Carbon Plantations in the IMAGE Model
- Model Description and Scenarios -

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COOL

*C*limate *O*pti*O*ns for the *L*ong term

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Abbreviations and Acronyms

ABG	*A*boveground *B*iomass *G*rowth
CP	*C*arbon *P*lantation
IMAGE	*I*ntegrated *M*odel to *A*ssess the *G*reenhouse *E*ffect
IPCC	*I*ntergovernmental *P*anel on *C*limate *C*hange
MAI	*M*ean *A*nnual *I*ncrement
NEP	*N*et *E*cosystem *P*roductivity
NPP	*N*et *P*rimary *P*roductivity
SPP	*S*urplus *P*otential *P*roductivity

Summary

The Kyoto Protocol gives the Annex B parties to this protocol the opportunity to achieve their reduction commitments by enhancing the carbon sequestration capacity of the biosphere. The objective of this project was as a first step to estimate the potential contribution of global afforestation- and reforestation measures to the stabilization of the atmospheric CO_2 concentration. In this report we present a new sub-model of the integrated global model IMAGE (version 2.1.2) to include so-called carbon plantations. The extended IMAGE version was then used to investigate the medium- to long-term effects of sequestering CO_2 by plantations (1) on the global and regional land cover and (2) on the global carbon cycle between 1990 and 2100. The new concept of Surplus Potential Productivity (SPP) is introduced and the consequences of accounting the biospheric CO_2 uptake with SPP as opposed to accounting with NEP (Net Ecosystem Productivity) or changes in aboveground biomass, are shown in comparison.

Definition of carbon plantations

A carbon plantation is defined as an intensively managed forest stand that is planted with the main focus on sequestering a maximum amount of CO_2 under the given soil and climate conditions. It consists of one tree species of even age class within one stand and is harvested when the increase in net carbon uptake approaches zero. The result of this definition is a relatively short rotation period of carbon plantations (depending on the climate and soil conditions) and consequently a high production of wood from the harvested carbon plantations.

Definition of Surplus Potential Productivity (SPP)

The new concept of Surplus Potential Productivity (SPP) is an attempt to account for carbon sequestration in a way that the atmosphere explicitly benefits from the measure of planting carbon plantations. The uniqueness of this approach is that it does not only take into account the carbon stock of the growing carbon plantation but also accounts for the change in C stock of the vegetation that is under discussion to be converted to a carbon plantation. In the calculation of SPP three fluxes are considered:

1. The carbon accumulation (NEP) of the carbon plantation over the rotation time,
2. the carbon accumulation (NEP) of the original vegetation over the rotation time of the planned carbon plantation, which is usually quite low in the case of an e.g. mature forest and
3. the carbon flux resulting from the conversion of the original vegetation to the new carbon plantation, the so-called conversion flux, which is usually quite high in the case of a mature forest.

SPP is calculated by subtracting the conversion flux (flux 3) and the cumulated carbon of the original land cover over the rotation length (flux 2) from the cumulated carbon of the planned carbon plantation (flux 1). Only in the case of a positive SPP, i.e. flux 1 is larger than flux 2 and flux 3 together, an area may be converted to a carbon plantation.

The carbon plantation model

The carbon plantation model is integrated in the IMAGE land cover model and allows to compute the allocation of carbon plantation area as well as the consequences for the regional and global carbon cycle. These calculations can be summarized in three steps:
First, for each 0.5° x 0.5° grid cell of the IMAGE land mass the suitability for the establishment of carbon plantations is calculated assuming that climate conditions remain constant. This includes tree species, rotation length, average SPP, NEP and aboveground biomass growth (ABG).

In the second step, a given CO_2 sequestration demand (scenario value, e.g. 1 Gt C per year) by carbon plantations is checked against the current CO_2 uptake and if lower, land is allocated until the demand is met. Demand and production are given either as SPP, NEP or ABG. Starting with the grid cells having the highest production value, land is allocated globally to carbon plantations, if additional rules of land use change are met.

In a third step, the actual growth and carbon dynamics of carbon plantations are calculated under changing climate conditions. If a carbon plantation is harvested, wood is taken out, and balanced with a given wood demand. All harvested wood is allocated to a fast and a slow decaying wood product pool and thus returns to the atmosphere after a certain period of time.

Scenario exercise 1: Accounting concepts and their consequences

In the climate policy context one of the main questions is how to account for CO_2 sequestration in order to achieve future greenhouse gas reduction commitments. We evaluated the implications of three different accounting methods: (1) Aboveground biomass growth (ABG) which does not take into account soil processes but is the best verifiable indicator, (2) the change in Net Ecosystem Productivity (NEP) which accounts for soil processes but consequently its verifiability is lower compared to ABG, and (3) the Surplus Potential Productivity (SPP) which accounts for soil processes and additionally for the change in carbon stock of the previous land cover.

We performed three scenario runs each with the same demand for global carbon sequestration (2 Gt C per year between 1990 and 2100) and evaluated (1) the consequence for the atmospheric CO_2 concentration compared to the CO_2 concentration of the new IPCC A1 scenario (IMAGE version) and (2) the demand for carbon plantation area.

In 2100 the concentration of the A1 scenario reaches about 750 ppm CO_2 in the atmosphere, whereas under all three sequestration scenarios the concentration remains about 60 ppm lower. In the period 2010 to 2040, however, the SPP accounting method leads to a significantly lower CO_2 concentration compared to the NEP and ABG method. To fix 2 Gt C per year accounted as SPP needs an area of about 15 Mkm² globally in this period of time, whereas for the same amount of CO_2 accounted as NEP or ABG ”only” about 5 Mkm² are needed.

Scenario exercise 2: The potential contribution of carbon plantations to achieve a stabilization of atmospheric CO_2

The main purpose of the second scenario exercise was to estimate the maximum potential sequestration capacity of global carbon plantations. A key question here is the availability and suitability of land. In the two presented scenarios the availability of land is governed by three criteria: (1) land needed to satisfy the agricultural demand may not be used for carbon plantations, (2) on the remaining land not needed for agricultural purposes the SPP criterion must be positive, and (3) the remaining land that fulfills the first two criteria may not be covered with any kind of natural vegetation in order to be used for carbon plantations (Scenario I) or may be converted to carbon plantations without any further restrictions (Scenario II). In Scenario I only land taken out of agricultural production and the so-called regrowth forest[1] areas may be used for carbon plantations. The demand for agricultural land for both scenarios is prescribed by the assumptions for population growth and economic growth of the IPCC A1 scenario.

Since under the A1 scenario between 2040 and 2100 an area of about 13 Mkm² is set free from agricultural use worldwide, under Scenario I about 20 Mkm² are used for carbon plantations in 2100. Under Scenario II (where theoretically all natural vegetation may be converted to carbon plantations) an additional area of 18 Mkm² (38 Mkm² in all) may be used under the given restrictions. The carbon plantation areas result in a maximum CO_2 sequestration of 4.3Gt C per year in 2100 for Scenario I. Under Scenario II this amount doubles to 8.6 Gt C in 2100. Due to the short rotation periods of carbon plantations and the large areas converted, an enormous amount of wood is produced between 1990 and 2100. Before 2050 the wood production in carbon units is only slightly lower than the carbon uptake of the plantations. Between 2050 and 2100 the amount of carbon released as wood is equal or even higher than the amount of CO_2 fixed in carbon plantations. Summing up, we can say that a large amount of carbon can potentially be stored in the living biomass of carbon plantations on the global scale <u>but</u> since an optimization of the storage capacity of the plantations makes necessary short rotation periods, a large amount of wood is produced. Since wood products have only a limited lifetime the CO_2 will be released to the atmosphere again but with a delay in time.

[1] Regrowth forest areas originate from the clear cutting of natural forest areas with the purpose to satisfy the regional demand for timber and fuelwood. These areas are supposed to be reforested immediately after the timber harvest.

1. Introduction

The Kyoto Protocol gives the Annex B Parties to the Protocol the opportunity to meet their reduction commitments by enhancing the CO_2 uptake of the biosphere. Article 3.3 of the Protocol states that ”The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I....”. The wording of this article, however, raises many questions. Three questions dealing with this article and more general with the role of land-use change and forestry in stabilizing the atmospheric greenhouse gas concentration were given high priority at the 7th International Workshop on ”Using Global Models to Support Climate Negotiations” (September 1998 in Kassel, Germany):

1. What are the long term consequences of the carbon offset approach?
2. What are the policy implications of the biosphere shifting from a carbon sink to a carbon source?
3. What are the consequences of different definitions of the carbon sink issue of the Kyoto protocol?

To handle these questions with the IMAGE model it was necessary to develop and implement a new sub model within the IMAGE Terrestrial-Environment System (IMAGE-TES). This new sub model was planned to give some answers especially to the first of the questions mentioned above. It has a long term perspective on the sink issue of the Kyoto Protocol comparable to the time frame of the stabilization issue.

In this report we present the new model together with the results of two different applications. For answering the questions the enhancement of carbon sinks of Article 3.3 of the Kyoto Protocol were interpreted as an afforestation of areas with so-called carbon plantations. A definition of these carbon plantations as well as a description of the carbon plantation model can be found in section 2 of this report. In section 3 a new accounting method for the achieved carbon sequestration is introduced. The consequences of this new method are compared to two methods, that are currently under discussion in the climate negotiations. In section 4 we apply the new carbon plantation sub model to evaluate the maximum potential contribution of carbon plantations to stabilize the atmospheric CO_2 concentration using different rules for the allocation of carbon plantation areas. A more technical description of the carbon plantation sub model can be found in Appendix 1.

2. The Carbon plantation sub model

Why carbon plantations? One of the means of sequestering carbon currently discussed in the climate negotiation processes following Kyoto, is the enhanced planting of plantation species, i.e. a strategy of enhancing the carbon sinks rather than diminishing industrial carbon sources. The global potential of this strategy and the global and regional consequences can be studied with the integrated assessment model IMAGE, if this model is expanded by the new land cover type carbon plantation. The main target and questions handled by the model are the changes in global land cover and use, how much and where to plant plantations best, and the consequences of different accounting methods.

In the following this extension of the IMAGE model is described. A more technical description is given in Appendix 1.

2.1 The new land cover type: carbon plantation

2.1.1 Definition: carbon plantation

Our working definition of *Carbon Plantations* leans on the FAO-definition for forest plantations:

”Forest stands established by planting and/or seeding ... either of introduced species (all planted stands), or intensively managed stands of indigenous species, which meet all the following criteria: one or two species at planting, even age class, regular spacing.” (FAO, 1998).

Additionally, a carbon plantation is defined by the main reason of planting, i.e. the effective sequestration of CO_2. It is assumed that economic wood production is a desirable side effect in the establishment and maintenance of carbon plantations.

2.1.2 General

We have to simulate not only growth and yield of carbon plantations, but we also have to determine optimal sites for the establishment of plantations and how much area will be needed to satisfy a certain demand of CO_2 sequestration. This means that in the following, land use and land cover related rules are differentiated from the carbon accounting model.

2.2 Establishment of carbon plantations – land use change and rules

2.2.1 Demand for carbon plantation establishment

The demand for the establishment of new carbon plantations is given externally either on an IMAGE region or global base. The model thus refrains from imaging the feedback relationship between demand and supply, as would be done in e.g. an econometric type of model.

In characterizing demand we use carbon fluxes of the potential carbon plantations over their specific potential rotation length. In that way we acknowledge the importance of carbon fluxes in determining a sequestration potential.

Alternatively, a target CO_2 concentration in the atmosphere might be given. This information is translated into a carbon flux from the atmosphere to the to-be-established carbon plantations.
In both cases the scenario driven demand has to be compared against the actual ”supply” or ”production” of already installed carbon plantations. The difference is the demand for new carbon plantation allocation in that specific year.

2.2.2 High and low priority carbon plantation establishment

A number of different land uses compete with carbon plantations, notably the use of land for agricultural purposes. Therefore, in a first effort to find suitable grid cells, carbon plantations either have a higher or a lower priority than other land uses. High priority means that carbon plantations might be allocated also on agriculture grid cells, whereas in the case of low priority agricultural demand is always satisfied before the demand for carbon plantations. In that case, carbon plantations can only be established on productive agricultural land, if this land is not needed anymore for agriculture.

2.2.3 Accounting methods: the concept of Surplus Potential Productivity (SPP)

SPP is defined as the difference between the net ecosystem productivity of a carbon plantation (NEP_{CP}) and the net ecosystem productivity of the original vegetation in that grid cell (NEP_{VC}) as well as the carbon flux caused by the potential conversion from the original vegetation to a carbon plantation (C). Fluxes are calculated as means over the potential rotation length of the carbon plantation assuming constant climate conditions.
SPP describes the potential of a carbon plantation to absorb carbon in that specific grid cell. Basically, two cases are compared against each other: the no-action case (NEP_{VC}) and the case of establishing a carbon plantation with the trade-off of having to destroy (and release part of the stored carbon) the original vegetation (NEP_{CP}-C). Considering all these fluxes SPP provides a good first-order estimate of the carbon sequestration potential of an area.

2.2.4 Allocation rules

A number of different exclusion and inclusion rules might be set by the user of the model. These rules reflect assumptions about future political and economic pathways.

- Grid cells with bioreserves exceeding a certain percentage threshold of this area might be excluded from carbon plantation establishment. This seems sensible and self-explanatory.
- Grid cells where the average growth of woody biomass does not exceed a certain threshold value might be excluded. It is assumed that these plantations yield not enough wood to be economically feasible.
- In case of low priority: Abandoned agricultural land, caused by diminished regional crop demand, might be included for establishing carbon plantations. This rule reflects current practice in some parts of the world where the planting of plantation forests are supported to decrease agricultural overproduction (e.g. EU).
- In case of low priority: Marginal agricultural land that becomes discarded from agricultural use might be included for carbon plantations. Unfavorable land for crops might still

be suitable for some plantation species, so that this conversion would be an optimal solution.

- In case of low priority: Area which was clear-cutted to fulfill traditional wood demand might be included for carbon plantations.
- In case of low priority: Natural vegetation area might be included for carbon plantations. Whereas it might not be sensible to plant plantations within desert area, it might prove very useful and effective to plant in savanna or steppe areas.

Another rule that cannot be set by the model user is that carbon plantation areas might not be used for other purposes before the final harvest criterion is fulfilled.

2.2.5 Allocation of land for carbon plantations

Grid cells are weighted for their suitability taking into account the following:

1. SPP, NEP or ABG (according to a user-specified option). This index is normalized by dividing through the highest grid cell value of all grid cells.
2. A proximity index to existing agricultural land, regrowth forest, carbon plantations and water bodies.
3. A random factor.

All three factors are weighted equally. The weighted index is always zero or smaller than zero if the first index is negative. Grid cells are then sorted. Starting with the highest ranked grid cell new carbon plantations are allocated as long as the current demand is not satisfied. This operation is terminated if the weighted index becomes 0.
The weighting procedure has the same structure as used generally within the IMAGE model.

2.3 Carbon dynamics of carbon plantations

2.3.1 Carbon dynamics in land transformation

Five cases of land transformations have to be distinguished:

1. agricultural land -> carbon plantation
2. regrowth forest and natural vegetation -> carbon plantation
3. carbon plantation -> carbon plantation (after harvesting event)
4. carbon plantation -> agricultural land
5. carbon plantation -> regrowth forest and natural vegetation

The process of land transformation is coupled to a shifting in the biospheric carbon compartments, mainly a release of aboveground biomass to the atmosphere. In all of these cases similar mechanisms are used as in the original IMAGE.
Case 1. All biomass and litter is transferred to the humus pool.
Case 2. Depends on the natural vegetation in that grid cell and can be set by the user. Cases:

a. Burning: living biomass and litter is transferred to the atmosphere to a greater part and the rest is transferred to the humus pool. This transformation seems to be most likely for non-forested areas in developing regions.

b. Ploughing under: living biomass and litter are transferred directly to the humus pool: This transformation might be likely for non-forested areas in developed regions.
c. Harvesting: Stems and branches are harvested, and leaves, roots, litter are transferred to the humus pool. This transformation seems to be most likely for all forested areas.

Case 3: Stems and branches are harvested and leaves, roots, litter are transferred to the humus pool.

In all cases the living biomass is set to zero.

2.3.2 Selection of plantation species

It is assumed that for each site, i.e. grid cell, the optimal tree species is chosen for planting. The criterion of optimality is the grid cell suitability index, i.e. either SPP, NEP or ABG.

2.3.3 Carbon dynamics within the stand

The carbon dynamics are calculated in the same way as in the terrestrial carbon accounting model of IMAGE. It is assumed that within the rotation length no thinning operations occur.

2.3.4 Harvesting criteria

It is assumed (user dependent option) that there is a tree specific minimum and maximum rotation length, reflecting current silvicultural practice. The grid specific rotation length is always between these extremes. It is assumed that highly productive sites are harvested earlier than low-production sites, as can be observed in forestry practice regarding site class and rotation length. The base net primary productivity (NPP) of that site and tree species serves as a surrogate for site class.

A second harvesting criteria has also to be chosen by the user. A carbon plantation is harvested using one of the following options:

1. harvest if the slope of net ecosystem productivity becomes negative,
2. harvest if the averaged net ecosystem productivity over stand age becomes smaller. This is an optimum rotation length with respect to the total carbon exchange between forest and atmosphere.
3. harvest if the net primary productivity (NPP) is greater than 99 % of the maximum NPP,
4. harvest if the aboveground biomass growth slows down. This rule reflects the current silvicultural practice of maximizing mean annual increment (MAI).

The stand is harvested earlier under the first harvest criterion than under the second criterion.

2.3.5 Harvest and wood accounting

Harvested wood is classified in two classes, one coming from the stem compartment, the other from the branch compartment. As a first order approximation it is assumed that the stem compartment is identical with the wood class stemwood and the branch compartment with the wood class pulpwood.

All stem and branch mass are removed from the site, i.e. we assume a 100 % recovery rate. Leaf carbon enters the litter pool, whereas root carbon is transferred to the soil humus pool.
All harvested wood from carbon plantations is summed up over time for different regions. Depending on a user defined option this wood enters an infinite lifetime wood pool, i.e. the carbon content is removed totally from the carbon cycle, or it is taken into account with wood coming from traditional wood harvests. The first assumption describes a somewhat extreme scenario and allows a view on the maximum CO_2 sequestration achievable with carbon plantations.
In the second more realistic scenario, traditional wood demand as defined in the IMAGE base version and the harvested wood from carbon plantations are both taken into account in the same calculation. Reflecting the more intensive management of carbon plantations, wood from carbon plantations gets a higher priority than wood coming from natural vegetation. If there is a surplus production of carbon plantation wood in one region this wood is transferred into regions with less production than demand. Finally, the difference between wood production from carbon plantations and wood demand is filled for each region by harvesting of natural forests, i.e. traditional wood harvest. All harvested wood – from carbon plantations and natural vegetation – are transferred to a short- and long-living wood pool, as in the original IMAGE version.

3. The potential contribution of carbon plantations to stabilize the atmospheric CO_2 concentration: Accounting concepts and their consequences

3.1 Scenario Description

Why carbon plantations? One of the means of sequestering carbon currently discussed in the climate negotiation processes following Kyoto, is the enhanced planting of plantation species, i.e. a strategy of enhancing the carbon sinks rather than diminishing industrial carbon emissions. The global potential of this strategy and the global consequences might be studied with the integrated assessment model IMAGE, if this model is expanded by the new land cover class carbon plantation.

The main targets and questions here are:

1. Where is it possible and suitable to plant carbon plantations?
2. How many areas might be converted to carbon plantations in which global regions?
3. What are the consequences of using different accounting methods for carbon sequestration?
4. What is the consequence of carbon plantations with respect to the global carbon fluxes and carbon stocks?

In the first section we will present the new concept for accounting of carbon sequestration, the Surplus Potential Productivity (SPP). The consequence of using this method in comparison to accounting methods like NEP or aboveground biomass growth is presented.

3.1.1 Accounting for Carbon sequestration - The SPP concept

The carbon sequestration of a carbon plantation might be accounted for in a number of ways. Taking just the change in aboveground biomass (ABG) into account, one has a method of deep expert knowledge and verifiability. For climate protection, however, it would be better to take into account the soil and processes within, i.e. to use the Net Ecosystem Productivity (NEP). A disadvantage of this method is that it is not so easy to verify. Still, the NEP method does not account for the fate of the original vegetation on that site. Thus, to get a more realistic carbon exchange it would be better to compare the case ”no action” against ”planting” against each other. This is done with what we call the Surplus Potential Productivity (SPP). It describes the average gain or loss of carbon of the biosphere when a carbon plantation is planted over the rotation period of this plantation. For a clarifying description change also for Figure 1.

When applying this method of accounting (Figure 2), most of the boreal and tropical forested areas have a negative SPP. Some temperate forests, most of the non-forested natural vegetation areas, and agricultural land have a positive SPP. In case of the tropical forested areas, despite of high growth of carbon plantations, the setting off of the high standing biomass against carbon plantations with typically short rotation periods, leads to negative SPP values for most grid cells. In higher latitudes, the standing biomass is set off over a longer rotation period, but as the growth of carbon plantations is slower in these regions, SPP becomes also negative. Most of the non-forested natural vegetation and agricultural areas have a positive SPP, as there is only little carbon stored in the original natural land cover and with proper care carbon plantation species grow favourably.

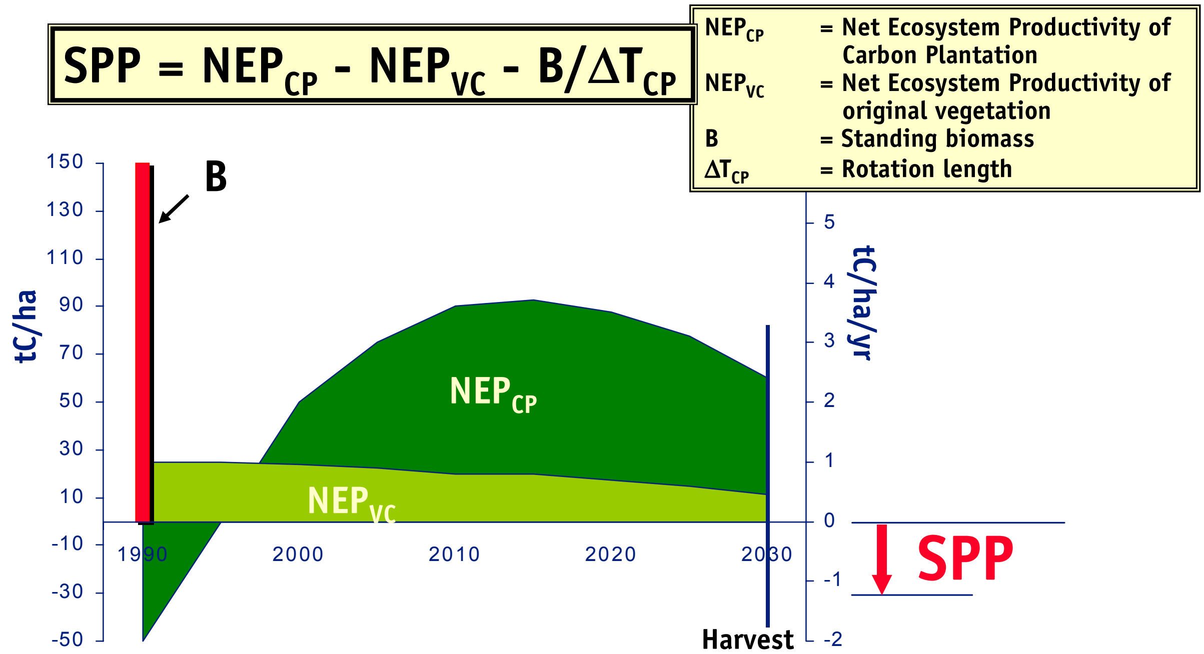

Figure 1 Description of the concept of Surplus Potential Productivity with a fictitious example.

The suitability for the establishment of carbon plantations for each grid cell is restricted by applying a climate envelope concept. Carbon plantations may be planted only for a range of annual precipitation and temperature, as well as a maximum length of dry season. As a consequence unproductive areas like deserts and ice-covered land may not be used for carbon plantations although their SPP value is slightly positive.

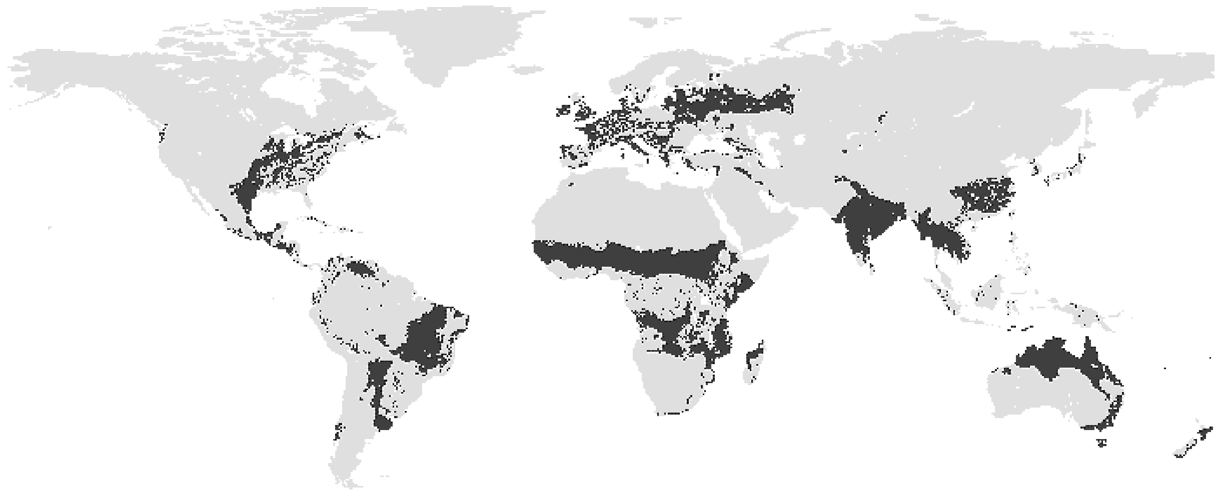

Figure 2 Surplus potential productivity (SPP) for 1990. Black areas depict land suitable for carbon plantations, i.e. areas with positive SPP.

3.1.2 Simulation experiment

We defined three scenarios based on the IMAGE A1 world to discuss the concept of SPP and its consequences in relation to using NEP or ABG as an accounting criterion. Starting in 1990, we assumed a global carbon sequestration demand of 2 Gt C per year until 2100[2].

Calculations of land cover change follow a number of rules:

1. Allocation of land to carbon plantations has a lower priority than agricultural lands.
2. Only grid cells of natural vegetation, abandoned agricultural land, and harvested land, are allowed for the establishment of carbon plantations.
3. The production criterion (i.e. ABG, NEP or SPP) must be positive.
4. The aboveground biomass growth of a grid cell must exceed 1 t C/ha/yr.

These assumptions reflect a world in which demands from the food sector are met first, and demands for carbon plantations second.

3.2 Results

Atmospheric CO_2 concentration increases to about 750 ppm in 2100 in the A1 scenario (Figure 3). All carbon plantation scenarios show a decrease of atmospheric CO_2 in the order of 60 ppm in 2100 compared to A1. With the establishment of carbon plantations in the period till 2000, a huge amount of carbon is released to the atmosphere, partly due to the conversion process and partly because young stands have a negative NEP.

[2] This number reflects the findings of a number of simulation runs where we found it to be a good compromise between feasibility and some maximum area that might be converted to carbon plantations.

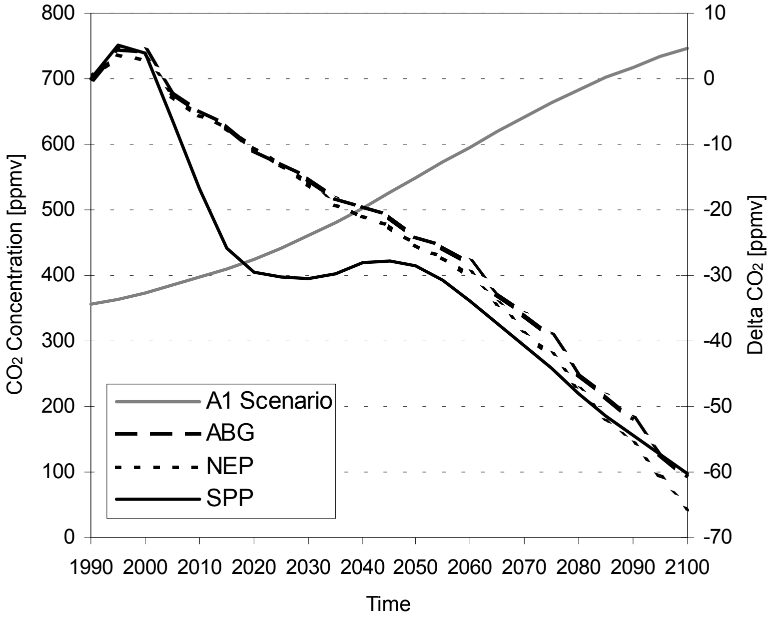

Figure 3 Atmospheric CO_2 concentration over time for the IMAGE scenario A1, and relative to this for the carbon plantation scenarios SPP, NEP, and ABG.

Land cover changes dramatically in the scenario SPP, when up to 20 Million km^2 are used for carbon plantations in 2010. Later, this changes to about 5 to 7 Million km^2, as also found for the scenarios NEP and ABG. This reflects the fact that SPP is nearly always lower than NEP or ABG, thus, more land has to be allocated to satisfy the given demand.

Table 1 Areas converted to carbon plantations and the change in forest areas in 2010 and 2100.

(Mkm^2)	year	A1	SPP	NEP	ABG
Carbon plan-tations	2010 2100		15-20 5-7	5-7 5-7	5-7 5-7
Forests	2010 2100	30-32 30-32	-0.5 +4	-2.5 +3.5	-3.5 +3

Only about 10 to 15 % of the allocated area are within Annex-I regions. A very large part of the global carbon plantations are allocated on savanna and shrubland in the tropical and subtropical regions, i.e. in Non-Annex I countries.

Despite the large amount of land needed for carbon plantations, the total agricultural area decreases only between 1 and 2 percent. Thus, there is no direct or indirect pressure by carbon plantations on the agricultural production under the prescribed global sequestration demand of 2 GtC/yr.

Initially, the area of natural forests decreases in all scenarios due to land-use changes to carbon plantations (year 2010: -0.5, -2.5, and -3.5 Mkm^2 in the scenarios SPP, NEP, and ABG, respectively). This effect is most pronounced for the ABG-scenario, as in this scenario carbon plantations are planted were ABG is highest, i.e. quite often in tropical regions with natural forest cover. In 2100 forest cover simulated with the carbon plantation scenarios is significantly higher, about +3-4 Mkm^2, than in the baseline scenario. This reflects the reduced use of natural forests for wood production, as the wood demand is increasingly satisfied by wood coming from carbon plantations.

3.3 Discussion and Conclusions

The global integrated model IMAGE (version 2.1.2) was extended to include carbon plantations. First, the concept of Surplus Potential Productivity (SPP) was introduced as a measure for the CO_2 sequestration effectivity of an area by planting carbon plantations. The emerging global land-cover patterns shows that the SPP concept protects most forested areas whereas agricultural land and savannah and shrubland regions do yield positive SPP values. If one uses only the NEP or biomass growth (ABG) of potential carbon plantations to measure the sequestration potential of an area, the patterns are totally different. For these cases, most tropical areas with high growth potentials would be suitable, but these methods would reflect only a part of the ”real” carbon exchange between this area and the atmosphere. The growth potential of the original vegetation and the conversion of this vegetation into a carbon plantation are important contributors to the ”real” carbon cycle. Including these factors, i.e. using SPP, results in a much more realistic assessment of the carbon sequestration potential of an area.

The simulation experiments show that for a 60 ppm reduction of the atmospheric CO_2 concentration in the year 2100 a conversion of 5 to 7 million km^2 of land to carbon plantations is necessary. Currently, forest plantations cover land in the order of 1 million km^2 globally. Thus, a major international effort would be needed, the plantation land would have to be increased 5 to 7 fold. At least 0.1 million km^2 would have to be converted over the next 50 years per annum, a number exceeding current plantation increment by a factor of 2 to 5.
On the other hand, wood harvested from carbon plantations exceeds current wood demand by more than a factor of 5 in these scenarios. The model assumes that this wood is indeed used within a very wood-friendly economy. Of course, also on this side, major rethinking in wood use related policy has to occur over the next decades.

It was shown that the concept of Surplus Potential Productivity (SPP) can be used as an assessment tool to indicate suitable land for the establishment of carbon plantations.
We conclude that carbon plantations and enhanced use of wood products can considerably temper the increase of the atmospheric CO_2 concentration. Very strong incentives, however, for the planting of carbon plantations and for using more wood in the economy have to be given to achieve the CO_2 sequestration of 2 Gt C per year.

4. The potential contribution of carbon plantations to stabilize the atmospheric CO_2 concentration: Scenarios with the IMAGE model

In this section we will present two scenarios, where carbon plantations (CP) are introduced to sequester a maximum possible amount of CO_2 on the global scale. We calculated where in the world and how much carbon could be fixed in the biosphere as well as the area required for this purpose. Additionally, the wood production, that accompanies carbon plantation measures was estimated.

4.1 Scenario description

In order to estimate the potential contribution of carbon plantations in stabilizing the atmospheric CO_2 concentration, a number of rules and options had to be set to allocate carbon plantation areas in competition with other forms of land use. These rules and options are presented in the following paragraphs.

4.1.1 Availability and suitability of land for carbon plantations

How large is the area available for carbon plantations? And which areas in the world are suitable for carbon plantations? These are the main questions to be answered if we want to estimate a maximum global sequestration potential. Obviously the available area is limited. First, due to a growing population in the near future, the demand for agricultural land will probably increase in many regions of the world. Thus, the expansion of land used for agricultural purposes will compete with the demand for land for CPs. Secondly, it will probably not be accepted that all areas with natural vegetation may be converted to CPs without limitation. It's not yet clear however, which natural vegetation classes will be converted to carbon plantations in the future, or if the option of sequestering CO_2 in forests becomes so important that natural vegetation will be converted at all. For this reason we developed two maximum scenarios where natural vegetation may be converted to CP without limitation or may not be converted at all:

- Scenario I: In this scenario no natural vegetation may be converted to CP. Only land that was previously used for other purposes (e.g. agriculture) and is not needed for this purpose anymore, may be used.
- Scenario II: In addition to the areas defined under Scenario I, CP may expand over all types of natural vegetation.

Defining the availability this way we span up a range of maximum CO_2 sequestration.

Regarding the suitability of an area to be planted with CPs two questions are important in our model: (1) Are the climate and soil conditions of a selected area suitable to establish plantations? And (2) What is the net effect for the atmospheric CO_2 concentration if we use a selected site for this kind of plantation? The second question takes into account the fluxes resulting from a change in land use.

Under both scenarios areas may only be converted, if there is a net benefit for the atmosphere, i.e. the Surplus Potential Productivity (SPP) must be positive.

Both scenario calculations are based on the demand for land resulting from the assumptions about population growth and economic growth of the new IPCC A1 scenario (IMAGE 2.1.2 version). Furthermore, we get GhG emission pathways from 1990 to 2100 and thus climatic conditions from this scenario. The results for land-use change obtained with the IMAGE 2.1.2 model are characterized by a 25% decrease of demand for agricultural land between 2040 and 2100.

4.1.2 Demand for CO_2 sequestration

The sequestration demand for both scenarios is set high enough, so that theoretically a stabilization of the CO_2 concentration at 450 ppm could be achieved by 2100. Thus, the prescribed demand increases from 1 Gt C per year in 1990 to 15 Gt C per year in 2100. This demand, however, is only thought to serve as an upper limit to estimate how much CO_2 can be maximally removed from the atmosphere and what CP can contribute to reach the specified stabilization target. The demand for CO_2 sequestration between 1990 and 2100 is prescribed on the global scale. A demand on the global scale means that CPs may be established in every region of the world irrespective of their belonging to the group of Annex B parties to the Kyoto Protocol or not.

4.1.3 Allocation rules for carbon plantation area

The change of land use and land cover in IMAGE is governed by a number of rules. The planting of CPs is integrated in this system of rules. A number of additional rules and options had to be introduced. The options for the two scenarios were set as follows:

1. The Surplus Potential Productivity (SPP) is used as a criterion for the weighting of areas. Only grid cells with a positive SPP may potentially be used for CP and the higher the SPP of an area, the higher is the probability that it becomes actually used for CPs.
2. The demand for CPs gets lower priority than the demand for agricultural land. Hence, the demand for agricultural land is satisfied first and CP may not expand over areas which are used for agriculture in the actual time step. If the demand for agricultural area increases, it does not expand over CP areas because these areas are used for CPs again if there is a demand for C sequestration to be satisfied.
3. Areas that get a high weighting to be used for CP:
    - areas with positive SPP
    - cells where the CP have just been harvested
    - agricultural land that is not needed anymore for agricultural production
    - marginal agricultural land
    - land that was harvested to satisfy traditional wood demand (regrowth forest)
4. CP can only be planted if a minimum for aboveground biomass growth per year is exceeded. This minimum is set at 100 t carbon per km^2 and year.

4.1.4 Change in carbon pools related to the establishment of carbon plantations

A number of conversions of carbon pools must be considered, if we want to estimate the effect of C sequestration on the atmospheric CO_2 content and the carbon fluxes that could be accountable for the fulfilling of commitments. In the carbon plantation model different options about how to handle the different carbon pools and fluxes can be chosen. For the two scenarios the change in three different carbon pools and the related fluxes must be considered:

1. *The change in original vegetation* (carbon stock) before a plantation is established: For consideration of the resulting flux we distinguish between different types of natural vegetation. The living biomass of the steppe, savannah and scrubland vegetation is added to the soil organic matter pool and is therefore released to the atmosphere according to the decomposition rate of the respective carbon pool. For the landcover types containing forests the wood is taken out and the rest of the biomass is also added to the soil organic matter pool. This is valid only for Scenario II where all types of natural vegetation may be converted to CP.
2. *Growth and rotation length of CP*: An area once planted with CP can be used for CP several times during the simulation period 1990 to 2100. The amount of CO_2 fixed in the CP biomass is determined by the growth conditions and the rotation length of CP. For the scenario results we present here, 8 typical plantation tree species were introduced, all with an own set of growth parameters. A CP is harvested, when the change in average NEP becomes equal or less than zero.
3. *Wood resulting from harvesting of CPs:* After harvest the wood from a CP is included in the two wood pools (10 and 100 years residence time) of IMAGE in a way that it is used to satisfy the regional demand for wood products. A positive side effect of this inclusion is that natural vegetation that would otherwise been harvested is protected.

4.2 Results

In the following we present the amount of CO_2 that could be fixed in carbon plantations year by year under the presented scenario assumptions, the global area needed for this purpose and the resulting wood release from carbon plantations.

4.2.1 Locations and Areas with Carbon Plantations in 2100

Since for both scenarios the SPP must be positive for the area under discussion for CP, large areas of the world may not be used for CPs. These are especially the areas covered with boreal forests in Canada, Scandinavia and Siberia, where a conversion to CP would bring no benefit because the growth rates of trees are so low that it would need centuries to restore the former carbon stock. The second type of protected vegetation are the tropical forests and partly the tropical woodlands of Latin America, Africa and South East Asia (e.g. Malaysia and Indonesia). In these areas the existing carbon stocks are so large that plantations with their relatively short rotation periods would not be able to build up a comparable or larger carbon stock in a reasonable period of time. Areas that are extensively used for carbon plantations in Scenario II in all regions of the world, are those which are covered with scrubland, savannah and grass-

land/steppe vegetation. In these areas the original biomass stock is quite low, so that managed plantations have a slightly positive SPP. Of course, the biomass productivity of carbon plantations is often also low, but it might be higher than could be expected under present conditions. Here the fertilization effect of an increasing CO_2 concentration and an enhanced water use efficiency lead to an aboveground biomass growth which is higher than the prescribed 100 tons C per km² and year. However, the model does not take into account the balance of nutrient supply. The nutrient availability, as one of the soil quality indicators, is held constant over time. This might lead to an overestimation of tree growth unless we assume additional fertilizer application and other management measures.
The expansion of CPs in Scenario I is governed by the changing demand for agricultural land. Since the population levels off in the underlying A1 scenario and the economy grows, the agricultural productivity increases in most regions. Thus, after 2035 large areas in Australia, parts of China and Eastern Europe are abandoned from agricultural production. These areas are preferred for carbon plantations because no standing biomass has to be accounted for and thus SPP becomes relatively high. Therefore, these are the areas where the carbon plantations of Scenario I are established beside the areas with regrowth forests.

4.2.2 Realized carbon sequestration

The global amount of CO_2 that could be sequestered under the specified conditions is presented in Table 2. The results look quite different for the two scenarios. Under Scenario I, where CPs are mostly established on areas that were taken out of agricultural production the amount of CO_2 fixed in the CP biosphere reaches 4.3 Gt C in 2100. Under the second scenario with no further restrictions for the planting of CPs than a positive SPP and the agricultural demand for land this amount increases to 8.6 Gt C in 2100.

Table 2 Realized CO_2 sequestration of carbon plantations (as net ecosystem productivity, NEP) of Scenario I and II. For comparison the Energy/Industry CO_2 emissions of the IMAGE A1 scenario are presented.

CO_2 Fluxes in Gt C per year

Year	NEP of CPs Scenario I (no nat. veg.)			NEP of CPs Scenario II (all nat. veg.)			Energy/Industry emissions Scenario A1		
	global	Annex B	N-Annex B	global	Annex B	N-Annex B	global	Annex B	N-Annex B
2000	-0.38*	-0.21	-0.17	2.1	0.03	2.1	7.2	4.4	2.8
2025	1.2	0.77	0.46	4.1	1.4	2.8	13.6	5.3	8.3
2050	1.8	1.1	0.66	5.6	1.8	3.7	18.9	5.1	13.8
2075	3.0	1.1	1.9	7.5	2.0	5.4	17.1	4.4	12.7
2100	4.3	1.5	2.8	8.6	2.3	6.3	12.6	3.9	8.7

*a negative flux is a flux out of the biosphere to the atmosphere

Even if an almost unrestricted expansion of carbon plantations would be realized (Scenario II) maximally 29% of the energy/industry emissions of the A1 scenario could be compensated up to 2050. After 2050 this share increases as the CO_2 emissions from the energy/industry sectors decrease and the area with CPs continues to increase. For the period 2050-2100 the percentage increases up to 68% for Scenario II. Under Scenario I maximally 34% of the CO_2 emissions of the A1 scenario can be compensated by an additional biospheric CO_2 uptake of carbon plantations.

4.2.3 Area converted to carbon plantations

To sequester 4.3 Gt of carbon in 2100 an area of 20 Mill km² is needed under Scenario I (see Table 3). Under this scenario only land that is taken out of agricultural production is used for plantations and about 13 Mkm² of agricultural land becomes available between 2040 and 2100 under scenario A1. This is quite a high number since in this case agricultural area is lower in 2100 than in 1990 whereas the global population is about 1 billion higher in 2100 compared to 1990.

In Scenario II 8.6 Gt C are removed from the atmosphere in 2100; this needs an area of 38 Mkm² to be planted with carbon plantations. Additionally, half of this area is non-forest vegetation (e.g. savannah, scrubland, etc.) with quite a low biomass productivity in 2100.

Table 3 Areas needed to sequester a maximum amount of CO_2 in the carbon plantation biosphere.

Scenario	**World**		**Non-forest veg. areas**		**Forest vegetation areas**	
	2100		2100		2100	
	Area Mkm²	NEP GtC/yr	Area Mkm²	NEP GtC/yr	Area Mkm²	NEP GtC/yr
Scenario I (no nat. veg.)	20	4.3	-	-	-	-
Scenario II (all nat. veg.)	38	8.6	19	2.6	19	6

4.2.4 Wood production from carbon plantations

The carbon plantations are included in our model with the main purpose to sequester as much CO_2 as possible in the standing biomass. As the carbon uptake of a stand diminishes with increasing age of the mature forest we defined the length of a rotation period in a way that the average NEP over a rotation period remains positive. Thus, we get a number of subsequent rotation periods, each finished by a harvest of the standing biomass. These harvests lead to a considerable amount of wood and other biomass. We assume that this wood is used to satisfy the regional wood demand which leads to a protection of natural forests which otherwise would have been harvested for that purpose. Nevertheless, wood is a product with a limited lifetime which leads to a return of CO_2 to the atmosphere after certain years or decades. The simulated wood production resulting from carbon plantation measures is presented in Table 4.

Table 4 Global wood production (in Gt C per year) from conversion of natural vegetation to carbon plantation and from harvesting of carbon plantations.

	Global wood production	
Year	Scenario I (no nat. veg.) [Gt C/yr]	Scenario II (all nat. veg.) [Gt C/yr]
2000	0.006	0.5
2025	0.5	3.4
2050	1.3	4.0
2075	2.9	7.6
2100	5.4	9.7

Under Scenario I the wood production reaches 5.4 Gt C per year in 2100. In Scenario II this amount is nearly twofold, namely 9.7 Gt C per year which is comparable to the amount of carbon fixed in carbon plantations or even higher. This is also valid for Scenario I. In this scenario, however, the wood production induced by the establishment of carbon plantations is comparable to the global wood demand throughout the whole scenario period. This is not the case for Scenario II, where the global wood demand is exceeded by a factor of four or more especially in the time period between 2050 and 2100. To sum up, we can say that carbon plantation measures under the given assumptions set free an amount of carbon bound in woody biomass, that is comparable or even higher than the amount of carbon fixed in the plantations at the same time. It is thus important to think about what could happen to these large amounts of wood and how wood production is considered in accounting methods for greenhouse gas emissions.

4.3 Discussion and conclusions

According to the presented scenarios an enormous amount of CO_2 could theoretically be absorbed by the establishment of carbon plantations on the global scale and on the long term. But what becomes also obvious is that an extremely large area must be afforested or reforested to achieve this CO_2 sequestration. An optimization of CO_2 sequestration by shortening the rotation period and harvesting of carbon plantations could lead to a over-production of woody biomass which makes it necessary to think about new ways of using wood products.

Apart from these insights the presented scenarios can be seen as a starting point for:

1. further improvements of the carbon plantation sub model. One of these improvements could be e.g. the inclusion of wood products from carbon plantations in the SPP concept, in that the harvested wood is treated like the conversion flux from natural vegetation.
2. The development of scenarios that are more realistic than those presented in this report. Here further restrictions to the speed of expanding carbon plantations e.g. by including a maximum planting rate [in e.g. km² per year] should be included.

3. A further point is to investigate the effects of using woody biomass from carbon plantations as a substitute for fossil fuels.
4. The analysis of side effects of the establishment of carbon plantations. Here an increase of other greenhouse gas emissions caused by land-use change, namely N_2O and CH_4 emissions should be investigated.

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6. Appendix

In the following, the technical aspects of the inclusion of the new model part "carbon plantation" are described. The inclusion refers only to the IMAGE model version 2.1.2 and was slightly changed in the process of integrating this part into IMAGE 2.2.

General guidelines

1. Change structure of IMAGE code as less as possible
2. New code is oriented on old IMAGE code and similar structures are used. This ensures that reprogramming work for IMAGE 2.2 is minimal.

New land cover type

1. The new land cover type (equals vegetation class) "carbon plantation" is introduced. The number is 3 (as vegetation class) or 6 (as land cover type). The number was chosen, as the type carbon plantation belongs to the man-influenced classes like agriculture and regrowth forest.
2. The original IMAGE code was changed to introduce this new class. In *image.fip* constants were defined which point to all vegetation classes (VC) and land cover types (LCT). The syntax is *_VC and *_LCT, e.g. CPLANT_VC or AGRICULTURE_VC. All explicit mentioning of VC´s and LCT´s are replaced by these constants.
3. The code containing the new land cover type was successfully verified against the old IMAGE code.

Outline of carbon plantation inclusion

1. The following new modules were included:
    a. *ccm/cplantinit.f* : initialization of carbon plantations
    b. *ccm/cplant.f* : calculation of surplus potential productivity (SPP)
    c. *ccm/cplantgrow.f* : calculation of NEP and harvesting decision of carbon plantations
    d. *lcm/lcmcplant.f* : calculates demand for carbon plantations and decides for low and high priority carbon plantations were they are to be planted
    e. *ccm/carbon.f* : added to original IMAGE-file: actual conversion of grid cells having to do with carbon plantations
1. Also parts of the general reading of options were extended. Additionally the land cover module (*lcm/lcm.f*) was changed slightly.
2. The general outline can be depicted from the following scheme: In the first IMAGE year, the carbon plantation part is initialized. Beginning with the first year of carbon plantation inclusion, first the demand for carbon plantation is calculated from the given demand scenario and according to a number of options. After this for each grid cell, the optimal carbon plantation tree species, rotation length, NEP, NPP, ABG (aboveground biomass growth), and SPP is calculated. In case of high priority carbon plantations, carbon planta-

tions are allocated to grid cells before the main IMAGE land cover model (ADM/LCM) calculations. If low priority carbon plantations are chosen, carbon plantations are allocated after the IMAGE land cover model. After this, transformation specific carbon flows are calculated. Finally, the carbon exchange of carbon plantations and the decision for harvesting are calculated.

Options

Options are read in into *gen/options/readoption.f* and have to be set within the INPUT-folder in *OPTIONS.DAT*. Additional options included are:

1. Indicator for carbon plantations inclusion: 0: No carbon plantations included, 1: Carbon plantations with highest priority included, 2: Carbon plantations with lowest priority included.
2. The first year that carbon plantations are to be included (real value).
3. Method: Calculation of C plant production for demand fulfillment: 0: Surplus potential productivity of cells, 1: Net ecosystem productivity of cells, 2: Aboveground biomass growth of cells.
4. Calculation of weighting of grid cells for C plant suitability: 0: Surplus potential productivity of cells, 1: Net ecosystem productivity of cells, 2: Aboveground biomass growth of cells.
5. Wood harvest option: 0: all wood from carbon plantations are transferred to an infinite lifetime wood pool and the traditional wood production remains the same; 1: carbon plantation wood supply feeds back on traditional wood demand and a simple trade model is included.
6. Rules that govern land cover changes for low priority carbon plantations:
    a. Rule: If abandoned agricultural land (caused by too much production) usable
    b. Rule: If marginal agricultural land usable (GMARG=0)
    c. Rule: If harvested land for traditional wood demand usable
    d. Rule-Array: If natural vegetation classes are usable or not, for all vegetation classes separately

1. If carbon plantation are allowed to grow over bioreserves & the threshold value there (1..100 % of land area), 0 = no restriction
2. Rule for priority of planting carbon plantations on recently harvested carbon plantation grid cells.
3. Two rules for harvesting (rotation length) of carbon plantation: 1:delta NEP<=0, 2:delta average NEP<=0, 3:delta NPP<=1%, 4: delta ABG<=0. The second rule: if additionally a tree and site specific minimum and maximum rotation length is used in the calculation (1=yes, 0=no)
4. If a climate envelope for the calculation of carbon plantation tree species is used (1=yes, 0=no)
5. Rule-Array: What happens to original vegetation if there is a conversion? 0: all living biomass to humus, 1: burning, 2: wood taken out; for all vegetation classes separately

6. Rule: After conversion from natural vegetation to agricultural land, this grid cell is allowed to be converted to CP (value=0) or it is allowed after a delay time (value to be given here in years). Delay time should be given as numbers dividable by 5.
7. Rule: If there is a food caloric intake restriction (value >0, given in kcal/cap/day) or not (value=0)
8. Rule: The lower boundary of profitable aboveground biomass growth (0= no restriction, other value in tC/km2/yr).

The rules 6 and 8 might take values between 0 and 9. 0 means that this rule does not apply, a higher value depicts the priority against other rules with which this rule applies.

Carbon plantation demand scenario

Has to be set within the INPUT-folder in *CPLANT.SCEN.*

Optionally a target CO2 concentration $[CO_2]_{tar}$ in the atmosphere (0) or absolute CO2 sequestration demands (1) can be given.

In the first case a time constant T between 1 and >100 years for achieving the given atmospheric concentration must be provided. The longer this time the less demand is calculated.

First, the difference between actual CO2 concentration in the atmosphere $[CO_2]_{act}$ and the target value $[CO_2]_{tar}$ is calculated with

$$\Delta[CO_2] = [CO_2]_{act} - [CO_2]_{tar}$$

Demand D is calculated with the conversion factor r_{CO2} (= 0.4688 ppmv/GtC, as given in IMAGE) and the time constant T with

$$D = \frac{\Delta[CO_2]}{r_{CO_2} T}$$

Additionally, demand for carbon plantations might be either given globally or on a regional scale. In the later case, for each region a certain percentage from the overall carbon sequestration must be given. Also included is a check of the sum of percentages of regional carbon sequestration (*lcmcplant.f*). If not equal to 100%, only a warning message is given.

Carbon plantation tree species

There is a maximum of ten different carbon plantation tree species included. Carbon fluxes and biomass compartments are calculated in the same way as for all IMAGE vegetation classes. No thinning is included, also no management factor, and no fertilization effect.

It is assumed that the scaling factors MULGRIC and MULREIC are both 1 (i.e. no scaling) for carbon plantations.

Harvesting of CP´s (only if the 2nd option for harvesting is true (=1)): Each tree species has a minimum and a maximum rotation length, L_{min} and L_{max}, resp. The grid specific rotation length is always between these extremes. It is assumed that highly productive sites are harvested earlier than low-production sites, as can be observed in forestry practice regarding site class and rotation length. Base NPP serves as a surrogate for site class and the realized rotation length L is assumed to be proportional to the fraction of realized NPP P to the given tree specific maximum NPP P_{max}:

$$L = L_{max} - (L_{max} - L_{min}) \frac{P}{P_{max}}$$

Second harvesting criteria: A carbon plantation is harvested depending on the user-changeable harvesting rule, i.e. either if delta NEP becomes negative, or if the averaged NEP over stand age becomes smaller, the NPP is greater than 99 % of the maximum NPP or if the above-ground biomass growth slows down.
The stand is harvested whenever one of the above criteria becomes true.

The calculation of carbon plantation tree species and their NPP, NEP, rotation length, and biomass growth is done for each grid cell excluding only cells with large cities in it. Because of the rather longish calculations they are done only in the first year that carbon plantations are included and then every 5th year (e.g. 1990, 1995, 2000 ...) .
Which tree species is chosen within a grid cell? It is assumed that always the tree species with optimal properties is chosen for planting. “Optimal” means with respect to the harvesting criterion.

If the option “include climate envelope” is true (=1), then the climate suitability of all plantation tree species is calculated. If a species is not suitable in that grid cell, it is excluded from the above calculations.
The climate envelope concept is in a slightly simplified form adopted from Webb et al. (1984) and Booth (1990). The following climate variables are calculated from IMAGE grid specific information and if all constraints are valid for that cell, the tree species might be planted there:

1. Minimum and maximum annual precipitation
2. Maximum length of the dry season, defined as months with less than 40 mm precipitation
3. Minimum and maximum mean monthly maximum temperature
4. Minimum and maximum mean monthly minimum temperature
5. Minimum and maximum mean monthly average temperature

Calculation of SPP

SPP = Surplus potential productivity
SPP is defined as the difference between the NEP of a carbon plantation (NEP_{CP}) and the NEP of the original vegetation (NEP_{VC}) as well as the flux through conversion (C):

$$SPP = NEP_{CP} - NEP_{VC} - C$$

All of the above fluxes are averages over the rotation length of the carbon plantation. All fluxes are calculated with the assumption that climate and CO2 content of the atmosphere will not change over the period.
SPP is the main index for suitability of a grid cell to be converted to a carbon plantation successfully.

Additional assumptions for the calculation of SPP are:

1. Initial condition for carbon plantation: all above-ground biomass is set to zero, all below-ground carbon is set to the original values of the grid cell.
2. Initial conditions for the original vegetation class in grid cell: all carbon compartments are left as they are. It is assumed that no migration takes place within the time horizon of calculation. All of these conditions are also true if the original vegetation class is already a carbon plantation.
3. All aboveground biomass of the grid cell is released to the atmosphere. This is the conversion flux C. Only if the original vegetation is already a carbon plantation, the conversion flux is set to zero.

Demand for carbon plantations

The demand is calculated as a demand for carbon sequestration by carbon plantations. Carbon sequestration can be interpreted in a number of ways (option): as SPP, NEP or ABG.
The actual demand is reduced by the realized "production". It is assumed that this realized production is just the grid cells (average over possible rotation length) SPP, NEP or ABG – as calculated in the SPP part – dependent on the chosen option.

Carbon plantations: high priority

If carbon plantations have the highest priority, they are allocated before the "normal" IMAGE allocation (adm and lcm).
All grid cells with a percentage of bioreserves that exceed a certain threshold are taken out (option).
Also grid cells with carbon plantations already there and which are not harvested, are taken out.
Also grid cells with an average ABG that is below a certain scenario dependent threshold are taken out (option).
Grid cells are weighted for their suitability taking into account the following:

1. SPP, NEP or ABG (according to a user-specified option). This index is normalized by dividing through the highest grid cell value (of all grid cells).
2. A proximity index to existing agricultural land, regrowth forest, carbon plantations and water bodies.
3. A random factor.

All three factors are weighted equally. The weighted index is always 0 or smaller than zero if the first index is negative. Grid cells are then sorted. Starting with the highest ranked grid cell new carbon plantations are allocated as long as the current demand is not fulfilled. This operation is terminated if the weighted index becomes 0 or negative. In this case a warning is issued.
The above procedure is handled globally or regionally (option).
The conversion matrix GCVEG is set for all grid cells that have to be converted.

Carbon plantations: low priority

If carbon plantations have the lowest priority, they are allocated after the "normal" IMAGE allocation (adm and lcm).

The weighting procedure is the same as described for the high priority carbon plantation. Additionally, all grid cells that do not meet one of the following rules are discarded:

1. Rule: If abandoned agricultural land (caused by too much production) usable
2. Rule: If marginal agricultural land usable (grid cells with GMARG=0)
3. Rule: If harvested land for traditional wood demand usable
4. Rule-Array: If natural vegetation classes are usable or not, for all vegetation classes separately

Apart from this additional discarding of grid cells the allocation procedure is the same as for the high priority carbon plantations.

Land cover model (old IMAGE)

In the original *lcm.f* – file some minor changes had to be introduced in order to avoid reallocation of high priority carbon allocations.

Land transformations

In the carbon plantation land cover model parts the conversion matrix GCVEG was set. In *ccm/carbon.f* the actual transformation takes place. The following cases have to be distinguished:

1. agricultural land -> carbon plantation
2. regrowth forest and natural vegetation -> carbon plantation
3. carbon plantation -> carbon plantation (after harvesting event)
4. carbon plantation -> agricultural land
5. carbon plantation -> regrowth forest and natural vegetation

In all of these cases similar mechanisms are to be used as in the original IMAGE.

1. All biomass and litter go to the humus pool. Living biomass set to zero.
2. Depends on the natural vegetation in that grid cell and the VC-dependent option. Cases:
   a. Burning (best for non-forest in developing regions): living biomass and litter is transferred to the atmosphere to a greater part and the rest goes to the humus pool.
   b. Ploughed under (best for non-forest in developed regions): living biomass and litter go directly to the humus pool
   c. Harvesting (best for forests): Stems and branches are harvested, leaves, roots, litter go to the humus pool.

   Living biomass is always set to zero.
1. Stems and branches are harvested, leaves, roots, litter go to the humus pool. Living biomass is set to zero.
2. Stems and branches are harvested, leaves, roots, litter go to the humus pool. Living biomass is set to zero.
3. Stems and branches are harvested, leaves are transferred to the litter pool. Living biomass is set to zero.

Carbon accounting

Carbon fluxes and biomass are calculated in the modules *carbon.f* and in *cplantgrow.f* (for carbon plantations).
Here, actual NEP, stand age and also the moment of harvesting are calculated.

Harvesting

This part is somewhat more difficult to solve than planting carbon plantations. IMAGE 2.1 calculates each year agricultural demand and production and associated land cover changes, but these changes are only stored every 5^{th} year. To be consistent with this practice carbon plantations are only allowed to be harvested each 5^{th} year, too.
Harvesting is calculated within *cplantgrow.f* (cf part: Carbon plantation tree species). If the carbon plantation reaches its final rotation length (calculated in the same manner each year as for the SPP calculation, see above) the grid cell specific array element of GCPHARVACT is set to 1 otherwise it remains 0. This area is investigated later on for new land uses and carbon accounting.

What happens after harvesting?

The problem is to ensure that after harvesting the cell is transformed to one of the vegetation classes carbon plantation (and replanting it with seedlings), agricultural land or natural vegetation/regrowth forest.
The solution is sketched in the following for a grid cell which was harvested the last time step so that GCPHARVACT()=1.
Case high priority carbon plantations:

1. (*lcmcplant.f*) If the rule “higher priority to harvested carbon plantation cells” is true, this cell gets a higher valuation.
2. (*lcmcplant.f*) The realized carbon production and the demand are updated by subtracting the grid specific carbon production.
3. (*lcmcplant.f*) If this grid cell was chosen for new carbon plantations: CPHARVACT() set to 0 and GCVEG is set to CP/CP/Act.Time
4. (*lcm.f/lcmtest.f*) If CPHARVACT() is still 1 and GCVEG(2,) not CP then this grid cell can be used for expansion of agricultural land. If it is converted to agricultural area, grassland or biofuel area, than set GCVEG to CP/Agric/Act.Time (GCVEG only set in *lcm.f*).
5. (*lcm.f*) If no conversion took place, i.e. GCVEG(2,) equals 0, than GCVEG is set to CP/Nveg/Act.Time
6. (*lcm.f*) CPHARVACT() set to 0.

Case low priority carbon plantations:

1. (*lcm.f/lcmtest.f*) If CPHARVACT() is 1 and GCVEG(2,) not CP then this grid cell can be used for expansion of agricultural land. If it is converted to agricultural area, grassland or

biofuel area, than set GCVEG to CP/Agric/Act.Time (GCVEG only set in *lcm.f*). Than also CPHARVACT() is set to 0.

2. (*lcmcplant.f*) If the rule "higher priority to harvested carbon plantation cells" is true, this cell gets a higher valuation.
3. (*lcmcplant.f*) If CPHARVACT() equals 1 or GCVEG(1,) is CP (i.e. grid cell was converted to agricultural land in step 1) the realized carbon production and the demand are updated by subtracting the grid specific carbon production.
4. (*lcmcplant.f*) If this grid cell was chosen for new carbon plantations: CPHARVACT() set to 0 and GCVEG is set to CP/CP/Act.Time
5. (*lcmcplant.f*) If CPHARVACT() still equals 1, CPHARVACT() set to 0 and GCVEG is set to CP/Nveg/Act.Time

After these steps the land conversion is calculated in the usual manner in the module *carbon.f* .

Wood accounting

Harvested wood is classified in two classes, one coming from the stem compartment, the other from the branch compartment. All harvested wood from carbon plantations are summed up over time for different regions. It is assumed that these wood products have an infinite lifetime (option CPWOODRULE = 0). This assumption is a somewhat extreme scenario and allows a view on the maximum CO2 sequestration with carbon plantations achievable.
If CPWOODRULE is 1, a more likely wood accounting scenario is assumed:

1. The traditional wood demand (WDEM, as defined in the IMAGE base version) and the harvested wood of the carbon plantations (CPHARVEST) are both taken into account in the same calculation.
2. It is assumed that wood from carbon plantations has a higher priority than wood coming from natural vegetation. This reflects the intensive management of carbon plantations.
3. Carbon plantation (CP) wood harvest is compared with traditional wood demand regionally. If the CP wood supply exceeds the wood demand this region might become an export region (WEXPORTQ=1), if not it might become an import region (WEXPORTQ=0).
4. The surplus production of all export regions is transferred to a common global wood pool.
5. Case: The global CP wood production/supply exceeds the global wood demand: All import regions import so much wood that there CP production equals there wood demand. The exporting regions have to re-import from the global wood pool in such a way that the trade balance remains stable. It is assumed that the re-import is proportional to the exporting percentage - with regard to the global wood pool - of this region.
6. If the above case is not true: There is no re-import of the exporting regions needed. It is assumed that the importing regions import wood proportional to the difference between wood production and supply in that region.
7. If the CP wood production exceeds the wood demand, no natural vegetation is harvested. If it does not exceed the demand, the difference between CP wood production and demand are harvested in each region (as in the original IMAGE version).

8. All harvested wood – from CP and natural vegetation – are transferred to a short- and long-living wood pool, as in the original IMAGE version.

Grid information stored to files

1. GCPNPP : Average NPP of carbon plantation over probable rotation length and with current climate
2. GCPNEP : Average NEP of carbon plantation over probable rotation length and with current climate
3. GCPABG: Average ABG (Aboveground Biomass Growth) over probable rotation length and with current climate
4. GCPHARV: Rotation length of carbon plantation with current climate
5. GVCNEP: Average NEP of current natural vegetation over rotation length of carbon plantation and with current climate
6. GCPREL: Averaged release flux over rotation length if current natural vegetation is transformed to C plantation
7. GCPSPP: Surplus potential productivity
8. GCPTREE: Carbon plantation tree species number realized in this cell
9. GDISTCP: Minimum distance to other carbon plantations, agriculture, regrowth forests, and water bodies
10. GWEIGHTCP: Weight of cells for allocation to carbon plantations
11. GCPAGE: Actual age of carbon plantations, if cell are allocated to carbon plantations
12. GCPNPPACT: Actual NPP of carbon plantations in current year
13. GCPABGACT: Actual ABG of carbon plantations in current year
14. GCPNEPACT: Actual NEP of carbon plantations in current year
15. GCPNEPAVGACT: Actual over life time averaged NEP of carbon plantations in current year
16. GCPHARVACT: If in that time step there is a harvesting (=1) or not (0)

Handling of grid files

After completing IMAGE all temporal grid files (see list above) are deleted.
In the options file *INPUT/FILEHAND.DAT* a number of carbon plantation specific grid files might be specified to be copied at certain times to the OUTPUT-folder, these include: GCPABG, GCPAGE, GCPHARV, GCPNEP, GCPNPP, GCPPROD, GCPREL, GCPSPP, GCPTREE, GVCNEP.

Region and global information stored to files

1. cp_area.out: Land area converted to carbon plantations from specified vegetation class and specified region for each year (in km2)
2. cp_conv.out: Number of conversions between C plantations and other type per region and globally. Rows: 1st: CP->CP, 2nd: Agricultural land->CP, 3rd: Regrowth forest->CP; 4th: Natural Vegetation->CP, 5th: CP->Agricultural land, 6th: CP->Natural Vegetation/Regrowth forest

3. cp_flux.out: Fluxes connected with C plantations per region and globally. Rows: 1st: NEP (MtC/yr), 2nd: NPP (MtC/yr), 3th-19th: Conversion flux (MtC/yr) from all vegetation classes
4. cp_prod.out: Carbon sequestration demand, production and total realized production (MtC/yr)
5. cp_prop.out: Carbon plantations biomass and soil pools: wood, branch, leaves, roots, litter, humus and charcoal, harvested wood biomass (MtC) total carbon plantation area, and harvested area (1000 km2)
6. cp_tree.out: number of grid cells containing certain carbon plantation tree species (1 to 10, per region and globally).
7. cp_weight.out: which rules within the weighting procedure applies (number of grid cells per region, and globally): positive weight, negative weight, already maturing carbon plantations in cell (not allowed), bioreserves (not allowed), not enough time after conversion from natural vegetation to agriculture (not allowed), vegetation was originally ice, hot desert or tundra (not allowed), cell in region with total caloric intake too small (not allowed), ABG too small (not allowed), if high priority carbon plantations and cell was recently harvested (cell gets higher weight), abandoned marginal agricultural area (cell gets higher weight), land not needed anymore for agriculture (cell gets higher weight), cells cleared for traditional wood harvest (cell gets higher weight), natural vegetation in cell is usable for CP (cell gets higher weight).
8. cp_wood.out: Wood demand and supply having to do with C-plants and traditional wood (per region, and globally): Traditional wood demand, Total wood production, Carbon plantation wood production, Wood export, Wood import from/to C plant (all in MtC/yr)

Files changed

The following files were changed:

1. image.f
2. ccm/carbon.f
3. ccm/carbondata.f
4. ccm/carboninit.f
5. ccm/mkccmlib
6. lcm/adjacentinit.f
7. lcm/lcm.f
8. lcm/lcm0.f
9. lcm/lcm70.f
10. lcm/lcminit.f
11. lcm/lcmtest.f
12. lcm/seeddisp.f
13. lcm/wood.f
14. lcm/woodinit.f
15. lcm/mklcmlib
16. luem/luem.f

17. tvm/evapovg.f
18. tvm/potvg.f
19. cbl/carbdata.cbl
20. cbl/files.cbl
21. cbl/image.fip
22. cbl/options.cbl
23. aos/atmos/averzone.f
24. gen/files/cpouttvm.f
25. gen/files/filehand.f
26. gen/files/writetes.f
27. gen/files/writetesinit.f
28. gen/options/readoption.f
29. gen/options/readfiles.f
30. postpr/loctemp.f
31. postpr/locgrowst.f
32. INPUT/FILEHAND.DAT
33. INPUT/OPTIONS.DAT
34. INPUT/LANDALB.DAT

And new files are:

1. ccm/cplant.f
2. ccm/cplantinit.f
3. ccm/cplantgrow.f
4. lcm/lcmcplant.f
5. cbl/cplantdata.cbl
6. INPUT/CPLANT.SCEN
7. INPUT/CPTREE.DAT

The following initial grid files (in OUTPUTTVM) have to be changed in IMAGE 2.1.2:

1. GVEG.UNF1
2. GNVEG.UNF1
3. GPOTVEG_1970.UNF1
4. GCVEG.3.UNF1
5. GCNVEG.3.UNF1

Here, the vegetation classes have to be transformed to the new classes. This procedure is done with the program *gridconvert* and checked with *check*. Both programs are to be found in the folder image212/convertgrid. The procedure should be as follows:

1. copybefore = copy original grid files
2. gridconvert = convert grid files, write it to x*.UNF1 files
3. check = check the new files against the old; only if there are doubts
4. copyafter = copies the x*.UNF1 files to *.UNF1 files, so that now image uses these files.

Data

Climate envelope data for important plantation tree species is compiled in table 1.

```
1. Eucalyptus camaldulensis: dry, tropical
2. E. grandis: wet, tropical
3. Pinus radiata: rel. dry, trop & subtrop, not too hot
4. Pinus caribaea: wet, tropical
5. Acacia mangium
6. Tectona grandis
7. Populus clones, temperate
8. Picea higher yield, temperate
9. nothing specific
10.nothing specific
```

NPP and climate										
NPPI	1000.0	1000.0	1300.0	1300.0	1000.0	1000.0	1100.0	1000.0	1000.0	1000.0
INCNPPC	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5
TMPMIN	0.0	0.0	0.0	5.0	0.0	0.0	-5.0	-5.0	0.0	0.0
TMPOPT	25.0	25.0	20.0	25.0	25.0	25.0	20.0	20.0	20.0	20.0
TMPMAX	50.0	50.0	40.0	50.0	50.0	50.0	40.0	40.0	50.0	50.0
CORVEG	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
TABSWSGR	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Allocation										
ALLOCST	0.3	0.3	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
ALLOCBR	0.15	0.15	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
ALLOCLF	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
ALLOCRT	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Humification										
HUMFAC	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
CARFAC	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Longevity of compartments										
LONGST	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
LONGBR	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
LONGLF	1.0	1.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
LONGRT	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
LONGLT	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
LONGHM	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
LONGCH	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Density and carbon content										
DENSITY	0.5	0.5	0.4	0.46	0.5	0.5	0.34	0.5	0.5	0.5
DMTOC	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Min & max rotation										
ROTMIN	10.0	10.0	10.0	10.0	25.0	20.0	15.0	25.0	25.0	25.0
ROTMAX	60.0	60.0	60.0	60.0	60.0	80.0	60.0	90.0	60.0	60.0
Climate envelope										
PRECMIN	250.0	700.0	650.0	1050.0	1000.0	1250.0	600.0	500.0	9999.0	9999.0
PRECMAX	2500.0	4000.0	1600.0	2300.0	4000.0	3000.0	3000.0	3000.0	9999.0	9999.0
DRYSEASON	8.0	7.0	3.0	7.0	6.0	7.0	1.0	3.0	6.0	6.0
TEMPMAXMIN	28.0	25.0	20.0	24.0	30.0	21.0	22.0	15.0	999.0	999.0
TEMPMAXMAX	40.0	34.0	30.0	38.0	40.0	34.0	30.0	25.0	999.0	999.0
TEMPMINMIN	6.0	3.0	-2.0	14.0	10.0	14.0	-10.0	-20.0	999.0	999.0
TEMPMINMAX	22.0	16.0	12.0	21.0	24.0	24.0	5.0	-5.0	999.0	999.0
TEMPAVGMIN	18.0	14.0	11.0	20.0	18.0	20.0	5.0	0.0	999.0	999.0
TEMPAVGMAX	29.0	25.0	18.0	28.0	28.0	28.0	15.0	10.0	999.0	999.0

Table 1 All tree specific parameters as compiled for the base run program version. Names of variables as in the original IMAGE, with the new variables:

DENSITY: density of wood (oven dry, t dry matter / m3)

DMTOC: ton dry matter per ton carbon content of wood

ROTMIN, ROTMAX: minimum and maximum rotation length (yr) of this species.

PRECMIN, PRECMAX: minimum and maximum required annual precipitation (mm/yr)

DRYSEASON: length of dry season (months)

TEMPMAXMIN, TEMPMAXMAX: Minimum and maximum mean monthly maximum temperature
TEMPMINMIN, TEMPMINMAX Minimum and maximum mean monthly minimum temperature
TEMPAVGMIN, TEMPAVGMAX Minimum and maximum mean monthly average temperature

				[mm] Annual Rainfall			[months] Dry Season		[°C] Mean max. month temp		[°C] Mean min. month temp		[°C] Mean annual temp		[°C] Absolute temp.
Species	Sub	Literature	Area	min.	max.	Distribut.	min.	max.	min.	max.	min.	max.	min.	max.	min.
Acacia	Mangium	Webb et al. (1984), p. 90	Trop/subtrop	1000	2100	winter	3	4	30	32	13	22	18	28	
		Viriyabuncha et al. (1996), p.22	Thailand	1000	4000	summer	0	4	30	40	10	24	18	28	
		Hong et al. (1996), p.26	China	1000	4000		0	5	30	40	10	24	18	28	0
		Nghia (1996), p.48	Vietnam	1300	2500	summer	0	6	28	35	10	22	22	28	
Acacia	Melanoxylon	Webb et al. (1984), p. 92	Trop/subtrop	900	2700	all	0	2	16	22	0	12	12	18	
Acacia	Mearnsii	Webb et al. (1984), p. 91	Trop/subtrop	700	2000	summer/uniform	2	3	18	24	2	8	12	20	
		Hong et al. (1996), p.26	China	700	2300		0	6	21	35	0	17	14	22	-5
Acacia	Auriculiformis	Webb et al. (1984), p. 85	Trop/subtrop	1300	1700	summer	4	6	28	34	20	24	24	29	
		Viriyabuncha et al. (1996), p.22	Thailand	760	2000	summer	0	6	28	39	12	24	24	29	
		Hong et al. (1996), p.26	China	760	2000		0	6	28	39	12	24	24	29	0
		Nghia (1996), p.48	Vietnam	800	2500	summer	0	7	25	37	6	22	20	30	
Eucalyptus	Camaldulensis (North)	Webb et al. (1984), p. 142	Trop/subtrop	250	1250	summer	4	8	28	36	10	22	19	26	
		Viriyabuncha et al. (1996), p.22	Thailand	400	2500	summer	2	8	28	40	6	22	18	29	
		Hong et al. (1996), p.26	China	400	2500		2	8	28	38	6	22	18	28	-3
		Fryer (1996), p.51	Central America	400	2500	summer	2	8	28	40	6	22	18	28	
		Nghia (1996), p.48	Vietnam	800	2500	summer	2	6	28	38	10	22	20	28	
Eucalyptus	Camaldulensis (South)	Webb et al. (1984), p. 143	Trop/subtrop	400	1000	winter	4	6	22	30	8	14	16	22	
Eucalyptus	Grandis	Webb et al. (1984), p. 154	Trop/subtrop	1000	4000	summer/uniform	0	2	28	35	10	18	17	26	
		Booth (1990), p. 51	Trop/subtrop	700	2500	summer/uniform			25	34	3	16	14	25	-8

		Fryer (1996), p.51	Central America	700	2500	all	0	7	25	34	3	18	14	25	
		Hong et al. (1996), p.26	China	900	2500		0	6	25	34	3	16	14	25	-6
		Viriyabuncha et al. (1996), p.22	Thailand	700	2500	summer/uniform	0	7	25	36	3	20	14	27	
		Nghia (1996), p.48	Vietnam	1200	2200		2	6	23	30	5	18	18	25	
Eucalyptus	Globulus	Webb et al. (1984), p. 152	Trop/subtrop	550	1500	winter/summer	2	3	20	30	4	12	12	18	
		Hong et al. (1996), p.26	China	550	1500		0	6	19	30	2	12	9	18	-7
Eucalyptus	Cloeziana	Webb et al. (1984), p. 146	Trop/subtrop	900	1650	summer	0	2	28	32	6	14	18	26	
Eucalyptus	Obliqua	Webb et al. (1984), p. 163	Trop/subtrop	700	1500	winter/summer	0	2	27	32	2	5	9	16	
Eucalyptus	Fastigata	Webb et al. (1984), p. 151	Trop/subtrop	750	1100	all	1	2	22	26	0	4	13	18	
Eucalyptus	Nitens	Webb et al. (1984), p. 162	Trop/subtrop	750	1500	winter/uniform	0	2	20	22	-1	4	9	15	
Eucalyptus	Tereticornis	Webb et al. (1984), p. 176	Trop/subtrop	500	1500	summer	4	7	22	32	2	12	17	27	
		Booth (1990), p. 55	Trop/subtrop	500	1500	summer	4	8	22	42	2	19	17	27	
Eucalyptus	Deglupta	Webb et al. (1984), p. 149	Trop/subtrop	2000	5000	uniform	0	1	24	32	21	26	20	32	
Eucalyptus	Saligna	Webb et al. (1984), p. 171	Trop/subtrop	800	1500	summer/uniform	0	4	28	30	3	4	15	23	
Eucalyptus	Urophylla	Webb et al. (1984), p. 178	Trop/subtrop	1100	1950	summer	2	6	20	26	8	12	18	28	
		Nghia (1996), p.48	Vietnam	1500	2500	summer	0	4	23	35	8	18	20	26	
Tectona	Grandis	Webb et al. (1984), p. 249	Trop/subtrop	1250	3000	summer	3	6	25	32	18	24	22	26	
		Nghia (1996), p.48	Vietnam	1300	2500	summer	4	7	21	34	14	20	20	28	
Pinus	Merkusii	Webb et al. (1984), p. 216	Trop/subtrop	1000	2800	summer	2	5	24	32	18	24	21	28	
	Jungh.; contin.	Nghia (1996), p.48	Vietnam	900	2000	summer	2	6	26	35	5	18	23	28	
Pinus	Taeda	Webb et al. (1984), p. 231	Trop/subtrop	900	2200	summer/unifor	0	2	20	25	4	18	14	20	

						m								
Pinus	Radiata	Webb et al. (1984), p. 229	Trop/subtrop	650	1600	win-ter/uniform	2	3	20	30	2	12	11	18
		Booth (1990), p. 55	Trop/subtrop	650	1600	win-ter/uniform	0	3	20	30	-2	12	11	18
Pinus	Elliottii	Webb et al. (1984), p. 212	Trop/subtrop	650	2500	summer	2	4	23	32	4	12	15	24
Pinus	Oocarpa	Webb et al. (1984), p. 221	Trop/subtrop	750	1500	summer	2	6	20	30	8	16	13	21
Pinus	Caribaea , var.	Webb et al. (1984), p. 209	Trop/subtrop	1050	1800	summer	2	4	30	34	16	20	24	26
	Caribaea	Nghia (1996), p.48	Vietnam	1200	2300	summer	0	7	24	38	14	21	20	28
Pinus	Kesiya	Webb et al. (1984), p. 215	Trop/subtrop	700	1800	summer	2	6	26	30	10	18	17	22
		Nghia (1996), p.48	Vietnam	1400	2200	summer	1	6	20	27	3	18	18	23
Pinus	Patula	Webb et al. (1984), p. 223	Trop/subtrop	750	2000	summer	0	3	20	29	6	12	12	18
Crytomaria	Japonica	Webb et al. (1984), p. 131	Trop/subtrop	1500	2500	all	0	2	18	25	2	13	10	18
Gmelina	Arborea	Webb et al. (1984), p. 184	Trop/subtrop	1000	4500	summer	2	4	24	35	18	24	21	28
Albizzia	Falcataria	Webb et al. (1984), p. 100	Trop/subtrop	2000	4000	uniform	0	2	30	34	20	24	22	29
Populus	Deltoides	Webb et al. (1984), p. 232	Trop/subtrop	1200	3000	uniform	0	1	22	30	2	12	12	16

Table 2 Listing of climate envelopes of some important plantation species.