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AN INTEGRATED DECISION SUPPORT TOOL FOR THE PREDICTION AND EVALUATION OF EFFICIENCY, ENVIRONMENTAL IMPACT AND TOTAL SOCIAL COST OF FORESTRY PROJECTS IN THE FRAMEWORK OF THE KYOTO PROTOCOL

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Abstract

For the implementation of the Kyoto Protocol, governments of annex I countries need to develop strategies and policies for greenhouse gas reduction. Land use, land use change and forestry (LULUCF) offer CO_2 emission reduction opportunities both home and abroad. Selection of effective forestry opportunities is a complex decision process based on multiple information concerning the greenhouse gas emission reduction potential, the environmental impacts and the cost efficiency of potential scenarios. In this paper, a decision support framework to evaluate forestry scenarios for greenhouse gas emission reduction was presented and tested on five different scenarios (existing and new multifunctional forest in Flanders, Belgium, energy crop with short rotation poplar, energy crop with annually harvested *Miscanthus*, forest plantation in the subtropics, and conservation of tropical rainforest). The framework is organized as a serial connection of a carbon accounting module, an environmental module and an economic module. Modules include a combination of models and quantitative assessments procedures. In order to make scenarios comparable, the environmental and economic modules calculate their outputs on a functional unit basis of 1 ton CO_2 emission reduction. The framework is universally applicable, straightforward, transparent and quantitative. Data requirements are medium, but applicability is fairly complex due to the interdisciplinary character of the tool. Further developments would require automated data flows between models and a user interface.

As to the results of the scenario analysis, the only attractive possibility for sinks in Flanders is the establishment of new multifunctional forests. This even yields a net benefit because it replaces the generally loss-making agriculture and, in addition, yields other environmental and recreational benefits. The establishment of bioenergy plantations is a very efficient way of reducing CO_2 as far as land occupation and environmental impacts are concerned. However, it also turns out to be a very expensive option. Plantation forestry in the tropics is advantageous when evaluated over longer periods of time. Conservation of tropical forest does not come into consideration as a CDM project, but is nevertheless economically attractive for Flanders since the cost per ton CO_2 emission reduction is in the neighborhood of the world market price.

Key-words: CO2 emission reduction, carbon balance, Life Cycle Assessment, Land use impact, Cost benefit analysis

1. Introduction

For the implementation of the Kyoto Protocol, governments of annex I countries need to develop strategies and policies for greenhouse gas reduction. Land use, land use change and forestry (LULUCF) offer CO_2 emission reduction opportunities both home and abroad. But emission reduction options attractive at first sight might turn out unsuccessful because they cause undesirable effects on the local environment, or because they are just too expensive. Therefore, the selection of effective greenhouse mitigation strategies in the forestry sector is a complex decision process based on multiple information, not only concerning the greenhouse gas emission reduction potential of the option, but also concerning its environmental impacts and its cost efficiency. Several similar studies have been described in literature, but mostly analysing a very limited number of scenarios or using simplified growth and yield models, ignoring the substitution of fossil fuels or the recreational value

(Schwaiger and Schlamadinger, 1998; Scholes, 1998; Hektor, 1998). In this project we have tried to improve the simulation procedure on all of these points.

In this paper we present a serial three step decision support procedure first modelling the CO_2 emission reduction, then calculating the environmental impact and finally accounting the total social cost of the evaluated scenarios. In Life Cycle Assessment (LCA) production scenarios are made comparable by expressing all environmental impacts per functional unit, i.e. one unit of the final product. In a greenhouse gas mitigation project, the product aimed at is greenhouse gas emission reduction. We therefore opted to express all environmental impacts and cost/benefits in this research per functional unit of 1 ton CO_2 emission reduction.

With the developed procedure we were able to evaluate and compare the opportunity for the Flemish Government (Belgium) of five LULUCF greenhouse gas reduction scenarios: local multifunctional forest, local bioenergy tree crop, local bioenergy agricultural crop, plantation forestry in the subtropics and primary forest conservation in the tropics.

The objective of this paper is to present a decision support framework for choosing efficient, environmentally sound and economically feasible greenhouse gas emission reduction scenarios in forestry, and to test this framework on a series of realistic scenarios including forest conservation, forest expansion, forest management, use of forest products and substitution of woody biomass for fossil fuels. Both domestic and foreign scenarios are examined in function of their relevance for Flemish policy. For the various land-use systems, the following outputs are sequentially produced: emission reduction efficiency expressed as land occupation (ha*yr) per ton CO_2 emission reduction; land use impact of the mitigation initiative on soil, water, vegetation structure and biodiversity expressed per ton CO_2 emission reduction; net social cost of the initiative per ton CO_2 emission reduction.

2. Evaluated scenarios and their system boundaries

2.1. Scenarios

Five land-use scenarios are compared, three at home and two abroad. Scenarios abroad are motivated in view of the limited available surface area in Flanders, Belgium, and in view of the productivity being considerably higher in tropical areas. The home scenarios are afforestation and management of multifunctional forest, short rotation coppice of willow and poplar for bioenergy, and Miscanthus cultivation for bioenergy. The scenarios abroad are afforestation with pine in the subtropics and conservation of tropical rainforest.

Local multifunctional forest (LOMUFOR)

A forest where wood production is combined with high ecological and recreational values, characterized by long rotations (150 years), managed with a thinning frequency of once every 10 years and regenerated with a group selection system. Both an existing multifunctional forest and an afforestation on agricultural land are examined. For the simulation of the existing forest, we used inventory data of Meerdaal Forest near Leuven, Belgium (50°48’ N, 0°20’ E). It is a 1200 ha Forest Stewardship Council certified ancient woodland, dominated by pine, oak and beech. In the simulation pine stands were progressively replaced by oak and beech according to the actual management plan. For the afforestation we considered 250 ha of agricultural land north of Meerdaal Forest, on which we simulated the establishment of a similar mixed oak-beech forest with a normal age class distribution after 150 years. This was done through a provisional forest with a steadily decreasing share of poplar stands.

Local Short rotation coppice (LOSRC)

For the production of bioenergy simulations are run during which the same agricultural lands are planted with the best available willow and poplar clones. The highest yields are reached in a 3-year rotation cycle for the above-ground biomass and a 25-year rotation cycle for the below-ground biomass. Biomass is harvested fully mechanized, chipped and gazified for electricity production using state-of-the-art decentralized technology. After 25 years, stumps are removed and the plantation is re-established.

Local Miscanthus (LOMISC)

A comparable scenario as LOSRC, except for the used species, here elephant grass (*Miscanthus x giganteus*), the rotation for the above-ground biomass, which is annual, and the management and harvesting techniques used.

Pine plantation subtropics (PLANTROP)

Simulations are run for afforestation of semi-natural scrubland with *Pinus radiata* based on input data from the FSC certified Jonkershoek plantation near Stellenbosch, Western Cape, South Africa (18°55’ E, 33°57’ S). The rotation length is 30 years and includes two thinnings and a final clearcut.

Tropical rainforest conservation (CONTROP)
Simulations are run based on multiple literature data. The assumption is made that the forest would be transformed into grassland without the project. It is important to mention that during the course of our study, it was decided in Marrakech at COP9 that conservation of tropical rainforest is not accepted as an option for Clean Development Mechanism (CDM) projects during the first commitment period of the Kyoto Protocol.

2.2. System boundaries

The scenarios were simulated for particular areas sufficiently large to comprise various soil types. The analyses are first conducted per soil type and then spatially scaled up in a GIS environment for the entire area (spatial analysis).

The carbon budget of all scenarios was fully accounted including:
- sequestration in above- and below-ground biomass, detritus and soil of the delineated study areas;
- sequestration in harvested wood;
- emissions by management, harvesting and processing activities;
- substitution of bioenergy for fossil fuels.

Substitution of wood for energy-intensive materials was not accounted due to lack of accurate data.

The environmental impact assessment focused on the land use impact, including impacts on water balance, soil fertility, vegetation structure and biodiversity.

In the economic analysis, the following costs and benefits were taken into account and, if relevant, compared to present land use:
- Investment and operating costs (costs of establishment, management, and harvesting, costs of energy production);
- Yield (various forest products, costs of avoided fossil-fuel energy production);
- Environmental costs (except for climate changes);
- Avoided environmental costs by substitution of fossil-fuel energy production (except for climate changes);
- Value of the area for recreation; non-use value of the area.

The economic analysis of the foreign scenarios is conducted from the position of the Flemish Government (and thus does not concern the costs and benefits of the foreign country involved).
For all analyses, the most probable and/or most appropriate management, climate, cost, etc. were used. However, to evaluate the influence of the selected input parameters, a number of sensitivity analyses were conducted with changing boundary conditions. The sensitivity analyses conducted were:
- for the carbon modelling: the influence of nitrogen fertilization, irrigation, rotation time, and expected climate changes (global change);
- for the environmental impact assessment: influence of climate, soil and vegetation characteristics;
- for the economic evaluation: influence of the discount rate.

All simulations were made for 150 years (the rotation time of an oak-beech forest). In addition to the end value after 150 years, the outputs after 10 and 20 years of simulation as well as the averages over the first 10 and 20 years and over the entire 150 years are calculated. Results after 10 and 20 years are relevant in connection to the commitment periods of the Kyoto Protocol; 150 years simulations show the trends in the long term.

3. Methodology

The structure of the decision support tool consists of three serial modules: a carbon assessment module, an environmental assessment module and an economic assessment module (figure 1).

3.1. The carbon assessment module

The carbon assessment module consists of two serially linked models: the mechanistic forest model SECRETS and the carbon accounting model GORCAM. The principal output of this module is the CO_2 emission reduction per hectare per year, and its inverse, the space*time requirement (in ha*yr) per functional unit of 1 ton CO_2 emission reduction.

SECRETS

Although many forest models exist (see review in Tiktak & van Grinsven 1995), most are only able to simulate one kind of species or type of forest (Clifton-Brown *et al.,* 2000; McMurtrie, 1992; Isebrands and Host, 1996). Furthermore, it was shown by Carey *et al.* (2001) that the use of models for single species in even-aged stands can underestimate NPP of natural ecosystems by 50-100% and as a result upscaling from such models could account for 4-7% of the missing carbon.

The forest growth model SECRETS (Stand to Ecosystem CaRbon and EvapoTranspiration Simulator), is a modular, process-based model, that can simulate a forest consisting of different patches with different species in the over- and understoreyIt has been previously used and parameterised to simulate mixed stands of pine, oak and beech in Belgian forests (Sampson and Ceulemans 2000; Sampson, Janssens et al. 2001). The biomass allocation module has recently been adapted to simulate short rotation coppice and subtropical pine plantations and parameterised using data from an experimental poplar plantation in Flanders, Belgium and from Jonkershoek estate in South Africa respectively (unpublished data). The model simulates all carbon and water fluxes to and from the above – and below-ground biomass, as well as to and from the soil. Additional changes to the model were made to allow the simulation of forest management such as thinning and coppicing.

For the local scenarios a set of weather data including hourly values of irradiation, rainfall and humidity, day- and night temperatures was created with a weather generator (Rasse *et al.,* 2001) based on a data set from the pine forest in Brasschaat. For the subtropical plantation daily values were available from a nearby weather station. Although the model yields hourly values of photosynthesis and respiration and daily values of growth, for this application yearly values only were used. The tropical rainforest was not modelled with SECRETS, but data were extracted from the literature.

GORCAM

The model GORCAM (Graz Oak Ridge Carbon Accounting Model, Schlamadinger and Marland, 1996; Schlamadinger *et al*., 1997) is a mathematical spreadsheet model that calculates the input/output balance of CO_2 fluxes from and to the atmosphere associated with bioenergy and forestry activities. It allows to extend the system boundaries of the forest production system to include the fate of the forest products. In order to calculate the carbon balance of the system, it takes into account carbon sequestration in living biomass, detritus and soil, carbon sequestration in wood products, carbon emission reduction due to substitution of woodfuel for fossil fuels and of wood products for other materials, and carbon emission during forestry activities, harvesting, transport and conversion.

GORCAM is normally used stand-alone, based on input from literature sources and expert knowledge and driven by a forest growth curve derived from an empirical yield table. Empirical yield tables are able to run GORCAM under well-established conditions from the past, but are unable to cope with changes in climate and management. This becomes perfectly possible by a serial connection of the mechanistic model SECRETS with the accounting model GORCAM. Growth curves produced by SECRETS under changing conditions of climate and management are fitted to a Richards function and used as an input for GORCAM.

Other outputs of SECRETS used as an input for GORCAM are the biomass allocation, litter production and decomposition rates. Harvested biomass was sorted in different product categories according to wood quality. The procentual portion of each category in the total aboveground biomass, its lifetime and its recycling rate are given in Table 2. A lifetime of x years indicates that 50 % of the product mass has come to end of life and is being recycled 0.5x years after harvest. Due to lack of reliable data for Belgium, life expectancy and recycling rates are kept low. Fossil fuel substitution factors were based on present-day technologies. No substitution of wood products for other materials was considered.

3.2. The environmental assessment module

Land use impact indicator method of Muys and Garcia Quijano (2002)

For the assessment of environmental impacts of carbon projects, different approaches exist, such as Criteria & Indicators for sustainable forest management, Environmental Impact Assessment and Life Cycle Assessment (LCA). Because of the requirements for a quantitative approach, universal applicability and intercomparability between projects worldwide, and for the possibility to express results per functional unit, an LCA related approach is the better option. Within LCA, different land use impact assessment procedures were proposed (Baitz et al. 1998, Giegrich and Sturm, 1998). In the decision support framework we integrated the method of Muys and Garcia Quijano (2002). This method adopted the strengths and eliminated the weaknesses of earlier methods in accordance to the guidelines for land use impact assessment formulated by COST E9 (Schweinle, 2002). The method describes the land use impact by 17 quantitative indicators divided over the 4 themes soil

(soil compaction, soil structure disturbance, soil erosion, cation exchange capacity and base saturation), water (evapotranspiration and surface runoff), vegetation structure (total above-ground biomass, leaf area index, height, free net primary production and crop biomass) and biodiversity (artificial change of water balance, liming, fertilization and empoverishment, biocides, cover of exotic species and number of plant species). Indicators were chosen based on the hypothesis that the driving force of ecosystem development is towards maximisation of control over exogenic exergy flows. The natural climax vegetation at the studied site is chosen as the reference system with indicator score 0, because it has the highest possible site-specific exergy control under natural circumstances. Indicator scores are then calculated by comparing the actual land use with the natural climax vegetation and can range from an arbitrarily chosen minimum threshold of –25% for situations in which human activity could induce a level of ecosystem control and stability exceeding that of the natural climax, to 100% for degraded near to dead systems with high entropy. Where the study area is a mosaic of different site qualities and land uses, it has to be divided in homogeneous site*land use clusters. The level of detail to do so is depending on data availability. Indicator scores for the total area are obtained by area weighted averaging of the indicator scores for each cluster. The indicator scores for the total area are finally aggregated into four thematic indicators by averaging soil, water, vegetation cover and biodiversity indicators respectively. Most of the indicators are calculated with input data derived from literature and expert knowledge. The two water indicators and the soil erosion indicator were calculated with the SWAT model.

SWAT

Many models are available that can simulate these indicators, but they are not all equally useful for our application. From the available models, we selected the SWAT model (Soil and Water Assessment Tool, Neitsch et al., 2001). This model is situated midway between a point model and a spatial model. It gives results not only per spatial unit (that is, per soil/land use combination) but also the global response of the basin. This enables alternative land-use scenarios to be compared.

The SWAT model has an ArcView interface (DiLuzio et al., 2001), which facilitates the creation of input files and the spatial interpretation of the output. Input data are climatological data with a daily resolution (for the home scenarios produced with a weather generator and for the South African scenario observed data from a nearby weather station), digital elevation model (DEM), soil data (texture, saturated hydraulic conductivity, soil organic matter) and land use data (leaf area index, canopy height, root depth). The position of the water courses is derived from the DEM.

3.3. The economic assessment module

In this module, a social cost-benefit analysis (Layard and Glaister, 1994) is done to obtain the net social cost of one ton CO2 emission reduction, expressed in monetary terms, for each scenario. This net social cost is expressed as an annuity. It is a fixed annual payment that, accumulated over the duration of the project, has the same actualized value as the sum of actualised benefits (costs).

The following resource and environmental costs and benefits are taken into account:

1. Investment and operating cost of the project (IC)

   By this we understand the afforestation, regeneration and management costs of a forest or plantation. For the scenarios that result in energy production, the costs of processing the biofuels in power plants to produce electricity are also included. These are calculated based on the findings of the Belgian Ampère Commission, whose analysis used the data of the MARKAL database. We assume that a CPH unit on bioenergy will replace a CHP plant on natural gas (Ampèrecommissie, 2000). For natural gas, two types of CHP – STAG (combined heat and power - steam and gas) power plants of 30 MWe are considered, equipped with low NOx burners.

2. Profit of the project (Π)

   The profit includes the sales of wood from thinnings and final harvesting less the opportunity cost. Opportunity costs include the production that is lost when the agricultural land is converted into forest or poplar/Miscanthus plantations. For the bioenergy scenarios, the opportunity cost also includes the cost of the electricity production that can be substituted by making use of biofuels.

3. Environmental costs related to the scenario (EC)

   This concerns the impact of the scenario on water quantity and quality and on biodiversity. Damage/External costs due to the emission of greenhouse gasses in the production of energy on the basis of biomass and the like also belong to this. These external costs are costs imposed on society and environment that are not taken into account in the market price. They are derived from the revised report ExternE of the European Commission (CIEMAT, 1999).

4. Environmental costs avoided by substitution of other forms of energy by bioenergy (Environmental benefits) (EB)

This concerns the damages due to the emission of greenhouse gasses that are avoided when bioenergy replaces other forms of energy.

5. Other benefits related to the project (OB)

Multiple use forests deliver other services to society in addition to wood. They are places for recreation and they have a certain value that is not related to the actual use made of the forest. This is the so-called non-use value, which is based on the pure existence of the forest now and in the future. Monetary valuation is based on techniques such as the travel cost method (for recreation) and contingent valuation method (for non-use values). For the Meerdaal study area, an original valuation study was already conducted (Moons et al., 2000).

Three different net social costs are calculated for each of the scenarios. NSC_A includes investment and operating costs net of the profits. NSC_B adds environmental costs and environmental benefits and finally NSC_C adds other benefits as well and therefore is the most complete net social cost measure. The three net social costs are formally expressed as follows:

$$\begin{aligned}
NSC_A &= \sum_t \delta_t \left[IC_t - \Pi_t \right] \\
NSC_B &= \sum_t \delta_t \left[IC_t - \Pi_t + EC_t - EB_t \right] \\
NSC_C &= \sum_t \delta_t \left[IC_t - \Pi_t + EC_t - EB_t - OB_t \right] \\
with: \quad \delta_t &= discount\ factor\ (\text{exp}resses\ social\ time\ preference) \\
&= \frac{1}{(1+r)^t} (r = discount\ rate; t = time)
\end{aligned}$$

For the tropical forest, we distinguish between

- Net social cost A’ = the value of the tropical forest with commercial logging - the total value of the tropical forest under sustainable management;
- Net social cost B’ = the value of the tropical forest with agriculture - total value of the tropical forest with sustainable management;
- Net social cost C’ = net social cost A’ + value of selective logging;
- Net social cost D’ = net social cost B’ + value of selective logging.

3.4. Integration of the modules

The three modules are serially linked as illustrated in figure 1. The stepwise calculation for each of the scenarios is illustrated in figure 2. The inverse (1/R) of the CO_2 emission reduction, i.e. the time*space requirement per ton CO_2 emission reduction obtained as an output of the first module is multiplied with the land use impact scores S in order to obtain the land use impact per functional unit S/R. The environmental impact S is one of the cost factors in the total social cost per hectare C. Finally, the total social cost per hectare C is multiplied with the time*space requirement for one functional unit 1/R in order to obtain the total social cost per functional unit C/R.

4. Results and discussion

4.1. Greenhouse gas mitigation

Carbon sequestration in the ecosystem

The simulation results with SECRETS show realistic trends for all studied scenarios (table 1), The modelled yield of the short rotation coppice (20.7 t CO_2 ha^{-1} $year^{-1}$ or 11.3 t ha^{-1} $year^{-}$) is rather low compared to maximal values found in literature (Beale and Heywood, 1997), but compares well to average field data in Belgium (Laureysens *et al*., 2000). Improved clone selection and management could increase yield in future. Simulated Miscanthus yield is higher than SRC yield. Although there have not been extensive trials of Miscanthus in Belgium so far, these data compare well to values in UK, the Netherlands and Germany (Lewandowski *et el*., 2000; Scholes, 1998). As the crop is relatively new, further improvement of the yield is expected in future. The yield of the multifunctional forest and the subtropical plantation equal actual yield over the past years. The subtropical plantation simulated (Jonkershoek, South-Africa), has only a moderate yield, due to the specific climate and soil of the area. As expected, the yield of a multifunctional forest is very low at first (though this is partly compensated by planting poplar in the first year) and reaches stability only after 150 years, when yield becomes comparable to the existing forest.

Soil C plays an important role in the C sequestration of forests (McMurtrie *et al*., 2001). The soil C increased in all local scenarios, and most in the new multifunctional forest because of the lower management impact. Even soil C in the existing forest is predicted to increase further, as management is less intense compared to past management and soil C stabilises very slowly.

It appears from these results that SECRETS is able to realistically simulate a wide variety of species and management options with only minimal changes in the model. This is interesting since similar mechanistic models are only used for one species or type of species. Using the same model for all simulations greatly enhances the value of comparisons between results.

CO_2 emission reduction

The emission reductions achieved are given in Tables 2, 3 and 4. Negative values indicate emission of carbon into the atmosphere. They are found e.g. under consumption of fossil energy, which is higher in intensive systems and nil in the natural forest, or under replacement of previous land use in the PLANTROP scenario, where natural Fynbos vegetation must be removed before the plantation can be established. The tables show enormous differences in emission reduction between the scenarios. These differences very much depend on the time of the evaluation.

Upon evaluation after 10 years, energy crops score the absolute best, followed by new forest in Flanders. The other scenarios perform weakly. Energy crops score so strongly because of the substitution effect for fossil fuel. *Miscanthus* performs better than poplar because it produces even more biomass. Whether this is accompanied by an extra environmental burden must be shown by the environmental module. The good performance of new multiple use forest in Flanders is due to the provisional poplar forest, which allowed rapid build-up of biomass. The poor performance of plantation forest in the subtropics is the result of the fact that the plantation has replaced native scrub vegetation, which causes a great deal of CO_2 emission in the initial phase. After 10 years, this emission is not yet compensated for by the growing forest. Existing multifunctional forest and primary tropical forest score low because they are more or less in steady state. It is however important to emphasize that these values are positive and non negligible.

Upon evaluation after 20 years, we observe the same result with this difference that the tropical plantation scores better since the lost original biomass has already been amply compensated for by new growth.

Upon evaluation after 150 years, we see the same trends, with a pronounced top group of energy crops, a group with low reduction consisting of new forest in Flanders and the subtropics, and a tail-end group with multifunctional and primary forest. New forest in the subtropics grew more rapidly and yielded more products than new forest in Flanders, but in the latter, this was compensated by a higher degree of fossil fuel substitution and, due to longer rotations, by a higher average standing biomass.

*Time*space requirements*

In a world where land resources are scarce, it is very relevant to know the space requirements of an activity. As long as a forestry activity goes on, the land is occupied and cannot be used for other activities such as agriculture. But after termination of the forestry activity, the land may become available again for another land use. This illustrates that time and space interact: using a lot of land during a short time may yield the same emission reduction as a small amount of land during many years. The area occupation of the scenarios describes thus how much land is needed during one year to achieve 1 functional unit of 1 t CO_2 emission reduction and is given in Table 5.

Table 5 shows large differences in area occupation. If considered for the first commitment period of the Kyoto Protocol, natural forests and forests with long rotations, such as LOMUFOR, PLANTROP and CONTROP have an area occupation in the order of 0.25 to 0.5 ha.yr per ton CO_2, while short rotation systems use only 0.02 to 0.03 ha.yr for the same result.

In the next paragraphs it will be demonstrated that the time*space requirement of CO_2 emission reduction becomes essential when one wants to quantify any impact, cost or benefit related to that emission reduction, which was quantified on a time/space unit basis. These scores or amounts will be weighted with the time*space factor to obtain the result per functional unit.

4.2. Environmental impact

Water balance

In absolute terms, the evapotranspiration of intensive production systems such as bioenergy production and plantation forestry is higher than in more natural vegetation types. As a consequence the total discharge, it is the amount of water reaching the stream network and available for other purposes, is lower. The interpretation changes once the water indicators are expressed per functional unit. The highest water use efficiency in terms of water consumption (ET) per ton CO_2 emission reduction is found in the bioenergy crops (Table 6). The water availability for other purposes in terms of river discharge per functional unit remains however lowest for bioenergy crops. The water consumption per functional unit is highest in the forest plantation in South Africa, although the discharge per functional unit remains reasonable. This is interesting because such plantations pay already water consumption tax in South Africa. The high total discharge of the existing multifunctional forest is explained by its high precipitation excess combined with its low CO_2 emission reduction capacity.

Surface runoff and soil erosion are low for all the scenarios studied and do constitute a benefit more than a burden of forest scenarios, except perhaps during the very first years after the planting of the intensive systems. Because these systems sequester a large amount of CO_2 in the initial years, the increased erosion risk cannot be derived from the results per functional unit.

Land-use impact

Figure 3 shows the result of the land use impact assessment per functional unit for the various scenarios. In spite of the relatively high indicator scores for energy crops, their environmental impact per ton CO_2 emission reduction is very small, while the relatively low indicator scores of multifunctional forest give rise to a relatively high environmental impact per ton CO_2. These counter-intuitive results reflect primarily the emission reduction capacity of the scenarios: the multifunctional forest has a low land use impact per hectare, but, because of the very low emission reduction capacity, its impact per functional unit is higher than that of intensive plantation crops. These results suggest that it might be better as far as environmental impact is concerned to opt for scenarios with little land occupation and a moderate impact per hectare (such as short rotation coppice) than for scenarios with large land occupation and a low impact per hectare (such as the LOMUFOR scenario).

4.3. Net social cost

Table 7 compares the net social costs per ton CO_2 emission reduction for four of the scenarios studied. The LOMUFOR existing scenario, sustainable management of existing multifunctional forest is not shown in the table because the social cost involved is zero: this scenario is business as usual; no afforestation or changes in management are needed. Negative costs in the table are benefits. From the results, it appears that there are large differences in net social costs between the scenarios, on the one hand, and between the three cost criteria on the other hand. The time of evaluation, too, has a large impact on the net social cost.

The reason for the significant benefit realized by new multifunctional forest (LOMUFOR new) is that the opportunity cost for the society of the substituted agricultural land use after subtraction of the subsidies is negative. The net benefits are multiplied by a factor of more than 10 when non-use values are counted. Since LOMUFOR new involves a small extension of a large existing forest, no recreation benefits were charged. Creating a new forest without connectivity to an existing forest would make this alternative even more attractive.

Short rotation coppice of poplar for bioenergy production is economically unattractive at all evaluation time periods. The results are in the same line of the results found by Van Kooten and Bulte (2000) for the Netherlands. *Miscanthus* cultivation is even more expensive per ton reduced CO_2 emission. The primary reason for this is the high production cost per kWh of biomass electricity in comparison with electricity from a STAG power plant on natural gas. Plantation forestry in the tropics is advantageous when evaluated over a period of 20 years and particularly 150 years. However, when evaluated over a period of 10 years, then the costs per ton of CO_2 emission reduction are considerably higher. These costs are higher (except for the 150-year evaluation period) than the world market price of CO_2, which is at present estimated between € 5 and 20. Conservation of the tropical forest – with the alternative of deforestation for agricultural purposes – is under the present rules not eligible as a CDM project. Nevertheless, it is economically attractive for Flanders since the cost per ton CO_2 emission reduction is in the same order of magnitude as the world market price of carbon credits. A comparison of all the scenarios shows that afforestation of a multifunctional forest in Flanders yields the lowest net social cost (even a net benefit). *Miscanthus* cultivation is the most expensive option. New multiple use forest in Flanders is attractive primarily because of the extra non-marketable benefits and because it replaces agricultural production, which is loss making.

5. Conclusions

In this paper, a decision support framework to evaluate forestry scenarios for greenhouse gas emission reduction was presented and tested on five different scenarios (existing and new multifunctional forest in Flanders, energy crop with short rotation poplar, energy crop with annually harvested *Miscanthus*, forest plantation in the subtropics, and preservation of tropical rainforest). The framework is organized as a serial connection of a carbon accounting module, an environmental module and an economic module. Modules include a combination of models and quantitative assessments procedures.

The output of the carbon module is the CO_2 emission reduction and the land occupation needed per ton of CO_2 emission reduction. Simulations of growth and yield curves in SECRETS for all studied scenarios improves the general output as compared to using yield tabels or different models for each scenario, in several ways:

- All scenarios were simulated based on the same model assumptions
- SECRETS includes a detailed soil model, which is of great importance in the total C-budget (McMurtrie *et al*., 2001)
- All local scenarios could be studied using the same weather and soil conditions
- Management options (coppice and thinning frequencies) were realistically simulated (growth increases after thinning due to increased light availability)

To further improve the results a direct use of the output data from SECRETS in GORCAM would be necessary (without fitting a curve through the output data first) but this would imply rewriting the GORCAM model. An alternative option would be to calculate the necessary curves within the SECRETS model.

In order to make scenarios comparable, the environmental impact module and the economic module calculate their outputs on a functional unit basis of 1 ton CO_2 emission reduction. Such framework is universally applicable, straightforward, transparent and quantitative. Data requirements are medium, but applicability is fairly complex due to the interdisciplinary character of the tool. Further developments would require automated data flows between models and a user interface.

As to the results of the scenario analysis, the only attractive possibility for sinks in Flanders is the planting of new multifunctional forests. This even yields a net benefit because it replaces the generally loss-making agriculture and, in addition, yields other environmental benefits and recreational benefits. Furthermore, the substitution of fossil fuels in the multifunctional forest scenario (LOMUFOR) was quite low in this study, whereas a Swedish study has shown important substitution from logging residues, industrial residues and wood recycling (Hektor, 1998), A similar use of biomass for bioenergy in our scenario would further increase the cost-effectiveness. The establishment of short rotation energy forests (LOSRC) or energy crops (LOMISC) is a very efficient way of reducing CO_2 as far as land occupation and environmental impacts are concerned. For an emission reduction of 1 ton of CO_2 almost 10 times less space is needed for an energy crop than for the planting of a new multifunctional forest (LOMUFOR new). However, it also turns out to be a very expensive option: the net costs for collecting and using fuel in a power station are high with respect to the costs of electricity production in an efficient natural gas plant. Indeed, there is a significant net CO_2 emission reduction due to the substitution for fossil fuel but under the present conditions in Flanders it is done at a cost, which is too high with respect to the alternatives for CO_2 emission reduction. A recent study in the UK showed similar results: both SRC and Miscanthus plantations were shown to be economically unviable under the present conditions (Scholes 1998). Plantation forestry in the tropics (PLANTROP) is advantageous when evaluated over a period of 20 and particularly 150 years. However, when evaluated over a period of 10 years, then the costs per ton of CO_2 emission reduction are considerably higher. These costs are higher (except for the 150-year evaluation period) than the world market price of CO_2, which is at present estimated between € 5 and € 20. Conservation of tropical forest (CONTROP) – with the alternative of clearcutting the forest for use by the agricultural sector or commercial forestry – does not come into consideration as a CDM project and thus does not count for our Kyoto obligations. Nevertheless, it is economically attractive for Flanders since the cost per ton CO_2 emission reduction is in the neighborhood of the world market price.

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Table 1: Initial soil C, average yield, and carbon in standing biomass and soil after 150 years (legends to scenarios in the text under 2.1.)

Scenario	Initial soil C t CO_2 ha^{-1}	Soil C after 150 years t CO_2 ha^{-1}	Standing Biomass t CO_2 ha^{-1}	Yield t CO_2 ha^{-1} $year^{-1}$
LOMUFOR existing	645.1	707.5	450.5	8.1
LOMUFOR new	366.6	651.7	433.8	7.7
LOSRC	366.6	585.4	226.9	20.7
LOMISC	366.6	532.9	61.8	24.4
PLANTROP new	383.8	383.8	232.1	15.7
CONTROP	126.2	126.2	1260.3	0

Table 2: Average CO_2 emission reduction after 10 years (legends to scenarios in the text under 2.1.)

Scenario	Replacement of previous land use	Soil	Living biomass	Forest products Long	Forest products Short	Substitution fossil energy	Consumption fossil energy	Final balance
	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{1}
LOMUFOR existing	0.00	1.05	-1.23	-0.37	1.06	1.49	-0.15	1.85
LOMUFOR new	0.00	6.94	15.97	0.00	0.00	0.00	-0.04	22.87
LOSRC	0.00	6.42	11.35	0.00	0.00	27.89	-2.63	43.03
LOMISC	0.00	7.26	6.38	0.00	0.00	41.18	-1.67	53.14
PLANTROP new	-11.66	6.00	5.96	0.00	1.08	0.00	-0.12	1.25
CONTROP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.91

Table 3: Average CO_2 emission reduction after 20 years (legends to scenarios in the text under 2.1.).

Scenario	Replacement of previous land use	Soil	Living biomass	Forest products Long	Forest products Short	Substitution fossil energy	Consumption fossil energy	Final balance
	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}
LOMUFOR existing	0.00	0.91	-1.05	0.36	0.93	1.11	-0.15	2.11
LOMUFOR new	0.00	6.24	12.80	0.00	0.06	0.85	-0.14	19.81
LOSRC	0.00	4.20	2.60	0.00	0.00	27.89	-2.64	32.04
LOMISC	0.00	4.51	3.19	0.00	0.00	41.18	-1.67	47.20
PLANTROP new	-5.83	1.53	12.40	0.00	1.18	0.00	-0.09	9.19
CONTROP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.91

Table 4: Average CO_2 emission reduction after 150 years (legend to scenarios in the text under 2.1.)

Scenario	Replacement of previous land use	Soil	Living biomass	Forest products Long	Forest products Short	Substitution fossil energy	Consumption fossil energy	Final balance
	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}
LOMUFOR existing	0.00	0.42	0.06	0.05	0.09	0.66	-0.10	1.17
LOMUFOR new	0.00	1.90	2.89	0.22	0.30	1.77	-0.20	6.88
LOSRC	0.00	1.46	0.75	0.00	0.00	29.75	-2.80	29.16
LOMISC	0.00	1.11	0.43	0.00	0.00	41.18	-1.67	41.04
PLANTROP new	-0.78	0.01	3.57	1.27	0.56	0.24	-0.13	4.74
CONTROP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.91

Table 5: Area occupation of the scenarios in ha*year per t CO_2 emission reduction (legend to scenarios in the text under 2.1.)

Scenario	Evaluation period		
	10 years	20 years	150 years
LOMUFOR existing	0.54	0.47	0.85
LOMUFOR new	0.04	0.05	0.15
LOSRC	0.02	0.03	0.03
LOMISC	0.02	0.02	0.02
PLANTROP new	0.80	0.11	0.21
CONTROP	0.26	0.26	0.26

Table 6: Comparison of the water indicators for the investigated scenarios – Results per functional unit of 1 t CO_2 emission reduction (legend to scenarios in the text under 2.1.).

	ET l / t CO_2	SURFACE RUNOFF l / t CO_2	TOTAL DISCHARGE l / t CO_2	SEDIMENT LOSS t / t CO2
After 10 years				
LOMUFOR existing	2.65E+06	2.17E+05	1.74E+06	1.25E-02
LOMUFOR new	2.36E+05	7.07E+03	1.20E+05	2.92E-04
LOSRC	1.26E+05	2.31E+03	6.25E+04	1.00E-04
LOMISC	1.01E+05	4.12E+03	5.18E+04	3.07E-04
PLANTROP new	6.52E+06	1.32E+05	1.98E+06	2.42E-02
After 20 years				
LOMUFOR existing	2.33E+06	1.90E+05	1.53E+06	1.09E-02
LOMUFOR new	2.71E+05	9.08E+03	1.40E+05	3.47E-04
LOSRC	1.70E+05	3.10E+03	8.40E+04	1.34E-04
LOMISC	1.14E+05	4.64E+03	5.83E+04	3.45E-04
PLANTROP new	8.86E+05	1.79E+04	2.69E+05	3.29E-03
After 150 years				
LOMUFOR existing	4.18E+06	3.42E+05	2.74E+06	1.96E-02
LOMUFOR new	7.22E+05	6.03E+04	4.58E+05	1.36E-03
LOSRC	1.86E+05	3.41E+03	9.23E+04	1.48E-04
LOMISC	1.31E+05	5.34E+03	6.70E+04	3.97E-04
PLANTROP new	1.72E+06	3.47E+04	5.21E+05	6.38E-03

ET: evapotranspiration; SEDIMENT LOSS: soil loss by water erosion

Table 7: Comparison of the net social costs for the scenarios studied – results per t CO_2 emission reduction (legend to scenarios in the text under 2.1.).

Scenario	Year	Net social cost A € tCO_2^{-1}	Net social cost B € tCO_2^{-1}	Net social cost C € tCO_2^{-1}	
LOMUFOR new	After 10	-24.26	-24.26	-655.44	
	After 20	-16.96	-16.96	-213.04	
	After 150	-9.40	-9.40	-479.50	
LOSRC	After 10	454.49	454.49	454.49	
	After 20	476.80	476.80	476.80	
	After 150	454.74	454.74	454.74	
LOMISC	After 10	740.09	706.73	706.73	
	After 20	776.41	741.41	741.41	
	After 150	666.50	637.98	637.98	
PLANTROP	After 10	353.78	353.78	353.78	
	After 20	-1.21	-1.21	-1.21	
	After 150	-38.16	-38.16	-38.16	
		Net social cost A' € tCO_2^{-1}	Net social cost B' € tCO_2^{-1}	Net social cost C' € tCO_2^{-1}	Net social cost D' € tCO_2^{-1}
CONTROP	Now	0.59	0.55	1.94	1.91

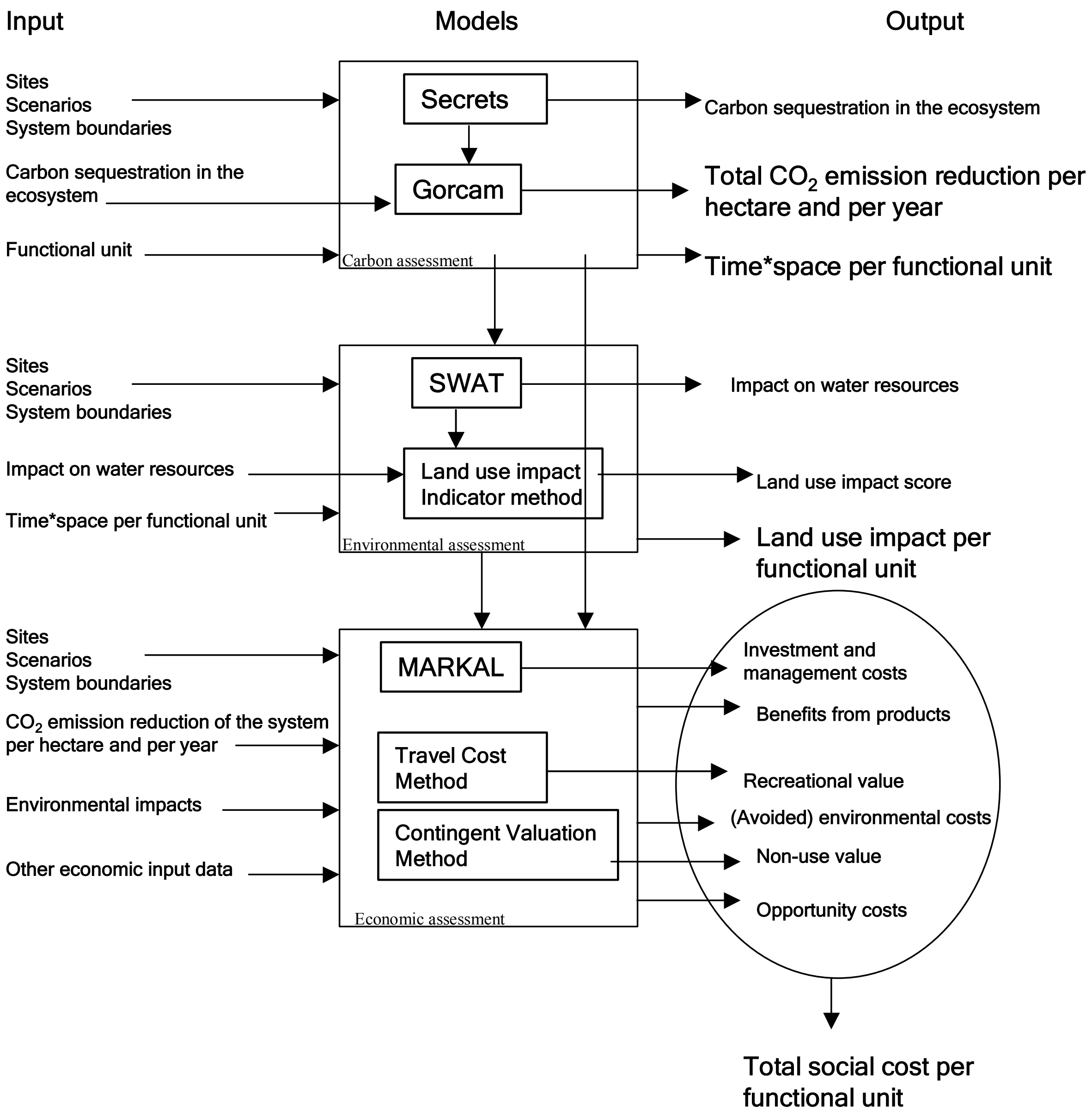
Terms: *Net social cost A=investment. and expl. costs – yield (incl. opportunity costs); Net social cost B= Net social cost A + environmental cost– environmental benefit; Net social cost C=Net social cost B – other benefits; Net social cost A'= value of the tropical forest under commercial logging – total value of the tropical forest under sustained management; Net social cost B'=value of the tropical forest under agriculture – total value of the tropical forest under sustainable management;*
Net social cost C'=Net social cost A' + value of selective logging; D'= Net social cost B' + value of selective logging – annuities – prices in euros 2000 – discount rate 2.5%.

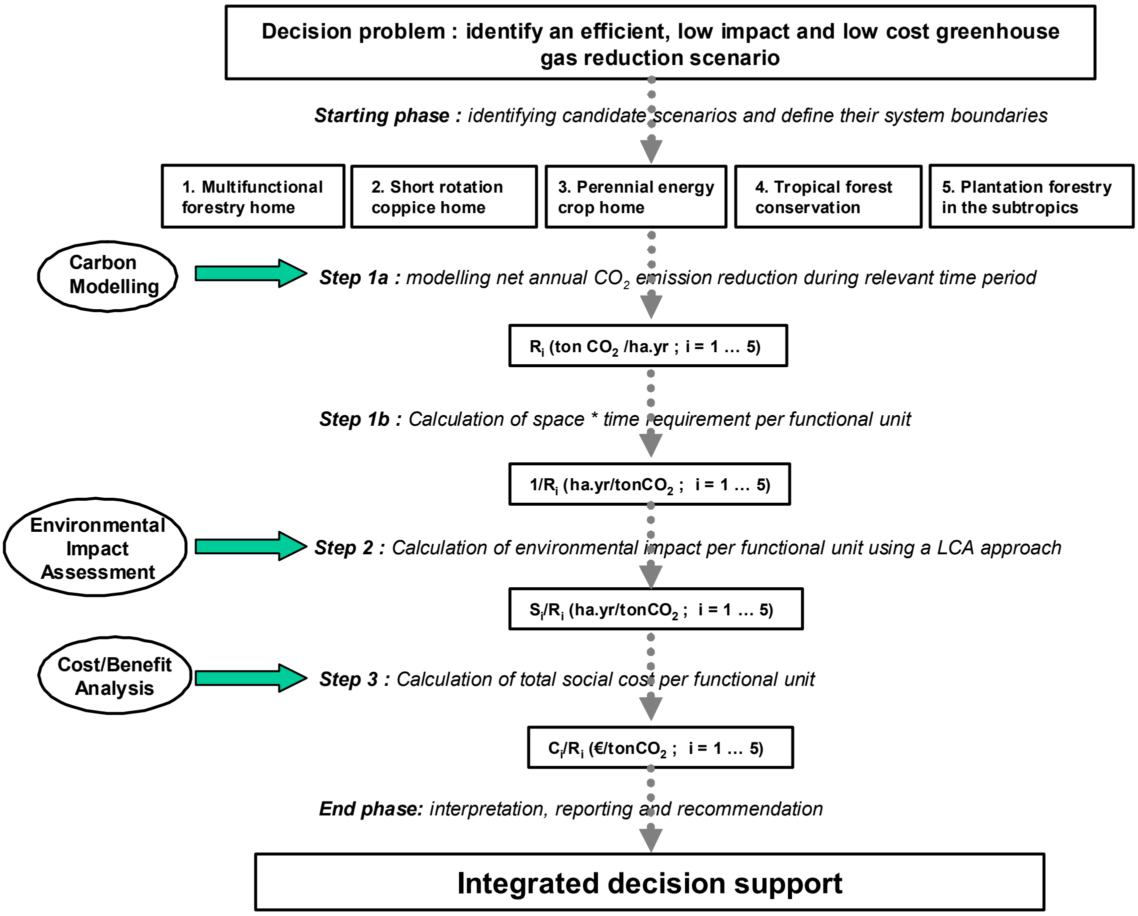
Figure captions:

Figure 1: Structural framework of the decision support tool with indication of inputs, outputs and modelling modules

Figure 2: Flowchart of the decision support tool for five selected greenhouse gas mitigation scenarios.

Figure 3: Thematic land use impact scores per functional unit (legend to scenarios in the text under 2.1.).


Input
Models
Output
Sites
Scenarios
System boundaries
Secrets
Carbon sequestration in the ecosystem
Carbon sequestration in the ecosystem
Gorcam
Total CO_2 emission reduction per hectare and per year
Functional unit
Carbon assessment
Time*space per functional unit
Sites
Scenarios
System boundaries
SWAT
Impact on water resources
Impact on water resources
Land use impact Indicator method
Land use impact score
Time*space per functional unit
Environmental assessment
Land use impact per functional unit
Sites
Scenarios
System boundaries
MARKAL
Investment and management costs
Benefits from products
CO_2 emission reduction of the system per hectare and per year
Travel Cost Method
Recreational value
Environmental impacts
Contingent Valuation Method
(Avoided) environmental costs
Other economic input data
Non-use value
Opportunity costs
Economic assessment
Total social cost per functional unit


Decision problem : identify an efficient, low impact and low cost greenhouse gas reduction scenario
Starting phase : identifying candidate scenarios and define their system boundaries
1. Multifunctional forestry home
2. Short rotation coppice home
3. Perennial energy crop home
4. Tropical forest conservation
5. Plantation forestry in the subtropics
Carbon Modelling
Step 1a : modelling net annual CO_2 emission reduction during relevant time period
R_i (ton CO_2 /ha.yr ; i = 1 … 5)
Step 1b : Calculation of space * time requirement per functional unit
$1/R_i$ (ha.yr/tonCO_2 ; i = 1 … 5)
Environmental Impact Assessment
Step 2 : Calculation of environmental impact per functional unit using a LCA approach
S_i/R_i (ha.yr/tonCO_2 ; i = 1 … 5)
Cost/Benefit Analysis
Step 3 : Calculation of total social cost per functional unit
C_i/R_i (€/tonCO_2 ; i = 1 … 5)
End phase: interpretation, reporting and recommendation
Integrated decision support

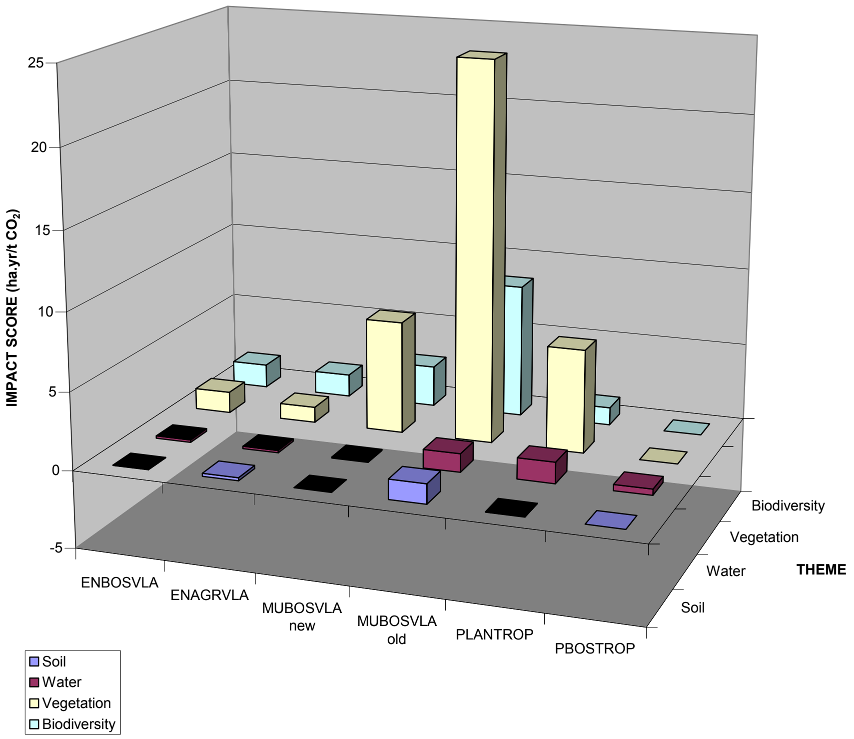
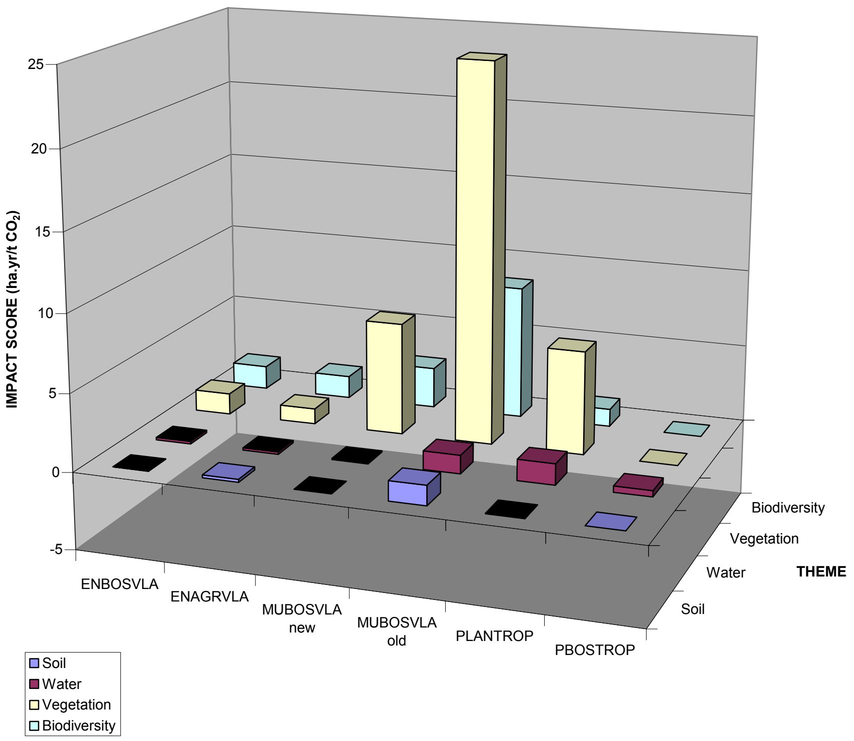


Figure 1: Thematic land use impact scores per functional unit



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