to be used by the decision model developed by the CORE team.

2.2 Risk analysis

Only fuel prices, electricity prices and emission permits have been analysed. For these risk factors, suitable stochastic models have been selected and calibrated in order to predict efficiently the behaviour of main risks factors.

2.2.1 Fuel prices and electricity prices uncertainty

The theory of real options was relatively poorly endowed in computational terms at the time the project started. This quickly showed up in the work as the first year of the projects revealed important difficulties. Energy prices do not follow the standard diffusion processes found in finance and extensively used in the work done at the time in real options.

The formalism of affine jump diffusion processes may present some mathematical difficulties, but it allows one to represent many of the idiosyncrasies of electricity prices. Specifically affine jump diffusion processes are quite suitable for modelling mean reversion (which is a characteristic of all energy prices) and jumps (which are particularly important in electricity but also arise in natural gas).

2.2.2 CO2 emissions mitigation uncertainty

Discussion with MIT specialist in emission trading Dr D Ellerman led us to model this uncertainty though prices of emission permits. Even though it is not certain that this policy instrument will prevail, the slow progress of the Kyoto protocol leads one to conjecture that some more structured arrangement will need to be developed and that emission permits on a global scale will emerge. Sticking to the overall methodology of real options, the problem is then to model the stochastic process that describes the evolution of the price of these permits. The idea was to fit a diffusion process with jumps at well specific periods of time. This suggestion emerged from discussion with Professor Emeritus A. Manne from Stanford University. Prof. Manne is directing the Energy Modelling Forum project on global working. The results of models run in the context of this project provide the necessary information to model this price process.

2.3 Plant valuation

The model developed gives the value of an investment realised at a certain date. The value of a plant is modelled as a strip of European options on spark spread between electricity and fuel prices (two stochastic factors model). In more usual terms, this equal to the integral, over the life of the plant, of an option on the difference between the price of electricity and the cost of fuel. In addition to the initial option to choose the type of power plant, one will be able to consider the option to stop or start-up the production of electricity depending on the price of electricity in market.

Progress on Fourier Transform analysis and Monte Carlo simulation, based on the affine jump formalism, have been written for this plant valuation process.

2.4 Investment decision model

To model the investment decision in power plants through a realistic and computable real option model, we retained the formalism of American options on differences (spread) between electricity and fuel (gas or coal) prices to do so. The payoff of this option, when exercised, is the value of the plant computed by the plant valuation model. American options on spreads are a novel problem. A program based on complementary formulation of this American option has been written. Consequently, in addition to above-mentioned options, one will be able to consider the option to delay the investment and consequently to find the optimal date for investment.

3. CASE STUDIES : NGCC VERSUS IGCC

A simple approach based on the real options theory has been proposed to determine the optimal investment decision for a new power plant in an uncertain context. Two projects are considered : a natural gas-fired CCGT power plant (NGCC) and a coal-fired IGCC power plant. In addition, the flexibility value of a phased construction for IGCC power plant is analysed (financial value for the repowering option to convert a NGCC unit into an IGCC unit). The uncertainty considered is the natural gas price evolution. A Geometric Brownian Motion (GBM) stochastic process has been used and calibrated by means of various historical data and scenarios.

3.1 Fuel prices evolution

In most scenarios, due to large reserve of coal and its wide distribution in the world, coal price is supposed to be stable over a long-term period. For that reason and to simplify real options computation, we consider a constant coal price over the entire period. Consequently, only the natural gas price is considered as a stochastic variable. Several calibration of the mean expected growth rate μ and the annual volatility σ of the natural gas price have been performed. A first approach was based on historical values for the Belgian borderprice "all gases" from 1982 to 2000 and a second approach was based on 15 fuel prices scenarios for the period 2000-2010 or 2000-2030.

Figure 3-1 illustrates the evolution of the probability density function $f_{t\,0}[P(t)]$ obtained for $\mu = 0,0299$, $\sigma = 0,1165$, corresponding to a positive value for the trend $\alpha = 0,0231$? and $P(t_0) = 4$ EUR//GJ.

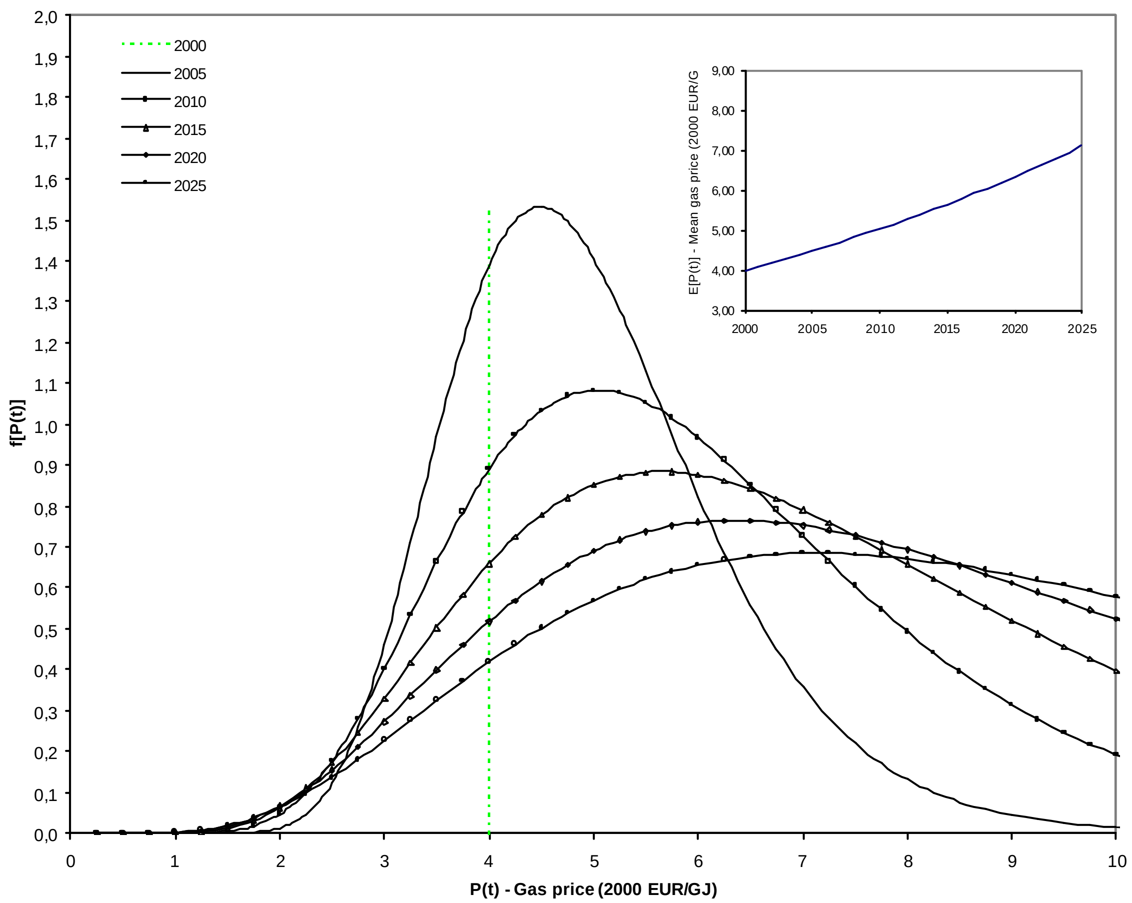

Figure 3-1 : *Gas prices evolution (µ = 0,0299 and s = 0,1165)*

3.2 Economic Analysis

NPV analysis

Calculations are based on the discounted cash flow techniques. Discounted electricity generating costs are calculated according to the UNIPEDE method.

A first step in the analysis is the comparaison of the Net Present Value (NPV) of an IGCC project versus a NGCC project where a mean natural gas price evolution is derived from a stochastic process. Table 3-1 summarises inputs used for the reference case calculation.

	NGCC	IGCC	
Investment	400	1200	EUR/kW
Efficiency	55	45	% LHV
Fuel price	4	1,5	EUR/GJ

Table 3-1 *: Data for the reference case*

Influence of the annual utilisation U on the discounted electricity generating cost is given by Figure 3-2 with μ = 0,0299, σ = 0,1165 and a 10 % discount rate. In this case, the trend α has a positive value. It shows that IGCC is less expensive for annual utilisation above 4500 hours a year (which is usual for such plants).

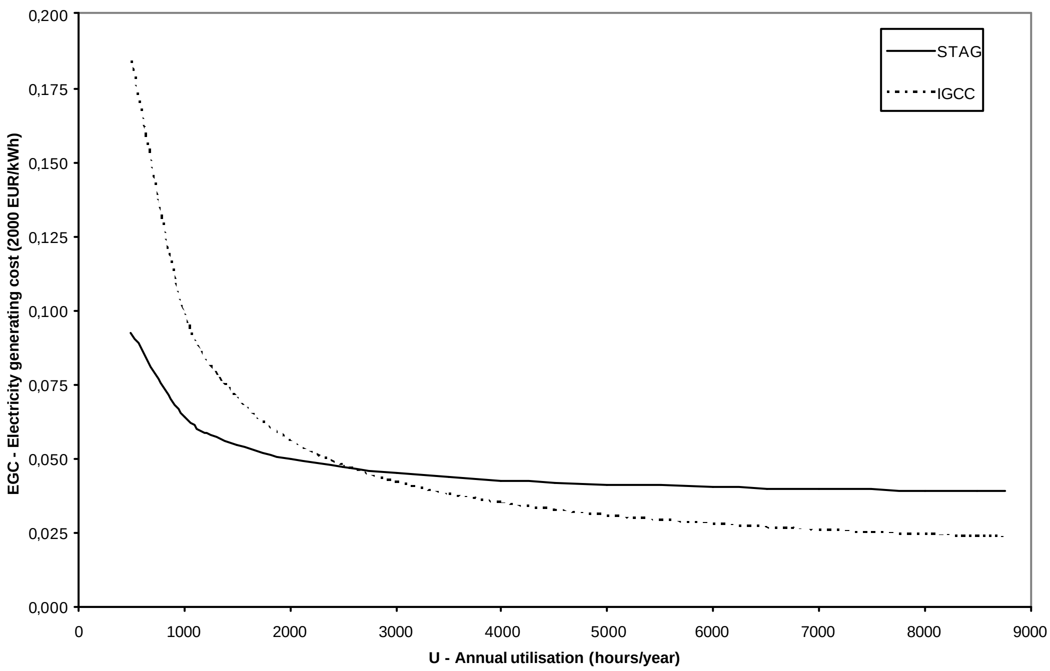

Figure 3-2 *: Influence of the capacity factor (µ = 0,0299, s = 0,1165, i = 0,1)*

3.3 Valuing flexibility

We consider now the possibility of a phased construction. Three new parameters could be considered, (1) the additional cost for STAG unit convertible into a IGCC power plant (fuel gas burner lines, space requirements, supply logistics,…) corresponding in financial term to the option cost (OC), (2) the net efficiency drop (ED) of such STAG units in comparaison with best available STAG units and finally (3) the repowering year. In this study, the potential increase of the power plant capacity when repowered to an IGCC has not been considered. Figure 3-3 shows the discounted cash-flow during power plant lifetime with a repowering occuring in 2010. No additional costs and no efficiency drop have been considered for this calculation. GBM considered parameters are μ = 0,0029 and σ = 0,2279 with discount rate of 5%.

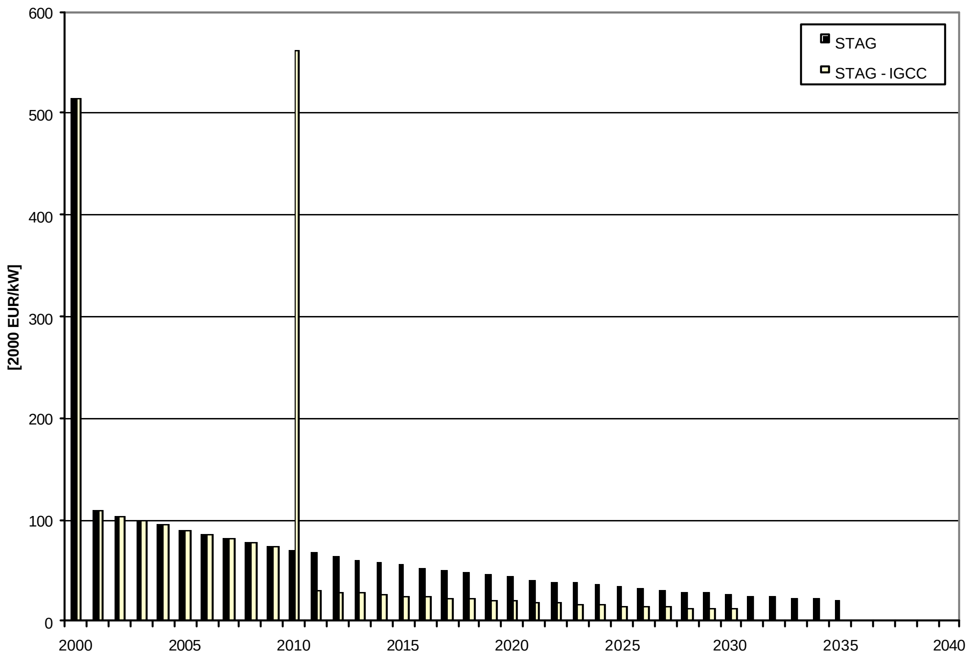

Figure 3-3 : *Discounted cash flow*

In the conventional analysis, the decision criteria is the difference between the expected net present value (NPV) of two projects, (1) STAG investment, (2) STAG investment and IGCC conversion at a fixed repowering year. The second project has to be selected if its NPV is better than the NPV of the STAG investment.

In the conventional analysis, the natural gas price evolution used for calculation is based on the price value at the reference year. In the real options analysis, the conversion to an IGCC power plant will only be done if the NPV of the conversion evaluated at the repowering year is positive (fuel price evolution are based on fuel price level at repowering year). The thresold of the observed natural gas price at the repowering year from which the NPV_r becomes positive and repowering has to be dediced in shown in the following figure for the reference case.

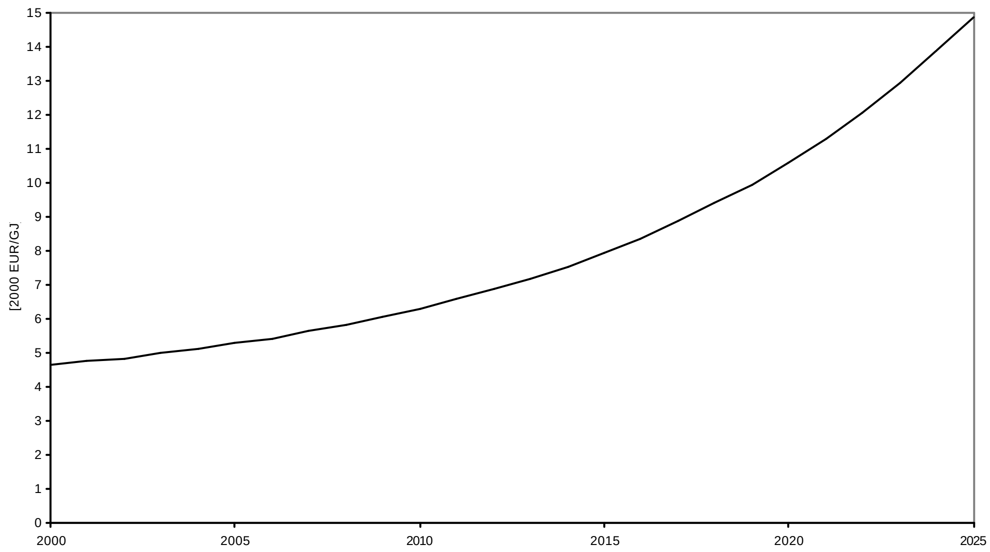

Figure 3-4 : *Evolution of the minimum gas price required at repowering year for IGCC conversion*

Figure 3-5 shows the evolution of the difference between the real options value (ROV) and the conventional NPV in function of the repowering year. This difference is corresponding to the so-called flexibility value (FV) for i=10%, OC = 0%, ED = 0%). In this case, the optimal repowering year for repowering is 2006.

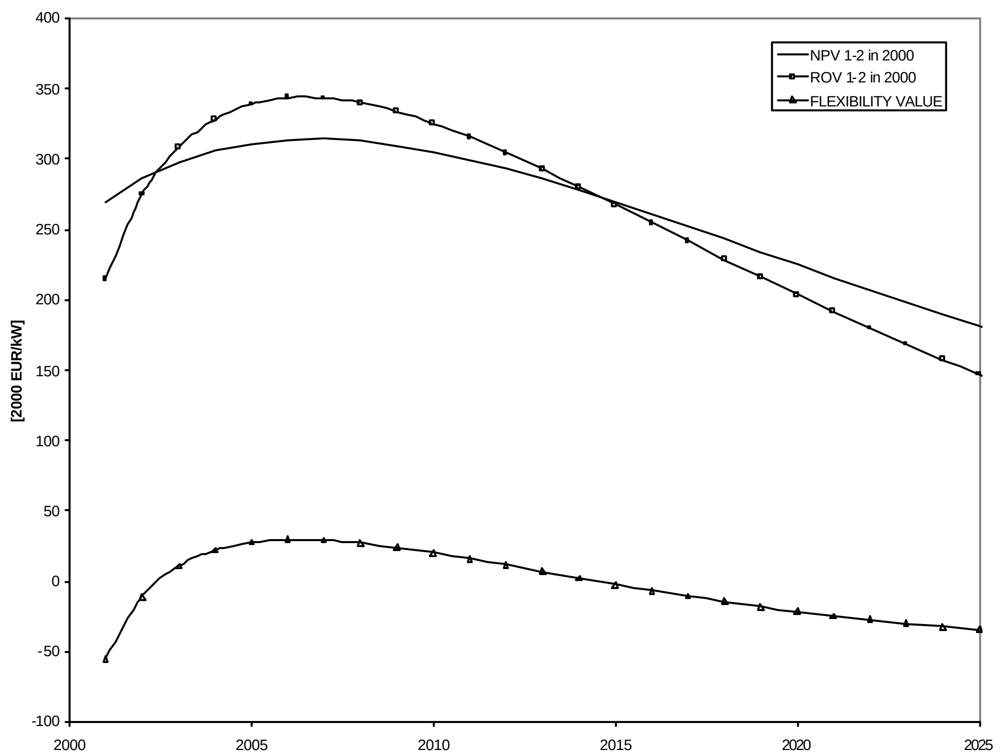

Figure 3-5 : *Flexibility value gives the optimal repowering year*

4. CONCLUSIONS AND PERSPECTIVES

4.1 Fossil-fuels performances

Methods for the optimisation of techno-economic parameters of power plants have been implemented on conventional thermodynamic models.

Results consist of databases, thermodynamic and techno-economic models, standard performance curves and scenarios for each technological options considered for gas and coal-fired power plants.

The methodology of "learning curves" is well suited for combined cycle technology and in particular to predict the evolution of power plants performance such as investment cost or efficiency.

In future projects, these methods will be applied to other types of thermal power plants (combined heat and power systems, biomass gasification systems,…).

4.2 Real options methodology

A simple method based on a stochastic modelling of the natural gas price evolution is now available. Calibration of the stochastic process for natural gas price provides a convenient way to compare on a same basis historical data and scenarios for fuel prices evolution. Nevertheless, the electricity generating cost derived from this method is still very sensitive to fuel price parameters and other economic parameters such as the discount rate.

A more innovative contribution of the real options theory is to give a monetary value of a phased construction flexibility as demonstrated in the case of a repowering option of a STAG unit into a IGGC unit. In addition, the optimal repowering year can be calculated.

Nevertheless, further developments have still to be performed such as the use of more suitable stochastic processes for coal and gas prices evolution, a better integration of the technology evolution by the use of experience curves. Another major improvements of the method in this context of competition is to consider a stochastic process for the capacity factor or the use of the maximisation of the spark spread between electricity and gas as decision criteria instead of minimisation of the electricity generation cost. These improvements require more sophisticated calculation methods.

4.3 Fossil fuels and climate change

For period 1990-2010, progress in gas-fired and coal-fired power plants have allowed a specific CO_2 emission reduction (g/kWh) of more than 15…20 %. In comparison to Kyoto targets, it seems to be significant but with respect to the climate change problem it seems to be insufficient. Consequently, new fossil fuel power plants require necessarily integration of CO_2 separation systems. In this context, IGCC systems seems to be a very promising technology even if a large amount of R&D is still required.

4.4 Competitive and uncertain electricity market

Basic case studies based on conventional analysis or real options analysis show that for period 2000-2010 more efficient coal power plant complying with more stringent emission standards will be competitive with gas-fired combined cycle. This is mainly due to the positive trend for the gas price evolution predicted in most scenario.

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CONTRIBUTIONS OF WOOD ENERGY TO SUSTAINABLE DEVELOPMENT IN BELGIUM (WOODSUSTAIN)

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This final summary has been written in September 2001 by Ivan Sintzoff (Groupe Energie Biomasse - http://www.term.ucl.ac.be/geb).

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Glossary & abbreviations

$kgCO_2$	1 kilogram of fossil carbon dioxide equivalent
odt	1 oven dried ton = 1 ton of dry wood
ha	1 hectare = a surface of 10,000 m^2
odt/a	1 ton of dry wood per annum
odt/ha	1 ton of dry wood per hectare
man-year	1 man working during 1 year.
ton	1 ton of matter
MW_{th}	10^6 Watt of thermal power produced or consumed.
MW_{el}	10^6 Watt of electrical power produced or consumed.
MWh	quantity of energy produced (or consumed) by a machine developing 10^6 watt during one hour, i.e. 3,6 10^9 Joule
MWh_{heat}	quantity of heat produced (or consumed) by a machine developing 10^6 watt during one hour, i.e. 3,6 10^9 Joule.
MWh_{elec}	quantity of electricity produced (or consumed) by a machine developing 10^6 watt during one hour, i.e. 3,6 10^9 Joule.
SRC	Short Rotation Coppice

1. SUMMARY

WOODSUSTAIN is a partnership of 5 research centres located in Belgium. Initiated and co-ordinated by GEB, the Groupe Energie Biomasse of the Université catholique de Louvain, WOODSUSTAIN aims to precise the wood energy potential available in Belgium and to assess the impacts of wood energy development on greenhouse gases emissions, on job creation and on the local economy.

In this project, GEB has calculated the life cycle analysis of number of wood energy systems in order to estimated the fossil energy consumption, the CO_2 emissions and the CO_2 reductions related to wood energy use. CRA, the Centre de Recherches Agronomiques working on wood resources and wood fuels handling, has estimated the quantities of wood resources available in the Belgian forests and the industry. ECOP, the Laboratoire des Grandes Cultures of the Université catholique de Louvain working on energy cultivation, has estimated the potential of short rotation coppice cultivation in Belgium. CEE, the Centre Entreprise Environnement of the Université catholique de Louvain, has estimated the job creation in wood energy systems and analysed the local economy of wood energy projects. PLECO, the Research group of Plant and Vegetation Ecology of the University of Antwerpen, has improved the mathematical modelling of poplar coppice growth.

The estimations of wood energy available are about 10,000 TJ/a in Belgian forests and 19,000 TJ/a in the wood industry (including construction and demolition industry). All this wood could not be completely consumed for energy purpose because other uses are already developed, mainly in the paper and panel industry where 35% of the industrial wood residues are recovered. In addition to this resource available from now, WOODSUSTAIN has estimated the potential for short rotation coppice cultivation in the next 10 years at 12,000 TJ/a. A reasonable projection is an increase in the wood energy consumption of 10% each year leading to 30,000 TJ/a in 2010 and 50,000 TJ/a in 2015. This wood energy consumption will avoid the burning of fossil energy and then reduce fossil CO_2 emissions in 2010 by 1.5 to 3.4 millions tons of CO_2 (i.e. 1.2% to 2.7% of the total 1990 equivalent CO_2 emissions in Belgium). The manpower needed to harvest and to prepare this local fuel will be between 2,000 and 3,000 mans fully occupied. The total investment required for having sufficient modern power plants and wood heating equipments has been evaluated between 250 and 2,500 millions euros.

2. MAIN RESULTS

2.1 The wood energy resources

2.1.1 Forest wood energy resources

CRA estimates that 224,000 odt/a of wood residues are annually abandoned in broadleaf forests and 321,000 odt/a of wood residues in needleleaf forests. Adding Brussels forest, that is about 546,000 odt/a of wood residues annually left in the Belgian forests. Based on an estimation of 290,000 ha of broadleaf forests and of 252,000 ha of needleleaf forests, the average wood forest residue is about 0.7 odt/ha/a in broadleaf forests and 1,3 odt/ha/a in needleleaf forests.

After integration and confrontation of these data with other studies, GEB notes that the CRA results must be carefully considered because this estimation is about 24% of the natural increment of matter in Belgian forests. This figure seems relatively high taking into account that the mean harvest ratio in Belgium is estimated at 65% (2,2 millions m^3/a harvested of the 3,4 millions m^3 biological growth [CdB, 1985]). If the 24% available as wood residues would be harvested for energy, the total harvest of woody material in our forests will be 89% of the biological growth. International experts recommend to limit the total removal of wood to be less than 80% of the natural growth. In this case, wood residues in forests available for energy purpose are limited to 15% of the biological growth, that is to say about 342,000 odt/a. CRA and CEE have evaluated the cost of harvesting these forest residues. Depending on the type of residue and on the choice of the harvesting practice, forest wood chips will cost between 40 EUR/odt and 80 EUR/odt.

2.1.2 Industrial wood energy resources

The data recovered from the CRA surveys precise the production of wood by-products (bark, off-cuts, shavings, sawdust, etc.) in the Belgian industry. The total production has been estimated at 857,000 odt/a. This wood is not fully available for energy because 35% is already consumed in the paper & pulp industry.CRA has estimated the price value of these by-products by asking to the companies what are the present prices they receive for their woody by-products : bark is valued between -40 and +50 EUR/odt, wood chips between 17 and 72 EUR/odt, sawdust between 0 and 50 EUR/odt, demolition wood between -75 and -25 EUR/odt. These prices vary mainly with the quality of the by-product, with the distance from an important consumer and with the volume of the production.

GEB notes that some uncertainty remains after the CRA surveys. In order to confirm these data, GEB has compared them with the French ratios obtained from a similar survey to 4,700 companies [CTBA, 1992]. Applying these ratios, a total of 808,000 odt/a wood residues could be available in sawmills, joineries and furniture manufactures while CRA obtains 685,000 odt/a. The difference is more important between CRA estimation and CTBA ratios for the furniture sector. The low representativity of the CRA sample (16 companies of 163) could be a reason. CRA has not taken into account the wood residues coming from used package as broken pallets. About 200,000 odt/a of pallets are not reused in Belgium [iTER, 1998]. About the estimation of wood costs, the uncertainties remain important. Wood costs depend on a lot of parameters : wood quality, distance of the main wood user, etc. Further, uncertainties on wood costs are also coming from the uncertainties on wood quality. The producers of wood by-products do not know very well their wood quality (moisture and volumic mass). It is still difficult to have a good estimation of the wood cost per energy unit (EUR/GJ), even when knowing the wood cost per volume or per ton (EUR/m^3 or EUR/ton).

2.1.3 Agricultural wood production

ECOP has proposed three scenarios for developing Short Rotation Coppice (SRC) as the main solution for wood production in the agriculture. The medium scenario suppose that 5% of the Total Utilised Agricultural Area will be converted to SRC cultivation. In this case, 66,000 ha will be planted. ECOP estimates at 717,000 odt/a the wood fuel production on agricultural land. These scenarios are in accordance with the European Commission scenario (White Paper, 1997) which propose a 6,3 millions hectares of cellulosic plantation for energy purpose in 2010. This is about 4-5% of the European TUAA. The average productivity estimated by ECOP at 10.8 odt/ha/a is not far from the European estimation of 10 odt/ha/a. We could then accept the medium scenario as a good estimation of the future development of agricultural cellulosic cultivation. If SRC was replaced by an other cellulosic plant (as miscanthus), the energy potential will not be so different.

2.1.4 Estimation of the total wood energy potential and of the costs

Table 2	Estim. quantity - TJ/an	Estim. deviation - TJ/an	Estim. mean cost - EUR/GJ	Min cost - EUR/GJ	Max cost - EUR/GJ
All forest residues without stumps	10,158	0	3.5	1.6	8.8
Scenario of SRC production	12,902	6,300	4.0	2.7	11.0
Sawmills by-products	7,506	468	0.3	-2.1	7.6
Joineries by-products	3,537	315	0.1	-1.2	1.6
Furniture manufactures residues	2,474	986	0.1	0.0	2.7
Residues from packaging industries	557	0	-0.1	-4.0	2.1
Construction & demolition wood	2,552	324	-0.6	-4.0	0.0
Wood residues from other industries	2,412	2,088	-0.6	-4.0	0.0
Total wood energy	42,098	10,481	2.1	-4.0	11.0

2.2 The wood energy technologies

2.2.1 Production of wood fuels

Different systems to produce wood fuels have been identified and assessed. The steps to produce wood fuels are : cultivate, harvest, chipping, transport, storage, drying, crushing, pelletizing/densifying. Depending on the wood resources and on the type of wood energy use, one or more of these operations will be applied. For example, wood fuels production by SRC cultivation could be decomposed in 4 steps (cultivate, harvest/chipping, transport and storage/drying) while producing wood pellets from sawdust needs 4 other steps (transport, storage/drying, pelletizing/densifying, transport).

With the help of ECOP and CRA, GEB and CEE have modelled the cultivation of SRC, the harvest of forest residues, the transport of wood fuels, the storage & the drying of wood fuels and the densification of wood sawdust. The production of wood fuels from SRC appears expensive relatively to the production cost of wood waste or to the market cost of fossil energy in the nineties. The lower medium cost for SRC wood chips is about 125 EUR/odt (about 50% higher than fuel-oil market price). SRC harvest and chipping is labour intensive, about 2.2 hours/odt. Energy consumption for SRC cultivation is mainly caused by fertilisers consumption and fuel for maintenance and harvesting. This energy consumption emits about 100 kgCO_2/odt, that is to say 5.5 kgCO_2 per GJ of primary energy.

The harvest of forest residues has been modelled with 6 scenario’s depending of the level of mechanisation. Low mechanised harvest is well suited for broad-leaved forests while high mechanised harvest is adapted after a complete cut-off of needle-leaved forest. Production of wood chips from forest residues costs 40-60 EUR/odt. Depending on the harvest type, manpower use is between 0.4-2.3 hours/odt. Fossil energy consumption is limited to fuel consumption for machines operation, between 0.3 and 0.7 GJ/odt, emitting 22-50 kgCO_2/odt (1-3 kgCO_2/GJ).

For industrial residues, fixed chipping has been analysed. Depending on the size of the chipper and on the annual production (odt/a), CEE has obtained a classical formula to calculate the chipping cost in EUR/odt (chipping_cost = a . (annual_production)$^{-b}$ with a = 7090 EUR/odt and b = 0.7026). This is about 50 EUR/odt for annual production lower than 2,000 odt/a, and about 10 EUR/odt for production bigger than 10,000 odt/a. Labour need is between 0.1 and 1.4 hour/odt. Energy cost of chipping is 0.3-0.8 GJ/odt (following the same formula with a = 13,726 MJ/odt et b = 0.4324), emitting 7-30 kgCO_2/odt chipped.

Wood chips must be transported from the production site to the utilisation site. Chips are transported in trailer or container. GEB and CEE have analysed 3 types of road transport : agriculture/forestry tractor and trailer, small truck (30 m^3) and large truck (90 m^3). Transport are estimated around 4.2 EUR/odt for short distance (20 km), 8 EUR/odt for regional transportation (75km) and 32 EUR/odt for international transport (300 km). These value are highly related to the distance (km) and the dry mass volume of the wood fuel transported (odt/m3). Manpower use is respectively 0.2 $\pm$ 0.1 (25 km), and 0.6 $\pm$ 0.4 (75 km) and 0.8 $\pm$ 0.3 (300 km) hour/odt. Energy consumption is respectively 0.17 $\pm$ 0.01, 0.18 $\pm$ 0.11 and 0.74 $\pm$ 0.44 GJ/odt, emitting 10 $\pm$ 1, 11 $\pm$ 7 and 46 $\pm$ 28 kgCO_2/odt.

Storage of wood chips could be done without or with ventilation and drying. Natural drying cost nothing except the area and avoid energy consumption but could led to wood matter losses resulting of the fermentation. After half a year, about 10-15% of wood is fermented and lost. When vented or dried, wood storage is relatively energy intensive 1.8 $\pm$ 0.2 and 2.7 $\pm$ 0.1 GJ/odt, and emitted carbon emissions 65 $\pm$ 10 and 205 $\pm$ 10 kgCO_2/odt.

Densification or Pelletisation are two final steps used to produce a standardised wood fuel. Wood pellets or wood briquettes are interesting is some private use of wood fuel. CEE has collected data on these operations given production costs between 20 and 250 EUR/odt, 5-25 hours/odt, 0.8-4.6 GJ/odt and 11-140 kgCO_2/odt. These figures are very uncertain cause of the type of wood densified and the type of densification.

GEB and CEE have analysed 11 types of wood fuels supply systems. Adding all these steps of wood fuels production, we have calculated the cost, manpower, energy and CO2 emissions in 11 types of wood fuels supply systems (see tables 3 & 4).

Table 3	**Production cost EUR/odt**	**Direct Manpower Hour/odt**	**Energy consumption GJ/odt**	**CO_2 emissions $kgCO_2/odt$**
Cultivation of SRC and harvest into chips :				
1. Low intensive with manual harvest in stems	153 ± 46	2.9 ± 0.2	1.15 ± 0.1	77 ± 11
2. Medium intensive with mechanical harvest in chips	126 ± 36	0.2 ± 0.2	2.00 ± 0.3	147 ± 32
3. High intensive with mechanical harvest in bales	180 ± 53	2.2 ± 0.0	1.41 ± 0.2	104 ± 17
4. High intensive with mechanical harvest in stems	128 ± 38	2.2 ± 0.2	1.36 ± 0.2	100 ± 17
Harvest and chipping of forest residues :				
1. 1 tractor + 1 small chipper + 2 mans	60 ± 26	2.3 ± 1.0	0.29 ± 0.3	22 ± 3
2. 1 tractor + 1 medium chipper + 1 grab + 1 man	48 ± 21	1.0 ± 0.3	0.44 ± 0.7	32 ± 6
3. 2 tractors + 1 big chipper + 2 man	45 ± 12	0.9 ± 0.2	0.67 ± 0.3	50 ± 20
4. 1 forester machine + 1 big chipper + 1 man	47 ± 19	0.4 ± 0.1	n.a.	n.a.
5. 2 forester machines + 1 big chipper + 2 mans	51 ± 13	0.6 ± 0.2	n.a.	n.a.
6. 1 forester machine + 1 tub grinder + 2 mans	42 ± 18	0.5 ± 0.2	n.a.	n.a.
Fixed chipping of industrial residues :				
1. less than 500 odt/a	90 ± 25	1.4 ± 0.7	0.75 ± 0.2	29 ± 13
2. 1,000-2,000 odt/a	50 ± 20	0.7 ± 0.5	0.6 ± 0.3	20 ± 10
3. 3,000-5,000 odt/a	23 ± 7	0.2 ± 0.1	0.4 ± 0.2	13 ± 6
4. More than 10,000 odt/a	10 ± 1	0.1 ± 0.0	0.3 ± 0.1	7 ± 2
Transport of wood chips :				
local transport by tractor & trailer (20 km)	4.2 ± 0.3	0.2 ± 0.1	0.17 ± 0.01	10 ± 1
regional transport by truck (75 km)	8 ± 4	0.6 ± 0.4	0.18 ± 0.11	11 ± 7
international transport by truck (300 km)	32 ± 17	0.8 ± 0.3	0.74 ± 0.44	46 ± 28
Storage of wood chips (6 months) :				
natural storage under shelter	0.1 ± 0.1	0	0	0
vented storage in silo	6.5 ± 2.5	0	1.8 ± 0.2	65 ± 10
dried and vented storage in silo	30 ± 7	0	2.7 ± 0.1	205 ± 10

Table 4		Production cost EUR/odt	Direct Manpower Hour/odt	Energy consumption GJ/odt	CO_2 emissions $kgCO_2$/odt
F1	Broadleaved forest residues harvested after 100 days with a small mobile chipper + local transport to a local user + wood chips storage (max. 180 days).	70 ± 26	2.6 ± 1.0	0.38 ± 0.04	27 ± 3
F2	Broadleaved forest residues harvested after 100 days with a medium mobile chipper + local transport to a local user + wood chips storage (max. 180 days).	55 ± 11	1.1 ± 0.4	0.57 ± 0.08	40 ± 6
F3	Broadleaved forest residues harvested after 100 days with a medium mobile chipper + regional transport to a regional user + wood chips storage (max. 180 days).	56 ± 13	1.6 ± 0.8	0.54 ± 0.13	38 ± 9
F4	Needleleaved forest harvested just after felling with a big forester machine + regional transport + vented storage during 30 days.	72 ± 17	2.2 ± 1.6	1.84 ± 0.53	185 ± 44
F5	Needleleaved forest harvested just after felling with a big forester machine + regional transport + drying storage down to 15% (max. 180 days).	73 ± 17	2.2 ± 1.6	2.25 ± 0.86	162 ± 63
C1	Low intensive SRC cultivation harvested in stems + storage of wood stems on the fieldside (max. 180 days) + chipping of stems + local transport	159 ± 43	3.1 ± 0.2	1.06 ± 0.15	77 ± 11
C2	Medium intensive SRC cultivation harvested in chips + local transport + sheltered storage (max. 180 days).	148 ± 38	1.0 ± 0.8	1.84 ± 0.45	133 ± 32
C3	High intensive SRC cult. + harvest in bales + local transport + chipping + sheltered stor. (max. 180 days).	194 ± 54	3.8 ± 1.5	1.55 ± 0.36	111 ± 25
C4	High intensive SRC cultivation + harvest in chips + local transport + sheltered storage (max. 180 days).	143 ± 41	3.8 ± 1.5	1.50 ± 0.36	107 ± 25
W1	Industrial waste chipped in joineries, chips storage and local use.	7 ± 0.2	0	0.21 ± 0.07	15 ± 5
W2	Industrial waste chipped in joineries, regional transport, final crushing and densification in pellets or briquettes.	142 ± 20	6.2 ± 0.9	2.06 ± 0.16	123 ± 10

2.2.2 Production of energy from wood fuels

GEB has classified wood energy technologies by power range and by type of usage : domestic heating, collective heating and/or power production and centralised power production.

For domestic heating (<100 kW_{th}), 4 different technologies are already available : logs stoves, pellets stoves, logs boilers, chips boilers. In addition, 2 new technologies could become available by 2010 : domestic Stirling engines and micro-gasification gensets. Wood stoves are the main wood energy technology installed in Belgian households. Energy efficiencies (25%-60%) and atmospheric emissions (200-2000 mg_{CO}/MJ_{comb}, 150-900 $mg_{particules}/MJ_{comb}$) have been well improved from 1970. Investment costs in modern wood stoves are very dependant of the stove type and the design, between 100-300 EUR/kW_{th} (classical stoves), 400-600 EUR/kW_{th} (ceramic stoves) [Karlsvik et Sonju, 1991, Senf, 1996, Strehler, 1998 and FEEDS, 1998]. Wood boilers are more and more installed in northern and eastern European countries (15,000 new wood boilers installed in 1996 in Austria, Lasselsberger et al. 1998). Important improve has been realised in boiler efficiency (70%-90%) and atmospheric emissions (50-1,000 mg_{CO}/MJ_{comb}, 50-350 mg_{NOx}/MJ_{comb} and 20-100 $mg_{particules}/MJ_{comb}$). Investments depends on boiler type and power range : 200-400 EUR/kW_{th} for a logs boiler with its hot water tank for heat storage (20-50 kW_{th}), 300-700 EUR/kW_{th} for an automatic wood chips boiler (20-50 kW_{th}). Domestic power generation is at the early stage of development. GEB thinks that domestic cogeneration technologies will be more and more available in the future. 2 different technologies have been analysed : (1) combination of a wood boiler and a Stirling engine and (2) combination of a wood gasifier and a gas genset. These systems are not yet commercial but the technological demonstration is almost done. Global efficiencies will be as high as 70%-90% with 10%-25% converted in electrical power and 45%-80% in heat. The power range is 5-50 kW_e and 10-200 kW_{th}.

For collective heating (<10 MW_{th}), different technologies are available : clean wood boilers, contaminated wood boilers, power steam cycles and gasification gensets. Collective wood boilers could be design for clean wood or contaminated wood. Clean wood boilers are 3 to 5 times cheaper than contaminated wood boilers due to avoiding the investment in a flue gas cleaning system. Investment cost is very sensitive to the boiler size (200-600 EUR/kW_{th} for boiler smaller than 1 MW_{th}, 150-200 EUR/kW_{th} for boiler bigger than 2 MW_{th}, blue area and 400-1,000 EUR/kWth for boilers in the range of 2-5 MW_{th} and 300-650 when bigger than 5 MW_{th}). Thermal efficiencies are between 70% and 105% (for flue gas condensing boilers) with a mean value around 85%. Some wood boilers are integrated in a steam cycle designed in a cogeneration mode. This is rarely done with a boiler size smaller than 10 MW_{th}. Wood gasification gensets are now commercially available on the European market. This concept combines a wood fixed bed gasifier and an internal combustion engine coupled with an alternator. Investment costs are relatively high (2,500-5,000 EUR/kW_e). Total efficiency could reach 70-90% if heat is well recovered:

electrical efficiencies are 18-27% and thermal efficiencies 40%-70%. Atmospheric emissions are still high for carbon monoxide (50-250 mg_{CO}/MJ_{comb}, 10 mg_{NOx}/MJ_{comb}).

For centralised power production (> 10 MW_e), technologies are : power steam cycles, biomass integrated combined cycles and co-firing of wood and coal. Steam cycles between 10 MWe and 50 MWe obtain an electrical efficiency between 24%-40% with an important scale effect. For power range bigger than 10 MW_e, investment costs are between 1,500-2,700 EUR/kW_e. Centralised wood gas combined cycles power plants are still in the technical demonstration phase. Electrical efficiencies will reach 35%-40% for 25-30 MW_e. Investments costs are estimated between 1,000 and 2,700 EUR/kW_e for power range bigger than 10 MW_e. The cheapest solution for centralised power production remains the repowering of existing coal power plants in wood and coal co-firing power plants. This has already be done in North America and in Europe in dozen of power plants. For a limited investment (between 100-500 EUR/kW_e), electricity producer could convert an existing coal power plant in a partially wood power plant.

2.3 Contributions of wood energy to sustainable development

2.3.1 Wood energy reduces greenhouse effect

Even after taking into account the fossil fuel consumed for producing wood fuels, GEB concludes that wood energy technologies reduce very much greenhouse gas emissions.

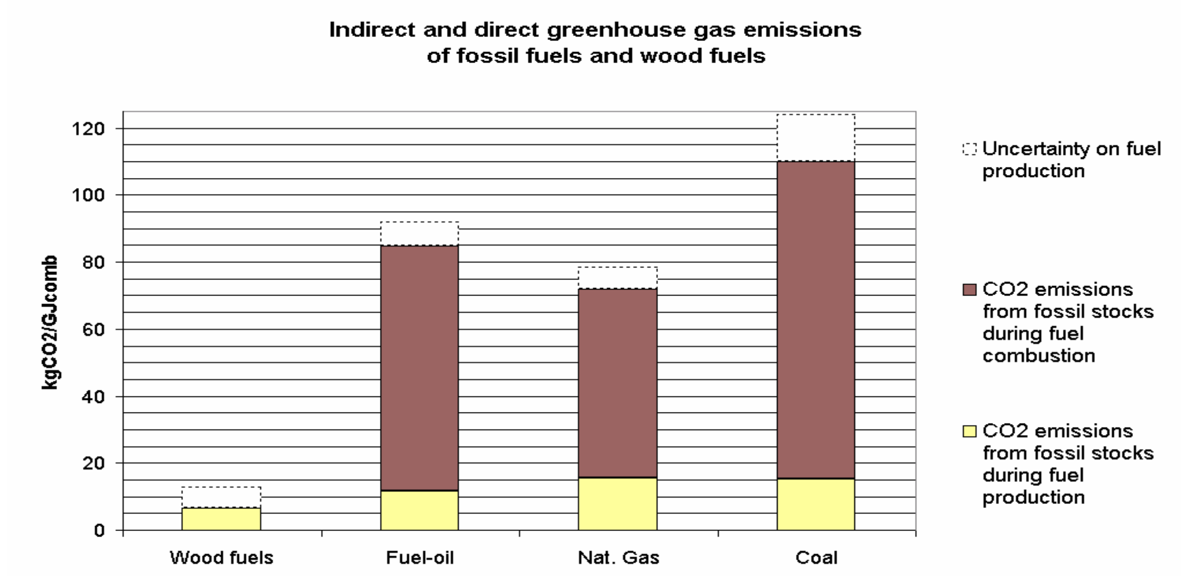

Figure 10 *- Emissions of greenhouse gases of main fuels (GEB).*

1. Producing wood energy emits between 10 and 230 $kgCO_2$/odt, that is about 0.5-12.8 $kgCO_2/GJ_{comb}$ while the production of fossil fuels emits between 4.4-18.7 $kgCO_2/GJ_{comb}$ for oil, 9-22.5 $kgCO_2/GJ_{comb}$ for natural gas and 1.0-29.8 $kgCO_2/GJ_{comb}$ for coal. We conclude that for the production cycle of fuel, wood energy has a slight greenhouse impact. When taking into account the direct emissions due to the combustion of the fuels, the figures are much more interesting for wood : 0$kgCO_2/GJ_{comb}$ for wood fuels, 74 kgCO2/ GJ_{comb} for fuel, 56 $kgCO_2/GJ_{comb}$ for natural gas and 94 $kgCO_2/GJ_{comb}$ for coal fuels. When burning wood fuels, the CO_2 released in the atmosphere is exactly the same quantity of CO_2 that has been trapped by the tree during the photosynthesis. Wood fuels are then considered as carbon neutral fuels. In the total life cycle of the fuels, wood emits 10 to 17 less times CO_2 than fossil fuels (see Figure 10).

2. GEB has assessed the reduction of greenhouse gas emissions that could be done in Belgium by replacing fossil fuels technologies by wood fuels technologies. Depending on the hypothesis chosen (cfr. above), the results vary between 750 and 1,700 kg CO_2 avoided by ton of wood consumed. Taking into account that the wood energy resources have been estimated to about 2 millions of tons per year in Belgium (340,000 in forests, 970,000 in the industry and 710,000 in the agriculture), GEB estimates that 1.5 to 3.4 millions tons of CO_2 could be avoided by using wood energy in Belgium (i.e. 1.2% to 2.7% of the total 1990 equivalent CO_2 emissions in Belgium[2]). For each project, the avoidance of CO_2 emissions will depend on the efficiency of the technology, the consumption of fossil energy for wood fuel production and the effective recovery of the heat. For example, Figure 11 compares the reduction of CO_2 emission by consuming 1 ton of wood in different wood energy technologies. The important uncertainty for technologies producing electricity results of the different choices possible for the reference case (cfr. above).

GEB's conclusions are that wood energy systems are drastically reducing fossil CO_2 emissions. In order to profit at the best of the wood resources available in Belgium, high efficiency heating (i.e. collective wood heating) or cogenerating of heat and power (i.e. wood gas gensets or steam cycles) must be installed.

[2] Estimated by the Bureau Fédéral du Plan to 126.1 millions tons of equivalent CO_2 (BFP, 1996).

2.3.2 Jobs creation in the wood energy production

CEE has estimated the manpower needed to produce 1,000 TJ of wood energy at 24-350 man-year. That must be compared with the 8 man-year needed for coal production [B. Hektor, 1999]. Applying the CEE estimations to the Belgian wood resources, GEB drawn the curve of job creation in the production of wood fuels. It appears that new jobs will only become important when the demand of wood energy will be big enough to harvest forest residues and SRC. The recuperation of wood waste coming from the industry does not create a lot of jobs in the fuel chain. In Belgium, the job creation in the wood fuel production is estimated to 2,200-3,000 jobs.

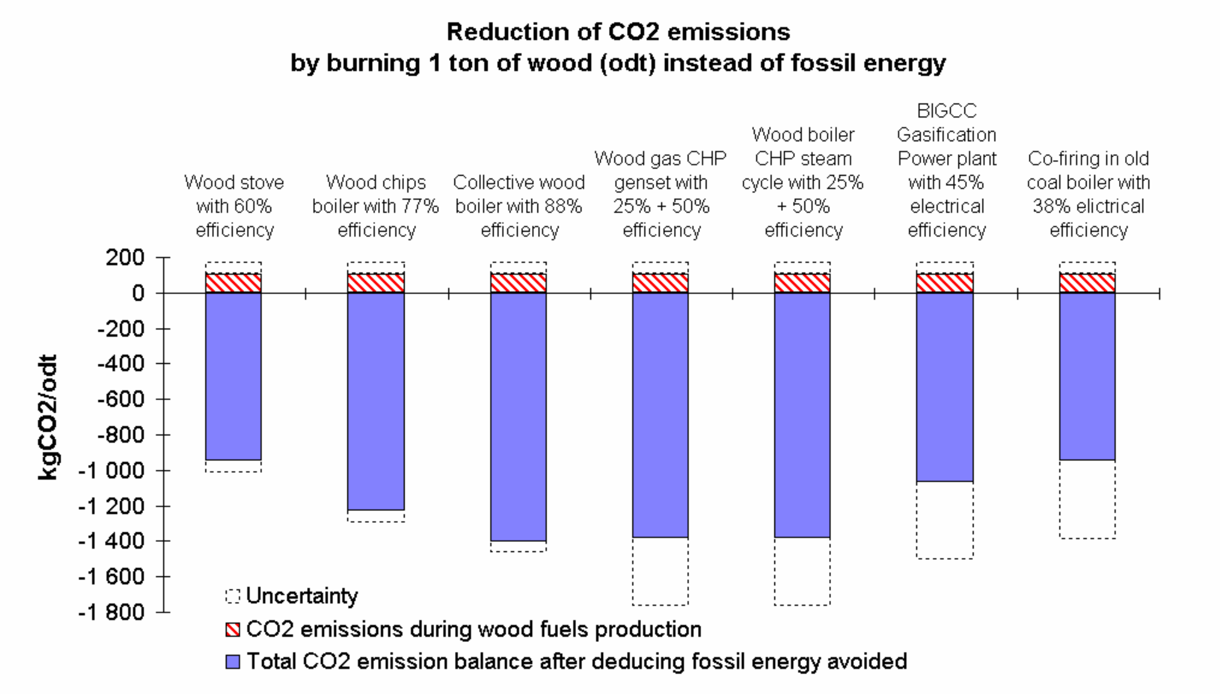

Figure 11 *- Reduction of greenhouse gases emissions by replacing fossil fuels with wood fuels (GEB).*

2.3.3 Profitability of the wood energy production

CEE has analysed the profitability of wood energy technologies. The comparison between 14 technologies has been done. For the domestic heating, it appears that wood energy becomes profitable if the price of wood fuels is lower than 90-125 EUR/odt. For collective heating or cogeneration of heat and power at small-scale (<10 MW_{th}), clean wood fuel cost must be lower than 160-140 EUR/odt. Cost of contaminated wood fuels must be lower than 15 EUR/odt. For power production, even with wood cost at 125-260 EUR/odt, power plants are profitable.

GEB considers that these results must be considered very carefully because of the choice of assumptions. CEE supposes that the electricity and the heat produced will be sold always at the same prices. These prices have been chosen by CEE as high as 148 EUR/MWh$_{el}$ and 43 EUR/MWh$_{th}$. A second important factor is the annual operation time of each technology. CEE has chosen 4,000 hours per year for all technology. The third assumption that we must take into account is the rate of discount chosen. CEE has always applied the same rate equals to 6,75%. Finally, the fourth assumption is the life duration of each technology.

2.4 Modelling of the poplar coppice growing

PLECO has developed and utilised two models : (1) a tri-dimensional model of the coppice architecture (FRACPO) and (2) a model of the light radiation interception (RATP). There are 20 input parameters for the FRACPO model and 12 for the RATP model. In the FRACPO model, 12 parameters have been measured, the rest has been found in the literature. In the RATP model, 10 parameters have been measured by PLECO.

Experimental observations of the structure and its evolution in the time have been done on 3 clones (Wolterson, Fritzi Pauley et Hoogvorst) in 1999. These results allow to (1) test, adapt and validate the FRACPO model and (2) to simulate the carbon accumulation for the experimental surfaces, in one or more growth season with the RATP model. The modelled results are compared and validated with the experimental results measured on the accumulated biomass quantity after three years of growth in the stems and branches of a poplar coppice.

2.5 Advising the regional and federal decison-makers

From 1999, GEB has contacted and advised decision-makers in Belgium in order to prepare the development of wood energy. Main advice has been done on the production of electricity from renewable resources because of the liberation of the electricity market was the major preoccupation of decision-makers. GEB has deeply analysed the different political systems available for developing the production of renewable electricity despite their higher production cost. Main conclusions are that (1) premiums or quotas must take into account the different production cost of the different renewable sources and systems, (2) premiums or quotas must favour the more efficient technologies, (3) premiums and quotas must take into account the real CO_2 emissions of the renewable technologies (using the ISO 14040 standard). GEB has proposed different solutions in order to implement some of these recommendations in the framework of the new laws and orders to liberalise the electricity markets. Some of these recommendations have been taken into account in

Flanders or in Wallonia (minimum and maximum prices for green certificates, fixed objectives on a medium term period).

3. FINAL EVALUATION & FUTURE PROSPECTS

WOODSUSTAIN has reduced uncertainties about renewable energy resources in Belgium. Figures indicate that wood energy could play an important role in reducing the emissions of greenhouse gases in Belgium. An increase in wood energy use at a rate of 10% annually seems reasonably reachable in consideration of the wood resources presently wasted in Belgium and in consideration of the agricultural potential for short rotation coppice. Energy from wood fuels would then represent 30,000 TJ/a primary energy, reducing the carbon dioxide emissions of about 1.2 to 3.4 millions tons equivalent CO_2 per year and employing about 1,500-2,500 more unskilled mans for the production of the wood fuels. The consumption of this local source of energy will reduce national imports of fossil energy of 100-200 millions euros per year. The development of wood energy at this annual rate will require new investments of 25-250 millions euros per year.

However, this objective could not be reached without new political decisions. Depending of the evolution of the fossil energy prices, wood energy could be or not profitable. Investors must be reassured on the future evolution of energy prices. Different measures could be chosen by decision-makers (1) to maintain energy prices at a sufficient high level so that wood energy will be competitive (environmental taxes and detaxation of renewable energy), (2) to force energy suppliers to distribute quotas of renewable energy (green certificates). The production of wood fuels must be assured by helping new cultivation of SRC and forest residues harvest.

In the future, these political instruments must be more precisely studied. In particular, decision-makers have decided to impose quotas of renewable electricity in Belgium via a green certificates system. This system could create important distortion between heat production and electricity production. The international trading of green certificates will also create important risk for renewable energy producers. Other important issues are (1) Who will benefit of the Kyoto credit for the CO_2 reduction in relation with the green certificate trade ?, (2) How to create a green certificate system for heat production and for transportation fuels ?, (3) How to avoid the competition between energy use and material use of wood resources ?, (4) How biomass fuels could be imported from infinite resources (world biomass production is 6 times more than the energy consumption of the humanity)?

CG/04/30

INVENTORY AND APPROACH TO BARRIERS FOR THE CLIMATE POLICY

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1. PROJECT SUMMARY

The promoter of this project, professor Aviel Verbruggen, participated in 'Working Group III of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)'. Working Group III treats 'The Mitigation of Climate Change'. To support this contribution to IPCC we focused our research on the barriers, opportunities and market-potential of technologies and methods. In particular we investigated two specific barriers: the pricing barriers and the cogeneration barriers.

2. ACTIVITIES

The research revolved around two main topics :

2.1 Pricing barriers and barriers that limit the development of cogeneration, as barriers to energy-saving technologies and methods

The work was split up in 3 phases :

- The first phase involved an extensive literature study. The goal of this phase was to gain a profound insight in the new developments in the pricing and cogeneration domain;
- In the following phase, we analysed the pricing and cogeneration barriers and formulated solutions to remove the barriers;
- In the third and final phase, we made a contribution to Working Group III of the Third Assessment Report of the Intergovernmental Panel on Climate Change. The promoter of the project, prof. Aviel Verbruggen, participates in 'Working Group III of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)'. Working Group III treats 'The Mitigation of Climate Change'.

2.2 Cost efficiency of privately and publicly owned electricity systems

We tried to analyse the productive efficiency (cost efficiency) of electricity distribution systems in Flanders. In particular, we tested the null hypothesis that privately owned and publicly owned electricity systems do not have significantly different costs.

In order to do this, we used a relatively new method, called Data Envelopment Analysis (DEA). The DEA technique involves a non-stochastic approach to the measurement of productive efficiency, which allows the disaggregation of that measure into several mutually exclusive and exhaustive components. The technique is essentially comparative, in that the overall efficiency measure compares the average cost of an electricity distribution system to the average cost of least cost electricity distribution systems.

3. RESULTS

3.1 Prices as barriers and opportunities for mitigation policies

"The price of a good or service is what it costs the buyer to acquire it from the seller; the same price is what the seller rewards for giving up its property rights on the good or service". The Webster's definition of 'price' is clear. However, in economic theory and practice, pricing is a complex issue with several unanswered questions. Delimiting what on pricing is covered in this report is necessary.

3.1.1 The Roles of Prices in Society

Economic theory proofs that in a simple society of optimising consumers and producers interacting through markets, clearing prices maximise overall welfare. Notwithstanding the many criticisms and the non-plausibility of several assumptions, the theory's golden rule that prices should be set equal to the marginal cost of supply remains the beacon of most policies addressing pricing in e.g. regulated markets or controlling monopolistic behaviour of corporations.

Market transactions continuously reallocate the wealth of the world and allocate the growth in wealth. Prices therefore are important distributors.

Prices are ubiquitous. Particular categories of goods or services are endowed with a specific price-name, e.g. wage as the price of labour, interest rate as the price of capital, discount rate as the price of time, risk premium as the price of uncertainty, etc. Some argue that everything has its price, if not explicit than implicit, because in our societies all can be, and mostly is, traded against priced goods. This argument is the basis for assessing monetary prices for all values that are not tagged with explicit prices in some market place, e.g. natural amenities, social relationships, cultural values, and also human life.

Descriptive prices, i.e. actually observed prices, include all the effects and biases occasioned by prescriptive policy interventions. The price of oil is loaded with rents (royalties) to oil companies and to well owners. One step further, most prices in our economies are affected by the price of oil and thus by its embodied political and distributive character. In addition, many prices are directly influenced to a smaller or larger degree by policy interventions, such as taxes, subsidies, regulatory prescriptions, market structuring, etc. Attention should be focussed on where, how an to what degree prescriptive intervention should affect observed prices.

3.1.2 Barriers related to Pricing

The golden rule of the market price system is only golden when markets exists for all goods and services, and when these markets function properly. In practice, these conditions are not met.

1. Not all goods and services are dealt with in market places. There exist public goods that cannot be priced because enforcing property rights is impossible or extremely impractical and costly. Externalities are ubiquitous, and only a few can be internalised by suitable policy instruments;

2. Future markets and contingency markets are only partly developed;

3. When goods and services carry a price tag, the prices do not necessarily represent their true scarcity or convey the full message to consumers (see Distorted Prices).

In the real economy prices are posted by the seller, although for many products the initial posting may be only the start of a bargaining process among buyer and seller (Dorward, 1987). For many other goods and services (e.g. electricity, natural gas, oil sales to end-users) posted prices are imposed on end-users who only can decide to take or to leave the offer. The seller tries to extract the maximum out of the deal and to transfer to the own account the maximum of the benefits the buyer could get from the purchase. The seller often will obfuscate the prices e.g. by applying complex tariff schedules (electricity, gas), by bundling offers in complex trade-offs, etc. A number of marketing tools help to overcome the reluctance of the buyers before obfuscated prices and to step in the deal anyhow.

There are several reasons why real-world prices do not conform the equality to marginal costs.

1. The definitions of marginal cost is not unique. Definitions differ in the extent to which they stress the importance of short-run as opposed to long-run costs, and changes in consumption in different time periods;

2. Real markets are far from perfect;

3. Very few goods are homogeneous. Even a uniquely defined product as ‘electricity’ is heterogeneous with a different value depending on the time, the place (voltage level) and the reliability of its availability. Because a price is an amount of money for a unit of a good, prices are more unclear the more it is unclear what a unit of the good really covers. Mostly one gets an indication of the physical quantity of the good but major other attributes may remain unspecified and poorly understood.

The impact on the demand for a good by changes in its price is expressed by the (own) price elasticity. Demand also depends on prices of other goods (cross price elasticity) and on several other variables, such as household composition and income (wealth) levels. The form of a demand curve itself may be less relevant than the shifting of the curves due to variables other than the own price.

Bills convey clear messages but their impact depends on their share in the overall budget of the decision-maker being it a household, company or institution. Low prices and limited bills for carbon goods and related technologies (e.g. energy consuming equipment such as lighting appliances, air conditioners, automobiles), have resulted in high energy intensities of most human activities in industrialised nations. This situation is not favourable to the development of renewable energy resources that are characterised by low densities and intermittent supplies.

Rebound effects can diminish the effectiveness of higher energy prices (taxes). Thanks to efforts in energy conservation, the expenses for meeting particular energy services can come down significantly and economic agents save resources that can be allocated to other preferences. E.g. by installing high-efficient heating equipment in its property, the owner-occupier may reduce his personal effort in saving energy (closing doors and windows, limiting the heating of rooms that are not occupied). The sloppy behaviour is the result of low bills, because they do not warrant the time and effort to further lower the bills. In addition, energy conservation increases the budget that can be spent on other goods and services (the ‘income effect’), e.g. on particular (energy-consuming) appliances or on (airborne) trips.

Non-linear price schedules, in particular two-part and block tariffs, are popular in energy pricing (figure 1). They are argued to best reflect the cost structure of the energy supplier (with a high share of fixed costs), and to be efficient in making customers pay for these costs. However, the consumer receives little incentive to conserve energy, cause success in reducing consumption is not rewarded by a proportional decline of the bill.

Other examples of split incentives are present in contracts paying fees to architects and technical advisors that are measured as a percentage of total project investment giving rise to over-sizing and to gold-plating without sufficient attention to the (energy) performance of the investments.

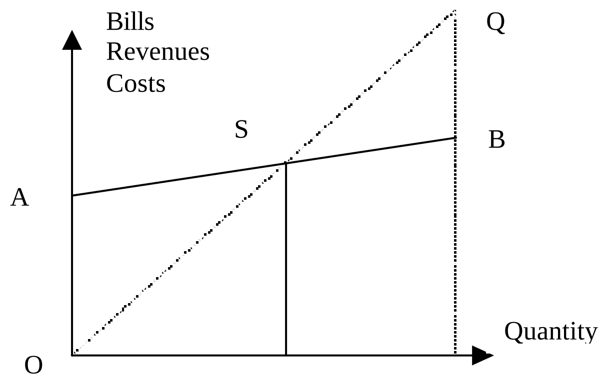

Figure 1: *linear and non-linear tariffs*

Price fluctuations cause economic optima to be ephemeral. Because most decisions involve commitments over longer-term periods, continuous adaptation to the latest energy price fluctuation is unpractical and unfeasible. This creates technical and allocative inefficiencies. The long-run evolution of energy prices is rather erratic.

3.2 CHP-barriers

Introduction

Combined heat and power (CHP) generation or co-generation is a substitute for the separate supply of heat (mostly from fossil fuels) and electricity (mostly from the interconnected grid fed by nuclear or fossil fired thermal stations, hydro or other large-scale renewable energy sources). Co-generation projects can conserve significant quantities of fossil fuels occasionally depending on the design, technology and performance of the project and depending on the efficiency and fuel type of the separate production alternatives.

3.2.2 Informal barriers

Efficiencies and reliability have gone up, and investment and operation costs have come down, but this information is not spread widely enough. Also on new developments (e.g. fuel cells, micro gas-turbines) little documentation is spread. Optimisation of co-generation projects requires extensive information about many determinants of profitability. Heat and power end-uses of the application and in particular the simultaneity of the load patterns, costs and tariffs of grid electricity and the terms of exchange of power with the grid, and the evolution of the fuel / energy markets should all be studied. Several key variables may change during the life-time of the plant and make investment risky. Examples of uncertain variables are fuel prices, fuel availability, regulatory conditions, environmental legislation, terms of trade with the power grid.

3.2.3 Barriers related to the decentralised/distributed character of the technology

Investment money for co-generation projects is more difficult to get and carries higher interest rates than funds for grid power supply extension and funds for conventional heat supply systems. Because distributed generation has to compete in many places with central supply alternatives, the much looser profitability criteria applied on the latter result in a under-development of distributed sources.

Because distributed generation has to compete in many places with central supply alternatives, the much looser profitability criteria applied on the latter result in a under-development of distributed sources. Natural gas is the most commonly used fuel for most new co-generation installations in the industrialised nations. Countries without a link to gas supply networks, or those with only a limited network, therefore face an immediate disadvantage.

Because co-generation technologies are in many countries developed by independent power producers they must compete with established pools of centralised generators that benefit from discounted fuel prices.

Procedures for authorising the construction and the operation of co-generation facilities can be bureaucratic, complex and time consuming because most were developed for central power production installations. In some countries the investments in power generation are subjected to a particular planning process, involving official hearings by parliamentary or regulatory commissions.

A small co-generation engine may be treated as a large-scale power producer, having the same (e.g. administrative) obligations in obeying environmental and emission rules. Also the higher conversion efficiency of co-generation may not be credited sufficiently by regulations directed to the conventional power sector. Environmental standards also may forbid explicitly or hinder implicitly the use of particular fuels or of particular technologies, overall or on the location of the distributed project. For example, co-generation in the built environment may have to obey very strict standards of flue gas emissions and of noise and vibration levels.

3.2.4 The terms of grid connection

In many power supply systems by now, there is not yet an independent system operator available that balances the offers from the various competitive suppliers. Mostly the system operator was (and in many countries still is) a part of a vertical integrated electricity supply company that moreover enjoys a monopoly position. When such electricity monopolies function within a regulatory environment of making profits proportional to electricity sales volumes, distributed generation will be approached as a loss of sales that should be avoided on all occasions.

Incumbent power companies sometimes impose very heavy regulations on producers or industries that file for a connection to the electric grid. On occasions the demander is requested to install a separate link to the next-by transformer station in the grid. The connection, the metering, the safety equipment, etc. all may be extra-ordinarily loaded to discourage independent producers.

There are three types of power flows that can be exchanged between an independent producer and the grid.

1. Surplus power that the distributed generator delivers to the grid.

2. Shortage power bought by the distributed generator at the grid: make-up (additional, complementary).

3. Shortage power: back-up.

The remuneration of surplus power is based on the principle of ‘avoided costs’ by the grid-system. In practice, one should measure the instantaneous marginal cost of the integrated power supply system taking into account generation plants’ constraints, grid constraints and reliability aspects.

Regulated ‘avoided costs’-prices and competitive marginal cost prices will entail an impediment to the development of distributed resources, when the latter generate electricity at a higher marginal cost. This can be due to a number of factors.

1. The central power may be subsidised;

2. The central system may be run on hydro-power or on nuclear power, that are both characterised by low short-run marginal costs;

3. Central power systems may face significant over-capacities in generation plant that depress short-run marginal costs below the long-run ones;

4. The marginal cost of electricity transport over the grid may increase because of growing power trade and because of difficulties in getting licenses for new lines.

Make-up power is the power in top of the own production required by a distributed generator for meeting the own end-uses. Depending on the heat and electricity load profiles, the amount of make-up power tapped from the grid may be large or small, stable or fluctuating over time. In principle, make-up power should be billed to the distributed generator at the same tariffs conventional customers are charged. This is not always the case, because in some countries make-up power is charged at special rates based on arguments that make-up power shows more irregular load profiles than normal electricity demand.

When the own generation plant is in forced outage most distributed generators will want to tap power from the grid, especially when the end-uses serve processes of high value or urgency. In many systems back-up power supplies by the grid carry high prices. This is the result of the joint occurrence of on the one hand applying the overall customer tariff on the back-up supplies, and on the other hand the property that most of these tariffs encompass a high fixed (per kW) term.

On some occasions, distributed generators may want to wheel power over the grid to related companies or to customers that are willing to pay a higher price for the surplus power or to producers that are charging a lower price for shortage power. These transactions are impeded when transporting power over the grid is loaded with predatory tariffs.

As far as energy policy is concerned, a distinction has to be made between co-generation linked to district heating (utility co-generation) and on-site independent co-generation is necessary.

Very few nations in the world own the intellectual and administrative capacity to realise a full-scale and comprehensive integrated energy policy plan, that preserves the place for district heating and related co-generation. This option is a very capital-intensive one, but also a long-lasting and environmentally resilient one. Only when the time preference (discount rate) of energy planning authorities is low and when externalities are considered as important factors in weighing energy supply alternatives, can district heating thrive in urban settlings.

Distributed generation will develop more fully when electricity markets are opened to competition that brings more exit and entry opportunities and more choice for market participants. Competition should then develop power tariffs reflecting the short-run marginal costs of supply. It should bring forward ranges of contracting opportunities (e.g. also covering reserve power deliveries) and it should free the access to the electricity transmission grids for third parties. However, fair competition in the electricity sector must be organised by enlightened regulators. Firm public policy and regulatory authority are necessary to install and safeguard harmonised conditions for all participants, transparency of the processes and unbundling of the main power supply functions. Most countries lack the intellectual and administrative capabilities for the foundation of authoritative regulatory services. This will lead to sub-optimal returns from the liberalisation process for options such as distributed generation and co-generation.

3.3 Cost efficiency of privately and publicly owned electricity systems

Productivity is simply the ratio of a firm's output to its input. To calculate total factor productivity, multiple outputs and multiple inputs are aggregated such that output and input are each represented by scalars. Productivity will vary depending on technology and many other factors. *Productive efficiency* refers to the optimal use of resources in the production process. To achieve productive efficiency, a firm wants to reap all possible economies of scale and produce at the lowest possible per unit cost, i.e. at the minimum point of the average total cost curve.

We used a relatively new method, called Data Envelopment Analysis (DEA) to analyse the productive efficiency (cost efficiency) of privately and publicly owned electricity distribution systems.

3.3.1 DEA in a nutshell

DEA is commonly used to evaluate the efficiency of a number of producers. In the DEA literature, a producer is usually referred to as a decision making unit (DMU).

DEA is an extreme point method, and compares each producer with only the ‘best’ producers. The heart of the analysis lies in finding the ‘best virtual producer’ for each ‘real producer’. If the virtual producer is better than the original producer by either making more output with the same input, or making the same output with less input, then the original producer is inefficient. The procedure of finding the best virtual producer can be formulated as a linear program (LP). An LP of that form must be solved for each of the DMUs.

DEA can easily handle multiple input and multiple output models, it doesn’t require an assumption of a functional form relating inputs to outputs, DMUs are directly compared against a 'best performing DMU' or combination of 'best performing DMUs', and inputs and outputs can have very different units. Some of the advantages of non-parametric DEA approach over parametric approaches are the robustness of the linear programming methods used to solve the DEA problems, and the fact that a variable that is neither an economic resource nor a product, but is an attribute of the environment or of the production process, can easily be included in a DEA-based production model.

DEA also suffers from a number of limitations.

- Noise (even symmetrical noise with zero mean) such as measurement error, can cause significant problems;

- DEA is good at estimating 'relative' efficiency of a DMU, but it converges very slowly to 'absolute' efficiency. In other words, it can tell you how well a DMU is doing compared to its 'best performing DMUs, but not compared to a theoretical maximum;

- statistical hypothesis tests are difficult (DEA being a *non-parametric* approach);

- large problems can be computationally intensive.

3.3.2 Results

To date, there is a vast literature in microeconomics that addresses the question of why ownership matters. Empirical implications to test whether ownership indeed matters are:

- Publicly owned enterprises in competitive environments do not perform better than privately owned companies in the same circumstances in terms of profitability and efficiency, and could perform worse;

- One should expect important efficiency gains from the change in ownership structure in competitive sectors;

- Increases in profitability are not equivalent to increases in efficiency in general. This will only be true in a competitive environment;

- Fully privatized firms should perform better than firms that have been partially privatized, under the same conditions.

A paper written by M. Pollit [Pollit, 1997] discusses the effect of ownership on productive efficiency in electric utilities. According to Pollit the UK seems to be a case where privatisation had resulted in lower costs of production. This however does not mean that ownership change per se would lead to lower costs. The evidence from the US is that there was no difference in costs between private and publicly owned electric utilities. The lesson for other countries is that small municipally owned electricity distribution companies might well be just as efficient than large privately owned distribution systems

Massimo Filippini and Jörg Wild are conducting a similar study for Switzerland, namely investigating the influence of institutional form and ownership on the efficiency of the 1.000 or so utilities that make up the Swiss electricity industry. They have not produced any results so far.

Our own research for the Belgian electricity distribution systems seems to indicate that privately owned electricity distribution systems are not necessarily more cost efficient than publicly owned ones.

3.3.3 Conclusions and suggestions for further research

The non-parametric methodology has seen extensive application for the analysis of utilities (gas, water and electricity companies). Many of these studies are performed to assist the regulation of utilities by government institutions. Some apparent shortcomings are:

- errors-in-variables appear highly relevant, e.g. due to the freedom firms have in allocating their costs to different periods and different activities;
- the small number of firms in the sector can cause small sample error;
- local market conditions suggest that electricity prices are endogenous and uncertain in a non-trivial way, and hence traditional methodologies do not apply.

There is a clear need for developing models that account for errrors-in-variables, sampling error and endogenous and uncertain prices. A research program founded by (amongst other) Thierry Post at the Erasmus University Rotterdam has the objective to extend the current non-parametric methodologies in order to take these shortcomings into account, and to apply the new methodology for assessing the efficiency and productivity for European utilities.

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CG/67/31B
CG/F/31C

GREENHOUSE GAS EMISSIONS REDUCTION AND MATERIAL FLOWS

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1. PROJECT SUMMARY

Ongoing climate policies intend to promote energy efficiency within all the different activity sectors. Domestic sector is one of those sectors where improvement of energy use efficiency is a major goal of the policies, including energy equipment efficiency improvement, better thermal insulation of buildings,…

A priori it seems however interesting to extend at least the reflection around consumer behaviour to consumer goods in general. Measures aiming at tackling the consumer side with respect to products should promote those that generate the lowest levels of greenhouse gas (GHG) emissions throughout the life cycle, namely from cradle to grave. Such a reflection necessarily implies to take into account technology improvement within the production system.

The project "Greenhouse gas emissions reduction and material flows", undertaken in the framework of the Action Plan for Sustainable Development (phase I) of the "Global Change and Sustainable Development" programme of the OSTC, aims at developing such a reflection through a quantitative way. The project has been carried out by Institut Wallon, Vito and IDD, being Institut Wallon the co-ordinator of the project.

In order to illustrate and quantify the impact of such an approach, we have analysed three product categories and their product system[3] : housing, beverage packaging and livestock products.

The aim is to evaluate the life cycle GHG emissions related to those three product systems as well as the ways to reduce these emissions both through measures addressed to the consumer and through measures implemented within the production system.

This document synthesises the results of the project. They are described in detail in the final report document (see Nemry F., Theunis J., Bréchet Th., Lopez P.)[4]

[3] The product system comprise the products use, materials manufacturing and transport and treatment of wastes generated after product use.
[4] Nemry F., Theunis J., Bréchet Th., Lopez P., 2001, Greenhouse gas emissions reduction and Material flows, Final report, For the OSTC.

2. THE OBJECTIVES OF THE STUDY

In the framework of the Kyoto Protocol, Belgium, as part of the European Union, has committed itself to reduce its annual greenhouse gas emissions by 7.5% in the period 2008-2012 compared to the 1990-1995 levels.

With regard to the substantial carbon dioxide (CO_2) emissions in Belgium (more than 80% of total GHG emissions), additional improvements in energy efficiency have to be pursued by all the activities sector. Due to the addition of other greenhouse gases (CH_4, N_2O, SF_6, HFC's and PFC's) in the Protocol, efforts should also be extended at the level of the industrial processes, products consumption and agriculture. Besides this, the reports from the Intergovernmental Panel on Climate Change (IPCC) (especially its recent Third Assessment Report) show the need to develop strategies for the long term to be continued beyond 2010.

As a result, considerable work is required to develop new options for GHG emissions mitigation as well as effective instruments that create synergies between the different actors involved. The project «Greenhouse gas emissions reduction and material flows », undertaken by IW, Vito and IDD and co-ordinated by IW, aims at identifying supplementary long-term options of GHG emissions reduction.

One main observation was a starting point for the project: Demand for products by households represents a demand for various materials. The resulting material flows on their turn represent energy flows and greenhouses gases emissions as materials are subject to successive transformations and transportation. However, except for final energy consumption, the influence of consumer choices is not really taken into account in present climate change policies.

The present study aims at answering three basic questions around the consumer role in environmental impacts through their consumer patterns simultaneously with a consideration of production side with its technological evolution, including environmental performance improvements:

1. What is the impact of consumer choices on GHG emissions, namely through the product-related life cycle emissions? Especially what could be the impact of changes in product choices and in materials contained in products?

2. What is the impact of process substitutions on GHG emissions?

3. What could be the contribution of consumer patterns changes to the GHG reduction emissions efforts for the first commitment period of the Kyoto Protocol (2001-2012) but also for the subsequent commitment periods?

The project intended to give first answers to these questions on the basis of three illustrative specific consumption categories: residential housing, livestock products and beverage packaging.

3. APPROACH AND METHODOLOGY

3.1 The approach

The analytical approach that has been followed is an end-use approach which means that the Belgian final demand for the three product categories (or for their function) was a starting element to be analysed in the project.

Moreover due to the “indirect” effect of consumer choices on resource consumption and environmental impacts, a life cycle approach imposed itself : this means that the environmental impacts to be considered in relation to the demand for defined products are those as produced from cradle to grave (from the extraction of raw materials to waste treatment).

At the same time, while the consumer demand was the main driving force considered it was important to evaluate both life cycle environmental impacts and potentials to reduce them, taking into account possible technological improvements within the upstream production system and downstream waste treatment system. For this reason, a dynamic approach has been adopted in order to take into account the evolution of technologies and consumption changes.

Finally, a double analytical work has been performed in order to meet a double concern, namely :

- to give an exhaustive picture of the three product systems, from the demand side to the production side and the waste treatment side, in order to draw the most realistic conclusions,
- to develop consistent insights on GHG emissions evolution and potentials for emissions reduction, including consistent cost evaluations,

This double analytical work has incorporated a detailed description of the product systems on one side and the application of MARKAL for two of the three product groups on the other side. Both approaches are mutually supporting.

2.2 The methodology

In order to implement this original approach, different steps were followed as explained below :

1. The demand for the three product categories has been analysed : based on various data sources (mainly statistical data), the existing demands for products and their recent evolution have been depicted and analysed. Then econometry has been used by IDD to develop scenarios for the future trends.

2. Then the main materials involved in the product systems were identified. The different material flows, namely imports, exports, domestic production and consumption (including, in some cases, flows of waste materials) were quantified essentially on the basis of statistical data from industrial federations. This part of the study allowed evaluating the importance of the domestic production compared to domestic consumption, especially consumption that could be attributed to the products studied.

3. Another step was the analysis of production processes as currently existing but also as potentially developing in the future. The GHG emissions and costs of the technologies were analysed. It is to be noted that this sub-task was more or less focused on the Belgian production system depending on the importance of the domestic production compared to the national consumption.

4. The previous steps allowed calculating the life cycle emissions for the different products, both at the level of the product and at the level of their Belgian demand.

5. The last step has consisted in the evaluation of GHG emission potential reductions at the different levels of the product life cycles. This evaluation has been performed both with simplified scenarios and MARKAL applications. The latter allowed providing a dynamic, integrated and economic evaluation of the potential.

2.3 Three illustrative cases

The application of this approach and methodology for the three selected product categories is justified by the fact that all three products represent an important part of the day-to-day consumption. They are also complementary with respect to the need they relate to, the materials they involve and the GHG they emit (see Table 2) and by the fact that these product categories offer possibilities for reducing the GHG emissions during their life cycle. This selection also covers different sectors. Wood as a building material makes it possible to include the carbon sinks issue in the analysis. Finally, livestock allows including non-CO_2 GHG emissions in the analysis.

Partner	*IDD*	*Vito*	*IW*
Product category	**Livestock products**	**Packaging**	**Residential housing**
Products	Meat	Beverage packaging	Single family houses
“Materials” involved	animals, fertilizers, fodder…	Plastic, paper, glass, steel, aluminium	Steel, cement, concrete, glass, bricks, wood
Main GHG emitted	CH_4, N_2O, CO_2	CO_2	CO_2

Table 2 : *Main features of the product categories studied and the author of their evaluation*

2.4 MARKAL as applied to material flows

MARKAL (MARKet Allocation) is a Linear Programming model developed in the framework of the "Energy Technology Systems Analysis Programme" (ETSAP) of the International Energy Agency (IEA). It has been developed and used extensively to model the energy system in numerous OECD countries since 20 years, including Belgium. In Belgium, it has been used by KULeuven and Vito until present. In this usual application, the model selects the least cost combination of processes and flows that satisfies the exogenous demand for energy services over a given time period (typically several decades) under given exogenous constraints, starting from an existing exogenous transformation system and predefined alternative technological options. It calculates the resulting total system cost, total or specific emissions, energy flows, process activities, and shadow prices for produced goods.

MARKAL optimises the system over the entire time period and the entire system. It supposes rational decision making based on full foresight and full transparency.

Its high flexibility with regard to the description of technology, sectors and environmental impacts allowed developing a new MARKAL version to include an explicit description and modelling of material and product flows, and a more detailed description of competing technologies (including waste treatment technologies), materials and products. This was made for the first time in the framework of the MATTER[5] project (see ECN, The Netherlands). In this extensive and long term project, a global and consistent model was developed to represent an integrated energy and materials system for Western Europe.

Such a development is part of the current project. However, adaptations have been made to take into account some specificity of the present project with regard to geographic boundaries, the higher emphasis on product demand and the specific product categories envisaged. These adaptations resulted in the development of two separate models for residential housing and for beverage packaging. Then scenarios on GHG emissions evolution were carried out.

4. MODELLING DEMAND AND MACRO-SECTORAL FRAMEWORK

IDD was in charge of the determination of demand for the three chains considered in the project. An econometric model was developed for private consumption in which products are defined in physical terms inside a comprehensive socio-economic model describing household's consumption patterns. This model is called CORELLI. The main features of the CORELLI model are the following :

- It is an econometric model : the purpose of the model is to forecast the demand up to 2010, and econometrics is a technical way to provide reliable results, as far as the timespan is not too long. The demand equation for each category of product is estimated on the longest sample available.

- It is a bottom-up model : instead of disaggregating the overall consumption with a DLES, an AIDS or a Translog system, the model aggregates primary demand functions; these functions are estimated simultaneously in order to take care of crossed correlations.

- It is a model in which data can be expressed both in : this is the case for the products considered in the chains "meat products" and "packaging for

[5] See http://www.ecn.nl/unit_bs/etsap/markal/matter/main.html

beverages". The bottom-up structure of the model allows aggregating these two kinds of data.

Table 3 shows the consumption categories considered inside the CORELLI model. The model is able to provide forecasts up to 2010 and to evaluate the impacts of fiscal policies, both on the whole consumption patterns and on the most detailed categories.

As far as dwelling is considered, another model has been built. The demand considered for this chain is defined as the demand for new single family houses, expressed in m^2. The LOCATELLI model is a stock-flow model which describes the park of houses each year, depending on the rate of construction, demolition and renovation. The size of new houses is also endogenous. The model is characterised by the introduction of both socio-economic behaviours (validated with econometrics) and demographic components. Econometrics allowed quantifying the impact of real income, long term interest rates or ABEX index on the demand for dwelling. The demographic part of the model is considered from the decomposition of the total Belgian population in several types of households (singles, with or without children, etc…) ; each household is characterised by its preference towards one kind of housing. The evolution of these demographic components influences the demand for single family houses. LOCATELLI allows acquiring forecasts up to 2020 and the evaluation of many alternative scenarios.

Overall consumption	of which beverages (in liters per capita)	of which meat products (in kg per capita)
Food, beverages and tobacco	Carbonated waters	Beef
Food	Non-carbonated water s	Veal
Bread and cereals	Soft drinks	Pork
Meat	Milk and milk drinks	Sheep
Fish	Fruit juices	Horse
Milk, cheese and eggs	Beers	Chicken
Oil and fat	Wine and alcohols	Other poultry
Fruits and vegetables		Rabbit
Potatoes and tubers		Edible offals
Sugar		
Coffee, tea and cacao		
Others, incl. tins		
Non alcoholic beverages		
Alcoholic beverages		
Tobacco		
Other goods and services		

Table 3: *Consumption categories in the CORELLI model*

5. RESIDENTIAL HOUSING SYSTEM

Buildings, especially residential buildings, play a major role in satisfying human needs: the primary function, i.e. sheltering people is primordial for the satisfaction of other needs (heating, private life, leisure, aesthetic, space, health…). On the other side, building construction, which implies the use of different materials like cement, steel, glass, bricks, plastic…, is an important sector from a materials consumption point of view, so involving high levels of energy consumption. The potential role of wood in building poses also the carbon sink problem, which is an important issue in the Kyoto Protocol. Waste is also a significant issue regarding building materials.

The function studied is the “residential housing”. The analysis focuses on the functional group “single family houses” (SFH). This choice is justified by its quantitative significance (single family houses represent more than 80% of the total housings in Belgium) but also by the higher influence of individual consumer choices compared to multi-family houses.

5.1 Demand and product description

Housing is intensively described by statistical data (INS, National Statistic Institute). Every year about 20.000 new houses are built. The exact amount depends on different factors and there is no clear trend during the last years. On the opposite, there is an obvious increasing trend of total surface built per house. Besides new construction, renovation plays an important place in the building sector. Among all renovations with transformation, renovation with surface increases account for more than 80%.

Both new construction and renovation (especially with surface increases) represent significant material consumption and hence life cycle energy consumption and GHG emissions. Taking into account the importance of both options and the fact that they represent potential mutual substitutions, the analysis focused on them.

With regard to architectural types both with respect to shape and to material involved, the huge diversity within the Belgian market couldn’t obviously be taken into account. Consultation of experts from the sector (architects and entrepreneurs), the analysis of technical documentation combined with observation lead to a build up of a simplified market representation.

- A limited set of houses differing in the materials used has been selected, going from so-called “conventional houses” (concrete/brick or brick) to wooden houses (with brick or wood facing), also including intermediary cases like expanded clay or cellular concrete. All options were estimated to have the same thermal insulation level.

- Based on three actual recent new constructions for which precise quantified surveys were provided by architects, extrapolation curves were built in order to represent the different building elements size as a function of total built surface, so allowing to estimate the influence of surface on material consumption and hence life cycle emissions.

5.2 Material flows analysis

The analysis of material flows has been done for the main materials: cement, concrete, bricks, glass, steel, non-ferrous metals, making use of different data sources (industrial federations, statistical data, surveys by IW…). The analysis was somehow hampered by the availability and quality of some data. Some materials are particularly uneasily traced: for instance, this is the case of wood products and intermediary productions of the steel sector.

Nevertheless, the analysis showed that Belgian production of most building materials is relatively important with respect to the domestic demand. However, foreign exchanges are important for wood and reinforcement steel. The weight of consumption related to SFH new construction and renovation in particular is also variable from one material to the other (65% for bricks, 52% for cement and only 3% for glass and 6% for steel).

5.3 Material production processes description

The results of the material flow analysis justified to make an in-depth analysis of industrial processes with respect to the Belgian situation. This part of the analysis has described the main production routes in the Belgian industry, the fundamental processes and their relevant characteristics. Then alternatives for production and energy consumption of the Belgian industry existing world-wide are analysed. New and emerging technologies were also identified.

5.4 Life cycle emissions

The material intensity and the indirect GHG emissions[6] have been performed for

[6] We use the term “indirect emission” instead of “lifecycle emissions” because the analysis didn’t calculate explicitly the GHG emissions due to heating (thermal insulation was the same for all buildings). It has also to be noted that we use indifferently the terms “CO2 emissions and GHG emissions” because CO2 is the main GHG emitted by this product system.

each of the houses cases based on the previous GHG emissions estimations associated to the materials use and manufacturing. This was done through a systematic calculation for each building element (foundations, walls, floors, roof, windows,…).

Life cycle GHG emissions as calculated for different types of houses (200 m^2 total surface) are represented in Figure 6.

It shows that the construction of new conventional houses (brick and concrete) implies indirect GHG emissions ranging from 40 to 50 t CO_2 depending on the construction of a cellar. This represents from 7% to 14% of the direct emissions (house heating) during the whole life of the house. This percentage depends on the lifetime of the building and on the fuel used for heating (natural gas or oil).

The figure also shows the emissions reduction potential that exist at the level of individual houses, especially when shifting from conventional houses to wood construction and from new construction to renovation.

It is also to be noted that according to our estimations, the GHG indirect emissions increase by 38% when surface increases by 50%.

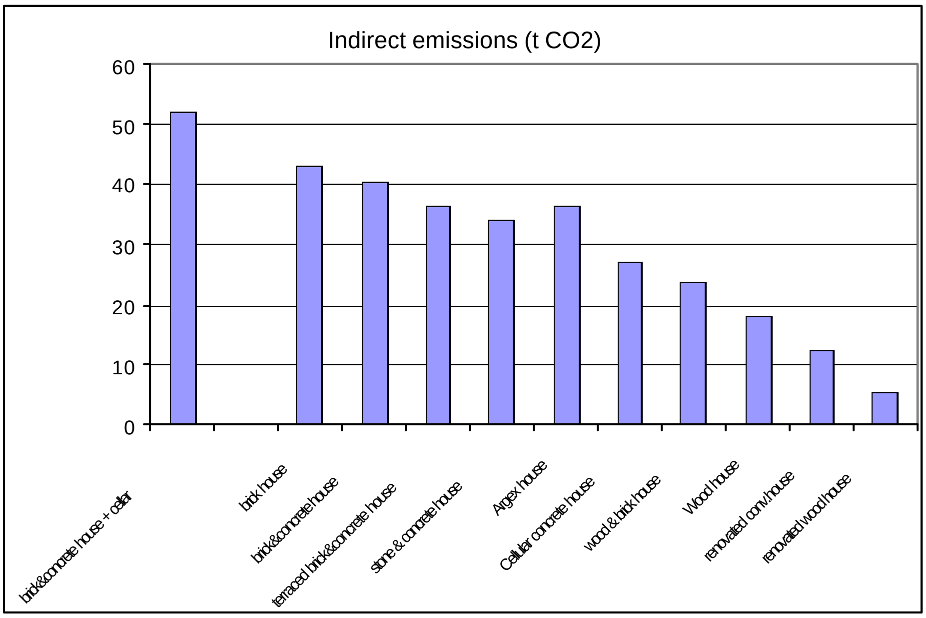

Figure 6*: Comparison of indirect GHG emissions for different houses (living surface : 200 m^2)*

Estimating the related indirect emissions at the level of Belgian demand for new construction and renovation requires to have an estimation of the present sharing of different types of houses in the market. Due to the lack of statistical data, we had to make own estimations based on expert judgements and observations. We have considered that about 80% of new houses are conventional houses, that 16% are intermediary cases (expanded clay or cellular concrete) and that 4% are wooden houses. Given this share and also taking into account renovation (mostly of conventional type) the total indirect GHG emissions can be estimated to 1750 kt CO_2.

5.5 Technical emissions reduction potential

In a Kyoto perspective it is interesting to estimate the potential evolution of indirect GHG emissions from new SFH constructions and renovations until 2010. The base case scenario for housing demand has been carried out by IDD with the Locatelli model. Two alternative GHG emissions curves have been calculated with this projection, assuming no technology changes within the production system : the first one assumes a constant share of houses types (as estimated for now), the second assumes an increasing contribution of intermediary houses types and wooden houses (30% and 25% respectively).

The resulting two GHG scenarios are represented in Figure 7.

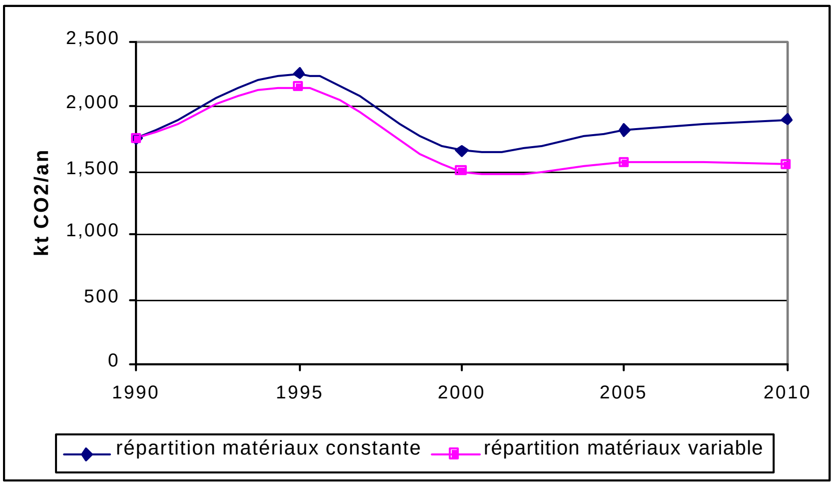

Figure 7 : *Indirect CO2 emissions scenarios*

The upper curve represents the first scenario and the lower the second. In the first case, GHG emissions could achieve 1900 kton in 2010 while they would attain 1550 kton in the second case, which represents a decrease of 11% compared to the BAU scenario.

These results provide an order-of-magnitude of the emissions reduction potential from built or renovated houses substitutions. This potentials are, however, theoretical potentials as they suppose that no technological evolution will occur within the building materials fabrication system. Nevertheless, it is opportune to evaluate the costs of eventual reductions.

A more integrated analysis has been carried out from the development of a MARKAL model specific to the housing system. This model has represented the different building materials fabrication processes as well as housing construction and renovation for different housing types. The exogenous demand for these houses (construction and renovation), is again based on the reference results of the model LOCATELLI developed by IDD.

Different scenarios have been built in this study taking into account the different demand hypothesis. They are described in the table bellow.

<table>
<tr><th>Scenario</th><th>Demand taken into account</th><th>Constraint on the CO_2 emissions</th><th>Other constraints</th></tr>
<tr><td>BASE</td><td>Residual demand</td><td>None</td><td>-</td></tr>
<tr><td>BASEHOUS</td><td>Residual demand + housing demand</td><td>None</td><td>-</td></tr>
<tr><td>KYOTO</td><td>Residual demand</td><td>Base level : emissions from residual demand in 1990

2010 : -7.5% compared to base emissions
2030 : -15% compared to base emissions</td><td>-</td></tr>
<tr><td>KYOTOH</td><td rowspan="2">Residual demand + housing demand</td><td rowspan="2">Base level : emissions from residual demand + housing demand in 1990

2010 : -7.5% compared to base emissions
2030 : -15% compared to base emissions.</td><td>-</td></tr>
<tr><td>KYOTOP</td><td>Contribution of wooden houses is imposed</td></tr>
</table>

Table 4 *: Scenarios for housing system*

Results from this model indicate that for the system studied, shift in technologies as a CO2 mitigation measure is more cost effective than shift in product types from more emitting products to less emitting products: In both scenarios KYOTO and KYOTOH, where the model chooses freely the technologies that allow the minimisation of the total cost, the same technology evolutions are observed. For the KYOTOH scenario, we observe that the additional emission reduction to be achieved compared with the KYOTO scenario is accomplished through additional technology shifts and that no change is made on the product side.

Next table gives the resulting costs for greenhouse gas emissions reduction for the three scenarios. They indicate that the cost increases slightly when reduction efforts cover the highest volume of emissions. When a constraint is put on the share of construction types, the cost is higher (128 Euro/t CO2 instead of 37 Euro/t CO2) than without any constraints.

Scenario	**Reduction cost (Euro/t CO2)**
KYOTO	28
KYOTOH	37
KYOTOP	128

Table 5 : *Cost for CO2 emissions reduction for housing system and residual demand of building materials*

This is due to the higher estimated price of “low emitting” houses (stone, cellular concrete, brick&wood and wood houses) compared with the price of the more conventional houses (especially brick&concrete house). Stone houses are about twice more expensive than conventional houses. Average price of cellular concrete houses appear to be 10% more expensive than conventional houses and brick&wood houses as well as full wooden houses are 20% more expensive. These overcosts are, comparatively to the overcosts involved in technological changes, higher and hence the model chooses this last emissions reduction measure in priority.

The result itself is however questioned by three major facts :

- The experience gained with this analysis indicated a substantial uncertainty on costs of technologies found in literature. Although these costs were adjusted in order to better reflect the market prices and better reproduce the comparative price of the different houses considered, there remains a high uncertainty on the costs of technology shifts and the costs of product shifts.

- Results have been obtained from a choice of the system boundaries. We can not disregard the possibility that another choice of the system boundaries would have led to the same conclusions. However, it was very difficult to check this possibility within the scope of this project.

- Then costs data assumed do not take into account a possible influence of the market development on technology costs.

Further analysis of the different uncertainties would be useful. However, a proper treatment of uncertainties is not straightforward with MARKAL and would require an intensive work which is out of the scope of this study.

5.6 Livestock products system

The function retained in this system for breeding products is defined as the quantity (in kg) of meat products per capita and per year. The demand for the nine meat products comes from the CORELLI model. A chain analysis is realized for the main categories : beef and veal, pork, poultry and sheep.

The indirect greenhouse gas emissions embodied in the production processes (considered from a LCA approach) have been calculated at each step of the chain. These steps are the following : production and use of fertilizers, production and use of pesticides, feed production, animal production (breeding), slaughtering, transport (between production and slaughtering and between slaughtering and consumption). The GHG considered are CO_2, CH_4 and N_2O. The major GHG are CH_4 and N_2O. These gas emissions have been aggregated with their Global Warming Potential over 100 years.

The table below displays the indirect emission coefficient for the three gas considered as a whole and they are expressed in CO_2-equivalent. The first column gives the emissions per kg of meat product and the second column gives the repartition between the three gases considered. CH_4 is the main contributor for beef, but also for pork whereas N_2O is mainly concerned in the sheep production. Poultry production is mainly responsible for CO_2 emissions. The level of emissions is very high for beef and sheep (14 and 18 kg od CO_2-eq per kg of meat product) and is low for pork and poultry (2 and 3 kg).

	Beef		Pork		Poultry		Sheep	
CO_2	3,4	23,2%	0,9	24,7%	0,8	37,4%	1,9	9,9%
CH_4	6,3	42,4%	1,7	46,2%	0,7	31,1%	7,6	40,5%
N_2O	5,1	34,5%	1,1	29,1%	0,7	31,5%	9,3	49,6%
Total	14,8	100,0%	3,6	100,0%	2,1	100,0%	18,8	100,0%

Table 6: *Indirect GHG emissions : in kg CO2-eq / kg of meat*

	Beef		Pork		Poultry		Sheep	
Fertilisers production	2 380	16,1%	442	12,2%	261	12,46%	1 719	9,15%
Feed production	4 669	31,6%	707	19,5%	699	33,38%	2 593	13,80%
Breeding	7 422	50,2%	2 045	56,5%	816	38,96%	14 216	75,67%
Transport	154	1,0%	205	5,7%	151	7,23%	122	0,65%
Slaughtering	14	0,1%	14	0,4%	15	0,74%	13	0,07%
Transport	154	1,0%	205	5,7%	151	7,23%	122	0,65%
Total	14 795		3 620		2 094		18 788	

Table 7: *Decomposition of indirect GHG emissions by source (in gr CO2-eq / kg)*

The analysis of material flows has provided a calculation of each emissions contribution in the global Belgian GHG emissions, considering imports at each level of the chain. These emissions represent around 4% of the total Belgian GHG emissions.

The baseline scenario considered from the CORELLI model shows that, considering the evolution of the consumption patterns, indirect emissions due to meat consumption should decrease from today till 2010. This is due to a relative preference towards white meats (poultry, veal…) and a very small increase in global meat consumption. Emissions involved in meat consumption achieve around 7,1 Mt CO2-eq in 2000 and they would decrease to 6,1 Mt in 2010.

Finally, the study reveals that consumption patterns can have a significant impact on indirect emissions. A reduction of the beef consumption by 10% compensated by an increase of poultry consumption in order to maintain the global meat consumption unchanged would reduce total GHG emissions by around 0.9 Mt CO2-eq. The mean costs for consumers would be 530 €/tCO2-eq. However, the evaluation of the direct and indirect impacts on sectoral activity reveals that employment would be reduced (around 1,200 jobs on the long term). The imposition of a tax proportional to the content in GHG for each meat must also be considered in order to evaluate the possibilities for substitution among the consumption pattern. For example, a tax of 250 €/tCO2-eq would reduce emissions from meat production by 9% on the long term. This represents 0.5 Mt CO2-eq. Methane would be the main contributor to this reduction.

6. BEVERAGE PACKAGING

In terms of packaging weight beverage packaging represents more than 40 % of the total end use of household packaging in Belgium. This high share is partially caused by the fact that 67 % of all beverage packaging are glass bottles.

6.1 End use demand and packaging options

The projected demand for packaging was derived from the projected demand for beverages provided by the Corelli model (see §4).

All beverages (excluding draught beer) were put into six groups according to their technical packaging requirements and matched with eight types of beverage packaging.

PET bottles are increasingly used for beverage packaging, also for applications from which they were excluded until now because of technical constraints. Reuse PET bottles are actually not used in Belgium. PVC has almost completely disappeared. The use of reuse bottles is declining.

6.2 Analysis of material flows and transformation processes

For most of the materials used for packaging, as well as for intermediates in materials production and for the packaging themselves (whether filled or not), imports and exports are quite important. Large discrepancies can exist between the end use of packaging, the intermediate use of packaging by packers of products and the packaging production. Changes in the Belgian final demand for packaging will have a limited influence on the production of packaging, packaging materials and intermediates in Belgium. Therefore, European standard processes and potential improvement options were analysed.

For treatment of used products on the other hand, two cases have to be distinguished:

- Waste collection, incineration or landfilling, and sorting are essentially local processes.
- Once waste streams have been sorted and can be valorised, they can cross boundaries.

For waste paper and cardboard, steel and aluminium, recycling is integrated in the standard production processes and international markets are well established. For plastics on the other hand recycling technologies are in full development and markets are underdeveloped.

6.3 Scenarios

Two complementary approaches have been used to estimate the greenhouse gas emissions and the emission reduction potential related to the end use of beverage packaging in Belgium:

- a base model (PackBase) based on average emission factors for materials and energy production, and fixed scenarios for changes in packaging use and recycling rates;
- a MARKAL partial optimisation model (PackMark) in which the choice of packaging and recyling rates is optimised on cost basis.

To calculate the potential reduction of greenhouse gas emissions, the PackBase model combines two sets of scenarios.

6.3.1 End use scenarios

Ranging from a stand-still, over moderate to rather drastic changes in choice of packaging: gradual replacement of packaging with higher emission factors (g CO_2 eq/l) with packaging with lower emission factors, taking into account technical and sociological constraints. In most cases it involves an increase of reuse (use of reuse PET wherever possible).

BAU	further decrease in reuse glass, replaced by one-way PET - one-way PET partially replacing cans - beverage cartons and reuse glass for milk products partially replaced by HDPE
FR	no changes in packaging choice
NIR	no increase in reuse - replacement by "best option" (except for ± 5 %)
RU1	increase of reuse (mainly reuse PET) - moderate use of PET and reuse PET for beer - wine and spirits : 90 % glass; 20 % reuse
RU2	more drastic increase of reuse PET - increased use of (reuse) PET for beer - wine and spirits : 85 % glass; 20 % reuse
RU3	maximum reuse (large: 90 %; small: 80 %, exc. wine: 30 %) - wine and spirits : 80 % glass

Table 8: *End use scenarios for the PackBase model*

6.3.2 Materials production and waste treatment scenarios

The emission factors for the different beverage packaging options (g CO_2-eq/l) change as a result of changes in weights and recycling rates.

FEF (fixed emission factors)	no changes in emission factor
M	decrease in materials use (weight) per packaging type
M+RW	increasing % waste recycling
M+RW+RP	increasing % recycled material in production

Table 9: *Materials production and waste treatment scenarios for the PackBase model*

In the PackMark model the BAU end use scenario has also been used. In all other scenarios (see Table 10) the possible shifts in end use were confined within specified ranges according to the maximum substitution potential that is considered to be achievable.

BAU	fixed packaging end use
OPT	end use optimisation without greenhouse gas emission limit
RE-15	end use optimisation - greenhouse gas emission limit at 85 % of the level of 2000
RE-30	end use optimisation - greenhouse gas emission limit at 70 % of the level of 2000
RE-MAX	end use optimisation - greenhouse gas emission limit at minimum possible

Table 10: *Scenarios for the PackMark model*

To take into account the uncertainty on the cost data all scenarios were run also with a decrease in specific packaging costs of 15% for reuse options.

6.3.3 Greenhouse gas emissions and improvement potential

Greenhouse gas emissions per packed liter of beverage are smaller for reuse packaging (glass and PET) than for all one way packaging options except beverage cartons. Greenhouse gas emissions related to materials use (including waste treatment) dominate greenhouse gas emissions during the use phase of the packaging (making, filling, cleaning, transport). They can be reduced significantly through decreases in packaging weight and increased recycling.

Results of the PackBase model are shown in Figure 8. Results of the PackMark model are summarised in Figure 9, which shows changes in end use of beverage packaging in a 15% greenhouse gas emission reduction case, and Figure 10, which shows the costs of emission reduction.

The total greenhouse gas emissions related to the end use of beverage packaging in Belgium can be estimated at 500 - 600 kton. In the absence of measures to reduce greenhouse gas emissions these emissions will increase by 50 to 100 kton.

Although the reduced use of materials per packaging unit (reduced packaging weight) as well as some of the changes that come into effect in a cost optimisation without emission limits, lead to reductions in greenhouse gas emissions, on the whole greenhouse gas emissions increase, because of the increase in beverage consumption and the gradual replacement of reuse packaging by one way PET bottles.

Calculations of the emission reduction potential show a maximum reduction potential of 300 to 350 kton. However, this implies drastic changes in the use of beverage packaging. More realistic estimates show a reduction potential of 250 to 300 kton.

Increased recycling is a cheaper option for greenhouse gas emission reduction, but it has a limited potential. Increased reuse gives significant additional benefits compared to increased recycling only (up to more than 150 kton).

Increasing the use of reuse bottles (mainly PET reuse) seems the most powerful strategy for reducing greenhouse gas emissions related to beverage packaging. However, the actual trend goes in the opposite direction. Only when imposing greenhouse gas emission limits, reuse PET becomes an attractive option.

The influence of some crucial parameters on the emissions and the emission reduction potential was tested. Although total emissions can change by 10%, the influence on the reduction potential is limited.

There is quite some potential for greenhouse gas reduction without additional **cost** compared to the actual situation and compared to a scenario with slight changes in packaging use. Compared to the BAU scenario, the changes in recycling rate and packaging use taking place in the 15% and 30% reduction scenarios, lead to a reduction in packaging cost.

However, when comparing emissions and costs of reduction scenarios to a situation in which packaging use is optimised without emission limits, the average emission reduction cost was estimated at 130 Euro/ton in case of a 15% emission reduction (compared to the 2000 level), and 228 Euro/ton in case of a 30% emission reduction. This result is very sensible to the price difference between one way and reuse packaging options. If the specific costs for reuse are reduced by 15%, the GHG emission reduction costs are reduced by 45% to 55%.

It should be kept in mind that the OPT scenario gives a very drastic view. Most probably, the average packaging cost will not fully reduce to the level of the OPT scenario. Hence, these emission reduction costs should be interpreted as upper limits.

Life cycle greenhouse gas emissions related to the end use of beverage packaging in Belgium represent about 0,3 to 0,4% of the total Belgian greenhouse gas emissions.

The calculated emission reduction potential corresponds to 1,1 to 1,4% of the total emission reduction effort that Belgium has to realise in the period 2000 – 2010 (approximately 22 Mton).

The comparison is however not fully correct because a significant part of the life cycle greenhouse gas emissions are related to imported materials or products, and will occur abroad. Hence, a significant part of the emission reduction potential will be realised abroad, and will not help Belgium in reaching its emission reduction targets. Similarly, Belgian production of (packaging) materials for export will contribute to the life cycle greenhouse gas emissions related to the end use of beverage packaging abroad.

- It is not clear which part of the emission reduction will be realised in Belgium. Taking into account the large imports of intermediates in material production, materials and packaging itself, and the export of waste materials (see Part III), the share of the "imported" emissions and "exported" emission credits will probably be at least 50 %.

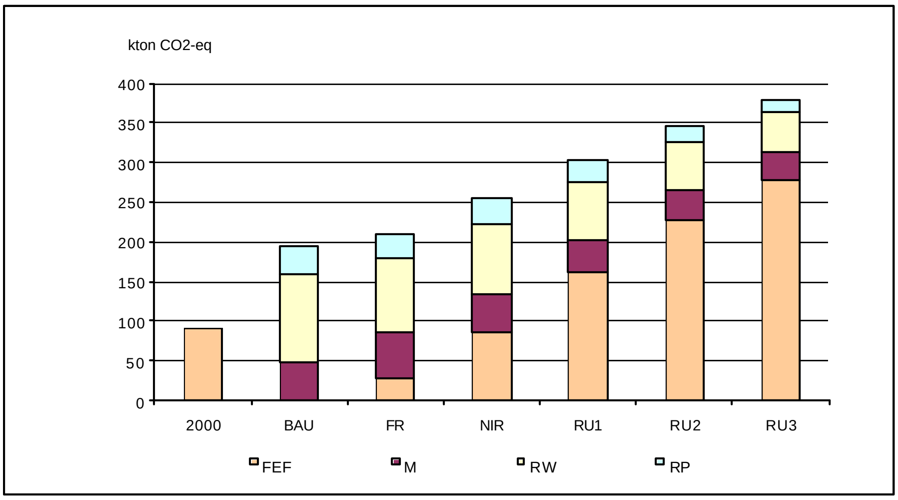

Figure 8: *Greenhouse gas emission reduction potential of combined end use scenarios and materials production and waste treatment scenarios*

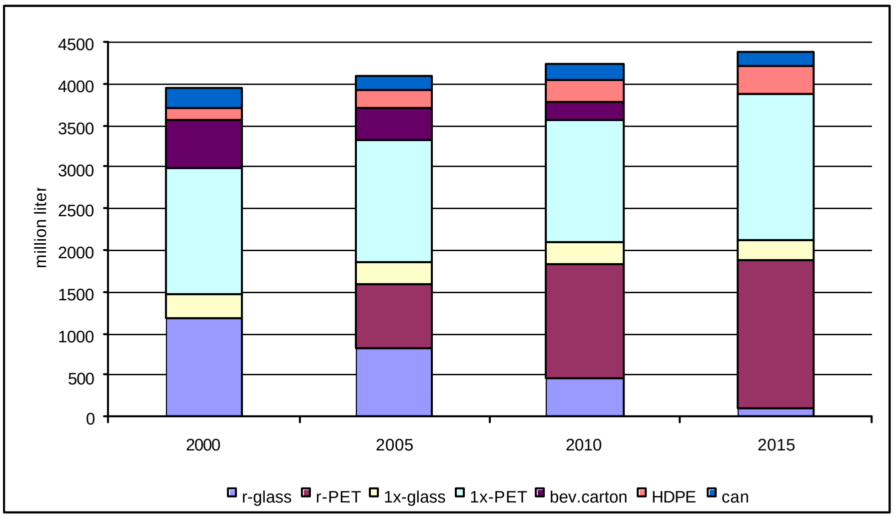

Figure 9: *End use of beverage packaging – 15% reduction scenario*

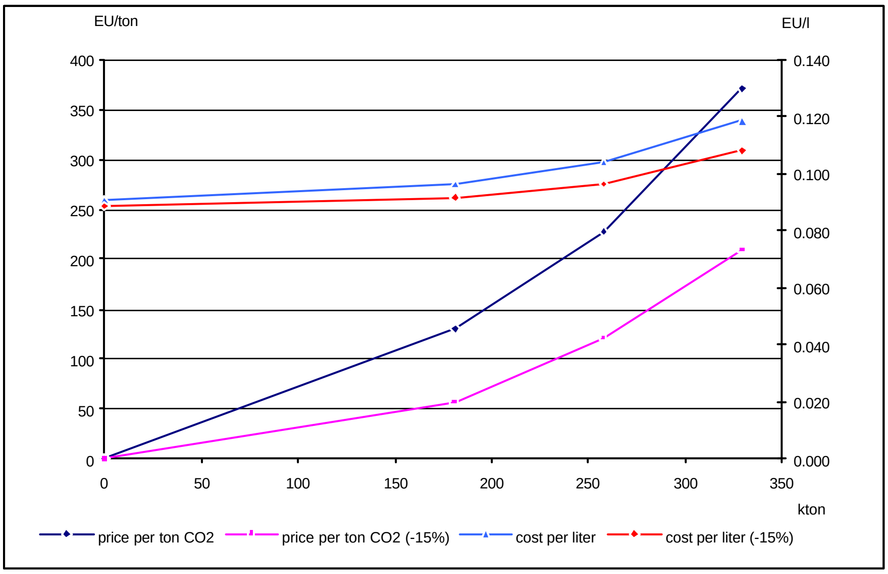

Figure 10: *Cost of greenhouse gas emissions reduction (compared to OPT scenario)*

7. CONCLUSIONS

The approach followed in this project aimed at giving insights in the greenhouse gas (GHG) emissions indirectly induced by the consumption of some product categories (single family houses, meat and beverage packaging). The aim was also to assess the possible contribution of consumer choices (including product substitution) to the reduction of GHG emissions. The assessment has been made taking into account the possible future evolution of the technologies involved in the life cycle of the products considered. Costs analyses were also carried out.

A substantial amount of work has been carried out in order to collect the numerous data needed in this project : these data relate to the different flows of materials involved in the three product systems, the description of technologies, the description of products and the market analysis.

Different methodological developments have also been undertaken in order to achieve the goals of the project :

A consistent modelling of the demand has been carried out for all three product categories : a bottom-up econometric model has been developed for the whole consumption pattern for breeding products and beverages and a stock-flow model has been developed for the housing demand.

While material flows have received very little attention in Belgium up to now, this study has constituted a first attempt to analyse the relevant material flows for the three product systems. The analysis has led to different conclusions for each product system : while foreign trade plays a small role for most building materials, the meat system and especially the beverage packaging system involves significant imports and exports both for intermediary materials and final products.

More fundamentally the ambition to quantify the greenhouse gas reduction potential related to the end use of specific product groups in Belgium has represented an important methodological challenge. An intermediary way between the development of a global and complex models such as the model built in the MATTER MARKAL study and the product-specific LCA approach has been found.

Linking projections on demand with technical improvement options and specific emission factors enabled us to give some insights in the possible impact of policies addressing consumption patterns and their environmental impacts. This macro-level quantification of the emission reduction potential gives relevant additional information in policy discussions, as compared to the results of LCA studies (e.g. in the discussion on reuse and one-way packaging).

To be able to take into account the cost factor, MARKAL models were developed for two of the product categories studied (housing and beverage packaging). MARKAL provides a structured framework for evaluating costs taking into account technical evolutions over a long time period. For the meat system, costs analysis were undertaken on an independent econometric analysis.

In absolute terms, the research has evaluated the life cycle GHG emissions related to three product categories to levels of less than 1% to 4% of the Belgian 1990 GHG emissions. At the same time it has revealed that, in relative terms, product substitutions within each product category may represent significant reductions of the life cycle emissions resulting from the Belgian demand for each of the product categories. The analysis suggested that in theory product substitutions could offer non negligible contributions to the fulfilment of the Belgian Kyoto target.

However given the low absolute levels of these potentials as compared to the total emission reduction that Belgium has to achieve, the important question is whether these specific product-related emission reduction potentials can be extrapolated to other products categories and other consumption patterns.

The cost analyses indicated that if the theoretical potential from product substitution is significant, this substitution seems to be less cost-efficient than technology improvements within the production and waste treatment system itself.

The level of confidence of this conclusion is however low given the high uncertainty level of the cost data for the different technologies and products.

Considering the weak quality of these data, an optimisation based on total system cost and an approach based on fixed scenarios and associated cost calculations, eventually using cost ranges, could be combined as mutually complementing tools.

The examples studied also indicated that both the necessary instruments and the geographical level for implementing them in order to achieve these potentials have to take into account the specificity of each product category : this specificity relates to uncertainty but also to the openness of the Belgian economy which is more or less important from one material to the other and hence from one product to the other.

Indeed, the European level could be more appropriate for some product categories. In general product-related measures also require European co-ordination. The Integrated Product Policy currently under discussion could offer such a framework.

Finally, this project has also shown the importance of systematic recording consumption figures of key product groups in physical terms (and not only financial flows data) as a condition for properly assessing the environmental benefits of changes in consumption patterns.

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CG/43/29B

EFFECT OF SWARD COMPOSITION AND QUALITY AND SUPPLEMENTATION ON METHANE EMISSION BY GRAZING CATTLE

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1. MOTIVATION AND PROJECT'S OBJECTIVES

Concern about global warming provoked by an increase in atmospheric concentration of greenhouse gases is growing and more attention is focused also on methane emissions (IPCC, 1996; Hansen et al., 1996, 1999). Due to its decay time (10 years), its global warming potential estimated to be 21 times greater than carbon dioxide, methane is an excellent target for control.

The contribution of agriculture, mainly cattle husbandry, is estimated to represent 45 and 60% of the total methane emissions in Europe and Belgium respectively (Organisation for Economic Co-operation and Development (OECD) 1998). Of course, these figures are based only on estimations as no method to quantify methane emission from ruminants on pasture was available. The set up evaluation of the method using the sulphur hexafluoride as a tracer gas (Ulyatt et al., 1999) and the micro-meteorological method (Harper et al., 1999) takes a long time (8 to 12 months). According to the Kyoto protocol (1997), European Union member countries should reduce the production of greenhouse gas by at least 8% during the first decade of the third millennium. Accordingly, the first objective of this project was the development of an easy, cheap and precise method for determination of ruminant methanogenesis.

As ruminant methane production represents a considerable feed energy loss, several antibiotics, ionophores and other chemical inhibitors of methanogenesis have been monitored and studied (Mbanzamihigo et al., 1995, 1996; Van Nevel and Demeyer, 1996). However, as the rumen is an integrated system, such manipulation of its metabolism is associated with negative effects on e.g. feed intake, fibre degradation and microbial growth efficiency whereas transient effects of additives have been reported (Russel and Martin, 1984; Immig et al., 1995). In addition, growing mistrust and reluctance of the public opinion concerning the utilisation of chemical products in animal nutrition increased the interest in both feeding and biological strategies to control methanogenesis. The use of lipids as methane inhibitors showed interesting results but their inclusion in the diet at levels above 5% inhibits fibre degradation in the rumen (Broudiscou et al., 1990; Machmuller et al., 1998). The Intergovernmental Panel on Climate Change (IPCC) (1996) stressed that improvements in animal feed quality and feeding system was one of the most attractive tools to reduce methane emissions from agriculture. Nitrogen supply in the pasture is used to increase plant biomass production and protein proportion in the grass. It has been shown *in vitro* in our laboratory (Demeyer and Van Nevel, 1979) and elsewhere (Cone and Van Gelder, 1999) that proteins produce less methane than carbohydrates. Hence, the increase in crude protein content of plant biomass through nitrogen supply to the pasture might be expected to decrease methane production in the rumen. Moreover, as organic matter degraded in the rumen is partitioned into microbial organic matter and fermented organic, matter generating methane, optimising microbial growth efficiency might redirect degraded organic matter from volatile fatty acids and methane production to microbial synthesis (Leng and Nolan, 1984; Beever, 1993). Hence, if synchronising nitrogen and energy would increase microbial growth (Sinclair et al., 1993), this result in a decrease of methane emissions. A second objective of this project was to support these hypotheses by experimental evidence.

2. EXPERIMENTAL DESIGN AND ACTIVITIES

In this project, we intended to develop a simple and cheap method for quantification of methane emissions from grazing ruminants and to study these emissions in relation to:

* Nitrogen fertilisation rate: fertilisation might induce differences in chemical characteristics of the grass (proteins, sugars, fibres) inducing changes in methane production (Kirchgeβner et al., 1995).

* Growth stage and growing season: physical and chemical characteristics can change with growth stage and season (Peyraud and Astigarraga, 1998) inducing seasonal changes in methane emissions.

* *Sward composition: fertilisation and period of the growing season may change sward composition of the pasture (Davies et al., 1991; Whitehead, 1995) (proportion ray grass/clover), resulting in different contents of secondary plant metabolites (e.g. saponins) in the pasture and hence in the diet, which might change efficiency of microbial growth (Beever et al., 1986) and protozoa numbers (Wallace, 1993) and hence eventually methane excretion figures.*

* Supplementation and supplementation system: grass based diets of current production systems inducing a desequilibrium between energy and nitrogen supply for rumen microbial growth result in important urinary nitrogen losses (Peyraud and Astigarraga, 1998) supplementation of energy (e.g. maize silage) reduces this desequilibrium (Van Vuuren et al., 1993) and might optimise microbial growth efficiency (Kirchgeβner et al., 1995). Moreover, supplying an energy source (maize silage) in a synchronised way might optimise microbial growth efficiency additionally (Sinclair et al., 1993). Finally, increased microbial growth efficiencies might decrease methane emissions (Leng and Nolan, 1984; Beever, 1993).

* In order not to shift from pollution with methane to pollution with nitrogen, next to methane emission, nitrogen utilisation efficiency has been monitored as well during this project.

The experiments ran during two years (1999-2000) and took place during two successive grazing seasons (June-July *vs* August-September). Sheep were used as model for methane emissions from ruminants. During the first experimental year (1999), effects of nitrogen fertilisation rate (150 kg/ha/year) on sward and chemical composition of a mixed pasture (ray grass / clover) and methane emissions were studied. In the second experimental year (2000), the same parameters mentioned above were monitored using sheep and a ray grass pasture supplied with two nitrogen fertilisation rates (200 and 400 kg N/ha/year). As it could be anticipated that the higher nitrogen fertilisation rate (400 kg N/ha/year) would induce higher urinary nitrogen excretions studied synchronised and non synchronised maize silage supplementation were studied. An integrated evaluation approach including plant yield and chemical composition, total and rumen digestibility of the ration, nitrogen utilisation efficiency (microbial growth rate and urinary excretion), methane emission and rumen fermentation pattern were studied. This approach is crucial for a good methane excretion evaluation, results interpretation and finally advising an optimal integrated production system: optimal plant production accompanied with a optimal utilisation of the diets with lower excretions (methane and nitrogen) by ruminants.

3. MATERIAL AND METHODS

3.1 Dry matter production and sward composition

During the experimental period pasture were divided into two plots (first year: plot fertilised with 150kgN/ha/year fertilised and non fertilised plot, second year: plot fertilised with 200 and plot fertilised with 400kgN/ha/year). Grass samples were taken from each plot and effects of nitrogen fertilisation on sward composition (first year), total biomass production and chemical composition (first and second year) were evaluated. Chemical analysis including dry matter, ash, crude proteins, neutral detergent fibre, acid detergent fibre, crude fibre, crude fat, soluble sugars were done according to the association of official analytical chemists (AOAC) (1990). Nitrate concentration was measured chromatographycaly using an anion specific column (AS 4A, Dionex, Belgium).

3.2 Animal, diets and digestion parameters

For each year four different adult cross-breed rumen fistulated sheep were used. During the experimental periods, animals were housed indoors in metabolic cages to enable simultaneous measurements of feed intake, apparent total digestibility, nitrogen excretion in the urine, digestibility in the rumen and other rumen fermentation parameters. Experimental animal were fed *ad libitum* four times a day (10 a.m., 4 p.m., 10 p.m., 4 a.m). For feed intake measurement and total apparent digestibility determination, the feed offered, that refused and faecal material excreted were weighted fresh two times a week and a 50g sub-sample was used for DM measurement (70°C, 72h). This research protocol and animal treatment were approved by the Institutional Animal Care and Use Committee of the Ghent University (Belgium) (dossier number of the acceptance: 99/23).

3.3 In vivo methane production, pH, volatile fatty acids and ammonia concentration

Rumen fermentation parameters were monitored two times a week. Ethane, a gas behaving as methane was used as a tracer gas to evaluate methane production in the rumen as adapted from Moate et al. (1997). Ethane (Air Liquide, Belgium) was infused continuously through the rumen fistula during 6h at an exactly known infusion rate of 10ml/minute using a dosimeter (Brooks instruments B.V., G/T 1000, the Netherlands) between 10 a.m. and 4 p.m. or 10 p.m.. In preliminary *in vitro* incubations, it was shown that addition of ethane (% gas phase) has no effect on rumen fermentation pattern and was not metabolised or oxidised. Total gas expelled through the rumen fistula of each sheep was collected in large PVC columns (see Van Nevel et al. 1970b and Mbanzamihigo et al. 1995). At the end of the gas collection, rumen gas produced during 6h or 12h, mixed with ethane was sampled (1ml) using gas tight syringes and analysed for methane and ethane by chromatography. As ethane behaves as methane, the total methane produced in the rumen (MPR) can be calculated from the total ethane infused in the rumen (EIR) and the proportions of CH_4 (% v/v CH_4) and C_2H_6 (% v/v C_2H_6) in the collected gas as follows: MPR(l) = (% v/v CH_4 / % v/v C_2H_6) * EIR(l). Methane produced over the 6h or 12h was assumed to be a quarter or half of the daily production. Simultaneously with gas collection, rumen contents were sampled for pH and volatile fatty acids measurement. During the first season of each year, *in vitro* incubations were done to confirm *in vivo* results. Simultaneously with methane collection, rumen juice was sampled and pH, volatile fatty acids and ammonia concentration measured.

3.4 In sacco degradability and rumen passage rate

Once a week, *in sacco* degradability was measured by introducing 2.0g of sample in polyamide bags (Solana, Edegem, Belgium, pore size 37-50µm). One bag was not incubated and immediately washed for determination of the soluble fraction whereas the incubated ones were removed from the rumen at different periods and washed in a mini-washing machine, dried (65°C, 72h) and weighed for degraded dry matter determination. Rumen passage rate was determined using the Cr-mordanted hay procedure (Uden et al., 1980). From *in sacco* degradability and rumen passage rate, the effective degradability has been calculated according to Orskov and McDonald (1979).

3.5 Statistical analysis

Effect of nitrogen fertilisation on parameters studied was statistically evaluated using General Linear Model (GLM) procedures with fertilisation rate, season and animals as main factors and the Duncan test to distinguish statistically different groups of animals. In a second step, ANOVA was used to evaluate animal and season effects independently from the treatment (nitrogen fertilisation). All these tests were done using SPSS statistical program (SPSS, software for Windows release 9.0, (SPSS, Inc., USA)). Data are presented as means and standard deviations and significance is declared at $P<0.05$.

4. RESULTS AND DISCUSSION

4.1 First year (1999)

4.1.1 Dry matter production, sward and chemical composition of the pasture

Compared to the control (non fertilised pasture), nitrogen fertilisation increased the dry matter production per ha as well as the ray grass production at the expense of clover during the two seasons. However, the magnitude of the differences were season dependent. Hence, on average, in early summer (June-July: season 1), supplying 150kg nitrogen/ha/year increased dry matter production by 29%, and reduced by half the clover proportion in the total dry matter. In late summer (August-September: season 2), dry matter production was increased by 46% while the clover proportion was only 10 points lowered. The effect of season on biomass production was more outspoken than that of fertilisation, since dry matter produced per ha was more than twice as high in the first compared with the second season irrespective of the treatment.

For chemical composition of the swards, our attention was focused on key grass compounds susceptible to have a direct or indirect effect on methane production: crude protein, neutral detergent fibre, water soluble carbohydrate and crude fat percentages in the swards. Nitrogen fertilisation did not change clearly the crude protein percentage (season 1: from 12.2 to 13.8% ; season 2: from 21.9 to 23.2%) within each season while pasture total crude protein yield was increased by 46 and 53% in season 1 and 2 respectively. The season effect was more outspoken than the effect of nitrogen fertilisation, the crude protein percentage being higher in season 2 (22.5%) than in season 1 (13.0%) while the reverse occurred for total crude protein production. No significant effect of nitrogen fertilisation is observed on fibre content (season 1: from 49.5 to 49.4% ; season 2: from 58.7 to 60.8%). However, again, a strong season effect occurred. In all seasons, nitrogen fertilisation increased nitrate accumulation in the grass (season 1: from 55 to 250ppm ; season 2: from 1402 to 3475ppm) and this accumulation was higher in the second than in the first season. No effect of nitrogen fertilisation on water soluble carbohydrate concentration was observed (season 1: 13.4 to 14.1% ; season 2: from 5.0 to 4.9%), but again a strong seasonal effect ($P<0.001$) was apparent. On average the crude fat percentage was low (*c.a.* 4.5%). Neither nitrogen fertilisation rate nor season induced differences of this parameter.

4.1.2 Methane emissions and pasture digestion in the rumen

Neither level of nitrogen fertilisation, nor season affected *in vivo* rumen methane emission per kg of dry matter ingested and fermentation pattern volatile fatty acids, which has been confirmed through *in vitro* results. It is surprising that no difference in methane production between the two seasons was found despite the clear difference in crude protein percentage (13% in season 1 *vs* 22.5% in season 2). A significant ($P<0.05$) animal effect was observed however: on all diets, one animal produced on average less methane (20.3±3.1l /kg dry matter ingested) than the three others (27.6±4.1l/kg dry matter ingested). The lower methane production per kg of dry matter ingested observed in that sheep was accompanied by a lower daily average pH (5.92 *vs* 6.52), a higher total volatile fatty acids concentration (135.5 *vs* 97.6 mmols/l), a lower degradation rate (4.2 *vs* 7.2%/h) inducing a significantly ($P<0.001$**)** lower effective dry matter degradability in the rumen (61.7 *vs* 68.4%) while the degradation extend is comparable to that of other sheep (87.5 *vs* 87.1%). There is no difference between sheep concerning apparent total digestibility (76.2 *vs* 75.6%). One could expect that the lower methane produced by one sheep is only due to the lower effective dry matter degradability. Nevertheless, *in vivo* methane production calculated per kg of effectively degraded dry matter in the rumen shows persistent animal effects and animal effects tended to remain when *in vitro* incubations were performed suggesting animal differences in rumen microbial population. Methane released from each sheep per year was estimated and compared with methane calculated using equations recommended by the Intergovernmental Panel on Climate Change for national greenhouse inventory (IPCC, tier 1 and 2) (IPCC 1996). Although all the sheep received the same diet, one sheep produced considerably less methane. Relative differences between methane emission observed and methane calculated from IPCC values are considerably high for sheep A while for sheep B, C and D, both the default emission factor, IPCC tier 1 (8 kg methane / animal / year) as well as methane calculated using IPCC tier 2 (7.4-8.5kg methane / animal / year) is in the range of our methane production observed.

4.1.3 Nitrogen utilisation efficiency

A comparison between protein and dry matter degraded in the rumen gives an indication on possible imbalance between energy and nitrogen in the rumen. It has been evidenced in our experiment that no nitrogen lack occurred. Instead, a nitrogen surplus (>165g of protein incorporated per kg of dry matter degraded) higher in the late than in the early grazing season was observed. Hence, this nitrogen surplus induced a lower nitrogen utilisation efficiency through improved urinary nitrogen excretions.

4.1.4 Effect of clover saponins on methane production

In vitro trial with rumen contents were done with and without different doses of clover extract containing saponins. After incubation, methane, volatile fatty acids production were measured and protozoa counted. Results show exponential decrease of methane production relative to volatile fatty acids at low doses accompanied with a decrease in protozoa number for all doses. For doses higher than 6-9mg/ml, the volatile fatty acids and gas production decreased and even stopped at 24mg/ml. As clover saponins are known to be triterpenoid glycosides (Sakamoto et al., 1992), results contradict the general opinion that triterpenoidal saponins have no antibacterial activity (Hostettman and Martson, 1995; Lu and Jorgensen, 1987).

4.2 Second year (2000)

4.2.1 Dry matter production and chemical composition of the pasture

Compared to 200kg nitrogen/ha/year, supplying 400kg nitrogen/ha/year in a ray grass pasture increased the dry matter production in early summer (June) by almost 70% while in late summer (august), the biomass production was doubled. Irrespective of the fertilisation rate, a seasonal effect on dry matter production towards more dry matter production in early than in late summer season was observed. Indeed, dry matter production released after 22 days of regrowth in early summer only was reached after 39 days during the late summer season for the lowest fertilisation rate. For the higher fertilisation rate (400kg N/ha/year) 17 addition growth days in the second season induced an increase in the dry matter yield for 600kg/ha. The higher nitrogen fertilisation rate induced a higher crude protein percentage in the two seasons: (13.6 *vs* 20.1% in the first season and 13.1 *vs* 15.7% in the second season for 200kg nitrogen/ha/year and 400kg nitrogen/ha/year respectively. The increase in crude protein percentage was accompanied by a decrease in water soluble carbohydrates (season 1: from 10.8 to 7.3%, season 2: from 16.3 to 12.7%) and an increase in nitrate concentration (season 1: from 186 to 2697 ppm, season 2: from 211 to 2452 ppm) while neutral detergent fibre content did not change significantly (season 1: 49.7 *vs* 50.2%, season 2: 50.9 *vs* 52.7%).

4.2.2 Methane emissions and pasture digestion in the rumen

In season 1, compared to 400kg, 200kg nitrogen per ha per year was associated with an increase (20-40%) in methane production per kg of dry matter ingested for two sheep only. It is clear that the higher methane production observed here was linked with the lower ingestion rate as the two sheep ingested (25-70%) more dry matter when grass from the higher fertilisation rate was offered. The lack of nitrogen fertilisation rate effect on methane emission was confirmed by *in vitro* results. The higher ingestion rates induced higher passage rates and a lower methane productions in the rumen. Moreover, the shift of fibre digestion from the rumen to the hindgut induces a lower total methane emission as methane synthesis is partially replaced by acetate in the latter fermentation chamber. No clear change in volatile fatty acid concentration has been observed, confirming that the lower methane emission was effectively due to a shift of dry matter digestion from the rumen to the lower parts of the digestive system. There was no difference in methane emission between the two fertilisation rates in the second season where no difference in ingestion occurred.

4.2.3 Supplementation strategies and methane emissions

There is no difference between synchronised and non synchronised supplementation systems in methane emission per kg of ingested dry matter (27.6 *vs* 26.9 l for respectively synchronised and non synchronised supplementation system). The hypothesis was that by synchronising nitrogen and energy supply, more organic matter digested should be used for microbial growth decreasing the organic matter fermented and thus, generating less methane. The absence of synchronisation effect on methane production could be explained by the relatively slow rate degradation of maize silage, masking the difference between the synchronised and the non synchronised situations.

4.2.4 Nitrogen efficiency

Increased N fertilisation rates induce higher urinary N losses through inefficient utilisation of N in the rumen. These high urinary N losses could be predicted by the OEB-value of the diet. A reduced rumen degradable protein balance (OEB) either through feeding less fertilised or older grass or through supplementation of maize silage synchronously or asynchronously will induce a proportional decrease in urinary N excretion.. Moreover, animal differences in urinary urea excretions (at the same OEB level) could be observed. Hence, from an integrated evaluation of both the OEB-value of the diet and the milk urea content per cow or lactation group, dietary adaptations to improve N utilisation efficiency of the grazing dairy cow might be proposed. During this research no effect of synchronisation of energy and nitrogen supply in the rumen, on microbial growth efficiency could be observed. However, it is still unclear whether synchronisation is not important for high productive dairy cattle.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Method for determination of methane emission.

A method for determination of rumen methane production using ethane as a tracer gas was perfected and used, giving results comparable with those obtained with other more expensive and complicate methods (sulphur hexafluoride as a tracer gas or micro-meteorological method). Determination of organic matter effectively degraded in the rumen, rumen concentrations of volatile fatty acids and methane production thus determined *in vivo* fit the stoichiometric model of rumen fermentation as developed from *in vitro* incubations (Demeyer, 1991).

5.2 Effects of nitrogen fertilisation on grassland production.

A moderate nitrogen fertilisation rate applied on a mixed pasture (ray grass/clover) increases the dry matter production but decreases clover proportion in a mixed pasture (ray grass / clover). In both experiments, nitrogen fertiliser is more efficiently utilised for biomass and protein production in early than in late summer.

5.3 Effect of nitrogen fertilisation on methanogenesis.

No clear effects of nitrogen fertilisation, and thus, of grass crude protein content, were observed on rumen methanogenesis, expressed per kg organic matter intake or organic matter totally digested (faeces), contrary to the hypothesis. In both experiment, rumen methanogenesis more determined by animal than by dietary effects. In the second experiment animal variability could be explained by differences in grass intake. A higher intake produces a shift in digestion from the rumen to the large intestine.

However, the increase in dry matter production induced by nitrogen fertilisation increases stocking rate and hence methane emission per ha. Individual (between animals) variation in methane emission is important and further insight in this animal variability concerning feed intake and side of digestion is needed both

- to understand differences in feed utilisation efficiency,
- to develop mitigation strategies to control methane emission by e.g. selection-breeding
- to improve the reliability of IPCC estimations of methane emissions from livestock. Incorporation of the level of feed intake in these estimations seems desirable.

In attendance of these possible refinements, IPCC (1996) estimations, expressed as kg methane production per animal per year, can be used. Indeed, both the average value for sheep, calculated from our experiments (11.1 kg animal-1 year-1) and the variability (variation coefficient = 19%) remain within the ranges proposed by the IPCC (1996): average of 11.7 and predicted variation coefficient of 20%. There is no reason to assume this conclusion to be different for other ruminants.

5.4 Grass feeding and efficiency of N utilisation

Concerning N utilisation efficiency of grass fed or grazing animals, CP levels of the diet should be pursued to ensure efficient N capture by the rumen microbes (balanced degradable protein balance, OEB = 0). Indeed, positive OEB-values are known and have been confirmed during our experiments to induce proportional urinary urea excretions. Rumen degradable protein balance of grass based diets could be reduced either by feeding less fertilised or older grass or by supplementing energy rich forage or concentrate (e.g. maize silage) synchronously or asynchronously.

In spite of a slight increase in rumen microbial growth yield at higher levels of intake, microbial protein supply to the small intestine - per kg OM apparently digested - decreased, suggesting the increased importance of post-ruminal digestion (in particular in the hindgut) at higher levels of intake. Hence, when protein supply is limiting milk production, this shift is not desirable from the 'N point of view'.

In order to reduce urinary urea excretions, increased crude protein concentration, as observed at the end of the grazing season, should be avoided, eventually through supplementation of energy rich-protein poor forage or concentrate.

5.5 Second year (2000)

The higher nitrogen fertilisation rate applied on a ray grass pasture induces a higher biomass production and higher crude protein contents. As observed in the first year, nitrogen fertilisation in more efficient for biomass production in early than in late summer. There is no effect of nitrogen fertilisation rate on methane emission, only an effect of ingestion level was apparent. A higher ingestion rate induces a beneficial shift of dry matter digestion from the rumen to the hindgut known to induce lower methane productions to the advantage of acetate, a high energy compound. This confirms that ingestion level should be incorporated in a model for estimation of methane emission from livestock in order to improve the IPCC estimations.

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PART 2: TO PROVIDE SCIENTIFIC SUPPORT FOR BELGIAN POLITICS

Tropospheric ozone: reducing background concentration and preventing peaks

CG/11/26

ELECTRIC AND HYBRID VEHICLES: A MEASURE TO REDUCE THE TROPOSPHERIC OZONE?

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1. GENERAL CONTEXT

This project was carried out at the Centre for Economic & Social Studies of the Environment (CESSE) of the *Université Libre de Bruxelles* and comes under the general heading of the support to decision making for the control of photochemical pollution in urban and suburban areas.

Taking into account the particular nature of tropospheric ozone - secondary pollutant formed from precursors such as nitrogen oxides and volatile organic compounds -, the complexity of the chemical reactions taking part in its formation and its destruction and the number of implied polluting sources, the definition of strategies of control of photochemical pollution is not easy and requires the development of adequate tools which are often difficult to implement.

The measures taken for the control of photochemical pollution are often corrective and relate to the short term. They consist of a reduction in the peaks of pollution by a drastic limitation of the traffic in the urban areas. Measures of long term are currently still slightly developed.

Among the measures likely to improve the long-term situation, the promotion of the electric and hybrid vehicles which only emit very little or no ozone precursors constitute a potential preventive solution.

2. OBJECTIVES

The main objective of this project is to clarify the definition of strategies of control of photochemical pollution, by specifically analysing a technological-type measure consisting of the introduction of electric or hybrid vehicles into the Brussels-Capital Region.

A more general objective of the undertaken study relates to the development of a tool of support to decision-making likely to help the decision makers in term of control of photochemical pollution. A particular attention was thus carried to the methodological developments necessary to approach these problems seriously.

From this point of view, the undertaken study developed according to an economic section, on the one hand, and an environmental section, on the other hand, in order to be able to compare these two significant aspects of the evaluation of new technologies of transport.

Concerning the economic aspects, taking into account the data available at the moment of this study, only the electric vehicles could be the subject of a detailed economic analysis. Within the framework of this analysis, the costs of implementation specific to the electric vehicles first of all were evaluated and compared with those of their internal combustion counterparts. The costs of implementation of various scenarios of integration of these vehicles in the Brussels-Capital Region were then evaluated.

Within the framework of the environmental analysis, the potential contribution of the electric and hybrid vehicles in the general context of the evolution of road traffic emissions in the Brussels-Capital Region since 1990 is first determined. To this end, the emissions of the electric and hybrid vehicles are first of all compared with those of their internal combustion counterparts. The effects of various scenarios of introduction of these vehicles into the Region are then evaluated in terms of reduction of the atmospheric pollutants emissions. Next, the methodology developed for the evaluation of photochemical pollution and its application for the evaluation of various general strategies of reduction are presented. The potential effects of the introduction of electric vehicles into the Brussels-Capital are also evaluated.

3. ANALYSIS OF THE ECONOMIC ASPECTS

This part of the study aimed to carry out an economic assessment relating to the use of the electric vehicles within the Brussels-Capital Region.

A first part of this analysis concerns thus the cost-in-use specific to the electric vehicles. These costs, expressed in terms of fixed costs and variable costs, are compared with those relating to the traditional gasoline and diesel vehicles. It is also held account in this part of the influence of the average annual course carried out by the vehicles as well as the influence of the amortisation period. Moreover, one scenario by 2010 is considered. This scenario takes account of the trend of the price of electricity (taking into account the liberalisation of the markets of energy) as well as the trend of the price of the fuels. Finally, various incentive political measures in favour of the electric vehicle are also analysed in this part.

A second part of the economic analysis considers the costs of implementation of various scenarios of introduction of electric vehicles in the Brussels-Capital Region. These scenarios were defined by the team of Professor Maggetto of the VUB.

To finish, a short outline of the obstacles preventing the mass production of electric vehicles was drawn up.

At the end of this analysis, it could be concluded that at the present time, being given the narrowness of the market of the electric vehicles, it is difficult to imagine a massive introduction of this type of propulsion into the Brussels-Capital Region. The absence of mass production of these vehicles, involving purchase prices much too high, remains indeed a major obstacle for any potential buyer of this type of vehicle.

If we compare the cost-in-use per kilometre of an electric vehicle to that of its internal combustion counterparts, the additional cost for the electric vehicle is evaluated at 40%. This of course results from the high purchase price, which lies 70% higher than a similar petrol vehicle and 52% higher than a diesel. On the contrary, if you only consider other items such as insurance, maintenance, taxes and consumption, then the electric vehicle is getting much cheaper than the other propulsion modes. In conclusion, this is even more so, if we analyse the situation with a view on 2010. Indeed, both liberalisation of electricity markets and the expected increase of petrol prices will have favourable effects on electric vehicles use, as far as consumption is concerned.

As a consequence, if the authorities really wish to promote the use of electric vehicles in town, they absolutely have to introduce political incentives. We notably think of possible subsidies by the authorities for electric vehicles buyers, or a reduction of taxes or insurance premiums on this type of vehicle. Those different measures have already been experimented in other countries.

Furthermore, as seen before, the use of electric-driven transport is closely correlated to electrical infrastructure and town planning. Thus this type of propulsion needs to be supported, in its initial phase, by political measures to accelerate the installation of new infrastructures for the recharging terminals. The introduction of electric vehicles also largely depends on the implementation of policies aiming to stimulate new transport concepts. At this stage, different possible scenarios have been taken into consideration.

These scenarios concerned:

- the implementation of a network of stations of automatic hiring of electric vehicles inside the Brussels-Capital Region in complement with the public transport;
- the introduction of x% of the electric vehicles into the fleets of public or private companies;
- the access restriction in certain areas of the city giving a priority for the public transport and the electric vehicles;

- the implementation of goods distribution centres using of the electric vehicles in order to reduce the traffic of the heavy vehicles in the centre town in favour of the electric vans.

The economic analysis of these scenarios shows again that the purchase of electric vehicles is the highest financial burden, at least as far as scenarios such as a hiring network of electric vehicles or a goods distribution network are concerned.

This leads to the conclusion that, if they wish to favour the use of electric vehicles in the Brussels-Capital Region, the authorities first have to focus on smaller-scale scenarios. In fact, scenarios like access restrictions in certain areas in favour of zero emission electric vehicles, or replacement of internal combustion vehicles by electric vehicles in private as well as public captive fleets, seem to be the most financially viable at present. However, the other scenarios should not be excluded right away. They can be taken into consideration later on, insofar the experience generates a favourable return in the very case of the Brussels-Capital Region. The implementation of the two other scenarios will indeed allow us to analyse the behaviour of electric vehicles and recharging terminals users. The consequential analysis of this behaviour will help implementing more efficiently both a network of goods distribution and a network of electric vehicles hiring.

However, our conclusions remain very mitigated as for the eventuality of an expansion of the electric vehicles resulting in mass production. And yet, this mass production is indispensable for the development of this type of propulsion. However, we have seen that there remain many obstacles and that car producers do not benefit of economic incentives to encourage them to go over to mass production of electric vehicles.

To be complete, let us also point out the fact that we have not taken into account here the eventual promotion cost related to electric vehicles. We think of the cost of promotion campaigns aiming to initiate the public and promote these vehicles. Such expenses have of course to be taken into account and are to be added to the other costs evaluated in this part of the study.

4. ANALYSIS OF THE ENVIRONMENTAL ASPECTS

The analysis carried out within the framework of this project was twofold.

First, it was a question of approaching the problems of the air pollution in a global way by developing a tool allowing the modelling of episodes of photochemical pollution and the evaluation of the related damage. Various general strategies of reduction of precursors emissions thus could be evaluated to allow a better understanding of the situation around Brussels.

Second, the analysis considered a specific measure of introduction of electric vehicles into the Brussels-Capital Region in order to determine its potential benefits from the point of view of the reduction of pollution on the various scales (local, regional and global).

4.1 Methodology

With respect to the assessment of the effects of photochemical pollution in terms of its harmful effects on public health, damage to buildings and vegetation and the reduction of agricultural yield, for example, the overall methodology employed has as its basis an assessment of the damage costs. Also known as the 'impact pathway' approach, this methodology traces the progress of pollutants from their point of emission to their point of impact by following a series of logical steps.

The assessment of the external effects caused by the transport sector is thus the result of an analysis with four principal stages:

- the assessment of pollutant emissions caused by road traffic;
- the determination of the resulting concentrations of pollutants in the atmosphere (immissions);
- the calculation of the physical damage;
- its expression in financial terms.

The modelling of the "emission-immissions" relationship required a specific approach in the case of the photochemical pollution which requires to resort to deterministic models of pollutant dispersion as well as chemical models able to account for the physical and chemical phenomena leading to the ozone formation.

Use was made of the METHPHOMOD model developed by the numerical modelling group in the Atmospheric & Land Pollution Laboratory of the Lausanne Ecole Polytechnique Fédérale.

The use of this model required the establishment of a register for Belgium covering hourly emissions for a series of 36 pollutants such as methane, carbon monoxide, nitrogen monoxide, nitrogen dioxide and sulphur dioxide as well as 31 types of non-methane volatile organic compounds.

In terms of damage, the approach was limited to short-term effects (episodes) for which exposure-response functions were available. The analysis pays specific attention to repercussions on health in terms of acute mortality and hospital admissions as the result of respiratory problems during periods of photochemical pollution.

To begin with, the methodology enabled a photochemical pollution episode to be modelled. This episode, which occurred on 10^{th} and 11^{th} August 1998, was taken as reference case, and the methodology enabled the damage associated with it to be calculated over a 120 sq. km. zone centred on Brussels. The assessment produced external costs of 2.2 M€, 80% of which were associated with acute mortality.

On the basis of this methodology, various strategies and scenarios could be evaluated in the second part of the analysis.

4.2 General strategies of control of photochemical pollution

Within the framework of the evaluation of general strategies of reduction of precursory gas emissions, three scenarios involving the reduction of precursory gas emissions (nitrogen oxides and volatile organic compounds) were analysed. The strategies considered consisted of reducing the total emissions in the Brussels-Capital region in three ways, namely NOx emissions alone by 50%, COV emissions alone by 50%, and NOx and COV emissions together by 50%.

On the basis of this analysis it was not easy to decide univocally on the most efficient strategy to adopt with a view to improving the situation. In fact, as far as the most efficient strategy to reduce photochemical pollution is concerned, different conclusions can be arrived at depending on the criterion selected for assessment purposes and the geographical zone involved.

Whereas the reduction of COV emissions in the Brussels region seems to be the most efficient strategy to reduce the peak values observed in the area, the reduction of NOx is the most efficient approach in terms of decreasing the average values over the 8 hours associated with health effects.

The various scenarios considered all point to increases in ozone concentrations in the major urban areas (Antwerp, Brussels, Gent, Charleroi and Mons-Borinage), a factor which indicates that these areas are saturated in NOx and COV.

In the case of the Brussels-Capital region, the least deleterious strategy, i.e. the one which leads to the lowest increase in the concentrations, is that of reducing COV emissions alone.

In terms of damage to health, only the scenario involving a reduction in NOx emission results in a reduction in the external costs associated with the episode in comparison with the reference case. The two other scenarios result in slight increases (less than 1%) in this damage despite the overall effect of reductions in ozone concentrations.

This is explained by the fact that only damage to health is included in the assessment, and that the greatest increases in photochemical pollution occurs in major urban areas. Since the positive effects of a reduction in the precursors in the Brussels region are felt mainly in rural areas, the incorporation of the long term effects on vegetation and crops might well lead to different conclusions.

4.3 Environmental effects associated with the introduction of electric and hybrid vehicles in the Brussels-Capital Region

The general analysis of the environmental aspects which was carried out initially made it possible to highlight the principal advantages which have electric and hybrid technologies.

Two general scenarios of introduction of light vehicles using these technologies made it possible to estimate the reductions of pollutant emissions which can be expected from an introduction of 10% of electric vehicles and hybrid vehicles respectively into the road traffic in the Brussels-Capital Region. This general analysis also made it possible to highlight the potential environmental benefit - reduction of the external costs - which can be expected from a penetration of these technologies. Each % of market share of these technologies would represent an environmental benefit of 5.5 M€ in term of reduction of the annual external costs associated with the local damage. These scenarios also highlight significant reductions in the emissions of greenhouse gases (-5.9% for the electric vehicles and -3,6% for the hybrid vehicles) as well as precursors of tropospheric ozone.

The effects of the implementation of a more voluntarist policy which would lead to a more significant penetration of the electric vehicles in the Brussels-Capital Region thanks to various suitable measures (network of vehicles hiring, access restriction to certain areas for internal combustion vehicles, etc.) were specifically analysed. This scenario considers that the "share of market" of the electric vehicles is 50% in the centre town, 20% in an intermediate zone and 5% in the surrounding area.

While considering the local impacts - i.e. on the level of the Region itself - this scenario led to a 76 M€ decrease in the external costs related to the local damage which are mainly dominated by the effects on mortality associated with the particles.

In term of reduction of the greenhouse gas emissions, this scenario led to a decrease of 8% what corresponds to an environmental benefit of 0.144 M € in comparison with the reference situation for the year 1998.

This scenario also highlights a rather significant decrease in the emissions of precursors of tropospheric ozone: -7.3% for NOx and –13.4% for the COV. This consists in a global evaluation integrating the direct and indirect emissions associated with this scenario. Taking into account the complexity of the phenomena involved and their non-linearity, this analysis was supplemented by a simulation of the effects of these emission reductions on the photochemical pollution around Brussels.

The results of this simulation show a general decrease in the peak-values (-1.6% on average), in the maximum 8 hours average concentrations (-3.9% on average) characteristic of the effects on health as well as in the 24 hours average concentrations (-4.7% on average) representative of the damage on the crops and the vegetation. In term of health damage, this scenario of massive introduction of electric vehicles leads to a decrease of 1.8% in the external costs associated with the episode for the geographical area under study, that is to say a benefit of 40,000 € (1.6 MBEF). This significant reduction of the externalities on human health is mainly to relate to the positive effect of this scenario on the ozone concentrations in the two main urban areas which are Antwerp and Brussels contrary with what was observed for the scenarios of general strategy.

Indeed, with regard to the effects of this scenario specifically on the situation in the Brussels-Capital Region, simulations made it possible to show significant reductions in the maximum ozone concentration during the episode and in the maximum 8 hours average concentration. These evolutions lead to damage associated with photochemical pollution estimated at 0.33 M €, which represents a decrease of almost 4% in the external costs in comparison with the reference case.

5. ASSESSMENT OF THE ECONOMIC AND ENVIRONMENTAL ASPECTS

While referring to the scenario of introduction of electric vehicles of which the environmental effects are summarised above, it appears that this scenario makes it possible to improve the general situation with regard to photochemical pollution and led to significant environmental benefit in comparison with the damage caused during an episode. These benefit rise to 40,000 € (1.6 MBEF) for the geographical area considered and 12,355 € (0.5 MBEF) specifically for the Brussels-Capital Region.

As a reminder, within the framework of this study, we focused on only one episode, for a given area and that we considered only the short-term effects on human health. If one multiplies these amounts by the number of episodes or situations where ozone concentrations produce already effects on the population, the environmental benefit of such a measure could be much more significant. The integration of the short-term and long-term effects on crops and the vegetation should also lead to higher amounts.

In comparison with the environmental benefit associated with the local damage, the benefit associated with an improvement of the photochemical pollution is rather limited. For the same scenario, these benefit were quantified to approximately 76 M€ per annum. The benefit related to a reduction of the damage associated with the climate change had been estimated at 0.144 M€.

With regard to the annual costs of implementation of the various scenarios considered in the economic analysis, the economic analysis showed that they range from 0.1 M€ for the access restriction to certain areas of the Region to nearly 130 M€ for the implementation of a network of centres of distribution of goods coming by road exploited to the maximum. The annual costs of implementation of a general scenario integrating the various measures suggested but on a weaker level of exploitation as for them were evaluated with a little more than 70 M€.

To conclude, the reduction of the damage related to photochemical pollution that the introduction of electric vehicles in the Brussels-Capital Region allows does not compensate for with it only the costs of implementation of a voluntarist policy. On the other hand, the taking into account of the other positive effects which are associated with this introduction justifies such an investment mainly if one takes account of the health effects at the local level.

CG/67/28A
CG/E1/28B

ECONOMIC IMPACT MODULES FOR THE EUROS MODEL

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The project ‘Economic Impactmodules for the EUROS-model’ was worked out by VITO – Flemish Institute for Technological Research – in cooperation with ECONOTEC – a private consultancy company with a strong specialisation in environmental subjects.

In summertime, there are often high ozone concentrations. Because of its oxidising character, ozone is damaging for public health and vegetation. The formation of ozone results from the oxidation of volatile organic compounds (VOCs) in the presence of nitrogen oxides (NOx) and sunlight. If the ozone concentration is higher than 180µg/m³, the government warns the public for negative impacts on health. To reduce the ozone concentrations, both long-term and short-term measures have to be taken by the government. The Göteborg Protocol to the Convention on Long-Range Transboundary Atmospheric Pollution (CLRTAP) of the UN/ECE prescribes emission ceilings for the emissions of NOx, NMVOC, SOx and NH_3 in 2010. The European directive on National Emission Ceilings (NEC) is even stricter.

EUROS is a atmosferic dispersion model developed by RIVM (Netherlands) and adapted for Belgium by Vito, calculating ozone concentrations as a function of NMVOC and NOx emissions as well as meteorological and geographical data. The aim of the present project was to built a module for evaluation of costs and benefits of emission reduction scenario’s and hence of emission reduction policy measures.

An inventory of all available emission data was made up. All emissions were aggregated and the totals were compared with the totals registered by EMEP[7], the European Emission Inventory. A lot of attention was given to the inventorying of emissions.

In a study by J. Duerinck (article added) an analysis is made on the robustness of emissions reduction cost functions. A national emission reduction cost function for VOC emissions and the Monte Carlo Method are used to demonstrate the high degree of uncertainty in the global cost estimations due to uncertainties in volume components of the emission reduction cost function. It is demonstrated as well that uncertainties in the price components are less critical although a small downward bias is observed.

Also emission reduction technologies were inventoried. Emission reduction measures can be split up into primary and secondary measures. Primary measures prevent emissions, secondary measures abate emissions. The necessary information to be

[7] EMEP: Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe

able to link the technology with the installations were abatement efficiency, investment and operation costs and technical information.

A model was set up with the collected emission and technology data. In total 85% of the NOx-emissions from stationary resources are imported in the model. For each installation responsible for those emissions, technologies for emission reduction were identified. For NMVOC 65% of the emissions was identified in the model. All emissions in the model can be located geographically. They are divided into two categories: point sources and area sources. For NOx the greatest part of the stationary emissions are point sources.

The model allows to calculate for a certain year in the future the emissions in a business as usual scenario, the possible emission reduction for this year and the costs linked to this reduction. The model calculates also the mean and marginal costs for each combination. These data are used to calculate total costs and draw cost curves.

For the projection of the mobile sources, the results from the study of I. De Vlieger (VITO) et al. (2001) “Measures in the transportsector for the reduction of CO_2 and troposferical ozone” were used. These mobile emissions were considered as line sources. In the framework of the present study, they were split out over the belgian transport infrastructure (roads, railways & waterways).

In the following table an overview is given of the results of the different scenarios that are calculated. 1997 served as the reference year. All the collected data are for this year. For the business as usual (BAU)-scenario 2010, the data from 1997 are projected with sector evolution factors, taking into account the current legislation and known end-of-life replacements till 2010. The sector evolution factors used are from the MIRA-S scenarios (Flemish environmental report), calculated by the Federal Planing Agency and from the EPM model of ECONOTEC. Based on the data for 2010 the maximal reduction scenario is calculated. Because the hypothesis ‘the emissions grow as fast as the sector’ is contestable, we calculated a BAU-scenario with the hypothesis that the emission growth stands still and only reduction is possible.

Although the business as usual (BAU) scenario 2010 does not reduce enough to satisfy the Göteborg Protocol ceilings and the European directive on National Emission Ceilings (NEC), extra emission reduction measures could be found to satisfy the emission ceilings for the NOx-emissions, but not for the NMVOC-emissions. The volume of the NMVOC-emissions are not well known, nor costs and effectiveness of NMVOC-emissions reduction measures. Further research on this subject could reveal new reduction potentials.

Table 1: *Total emissions for the different scenarios*

kton	NOx	NMVOC
Göteborg	184	144
NEC	176	139
IIASA MFR 2010[8]	127	102
1997	305	292
2010 BAU	227	196
2010 BAU 0% growth emissions	204	179
2010 BAU MAX	159	174
2010 BAU 0% MAX	147	160

The emissions of the reference year, the BAU scenario 2010 and BAU 2010 maximal reduction were geographically split out and converted to a grid with square cells of 15 by 15 kilometers. Those grids were used by the EUROS model (EURopean Operational Smog Model) which calculates the ozone concentrations given the emissions. The ozone concentrations are used to calculate the benefits from ozone reduction. The emission data from the BAU-scenario with growth rate 0% are not imported in EUROS given the long calculation time of the EUROS model.

For the cost calculation, the emission reduction costs borne to satisfy current legislation or end-of-life replacements are not taken into consideration. Only the cost for extra reduction were calculated. Cost curves were set up based on the emissions for the BAU 2010 scenario. The BAU 2010 scenario was also calculated with 0% growth of the emissions to simulate a stand still of the emissions. Based on these emissions, cost curves for NOx and NMVOC were set up. The maximal reduction that could be reached by cost curves can be seen in the table above. The costs associated with it can be found in the table below. In an exercise was shown that the cost associated with a policy implementing norms for burners, based on the fuels used, are higher than the costs in the cost-effective case.

[8] Maximum Feasible Reduction scenario, as calculated by IIASA (International Institute for Applied System Analysis) in preparation of the Göteborg protocol

Table 2: *Maximal reduction (kton) and costs (MEURO) associated*

	NOx		NMVOC	
	kton reduction	MEURO	kton reduction	MEURO
2010 BAU MAX	68	392	22	372
2010 BAU 0% MAX	57	435	18.3	353

The benefits are ca lculated by a model that was set up. The model uses the ozone concentrations of ten points distributed over Belgium, generated by the EUROS model. Based on the difference between the ozone concentrations of two scenarios, the model calculates the benefits of NOx and NMVOC reduction. Benefits can be a direct or indirect effect of ozone reduction. With the direct effects is meant the change in health effects and agricultural effects caused by a change in ozone concentrations. Lower ozone concentrations gives lower health or agricultural effects, thus benefits, higher ozone concentrations means negative benefits or costs.

Indirect effects are effects caused by NOx in the formation of nitrates. The reduction of those effects is not a direct consequence of the reduction of the ozone concentration, but of the reduction of NOx.

Table 3: *Comparison between costs and benefits*

	Reduction (kton)		Costs (MEURO)		Benefits (MEURO)			
	NOx	NMVOC	NOx	NMVOC	Direct		Indirect	Total
					Health	Agriculture		
1997 – BAU 2010	78	96	-	-	7,5	12	236,9	256,4
BAU 2010 – BAU 2010 MAX	68	22	392	372	-5,1	5	334,1	334,0

In table 3, the costs and benefits of the transition from one scenario to another are put together. As mentioned before, the costs for satisfying current legislation or End-Of-Life replacements are not taken into account.

Based on the direct effects, benefits in health and agricultural effects, there appear to be no benefits from NOx and NMVOC reduction in BAU 2010 MAX.

This result is due to the fact that NOx-emissions can create and delete ozone. The relation between the amount of NOx-emissions and the ozone concentrations is non-linear. Till a certain point, ozone concentrations are increasing with lower NOx concentrations, after this point ozone concentrations are lowering. In this study, it was not possible to indicate how much NOx reduction gives lower ozone concentrations. The calculation time limited the number of scenarios that could be worked out. The only conclusion that can be drawn is that BAU 2010 Max creates no direct benefits in comparison with BAU 2010.

On the other hand, the indirect effects of NOx reduction, health effects from the reduction of nitrates, are more important then the direct effects, even taking into account the uncertainty of the benefits of the indirect effects. The indirect effects could make further NOx reduction profitable.

The estimations for the different scenarios were made with constant emissions for foreign countries. The effect from emission reductions abroad were not taken into account. The effect abroad from emission reductions in Belgium were also not calculated. Further research taking into account foreign countries, on this subject could be interesting.

It must be stressed that a complete cost-benefit analysis is an ambitious task because of the long calculation times of the EUROS model and the extensive work in making data compatible. However the cost and benefit modules could be used independently. The cost module could be applied to generate emission reduction cost curves in detail (sector, region, technology,...). The benefit module could be used to evaluate output of the EUROS model.

PART 2: TO PROVIDE SCIENTIFIC SUPPORT FOR BELGIAN POLITICS

Related supporting actions

AS/E1/001

EPM MODEL : EMISSION PROJECTION OF GREENHOUSE GASES IN BELGIUM IN 2010

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In the framework of the project “Analysis of emission reduction options for greenhouse gases and tropospheric ozone precursors”, ECONOTEC’s mission has consisted in continuing the development of the EPM (Emissions Projection Model) model, by making a new version of it in a database environment, and in applying the model to make a contribution to the preparation of emission reduction policies.

In a first phase, the efforts have been on NOx and VOC emissions. The results of these activities have been valorised in the framework of the preparation of the Gothenburg Protocol[9] and the European directive on national emission ceilings[10].

The second part of the research has been devoted to the main greenhouse gases concerned by the Kyoto Protocol, i.e., CO2, CH4 and N2O. The priority has been given to CO2, which relates to all economic activities and which, in tonnes of CO2-equivalent, represents over 80% of the total greenhouse gas emissions.

The tasks carried out have consisted in:

- the informatic data organisation, which has led to a complete reformulation of the model (from spreadsheets to the Access database software), which has significantly increased the model’s performance;
- the data collection and validation;
- the use of the model for constructing reference (business-as-usual) emission scenarios and the evaluation of emission reduction potentials of the various gases concerned.

The report describes the main characteristics of the EPM model and presents results of an emission projection analysis for CO2 and the other greenhouse gases in Belgium in 2010 (reference scenario, emission reduction potential).

[9] Protocol to the United Nations Convention on Long Range Atmospheric Pollution (CLRTAP).
[10] Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants.

A bottom-up model

The EPM model is a projection model of the energy demand and the main atmospheric pollutants, which covers the various sectors concerned (industry, residential, tertiary, transportation). It has been developed progressively by ECONOTEC since 1993 in the framework of a range of studies carried out for the public authorities, as well at the national as at the regional level.

Given the heterogeneity of "sectors" such as the iron & steel industry, the chemical industry or the residential sector, one must, in order to be able to make a good projection, take into account the internal structural effects of these sectors, that is the differential evolution of the main sub-sectors or production processes (for example the different workshops of the iron & steel industry), as far as their specific energy consumptions are different.

EPM is a simulation model, of the "bottom-up" type, i.e. explaining energy consumptions and CO2 emissions from, as far as possible, activity variables expressed in physical units, containing a detailed representation of emission sources and the main determining factors of the evolution of energy demand and the various types of emissions.

This methodological option is based on the observation that there do not exist simple and homogenous relationships between energy consumptions and macroeconomic variables expressed in monetary units.

The model, which includes a techno-economic data base on the energy consumption and emission reduction measures, is used in particular for:

- the construction of a *reference scenario* (business as usual), representing the most probable future evolution in the absence of any new emission reduction policy;
- evaluating economic emission reduction potentials;
- constructing emission *reduction scenarios*, based on the reduction measures with a marginal cost below a given ceiling;
- constructing *cost curves*, providing either the marginal or the total cost as a function of the level of emission or energy consumption reduction;
- assessing the impact of existing or draft legislations on energy consumptions, emission levels and costs.

The reference scenario is calculated from energy consumptions of a reference year (after climate correction), as well as from assumptions on the evolution of activity variables, specific energy consumptions and market shares of the different fuels.

Industry is represented by about a hundred activity variables (pig iron production, oxygen steel production, ethylene production, clinker production, flat glass production…). The large energy consumption branches are modelled in more detailed than the others. For example, iron & steel production is taken into account per workshop (agglomeration, blast furnace, oxygen steel production…) ; for the chemical industry about twenty basic products are distinguished.

A far as the residential sector is concerned, one distinguishes between existing and new houses, existing and new apartments (electric and non electric heated), domestic water heating and 10 specific uses of electricity (cooking, refrigerators, washing machines, dryers…). The heat load is estimated using a separate module, from a typology of the building stock composed of 14 type-dwellings, of which the dimensioning and the thermal characteristics are entirely defined. In this module, the energy consumptions are calculated using the performances of 15 heat production, distribution or emission systems.

In the tertiary sector, about 30 sub-sectors are grouped into 8 categories, and 5 energy uses are distinguished (heating, ventilation, cooling, lighting and other electric uses). The activity variable is the floor area of buildings.

In the transportation sector, one distinguishes between road transportation of persons, road transportation of goods, rail transportation and inland water transportation. For road transportation, the modelling is carried out in a separate module allowing to calculate emission levels as a function of the average specific energy consumptions of vehicles at the time of their first use and taking into account (European) regulations on polluting emissions applicable at that time.

The emission reduction potentials are calculated in the following way. For each sector, the energy consumptions are divided by use of energy (heating, fans, compressors, cooling, lighting…). For each emission source, the reduction measures are identified, as a function of the use of energy, and costs and performances are evaluated, as well as the technical potential of these measures. By measure, by sector, by energy use and by year, the model calculates the cost per tonne of CO_2 as the sum of the annualised investment cost and the operating costs, minus the value of the energy saving achieved. The latter is a function of the energy carrier, the sector, the year and a possible tax.

For CO_2, about a hundred measures are taken into account in the model, which may be specific to one or more sectors, to one or more energy uses or generic. These measures can be classified in the following categories: energy saving, cogeneration, renewable energy and energy substitution.

The ‘economic’ emission reduction potential is defined as the fraction of the technical potential with a marginal cost below a given ceiling (in €/t CO_2). In practice, it can be observed that the price of equipments, their utilisation rate, the installation and maintenance costs, as well as the emission reduction rate vary from one particular site or application to another. For this reason, the model takes into account a dispersion around the average cost of each measure, assuming a normal probability distribution. This prevents the economic potential of a particular measure to unrealistically jump from 0% to 100% when its cost decreases from just above the marginal cost ceiling to just under that ceiling, or vice versa.

Reference scenario

The table below shows the evolution of CO_2 emissions per aggregate sector for the reference scenario for the *Electricity sector* variant, where emissions of the centralised electricity production are ascribed to the electric sector.

Electricity sector variant*

BELGIUM	**CO2 emissions (Mt)**			**Evolution**		
	1990	1997**	2010	90-97	97-10	90-10
			Ref. sc.		Ref. sc.	Ref. sc.
Energy sector (without autopr.)	27,9	29,1	37,3	4%	28%	34%
Industry	42,2	41,4	47,4	-2%	15%	12%
of which process emissions	*8,6*	*12,5*	*13,7*	*46%*	*10%*	*60%*
Transportation	19,8	22,0	25,7	11%	17%	30%
Domestic and équivalent	27,6	34,1	35,3	24%	3%	28%
Total	**117,4**	**126,5**	**145,7**	**8%**	**15%**	**24%**

* *Emissions of the electricity sector ascribed to the electricity sector*
** *Climate corrected*

The figures for 1997, used as base year for the projection, are corrected so as to reflect an average climate. This climate correction increases the consumption of the residential sector by 7.8% and that of the tertiary sector by 5.6% (‘Domestic and equivalent’ sector). The year 1990 is not corrected, for it is the reference year of the Kyoto protocol, which does not foresee a climate correction.

In this table, the energy sector represents about a third of the total emissions. It essentially concerns the electricity production sector.

In the following table, the emissions of the electricity production sector are ascribed to the various final consumption sectors, as well as to the net export of electricity (*Final consumption* variant). Hence they are accounted as indirect emissions. The emission factor of the electric kWh used for this is the average emission factor of electricity production for the corresponding year.

The target of the Kyoto protocol for Belgium is an emission reduction of 7.5% in 2010[11] compared with 1990 for the total anthropogenic emissions of CO_2, CH_4, N_2O, PFCs, HFCs and SF_6, expressed in t of CO_2-eq.

Final consumption variant*

BELGIUM	**CO2 emissions (Mt)**			**Evolution**		
	1990	1997**	2010	90-97	97-10	90-10
			Ref. sc.		Ref. sc.	Ref. sc.
Energy sector (without autopr.)	6,8	7,8	8,4	15%	7%	24%
Industry	52,2	52,8	63,9	1%	21%	23%
of which process emissions	*8,6*	*12,5*	*13,7*	*46%*	*10%*	*60%*
Transportation	20,2	22,4	26,3	11%	17%	30%
Domestic and équivalent	36,9	44,9	49,5	22%	10%	34%
Net export of electricity	1,4	-1,3	-2,3	-193%	75%	-263%
Total	**117,4**	**126,5**	**145,7**	**8%**	**15%**	**24%**

** Emissions of the electricity sector ascribed to the final consumption sectors*
*** Climate corrected*

If one assumes that the reduction rate is applied to CO_2 only, this would imply a CO_2 emission level of 108.6 Mt CO_2 in 2010. But the reference scenario shows an increase in emissions of 24% between 1990 and 2010. Hence there is a gap of 145.4 – 108.6 = 36.8 Mt CO_2, i.e. 25% of the emissions of the reference scenario in 2010.

The following table shows a synthesis of the reference scenario for all greenhouse gases (GHG) concerned by the Kyoto protocol. Therefore it includes, besides CO_2, CH_4 and N_2O, also the fluorine containing gases HFCs, PFCs and SF_6.

In 2010, CO_2 represents over 83% of the total emissions, and CH_4 and N_2O together 14%. As to the emissions of the fluorine gases, which were still practically not existing in 1995, they are strongly increasing and could reach about 2% of the total.

[11] More precisely, for the average over period 2008-2012, which allows a smoothening of the climatic variation.

Overall, the CH_4 emissions decrease by 26% over the period 90-2010, while the N_2O emissions rise by 18% over the same period. The decrease in methane emissions is essentially due to the reduction in emissions of waste dumps.

The results obtained show that in the reference scenario, corresponding to the expected evolution of CO_2, CH_4 and N_2O emissions in the absence of any new emission reduction policy, the emissions of the six gases, expressed in t CO_2-equivalent, increase by 21% between 1990 and 2010. The gap to be filled in order to satisfy the Kyoto target is 41.2 Mt CO_2-eq, i.e. 24% of the emissions of the reference scenario in 2010.

It should be noted that there remains a significant uncertainty on the emission levels, especially for the non CO_2 gases. This uncertainty mainly concerns the emission factors, in particular in agriculture, and their future evolution.

BELGIUM - OVERALL EMISSIONS OF THE "KYOTO" GREENHOUS GASES, IN CO2-EQ
Reference scenario

(kt CO2-eq)	1990 (*)		2010		90-01 evol.
CO2					
Combustion	108.842	*75,6%*	132.015	*75,7%*	21%
Process emissions	8.553	*5,9%*	13.719	*7,9%*	60%
TOTAL	**117.395**	***81,5%***	**145.734**	***83,5%***	**24%**
CH4					
Energy	1.264	*0,9%*	1.101	*0,6%*	-13%
Combustion	311	*0,2%*	315	*0,2%*	1%
Natural gas grids	954	*0,7%*	786	*0,5%*	-18%
Industrial processes	37	*0,0%*	21	*0,0%*	-44%
Waste treatment	4.551	*3,2%*	1.612	*0,9%*	-65%
Agriculture	8.252	*5,7%*	7.700	*4,4%*	-7%
Enteric fermentation	4.855	*3,4%*	4.370	*2,5%*	-10%
Manure storage	3.397	*2,4%*	3.330	*1,9%*	-2%
TOTAL	**14.104**	***9,8%***	**10.434**	***6,0%***	**-26%**
N2O					
Energy	994	*0,7%*	1.696	*1,0%*	71%
Stationary combustion	711	*0,5%*	791	*0,5%*	11%
Transport	283	*0,2%*	905	*0,5%*	220%
Nitric acid production	3.057	*2,1%*	4.423	*2,5%*	45%
Agriculture	7.093	*4,9%*	6.552	*3,8%*	-8%
Emissions from soils	4.874	*3,4%*	4.565	*2,6%*	-6%
Manure storage	2.220	*1,5%*	1.987	*1,1%*	-10%
Forests	729	*0,5%*	729	*0,4%*	0%
Anesthesia	222	*0,2%*	222	*0,1%*	0%
Waste water treatment	0	*0,0%*	662	*0,4%*	
TOTAL	**12.096**	***8,4%***	**14.284**	***8,2%***	**18%**
HFCs, PFCs AND SF6 (**)	**442**	***0,3%***	**4.000**	***2,3%***	**805%**
GENERAL TOTAL	**144.037**	***100,0%***	**174.452**	***100,0%***	**21%**

(*) 1995 in the case of HFCs, PFCs and SF6.
(**) Preliminary estimate

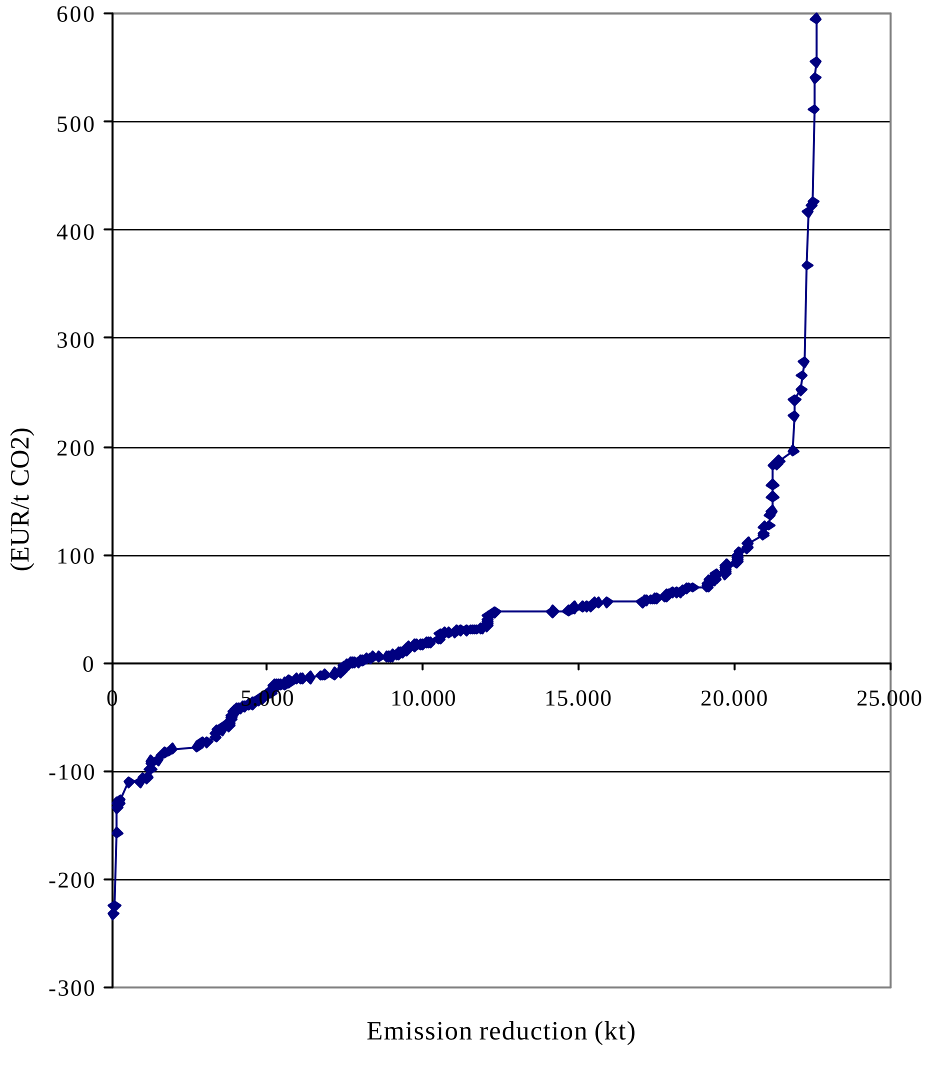
The Kyoto target for the six greenhouse gases CO2, CH4, PFCs, HFCs and SF6, to reduce emissions by 7.5% in 2010 in comparison with 1990 implies an emission level of 133.2 Mt CO2-eq in 2010.

But the reference scenario shows an increase in emissions of 21% between 1990 and 2010. The gap to be filled is 174.4 – 133.2 = 41.2 Mt éq-CO2, i.e. 24% of the emissions of the reference scenario in 2010.

Reduction potential

The emission reduction potential (from the reference scenario) has been evaluated in detail for CO2, for all emission sources outside the transportation sector. This potential is illustrated by the marginal cost curve on the figure below[12].

Marginal reduction cost of CO2 emissions in 2010
(from the reference scenario)
Belgium - ALL SECTOR (except transportation)
Depreciation rates 10-15-30%



[12] It should be noted that such a curve remains approximate, as it does not take into account the dispersion on the cost of reduction measures that has been introduced in the model. For this reason, the economic potentials that can be read on the curve only imperfectly correspond to those of the tables.

If the Kyoto target were to be applied to CO_2 only, the figures mentioned above for the reference scenario and the evaluation of the reduction potential give the following situation:

CO_2 emissions in 1990 :	117.4 Mt CO_2	100%
1990 emissions minus 7,5% (Kyoto target)	108.6 Mt CO_2	92.5%
2010 emissions in the reference scenario	145.7 Mt CO_2	124%
Required reduction for the Kyoto target		
(from the reference scenario):	37.1 Mt CO_2	100%
Potential of measures (*outside transportation*) :		
Technical potential	22.1 Mt CO_2	60%
Contribution of measures with negative cost	9.2 Mt CO_2	25%
Contribution of measures < 14 $€_{00}$/t CO_2 [13]	10.9 Mt CO_2	29%

The main options for filling the gap are the following:

- an increased substitution of natural gas in the residential and tertiary sectors;
- measures in the transportation sector;
- the impact on activity variables (lowering of certain production levels, of mobility…);
- a more than proportionate reduction of the emissions of non-CO_2 greenhouse gases;
- the use of flexibility mechanisms foreseen in the Kyoto protocol (emissions trading, joint implementation, clean development mechanisms).

The overall potential of emission reduction measures for CH_4 and N_2O has not been quantified, for two reasons. First, it is difficult to give a 'technical' potential for agriculture, the main emission source, because of the uncertainty remaining on key parameters such as the contribution of modifications of animal feeding, the possible size of livestock reduction, the type of treatment that will be chosen for eliminating excess manure, and the duration of manure storage.

[13] 14 $€_{00}$ represents the level of the CO_2 tax proposed in the National Climate Plan (11,5 $€_{90}$).

Second, the measures allowing to reduce the emissions of CH_4 and N_2O of agriculture are generally motivated first of all by the reduction of other pollutions (such as the concentration of nitrates in aquifers and ammonia emissions), so that it is difficult to evaluate the cost of measures to be ascribed to the sole reduction of CH_4 and N_2O, and so to determine an 'economic' potential for these gases.

However, an estimate can be made of the potential for the main other emission source, the production of nitric acid, for which several catalytic N_2O emission reduction processes are presently being developed or demonstrated. Tests carried out on real sites show that a reduction efficiency in the order of 80% can be achieved. If the results obtained can be confirmed and if this technique can be applied to the whole Belgian capacity until 2010, the corresponding potential would, on the basis of the emissions in our reference scenario, be of about 3.5 Mt CO_2. Depending on the technique used, the cost should not exceed 1 to 3 €/t CO_2.

The results above should not be considered as definitive. They derive from a large number of data and hypotheses, which are based on the best available information, but on which often remains a significant degree of uncertainty and which could have to be modified in the future.

Beyond the results presented in this report, the EPM model is above all a tool allowing to test hypotheses, and, as such, an instrument of dialogue with the actors concerned (public authorities, industrial sectors…).

In the framework of the project, ECONOTEC has, during the year 2001, collaborated with the Federal Planning Bureau on a coupling of the EPM model with the HERMES macro-sectoral model. This study has allowed the construction of CO_2 emission scenarios where the macroeconomic impact of the emission potential estimated by the EPM model is taken into account. The results of this analysis have been used in the third Belgian 'National communication'[14] and in the National Climate Plan 2002-2012.

Besides, the model has also been used in the framework of the preparation of the 'Air Plan' of the Walloon Region.

[14] In the framework of the United Nations Framework Convention on Climate Change.

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