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Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach

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Abstract

The paper describes the Version 2 of the CO2FIX (CO2FIX V.2) model, a user-friendly tool for dynamically estimating the carbon sequestration potential of forest management, agroforesty and afforestation projects. CO2FIX V.2 is a multi-cohort ecosystem-level model based on carbon accounting of forest stands, including forest biomass, soils and products. Carbon stored in living biomass is estimated with a forest cohort model that allows for competition, natural mortality, logging, and mortality due to logging damage. Soil carbon is modeled using five stock pools, three for litter and two for humus. The dynamics of carbon stored in wood products is simulated with a set of pools for short-, medium- and long-lived products, and includes processing efficiency, re-use of by-products, recycling, and disposal forms. The CO2FIX V.2 model estimates total carbon balance of alternative management regimes in both even and uneven-aged forests, and thus has a wide applicability for both temperate and tropical conditions. Results for the model testing and validation in selected temperate and tropical forest management systems are presented and discussed.

Keywords: Model; Forests; Carbon sequestration; Forest management; Afforestation; Agroforestry; Kyoto Protocol

1. Introduction: forests and climate change

Forests play an important role in the global carbon cycle. Their temporal carbon dynamics are characterized by long periods of gradual build-up of biomass (a sink), alternated with short periods of massive biomass loss (source). Forests thus switch between being a source or a sink of carbon, depending on the succession stage, specific disturbance or management regime

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and activities. Tropical forests as a whole, for example, are usually seen as a net carbon source because of the deforestation that is taking place locally. However, recent evidence suggests that the vast areas of remaining tropical forests are not in equilibrium, but may function as a net carbon sink (Grace et al., 1995; Phillips et al., 1998). The global terrestrial biosphere is thought to have been acting as a sink of approximately 2.3 Gt C per year in the 1990s. This sink was partly caused by large-scale vegetation rebound in the Northern Hemispheric forests in combination with possibly a CO_2 fertilization effect (Watson et al., 2000).

Available estimates suggest that forests may mitigate additionally from 1 to 2 Gt C per year between 1995 and 2050 (Brown et al., 1996; Kauppi et al., 2001). However, achieving the full carbon mitigation potential will require, among other things, accurate methods to assess the dynamics of carbon fluxes and storage under alternative management regimes. Accurate estimates of the potential dynamics of carbon fluxes in forest ecosystems and afforestation projects are also needed for the adequate implementation of the Kyoto Protocol, which currently allows for the so-called ARD activities (afforestation–reforestation–deforestation), as well as re-vegetation and forest management projects. Models will be particularly critical for the examination of alternative carbon crediting schemes of Joint Implementation (JI)- and Clean Development Mechanism (CDM)-related projects.

Furthermore, quantifying the likely results of the above-mentioned options is difficult because carbon sequestration in forests consists of stocks and fluxes in various compartments of the forest stands—including soil and dead wood—as well as in the manufactured wood products. Management that focuses on enhancement of carbon in, e.g. forest biomass therefore has an impact on soils and wood products as well. Also, study results are difficult to compare because of differences in the forest types, site types, management systems, monitoring methodology used, because only parts of the carbon cycle of a forest ecosystem-wood products chain are regarded, or because different time scales are used.

Up to date, several models have been developed that analyze and simulate carbon budgets and fluxes at the level of the forest stands. These models range from very detailed ecophysiological models used in climate impact assessment, to very general empirical, descriptive models of carbon budgets within forest stands (see, e.g. Mohren, 1987; Dewar, 1991; Mery and Kanninen, 1999; Kirschbaum et al., 1998; Schlamadinger and Marland, 1996; White et al., 2000; Karjalainen, 1996 for an overview). None of these models have been widely disseminated, and neither of them has been accepted as a possible standard for carbon crediting from projects.

In this paper we examine the structure of the CO2FIX V.2 model and illustrate its application to five case studies describing common management systems of temperate forests, tropical forests and agroforestry systems. This version of the CO2FIX program aims at a widespread applicability to handle uneven-aged, mixed-species forest-management regimes or multi-cohort systems (such as agroforestry or selective logging of tropical forests). The work builds on the experience of the previous model that has been extensively used and tested in many types of forest ecosystems throughout the world (Mohren and Goldewijk, 1990; Mohren et al., 1999). We begin the paper with a discussion of the project approach; we then describe the main characteristics of the model. In a third section we show the results and reliability of the application of the model in five case studies. We conclude the paper with a set of recommendations for future work.

2. The CASFOR project

The CO2FIX model was developed as part of the “Carbon sequestration in afforestation and sustainable forest management” (CASFOR) project, which was funded through the European Union INCO-DC program. The CASFOR project is a multi-institutional effort being carried out by ALTERRA in The Netherlands, the Instituto de Ecologia from the National University of Mexico in Mexico, the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Costa Rica, and by the European Forest Institute in Finland.

The research team already developed the CO2FIX V.1 model (Mohren et al., 1999), a forest-stand level, user-friendly model for quantification of the potential role of forests in the global carbon cycle, in carbon sequestration, and in carbon emissions offsets as part of the policy evaluation of the role of forests in mitigating the greenhouse effect. This version has been distributed as a free download through Internet since June 1999.[3] At the moment, there are 800 registered users in 72 countries. Some of the results of previous versions of CO2FIX have been used for quantifying C stocks and fluxes in a wide variety of forest systems ranging from even-aged single-species temperate forest stands to agroforestry system in the tropics (Mohren and Goldewijk, 1990; Nabuurs and Mohren, 1993; Nabuurs and Schelhaas, 2002; De Jong et al., 1998; Ordoñez and Masera, 2001; Olguín, 2001; Schelhaas and Nabuurs, 2001). Furthermore, some of the CO2FIX outcomes have been used in the IPCC 1995 climate change assessment (Brown et al., 1996).

The CO2FIX V.1 simulates the carbon dynamics in a single species (monoculture) stands, e.g. in forest plantations, which has been limiting its applicability. Therefore, the research team decided to develop a new version of the model, which would be able to simulate the carbon dynamics associated to more complex systems, such as selective logging of tropical forests, where multi-species (functional groups) and a multi-layer structure is common. The same is true for multi-tiered agroforestry systems and for the management of mixed-species, uneven-aged native forests. Furthermore, a new soil module and an improved wood product module were added to the new version of the model.

3. CO2FIX V.2 model structure

The CO2FIX V.2 is a model that quantifies the C stocks and fluxes in a forest stand, using the so-called full carbon accounting approach, i.e. calculating changes in carbon stocks in all carbon pools over time (Noble et al., 2000).[4] A stand is here defined as an area that can be considered as relatively homogeneous in terms of vegetation structure, growth dynamics, and species composition, and contains a number of trees for which a common set of characteristics can be created. The carbon in vegetation—above- and belowground, soils as well as in wood products derived from the management activities conducted within the stand are included. The approach of the model is comparable to stand-level carbon accounting models, such as GORCAM (Schlamadinger and Marland, 1996) and CAMFor (Richards and Evans, 2000), and cohort-type forest growth models, such as CAFOGROM (Alder, 1995). The GORCAM and CAMFor models are limited to one-species management regimes, while CAFOGROM only takes into account tree volume and basal area of various species cohorts.

The CO2FIX V.2 model has been programmed in C++ using an object-oriented programming environment. The model is divided in three main modules: biomass, soil organic matter and products, and runs with time-steps of 1 year (Fig. 1). The model produces output in tabular and graphic forms. It allows estimating the time evolution of total carbon sequestered at the stand level.

The total carbon stored in the forest stand at any time (CT_t) is considered to be

$$CT_t = Cb_t + Cs_t + Cp_t \quad (\mathrm{t\,C\,ha^{-1}}) \tag{1}$$

where Cb_t is the total carbon stored in living (above plus belowground) biomass at any time t, in metric tonnes per hectare ($\mathrm{t\,C\,ha^{-1}}$); Cs_t, the carbon stored in soil organic matter ($\mathrm{t\,C\,ha^{-1}}$), and Cp_t is the carbon stored in wood products ($\mathrm{t\,C\,ha^{-1}}$).

3.1. Carbon stored in living biomass

The carbon stocks and flows in the forests' living biomass (above- and belowground) are estimated using a "cohort model" approach (Reed, 1980). Each cohort is defined as a group of individual trees or species within the stand, which are assumed to exhibit similar growth, and which may be treated as single entities within the model (Vanclay, 1989; Alder, 1995; Alder and Silva, 2000). These cohorts may be, for example: (a) successional groups in a natural forest (e.g. pioneers, intermediate, and climax), (b) species in a mixed forests (e.g. mixed pine–oak forests); and (c) strata in a multi-strata agroforestry system (e.g. understory, middle layer, upper layer). The carbon stored in living biomass ($Cb_{t)}$ of the whole forest

[3] A more detailed description of the CASFOR project, and the different versions of the model can be found at http://www.efi.fi/projects/casfor.

[4] Here we present a conceptual description of the model. Refer to Nabuurs et al. (2002) for more details about the CO2FIX V.2 user interface and simulation options.

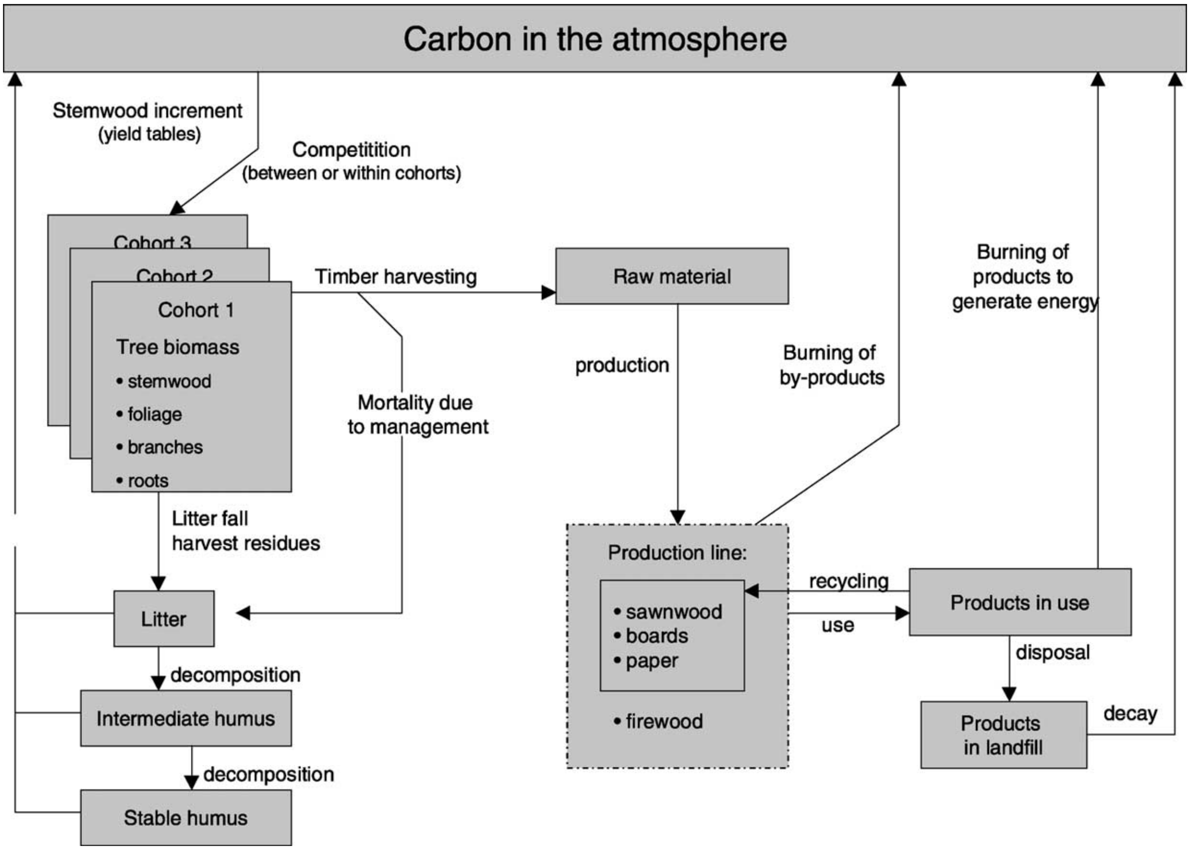


Fig. 1. Carbon fluxes/processes (arrows) and carbon stocks (boxes) in a forest ecosystem and its wood products as distinguished in CO2FIX V.2.

stand, can then be expressed as the sum of the biomasses of each cohort, i.e.

$$\mathrm{Cb}_t = \sum \mathrm{Cb}_{it} \quad (\mathrm{t\,C\,ha^{-1}}) \tag{2}$$

where Cb_{it} is the carbon stored in the living biomass of cohort i ($\mathrm{t\,C\,ha^{-1}}$).

For each new time step, Cb_{it} is calculated as the balance between the original biomass, plus biomass growth (Gb_{it}), minus the turnover of branches, foliage and roots (T_{it}), minus tree mortality due to senescence (Msb_{it}), minus harvest (H_{it}) minus mortality due to logging (Ml_{it}), i.e.

$$\mathrm{Cb}_{it+1} = \mathrm{Cb}_{it} + K_\mathrm{c}[\mathrm{Gb}_{it} - \mathrm{Ms}_{it} - T_{it} - H_{it} - \mathrm{Ml}_{it}] \quad (\mathrm{t\,C\,ha^{-1}}) \tag{3}$$

where K_c is a constant to convert biomass to carbon content (kg C per kg biomass dry weight).

3.1.1. *Biomass growth*

In order to simulate Gb_{it} the model uses as input the growth rate of stem volumes, which can be derived from conventional yield tables. From the growth rate of stem volumes, growth rates for foliage, branches and roots are calculated, using time-dependent allocation coefficients. Hence, the model uses stem volume growth in $\mathrm{m^3\,ha^{-1}}$ per year as the main input, and uses an allometric approach to derive net annual increment of the main biomass components from stem volume growth. These growth rates are later modified by the interactions of the cohort within itself and with other cohorts. To adjust for differences in site quality, yield tables derived for good-, medium-, and poor-site conditions may be used and other growth related parameters modified accordingly (Nabuurs and Mohren, 1995). Mathematically,

$$\mathrm{Gb}_{it} = \left(K_{\mathrm{v}} Y_{ist}\left(1+\sum(F_{ijt})\right)\right) \times \mathrm{Mg}_{it} \quad (\mathrm{t\,ha^{-1}\ per\ year}) \tag{4}$$

where K_{v} is a constant to convert volume yields into dry biomass (basic density, in kg dry biomass per m^3 of fresh stemwood volume); Y_{ist}, the volume yield of stem wood for each cohort "*i*" in $m^3\,ha^{-1}$ per year, F_{ijt}, the biomass allocation coefficient of each living biomass component "*j*" (foliage, branches, and roots) relative to stems, for each cohort "*i*" at time *t* (kg per kg) and Mg_{it} is the dimensionless growth modifier due to interactions among and within cohorts.

The model provides two alternative ways to define stem growth of each cohort: (a) as function of tree or stand age (conventional yield tables), and (b) as a function of the cohort total and maximum aboveground biomass. The latter input option has been added because in tropical forests often diameter-dependent instead of age-dependent growth of trees is used.

In order to be able to model the carbon stored and accumulated in multi-cohort stands, CO2FIX modifies the growth of each cohort due to tree interactions. This is because tree growth in a cohort is influenced by the presence of other trees. The major type of interactions is competition. For each cohort, the interactions can be caused by the same cohort, or by other cohorts. Three types of interactions can be described: (a) no competition, (b) competition, and (c) synergic effects.

There are various ways of modeling competition. In gap models, "growth modifiers" are used for this purpose (Botkin et al., 1972). It is assumed that trees grow at a maximum rate under optimal conditions, but that this growth can be affected by biotic and abiotic conditions of the environment. In growth and yield models, the growth modifier is usually defined as a function of stand-basal area or as a function of other variable indicating stocking density of the stand (Peng, 2000; Monserud and Sterba, 1996). The modifier values range from 1 (i.e. growth is not reduced) to 0 (no growth at all), to more than 1, when there are synergic effects (i.e. where growth is higher in the mixture than in the case of each cohort alone). This is relevant for multi-species and multi-strata situations (e.g. Beer et al., 1990).

In this model a single parameter is used to simulate the influence of the same cohort or the influence of other cohorts on the growth of the cohort in question. Mg_{it} is defined as a function of total biomass of the stand. The model provides two basic options for modeling the interactions between and within the cohorts: (a) Competition of a cohort as a function of relative total stand biomass (i.e. total aboveground biomass of all cohorts in a stand at any time "B_t" relative to the maximum total stand biomass of all cohorts "$B_{\max}$" in $\mathrm{t\,ha^{-1}}$). In this case, the interactions of this cohort with all the cohorts combined, including the cohort in question, is modeled. (b) Interactions of the cohort in question as a function of the relative biomass of each other cohort separately. Mathematically, we can express Mg_{it} either as

$$\mathrm{Mg}_{it} = f\left(\frac{B_t}{B_{\max}}\right) \tag{5}$$

or

$$\mathrm{Mg}_{it} = \prod \mathrm{Mg}_{ikt} \tag{6}$$

where Mg_{ikt} is the dimensionless growth modifier function of each cohort "*i*", relative to each of the other cohorts "*k*" and

$$\mathrm{Mg}_{ikt} = f\left(\frac{B_{it}}{B_{i\max}}\right) \tag{7}$$

where B_{it} and $B_{i\max}$ are the aboveground biomass of each cohort at time "*t*", and the maximum aboveground cohort biomass, respectively. Thus, if two cohorts are present, we have to include four possible growth modifiers, if three cohorts are present, then potentially nine growth modifiers might be defined, and so on. The maximum aboveground biomass of the stand—or of each of the cohorts—can be estimated from inventory data coming from undisturbed or lightly disturbed forests in or around the site area (typically forest stands with the highest basal area). Locally developed or published regression equations that convert inventory data to standing biomass should be used for this purpose (Brown, 1997). If only commercial volume data are available for the whole forest or the cohorts, standardized biomass expansion factors can be applied to these data. If no inventory or volume data are available, published data of forests under similar ecological conditions should be consulted.

3.1.2. Tree mortality due to senescence

Mortality due to senescence can be estimated as a function of tree age or as a function of the relative biomass (standing biomass divided by the maximum stand biomass).

$$\mathrm{Ms}_{it} = f(\mathrm{age}) \quad \text{or} \quad \mathrm{Ms}_{it} = f\left(\frac{B_{it}}{B_{i\max}}\right) \tag{8}$$

where, Ms_{it} is the cohort mortality due to senescence at time t in years. In the first case, it is assumed that all trees have a maximum age, and that the mortality (i.e. the probability of dying) increases when the age of the stand approaches the maximum age. In some situations, there may also be high initial mortality, for instance, of pioneer species in a natural succession (Vanclay, 1989). If data of mortality related to age is not available—a typical situation for tropical natural forests, the mortality can be modeled as a function of relative cohort biomass.

3.1.3. Turnover

In addition to tree mortality, an accurate estimation of carbon dynamics in living biomass needs to account for the turnover of foliage, branches, and roots. This turnover is also very important to adequately model the carbon dynamics of soil organic matter. We model the turnover for each cohort (T_{it}) as the sum of the turnovers of each component "j", which in turn is simply the existing biomass of the particular component "j" multiplied by a decay or turnover constant (K_{ijT}). Mathematically,

$$T_{it} = \sum B_{ij} K_{ijT} \quad (\mathrm{t\,ha^{-1}\ per\ year}) \tag{9}$$

where K_{ijT} ranges between 1 per year (i.e. all the component biomass is lost during the year) to 0 per year (no turnover at all).

3.1.4. Harvesting

If the particular forest ecosystem under analysis is managed, part or all of the tree biomass might be removed through thinnings, selective logging or clear-cutting. This harvested biomass is subtracted from the existing biomass, and is allocated to the products and soil modules (see the sections on soil organic matter and wood products below).

3.1.5. Mortality due to logging (harvesting) damage

Forest logging operations increase the mortality of the remaining trees. This damage depends very much on the type of forest and the type of technology and methods used in logging. In tropical forests, where traditional logging methods are used, mortality due to logging can be very high, up to 20% of the remaining basal area (Alder and Silva, 2000). The mortality due to logging is directly related to the intensity of logging, which can be expressed as the number of trees, basal area, volume, or biomass logged.

Also, the logging may cause mortality several years after the operation (Pinard and Putz, 1997). In many cases, the initial mortality is high during the first years after the logging, and the mortality decreases gradually, reaching 0 in 10–20 years, depending on the forest type and technology used (Pinard and Putz, 1997). In the CO2FIX V.2 model, we use a logging damage mortality coefficient (Kl_{it}) as a linear function of time (years after logging) with three parameters: (a) initial mortality (Mo_i), (b) duration of the damage (π), and (c) intensity of the initial logging (Io_i). Mathematically,

$$\mathrm{Ml}_{it} = B_{it} \times \mathrm{Kl}_{it} \quad (\mathrm{t\,ha^{-1}\ per\ year}) \tag{10}$$

where

$$\mathrm{Kl}_{it} = \mathrm{Mo}_i - \pi \times \mathrm{Io}_i \tag{11}$$

Parametrizing the biomass module involves getting information ranging from widely available yield tables on stem volume increment, wood density of species, and general knowledge on harvesting and thinning practices, to more detailed information on stem growth allocation coefficients, competition and mortality. A manual has been prepared and published on the Web to help users parametrizing the CO2FIX model (Nabuurs et al., 2002, available free of charge at http://www.efi.fi/projects/casfor). We refer readers to this publication for a detailed discussion on how to obtain the model parameters and how to find appropriate default values if needed. Five complete case studies describing common forest management systems are also provided with the model, which help users with the parametrization of similar systems.

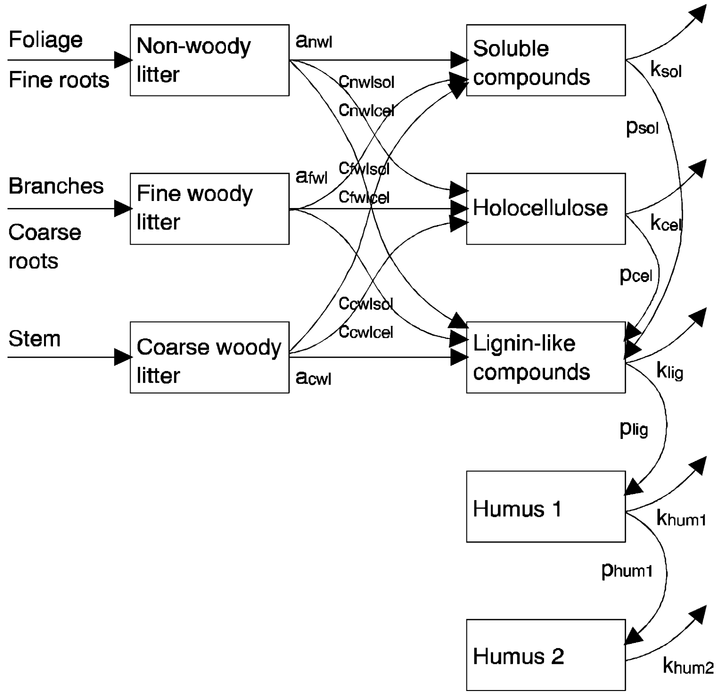


Fig. 2. Flow chart of the soil submodel. The boxes represent carbon compartments, the arrows carbon fluxes with associated acronyms of parameters controlling the fluxes.

3.2. Carbon stored in soil organic matter

To calculate the fluxes and stocks of carbon in soil, a dynamic soil carbon module called YASSO was adapted to the CO2FIX model. Among the many existing soil carbon models, this one was considered particularly suitable for this purpose. First, the soil carbon inputs could be derived in the required form from the vegetation module of the CO2FIX model. Second, the soil model did not require any special information that would not be generally available. Third, it used annual time step, like the rest of the CO2FIX model. The current YASSO model has been developed for non-waterlogged forest soils and tested to calculate decomposition of various litter types appropriately from arctic tundra to tropical rainforests (Liski et al., 2002).

YASSO consists of three litter compartments describing physical fractionation of litter and five compartments describing microbial decomposition and humification processes in the soil (Fig. 2). The litter compartments are for stem, branches plus coarse root, and foliage plus fine root litter. The five other compartments are for soluble, holocellulose, and lignin-like compounds and for two different humus types.[5]

For climate information, YASSO requires mean annual temperature, plus precipitation, and potential evapotranspiration values during summer (from May to September for the Northern Hemisphere). For tropical circumstances the year-round precipitation, and the year-round potential evapotranspiration, may be used but the accuracy of this approach has not been tested.

In the current application in CO2FIX, YASSO receives litter input (t C ha^{-1} per year) from living trees of each cohort from foliage, fine roots, branches, coarse roots, and stems. Those inputs are quantified during the simulation in other parts of the CO2FIX model from turnover rates, natural mortality, management mortality, and logging slash (Eqs. (8) and (11)). The user can initialize the module, i.e. determine the contents of the soil carbon compartments in the

[5] For a more detailed description of this model, write to Jari.Liski@efi.fi or see Karjalainen et al. (2002).

beginning of the calculations either by manually providing the carbon contents, just like giving the climate data, or by manually providing annual litter inputs of the vegetation type of the land-use before afforestation, and then letting the model calculate the associated equilibrium stocks. If no local litter fall data specific for the site are available, then an indication of litter inputs may be derived from annual NPP data for biomes. In case the latter option needs to be applied, then the soil initialization becomes very uncertain because of large spatial variability in soil types and carbon contents. All further soil output must in this case be regarded with great caution.

In YASSO, litter entering the soil from the various origins (see above, Eqs. (8) and (11)) is first divided between the three litter compartments according to the litter type (non-woody, fine woody or coarse woody litter). The fractionation rates of these litter compartments (a_i) determine the proportions that leave each of these litter compartments each year. The matter leaving the litter compartments goes to either soluble, holocellulose or lignin compartments according to its chemical composition (c_i). Each of these compartments, plus the two humus compartments have a specific decomposition rate (k_i) that determine the fractions removed from the contents each year. Fractions of matter (p_x) leaving the soluble, the cellulose, the lignin or the first humus compartments are transferred to the subsequent compartments as illustrated in Fig. 2 while the rest ($1 - p_x$) leaves the system.

The decomposition rates of the soluble, cellulose and lignin compartments as well as the transfer fractions between these compartments, have been determined using mass loss data from Sweden (Berg et al., 1991a,b). Also, the decomposition rates have been set to depend on annual temperature and precipitation minus potential evapotranspiration between May and September according to an analysis of Berg et al.'s (1993) data across Europe. The parameters related to the humus compartments have been determined using data on the accumulation rate of carbon along a soil chronosequence on the Finnish coast (Liski et al., 1998) and soil carbon contents at sites of different productivities (Liski and Westman, 1995). The decomposition rates of the humus compartments are set less sensitive to temperature than those of the other compartments (Liski et al., 1999; Giardina and Ryan, 2000).

The robustness of modeling climatic effects on decomposition in CO2FIX has been tested using data from litter bag experiments (Liski et al., 2002). These experiments have been carried out in a wide variety of environments ranging from arctic tundra to tropical rainforest across North and Central America, and using different foliar and fine root litter types (Moore et al., 1999; Gholz et al., 2000). The results show that, in most conditions, CO2FIX estimates the climatic effects on decomposition with little systematic error and good fit with experimental data (high R^2 values) (Liski et al., 2002). Under very continental climate, however, such as in the middle of Canada, the model seems to overestimate the climatic effects, because of a different relationship between annual mean temperature and temperature of the growing season. This problem will be fixed by replacing annual mean temperature with the effective temperature sum (degree) days in the next version of CO2FIX.

3.3. *Carbon stored in wood products*

The products module is a carbon accounting submodel that tracks the carbon from harvesting to final decay. It does this tracking through several intermediate processing and allocation steps. This module is based on a model developed by Karjalainen et al. (1994) and has been used for modeling the carbon budget in the Finnish forest sector (Karjalainen et al., 1995, 1999; Pussinen et al., 1997). A more detailed and newly parameterized version of the model has been applied to Finland (Liski et al., 2001), to Germany (Karjalainen et al., 2002) and to the European forest sector (Karjalainen et al., 2001; Eggers, 2001).

The outline of the wood product module is shown in Fig. 3. Harvested material from thinning and/or final felling is raw material for manufacturing, and is separated into logwood, wood for pulp and paper, and slash. Slash can either be left on the site and thus entering the soil pool, or can be used for producing energy. Manufacturing includes various categories of production lines, such as manufacturing of sawn wood, board and panels, pulp and paper, and wood fuels. In the manufacturing process, part of the raw material ends up as a primary product (e.g. sawn wood and later furniture), and part is allocated for secondary use (e.g. by products from saw mill are used for manufacturing boards and pulp and paper). Also part of the raw

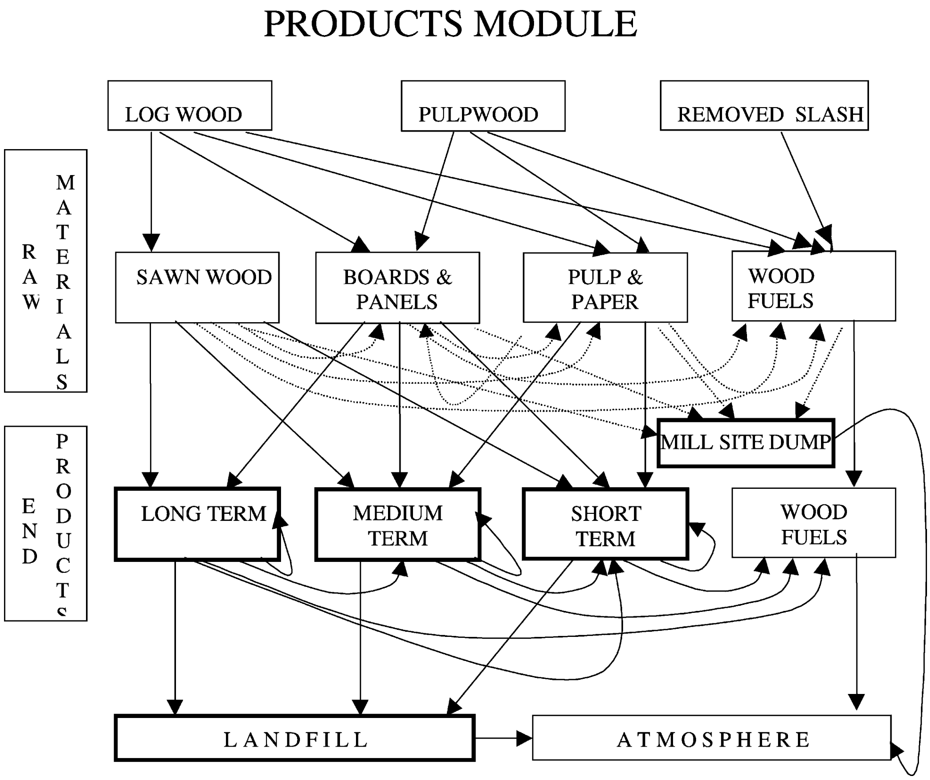


Fig. 3. Outline of the wood product module. Arrows show transfers of carbon between different phases of life span (from harvest to final allocation). Boxes with bold lines are stocks of carbon.

material can be used to generate energy (wood fuels) or set aside (no use). Manufactured products are distributed to different usage categories (long-term use, medium-term use, short-term use, wood fuels) according to average usage time. This last, shows how long (in years) products are assumed to be in use on average in each of the four broad categories. Every year the same proportion of products that are in use within each usage category is discarded from use, according to the exponential discard function:

$$\mathrm{Cp}_{mt+1} = \mathrm{Cp}_{mt} \times (1 - a_m) \quad (\mathrm{t\,C\,ha^{-1}}) \tag{12}$$

where Cp_m is the carbon stored in the wood usage product category "*m*" at time "*t*" and a_m is the share of the product that decomposes each year. If the average life span is 40 years, then a_m equals 1/40 per year, i.e. 2.5% of the products are discarded from use each year.

Finally, products can be disposed to landfills, used for energy generation or recycled. Carbon is released to the atmosphere either when byproducts are used for energy generation or are set aside to decompose in the manufacturing phase (i.e. in mill-site dumps), when wood fuels are burned or when products are used for energy production or decompose in landfills. The decomposition rate in mill-site dumps and in landfills is based also on an exponential discard function as above, but with different values for the parameter "*a*".

Because data on products average usage time and decomposition rates is not widely available, CO2FIX V.2 gives the user the opportunity to choose default parameters for even-aged, agroforestry or primary tropical forestry systems. Alternatively, users can choose to modify those default parameters based on own data. Default parameters are also provided for pioneer, intermediate and climax species. In addition, the model provides minimum and maximum values for each parameter, which provides a range that helps the user to modify them based on own data. Default parameters are based on available values from the literature, and have been described in Liski et al. (2001)

and Eggers (2001). Currently, the best knowledge is on the manufacturing phase parameters. Other parameters such as the average usage time of products and end-use of products, i.e. how much of the products are recycled, used for energy production or disposed to landfills, are known less accurately. Parameter values vary according to the infrastructure of the forest industry (manufacturing parameters), and the structure of society and behavior of consumers (product life spans and end uses). In general, parameter values are less accurate for tropical conditions, where information is more difficult to gather. For specific case studies, local saw mills and manufacturers of wood products might be able to provide data for parameters such as processing losses and allocation of harvested wood to different uses; for data on local use of products such as life span, ultimate disposal and recycling, knowledge of local conditions or information from companies selling wood products could be used.

4. Application to selected case studies

The model was tested and validated initially for five representative case studies of temperate and tropical forests: (a) even-aged Norway spruce of Central Europe; (b) even-aged mixed Douglas-fir-beech forest of Atlantic Europe; (c) mixed pine–oak native forest of Central Mexico; (d) multi-strata agroforestry system in Costa Rica; and (e) tropical rainforest in Costa Rica.

4.1. Even-aged monoculture of Norway spruce in regular rotation in Central Europe

This is a Norway spruce (*Picea abies*) forest planted on a fertile site in the middle mountain regions

Table 1
Main parameters used for simulating the even-aged spruce stand of Central Europe

	Spruce				
Cohorts					
Rotation (years)	95				
Initial humus content of the soil ($t\,C\,ha^{-1}$)[a]	142				
Basic wood density ($kg\,m^{-3}$)	430				
Carbon content (% of dry weight)	50				
Turnover rates					
Foliage	0.3				
Branches	0.04				
Roots	0.08				
	Year				
	25	45	55	70	95
Fraction removed during thinning or harvest	0.2	0.2	0.2	0.2	1
	Logwood	Pulpwood	Slash		
Product allocation for thinnings and harvesting					
Stem-thinning (average for the three thinnings)	0.3	0.6	0.1		
Stem-final harvesting	0.7	0.25	0.05		
Branch	0.0	0.15	0.85		
Foliage	0	0	1		
Expected life time of products (years)					
Long-term products	30				
Medium-term products	15				
Short-term products	1				
Mill-site dump	10				
Landfill	145				

[a] Includes humus, fine and coarse litter.

in Central Europe. The rotation length is 95 years. One non-commercial thinning is carried out in which 20% of the standing volume is removed. Then three commercial thinnings are carried out in which each time 20% of the standing volume is removed again. The mean annual volume increment is 14 $m^3 ha^{-1}$ per year (Schober, 1975). It was assumed that there is no competition effect (i.e. this is inherently incorporated in the yield table data). Furthermore, a moderate logging mortality of 4% with an impact time of 10 years was assumed. Efficient processing and recycling of wood products was assumed (Table 1). Previous land-use was assumed to be Norway spruce as well: thus the soil was initialized with 20 t C ha^{-1} coarse woody litter from logging slash (apart from humus stocks). For soil weather data the site 'Freiburg' was used from http://www.worldclimate.com (Tables 1 and 2).

4.2. Even-aged mixed stand of beech and Douglas-fir in regular rotation in Atlantic Europe

Douglas-fir (*Pseudotsuga menziesii*) and beech (*Fagus sylvatica*) are simulated in a rich, moist, loamy, (Brownearth) site. Yield tables from Jansen et al. (1996) were used. For Douglas-fir the site with a mean annual increment (MAI) of 14 $m^3 ha^{-1}$ per year was used, for beech the site with a MAI of 10 $m^3 ha^{-1}$ per year. Both species are planted in small groups of 200 m^2 in the same planting year. Both comprise 50% of the stand. Thus from the yield tables all values of increment were divided by 2. Both species are managed in rotations of 125 years. Douglas-fir is more vigorous and is therefore thinned away more often to release beech. Moderate logging mortality was assumed. Competition factors were derived from a long-term measurement series from

Table 2
Stem growth rates for the European case studies[a]

Douglas-fir		Beech		Norway spruce	
Age (years)	$m^3 ha^{-1}$ per year	Age (years)	$m^3 ha^{-1}$ per year	Age (years)	$m^3 ha^{-1}$ per year
0	0.5	0	0.5	0	0.2
10	6.1	10	1.0	10	6.0
15	8.0	15	2.5	20	17.2
20	8.8	20	3.5	25	19.2
25	9.1	25	4.2	30	19.4
30	8.9	30	5.7	35	19.4
35	8.4	35	6.2	40	19.1
40	7.7	40	6.5	45	18.6
45	6.9	45	6.7	50	18.1
50	6.2	50	6.7	55	17.4
55	5.5	55	6.7	60	17.0
60	4.9	60	6.6	65	16.4
65	4.3	65	6.5	70	15.8
70	4.1	70	6.2	75	15.2
75	4.0	75	6.0	80	14.6
80	3.9	80	5.7	85	14.4
85	3.8	85	5.5	90	13.8
90	3.7	90	5.2	95	13.2
95	3.6	95	4.8	100	12.6
100	3.4	100	4.6	105	12.1
105	3.2	105	4.2	110	11.6
110	3.0	110	3.9	115	11.0
115	3.0	115	3.7	120	10.6
120	3.0	120	3.4		
125	3.0	125	3.3		

[a] Current annual increment in volume as a function of stand age.

Table 3
Main parameters used for simulating the Douglas-fir and beech in Atlantic Europe

	Douglas-fir and beech				
Cohorts					
Rotation (years)	125				
Initial humus content of the soil ($t C ha^{-1}$)[a]	156				
Basic wood density ($kg m^{-3}$)	470, 680				
Carbon content (% of dry weight)	50				
	Douglas-fir	Beech			
Turnover rates					
Foliage	0.30	1			
Branches	0.05	0.03			
Roots	0.07	0.10			
	Year				
	35	50	70	90	125
Fraction removed during thinning or harvest					
Douglas-fir	0.27	0.25	0.23	0.2	1
Beech	0.1	0.15	0.15	0.1	1
	Logwood	Pulpwood	Slash		
Product allocation for thinnings and harvesting					
Douglas-fir					
Stem-thinning	0.5	0.4	0.1		
Stem-harvesting	0.6	0.3	0.1		
Branch	0.0	0.3	0.7		
Foliage	0	0	1		
Beech					
Stem-thinning	0.3	0.5	0.2		
Stem-final harvest	0.6	0.3	0.1		
Branch	0.0	0.2	0.8		
Foliage	0	0	1		
Average life time of products (years)					
Long-term products	30				
Medium-term products	15				
Short-term products	1				
Mill-site dump	5				
Landfill	145				

[a] Includes humus, fine and coarse litter.

the Forest Ecology and Forest Management Group, Wageningen University and Research (Tables 2 and 3).

4.3. *Mixed pine–oak stand of native forests in the highlands of Central and Southern Mexico*

The case study simulates the selective logging of pine (*Pinus* spp.)–oak (*Quercus* spp.) stands on predominantly andosol soils. Yield and competition tables were derived from local forest inventory data (CISJP, 1998; Cortez et al., 2002). Mean annual increment of pine trees was estimated at $8.9 m^3 ha^{-1}$ per year and for oak $5.9 m^3 ha^{-1}$ per year. Forest is harvested on a 50-year rotation cycle, applying silvicultural treatments every 10 years according to standard Mexican silvicultural procedures (Cano-Capri, 1988). Pine is harvested every 50 years. Thinnings are especially applied to oak in order to release pine from competition. Competition factors were derived from forest

Table 4
Main parameters used for simulating the uneven-aged pine–oak forest stand of Mexico

	Pine and oak				
Cohorts					
Rotation (years)	50				
Initial humus content of the soil ($t\,C\,ha^{-1}$)[a]	139				
Basic wood density ($kg\,m^{-3}$)	500				
Carbon content (% of dry weight)	50				
	Oak	Pine			
Turnover rates					
Foliage	1	0.33			
Branches	0.02	0.02			
Roots	0.03	0.02			
	Year				
	10	20	30	40	50
Fraction removed during thinning or harvest					
Pine	0.2	0.35	0.35	0.35	0.8
Oak	0.3	0.3	0.3	0.3	1
	Logwood	Pulpwood	Slash		
Product allocation for thinnings and harvesting					
Pine					
Stem-thinning	0.42	0.58	0		
Stem-harvesting	0.70	0.20	0.10		
Branch	0	0	1		
Foliage	0	0	1		
Oak					
Stem	0	0.92	0.08		
Branch	0	0.92	0.08		
Foliage	0	0	1		
Average life time of products (years)					
Long-term products	30				
Medium-term products	15				
Short-term products	1				
Mill-site dump	10				
Landfill	50				

[a] Includes humus, fine and coarse litter.

inventory data. Wood is processed for pulp and paper, logwood and slash, according to transfer coefficients obtained from a local forest enterprise (Tables 4 and 5).

4.4. Multiple cohort-agroforestry plantations in Costa Rica

The case study describes a coffee-agroforestry plantation in the tropics. The plantation was established on a degraded agricultural land with low initial soil humus content. The biomass carbon is simulating using three cohorts: (1) canopy layer (shade tree): *Cordia alliodora* (100 trees per ha); rotation 20 years, MAI 7 $m^3\,ha^{-1}$ per year over; (2) intermediate layer (service tree): *Erythrina poeppigiana*, leaves and branches pruned annually and left to decompose; rotation 10 years; (3) understory: *Coffea* sp., renewed every 10 years (Fassbender, 1993). The wood from canopy layer trees is used only for furniture (Tables 5 and 6).

Table 5
Stem growth rates for the Mexican case study and the Costa Rican agroforestry case study[a]

Pine		Oak		*Cordia*		*Erythrina*		*Coffea*	
Age (years)	$m^3\ ha^{-1}$ per year	Age (years)	$m^3\ ha^{-1}$ per year	Age (years)	$m^3\ ha^{-1}$ per year	Age (years)	$m^3\ ha^{-1}$ per year	Age (years)	$m^3\ ha^{-1}$ per year
0	0	0	0	0	0	0	0	0	0
10	4.6	5	6.2	3	1	4	6	3	1
20	13	10	7.8	6	4	6	8	6	4
30	18	15	8.2	10	13	12	6	10	13
40	17	20	7.9	15	14	25	0	15	14
50	14	25	7.2	20	7			20	7
60	11	30	6.4	25	0.5			25	0.5
70	7	35	5.5	29	0			29	0
80	3.8	40	4.7						
90	3.7	45	4.0						
		50	4.0						
		60	3.5						
		70	3.0						
		80	2.5						

[a] Current annual increment in volume as a function of stand age.

4.5. Multiple cohort selective logging systems in a degraded tropical rainforest

This is a selective logging system applied to a lowland wet tropical forest. In the past, the commercially valuable trees have been logged at least twice (about 20 and 40 years before the simulation starts) (Camacho and Finegan, 1997). Thus, the forest has low initial stocking density and biomass content. The Biomass Model has four cohorts: (1) traditionally commercial species; (2) potentially commercial species, (3) other species; (4) pioneers. Cohorts 1, 2 and 3 are harvested at 20 year cutting cycle. Wood is used for construction and furniture with a low processing efficiency (Tables 7 and 8).

5. Results and validation

Figs. 4–8 show the time evolution of carbon stocks in each of the case studies examined. Results are

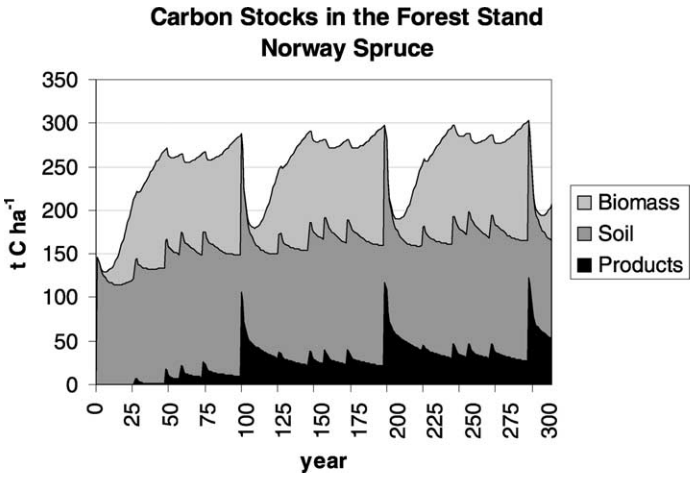


Fig. 4. Evolution of carbon stocks in a Norway spruce forest stand in Northern Europe.

Table 6
Main parameters used for simulating multiple cohort-agroforestry (coffee) plantation in Costa Rica

	Cordia	*Erythrina*	*Coffea*
Cohorts			
Rotation (years)	20	10	10
Initial humus content of the soil ($t\,C\,ha^{-1}$)[a]	10.5	9.3	9.9
Basic wood density ($kg\,m^{-3}$)	0.40	0.35	0.40
Carbon content (% of dry weight)	0.48	0.47	0.48
Turnover rates			
Foliage	0.5	1	0.3
Branches	0.05	1	0.05
Roots	0.05	0.07	0.07
	Year		
	10	20	30
Fraction removed during thinning or harvest			
Cordia	–	1.0	–
Erytrina	1.0	1.0	1.0
Coffea	1.0	1.0	1.0
	Logwood	Pulpwood	Slash
Product allocation for thinnings and harvesting			
Cordia			
Stem-harvesting	0.7	0.0	0.3
Branch	0	0	1
Foliage	0	0	1
Erytrina			
Stem	0	0	1
Branch	0	0	1
Foliage	0	0	1
Expected life time of products (years)			
Long-term products	20		
Medium-term products	10		
Short-term products	1		
Mill-site dump	10		
Landfill	50		

[a] Includes humus, fine and coarse litter.

presented separately for biomass (above- and below-ground), soil (including humus, fine and coarse litter), wood products, and the total carbon stock in the stand. Simulation periods are adapted to the dynamics of the systems analyzed; therefore, for long-rotations we use a 300-year simulation period, for mid-rotations 200-year period and for short-rotations, such as the agroforestry system, a 100-year period. In all the cases examined, the dynamics of the carbon stored in biomass and wood products are sensitive to the management practices (i.e. thinning and harvesting) applied to the forests, while changes in the soil carbon are less abrupt.

The simulations indicate that the long-term total carbon storage ranges from 141 to 271 $t\,C\,ha^{-1}$, depending on the particular system. Carbon stored in living biomass ranged from 62 to 103 $t\,C\,ha^{-1}$; carbon in soils ranged from 63 to 168 $t\,C\,ha^{-1}$, and carbon in products ranged from 5 to 37 $t\,C\,ha^{-1}$ (Fig. 9). As expected, soil carbon is larger in temperate and boreal conditions than in the tropical sites. The carbon stored in living biomass in the tropical rainforest is relatively low compared to the other systems due to the previous logging history of the site. Also, the continuous logging on the site does not allow the biomass to reach higher values. Therefore, the total carbon stock of this

Table 7
Main parameters used for simulating multiple cohort selective logging systems in tropical rainforests of Costa Rica

	Commercial species	Potentially commercial species	Other species	Pioneers
Cohorts				
Initial humus content of the soil (t C ha^{-1})[a]	28.2	20.7	22.7	9.12
Basic wood density (kg m^{-3})	0.60	0.60	0.60	0.30
Carbon content (% of dry weight)	0.50	0.50	0.50	0.50
Turnover rates				
Foliage	0.3	0.3	0.3	0.3
Branches	0.03	0.03	0.03	0.03
Roots	0.07	0.07	0.07	0.07
	Year			
	20	40	60	
Fraction removed during thinning or harvest				
Commercial species	0.2	0.2	0.2	
Potentially commercial species	0.2	0.2	0.2	
Other species	0.2	0.2	0.2	
	Logwood	Pulpwood	Slash	
Product allocation for thinnings and harvesting				
Commercial species				
Stem-thinning	0.7	0	0.3	
Branch	0	0	1	
Foliage	0	0	1	
Potentially commercial species				
Stem	0.7	0	0.3	
Branch	0	0	1	
Foliage	0	0	1	
Expected life time of products (years)				
Long-term products	20			
Medium-term products	10			
Short-term products	1			
Mill-site dump	10			
Landfill	50			

[a] Includes humus, fine and coarse litter.

Table 8
Stem growth rates for the Costa Rican selective logging case study[a]

Pioneers		Other/commercial/potential	
Biom/Biommax	m^3 ha^{-1} per year	Biom/Biommax	m^3 ha^{-1} per year
0	0.1	0	0.1
0.1	4.0	0.25	4.0
0.4	3.5	0.4	3.5
0.6	2.0	0.6	2.0
1.0	0.01	1.0	0.01

Note: Biom/Biommax is the ratio of actual stand biomass to its maximum biomass.
[a] Current annual increment in volume as a function of relative stand biomass.

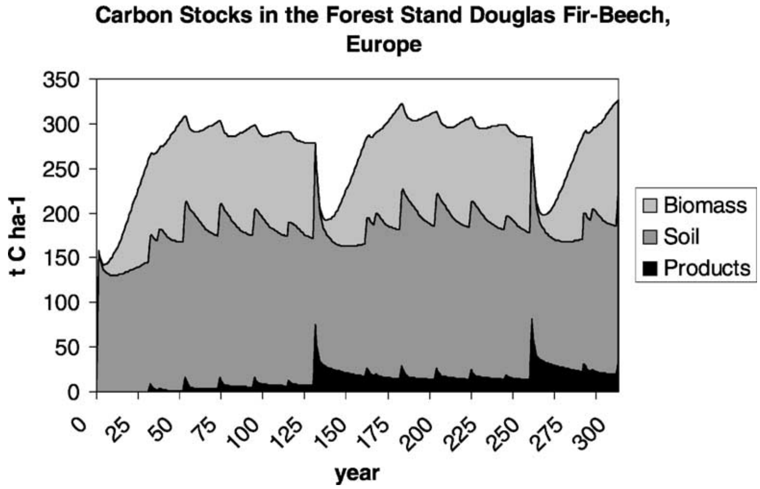


Fig. 5. Evolution of carbon stocks in an even-aged Douglas-fir-beech forest stand in Atlantic Europe.

case study is similar to the multi-strata agroforestry system.

Fig. 10 shows the net carbon flux associated to each system during the simulation period. The mean net annual flux for the first rotation period, reached 0.83 t C ha^{-1} per year for the Norway spruce, to 1.01 t C ha^{-1} per year for the Douglas-fir beech, 2.26 t C ha^{-1} for pine–oak; 8.00 t C ha^{-1} for the coffee agroforestry system, and −0.80 t C ha^{-1} for the selective logging system. In this last system the flux is negative as logging further reduces the carbon stock of the system.

The net carbon sequestration—estimated here as the difference between the long-term average carbon stock and the initial carbon stock in each of the systems—reaches 103 t C ha^{-1} for the Norway spruce, 114 t C ha^{-1} for the Douglas-fir-beech, 70 t C ha^{-1} for pine–oak; 99 t C ha^{-1} for the coffee agroforestry system, and −30 t C ha^{-1} for the selective logging system. It should be noted that the initial state differed between the case studies: the initial biomass for the Norway spruce, Douglas-fir-beech, and coffee agroforestry system was assumed to be very low, while it was assumed to be rather high in the pine–oak and

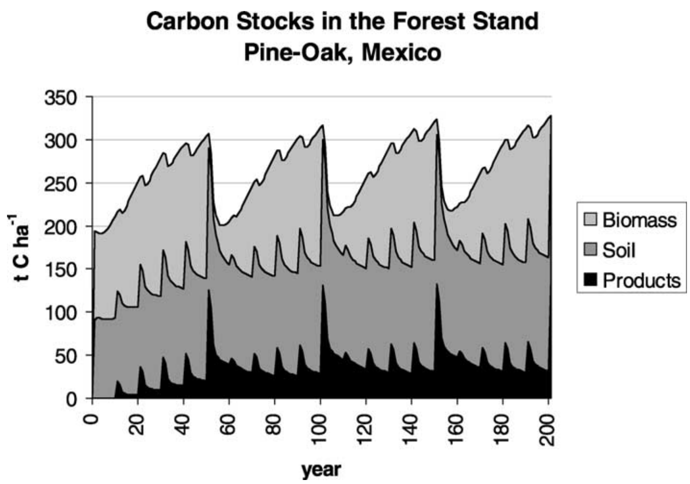


Fig. 6. Evolution of carbon stocks in an uneven-aged pine–oak native forest stand in Central Mexico.

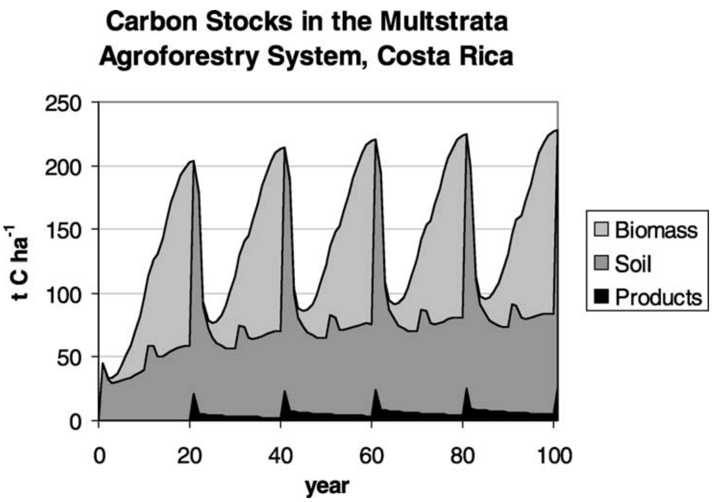


Fig. 7. Evolution of carbon stocks of a multiple cohort-agroforestry (coffee) plantation in Costa Rica.

tropical rainforest. If the simulation for the pine–oak system had been run assuming a very low initial living biomass, then total carbon sequestered would reach $173\,t\,C\,ha^{-1}$. As pointed out before, the negative carbon sequestration associated to the tropical rainforest is the result of a net decrease in total carbon stocks due to further logging. It is worth noting the high sequestration potential associated to the agroforestry system.

A preliminary validation of the model was done with the two case studies from Europe, where data is most accessible. We compared simulated versus field data derived from destructive biomass measurements on living biomass alone, as the carbon content of soils is more difficult to compare due to high site variability (Fig. 11) (DeAngelis et al., 1981; Cannell, 1982). Also data on wood products is not available for the sites. The simulated biomass carbon stock values are usually lower than those reported in the field, particularly for older forests. This result is to be expected, as the model inputs and simulations are for managed forests where regular thinnings are carried out, keeping the average carbon content at a lower level, while literature data come mostly from undis-

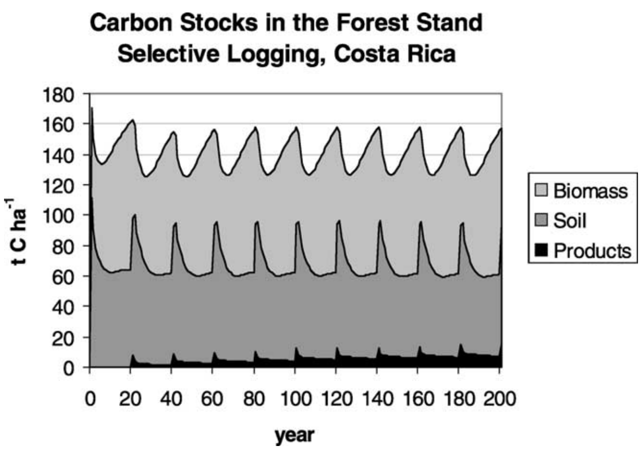


Fig. 8. Evolution of carbon stocks in a degraded tropical rainforest under selective logging in Costa Rica.

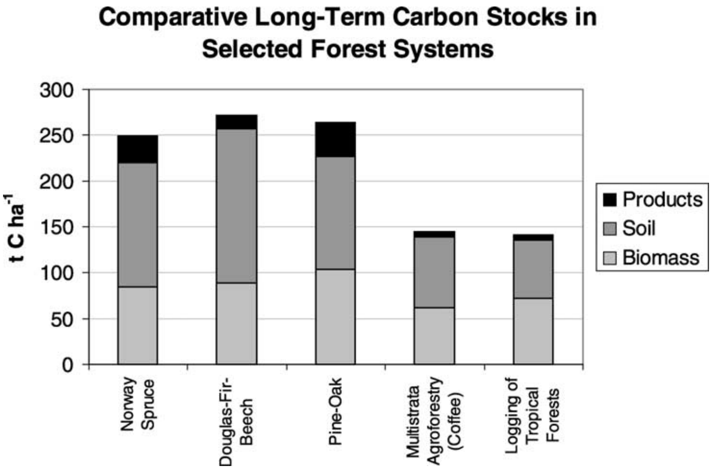


Fig. 9. Comparative long-term carbon stocks in biomass, soil, and wood products in five forestry systems.

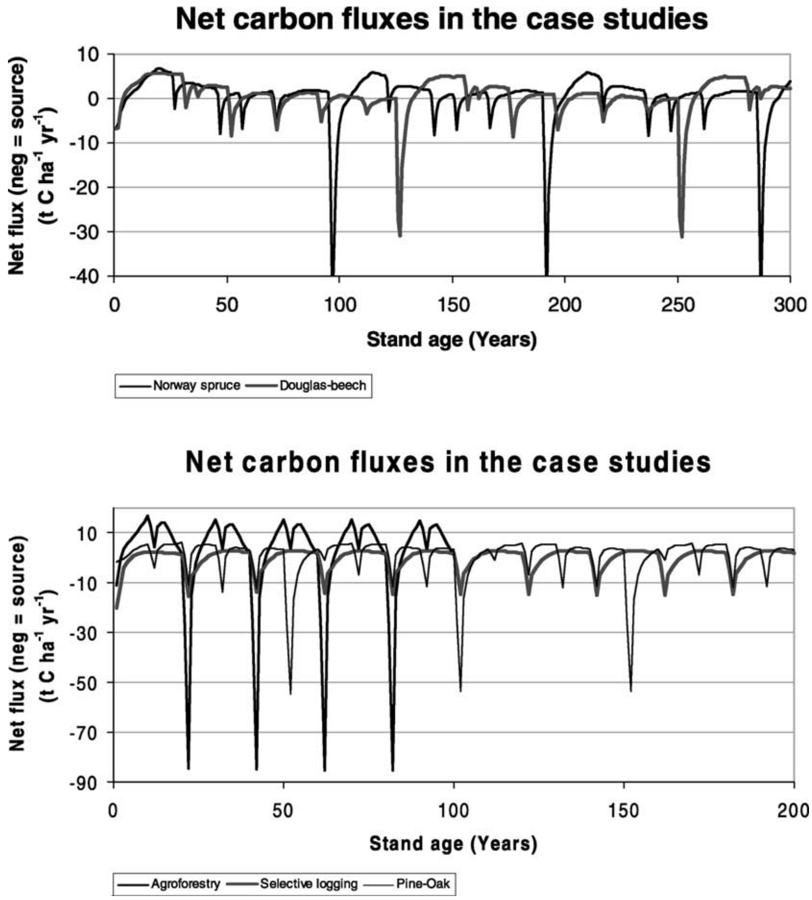
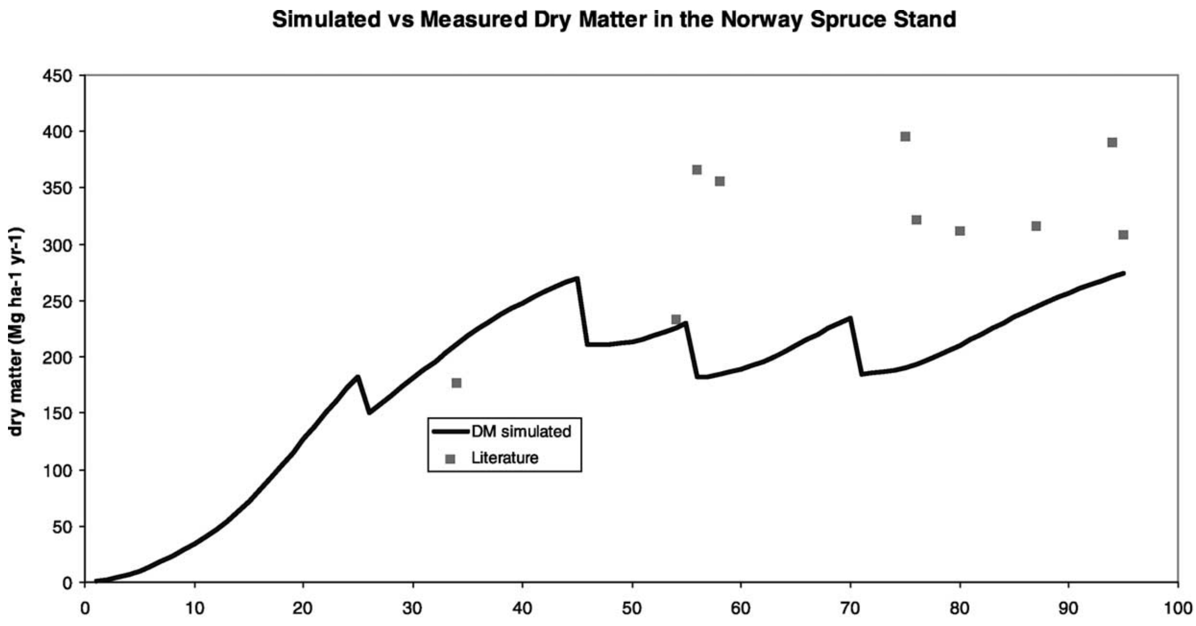


Fig. 10. Comparative net carbon fluxes in the five forestry systems selected.



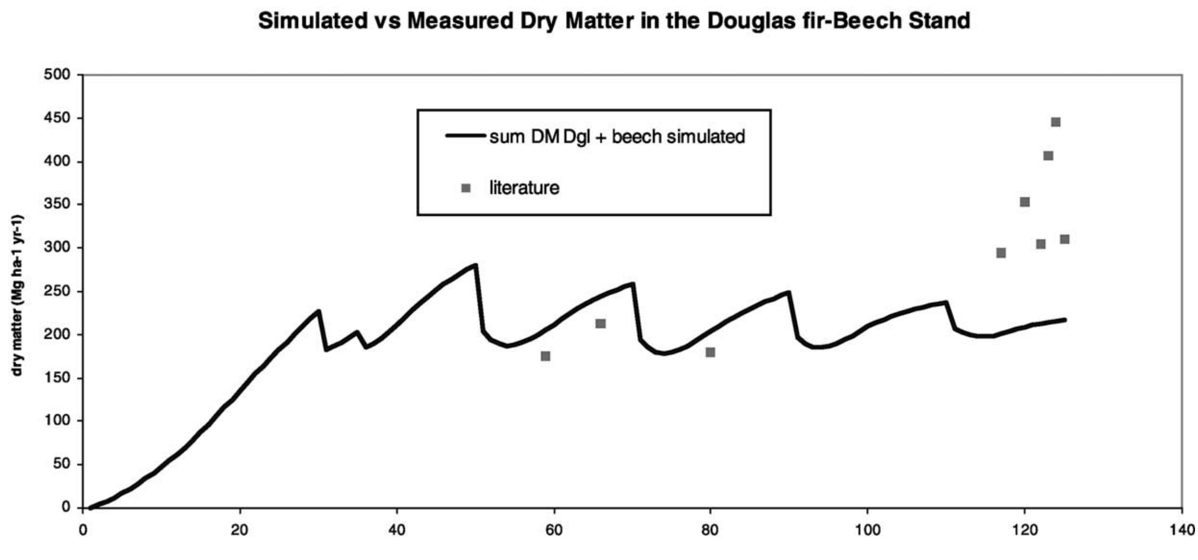


Fig. 11. Comparison of simulated dry matter stocks in the Norway spruce forest stand (top) and in the Douglas-fir-beech stand (bottom) with literature data. Sources for literature data are quoted in Nabuurs and Mohren (1993).

turbed systems, and are from various sources, representing slightly different sites. A sensitivity study done earlier on for the model showed reasonable model performance. The 95% confidence interval for the long-term average (after 300 years simulation) carbon stock of the whole system was found to be ± 23%.[6] Further validation is needed to test the adequacy of the model to tropical conditions.

[6] Van der Voet in Nabuurs and Mohren (1993) carried out an uncertainty analysis of the model CO2FIX for the Norway spruce forest type in Central Europe. For the 32 independent inputs to the model, he found that for the total carbon stock, the average

6. Conclusions

The CO2FIX V.2 provides a user-friendly public-access tool to dynamically estimate the carbon stocks and flows for a variety of forest stands around the world. Therefore, it is a valuable tool to improve the estimates of the carbon mitigation potential of forestry options, including ARD and forest management. It can also be used to estimate the carbon implications of CDM or JI projects in the context of the Kyoto Protocol.

The cohort approach and the possibility to simulate both age-based and biomass-based tree growth allowed the model flexibility to fit contrasting site conditions and systems. Hence, the model proved applicable both for tropical forest management, agroforestry systems, and temperate plantations. It also allows to simulate various management scenarios and to estimate differences in carbon dynamics associated to different forest management regimes, including the possibility to conduct sensitivity analysis for any of the parameters, or uncertainty analysis for sites that vary in quality and thus present natural variations in various parameters at once (Van der Voet and Mohren, 1994).

Currently, feedback from users is needed to better calibrate and further validate the model to a variety of systems, and very specifically to tropical forest conditions. The research group will continue to improve the model. Further work will include the strengthening of the users feedback, creating a users' support group and a case study database, with validated parameters for the most common systems around the world. The model will also be scaled up to the landscape level and will be integrated in a geographic information system (GIS); this will allow for easier application of the model in an actual project context, and it also enables easier analysis of land-use change such as through afforestation and deforestation. The current version of the CO2FIX model can be downloaded from http://www.efi.fi/projects/casfor.

amounted to 316 t C ha^{-1}, whereas the 95% confidence interval was 254–403 t C ha^{-1}. The main uncertainty was caused by uncertainty over the soil organic matter dynamics and the carbon content of dry matter.

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