CARBON SEQUESTRATION DYNAMICS IN FORESTRY PROJECTS: THE CO2FIX V.2 MODEL APPROACH

Omar R. Masera[1]

Instituto de Ecología, UNAM
A.P. 152 Pátzcuaro 61609, MEXICO
omasera@oikos.unam.mx

Abstract

The paper describes the CO2fix v.2 model, a user- friendly tool for dynamically estimating the carbon sequestration of forestry management, agroforesty and afforestation projects. CO2fix v.2 is an ecosystem-level model based on a carbon accounting of forest stands, including forest biomass, soils and products. Carbon stored in living biomass is estimated through a forest cohort model, that allows for competition, mortality, and logging damage mortality. Soil carbon is modeled using five stock pools that include litter and humus with different residence times. The carbon stored in wood products is modeled through a set of pools for short- medium- and long-lived products, and includes recycling.

Introduction: Forests and climate change

Forests play an important role in the global carbon cycle. They can be both sources or sinks of carbon, depending on the specific management regime and activities (IPCC, 2000). Tropical forests, for example, are usually seen as a net carbon source because of the deforestation that is taking place. However, recent evidence suggests that primary forests are not in equilibrium, but may function as a net carbon sink (Grace et al., 1995, Phillips et al., 1998). Available estimates suggest that forests have a large mitigation potential. However, achieving the carbon mitigation potential will require accurate methods to assess the dynamics of carbon fluxes and storage under alternative management regimes. This is relevant for boreal, temperate and tropical forests. Accurate estimates of the potential dynamics

[1] This paper summarizes the main features of the CO2fix V2 model. For a comprehensive description of the model and more applications refer to Masera et al. (2001) and Nabuurs et al. (2001).

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). Models will be particularly critical for the examination of alternative carbon crediting schemes of Joint Implementation (JI)- and Clean Development Mechanism (CDM)-related projects.

Up to date, several models have been developed that analyse and simulate carbon budgets and fluxes at the level of the forest ecosystem. These models range from very detailed ecophysiological models used in climate impact assessment, to very general empirical, descriptive models of ecosystem carbon budgets (see e.g. Mery & Kanninen, 1999, Schlamadinger & Marland, 1996, White et al., 2000, and Karjalainen, 1996 for an overview). None of these models have been used by a wide user group, and neither of them has been accepted as a possible standard for carbon crediting from projects.

The CASFOR project

The CO2fix model was developed as part of the “Carbon sequestration in afforestation and sustainable forest management” (CASFOR) project, 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), an ecosystem-level user-friendly model for quantification of the potential role of forest ecosystems in global carbon relations, in carbon sequestration, and in carbon emissions offsets as part of the policy evaluation of the role of forests in greenhouse effect. This version has been distributed as a free download through Internet since June 1999. 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 monospecific temperate forest stands to agroforestry system in the tropics (Mohren & Klein Goldewijk, 1990; Nabuurs & Mohren, 1993 and 1995; de Jong et al., 1998; Ordóñez and Masera, 2000, Olguín, 2001, Nabuurs & Schelhaas, 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 CO_2fix v.1 simulates the carbon dynamics in a single species (monoculture) stands, e.g. in forest plantations, which limits its applicability. Therefore, the team decided to develop a new version of the model, able to simulate the carbon dynamics in more complex situations. These situations are, for instance, the case of tropical forests, where multi-species (functional groups) and a multi-layer structure is common. The same is true for agroforestry systems and for the management of mixed-species, uneven aged native forests.

CO2fix v.2 Model Structure

The CO2FIX v.2 is an ecosystem-level simulation model that quantifies the C stocks and fluxes in the forest using a full carbon accounting approach. It 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 one year (Figure 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 ecosystem at any time (Ct) is considered to be

$$C_t = Cb_t + Cs_t + Cp_t \qquad (1)$$

where,

Cb_t is the total carbon stored in living (above plus belowground) biomass at any time “t”
Cs_t is the carbon stored in soil organic matter, and
Cp_t is the carbon stored in forest products

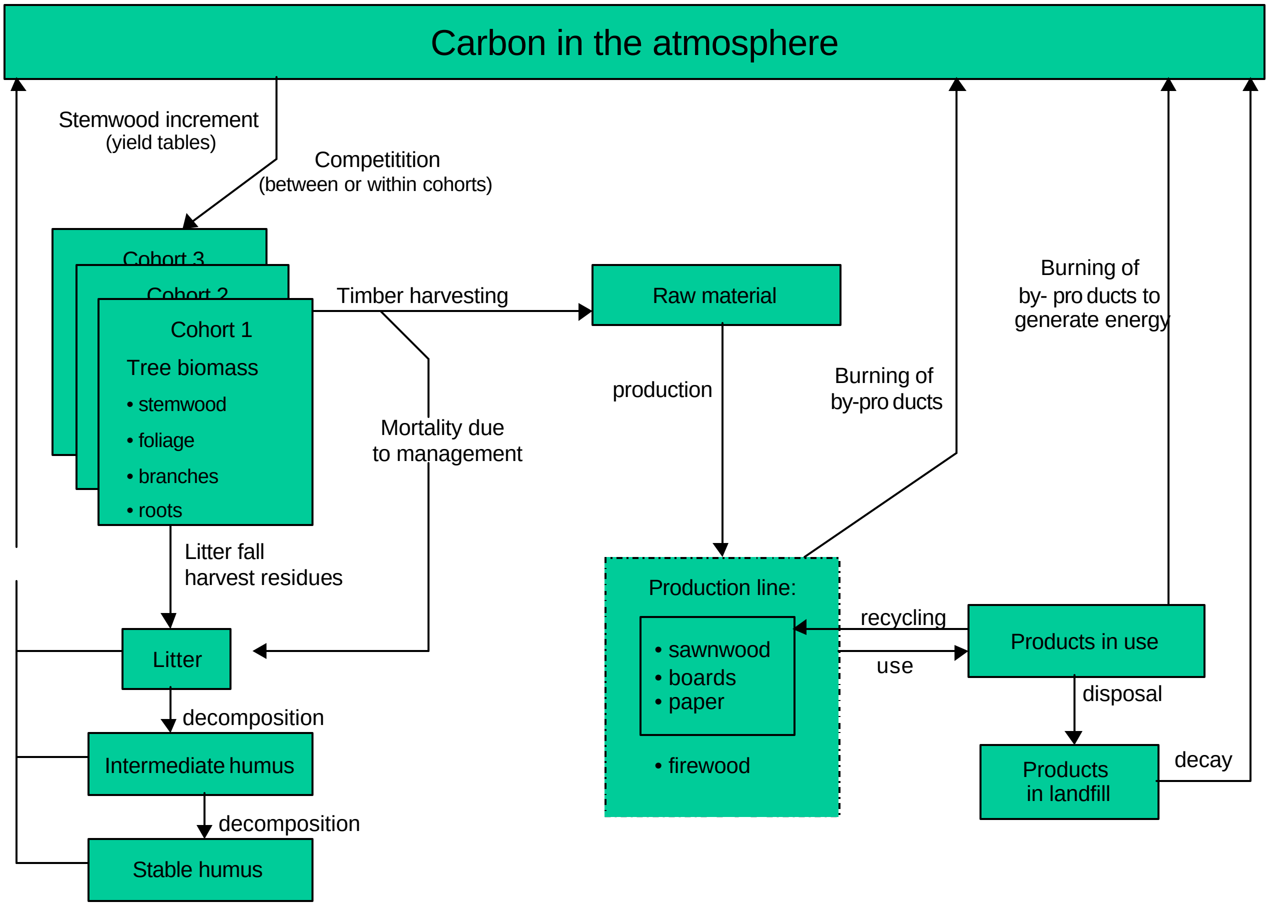

Figure 1. Carbon fluxes/processes (arrows) and carbon stocks (boxes) in a forest ecosystem and its wood products as distinguished in CO2FIX 2.1.

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, which are assumed to exhibit similar growth, and which may be treated as single entities within the model (Vanclay, 1989, 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 stand, can then be expressed as the sum of each cohort's biomass, i.e.,

$$Cb_t = \quad Cb_{it} \qquad (2)$$

where Cb_{it} is the carbon stored in the living biomass of cohort i.

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.,

$$Cb_{it+1} = Cb_{it} + Kc\,[Gb_{it} - Ms_{it} - T_{it} - H_{it} - Ml_{it}] \qquad (3)$$

where Kc is a constant to convert biomass to carbon content.

In order to simulate Gb_{it} the model uses as input the growth rate of stem volumes, which can be derived from yield tables. From the growth rate of stem volumes, growth rates for foliage, branches and roots are calculated, using time-dependent allocation coefficients. 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 many times diameter dependent instead of age dependent growth of trees is used.

Stem growth rate is later modified by the interactions of the cohort within itself and with other cohorts. Three types of interactions can be described: a) no competition, b) competition, c) synergic effects. 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 The model provides two basic options for modeling the interactions between and within the cohorts: a) Competition of a cohort as a function of total stand biomass (total biomass of all cohorts in a stand), i.e. the interactions of this cohort with all the cohorts combined, including the cohort in question; and b) Interactions of the cohort in question as a function of biomass of each other cohort separately.

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). 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. 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. The turnover for each cohort (T_{it}) is estimated as the sum of the turnovers of each component (branches, roots, and foliage), which in turn is simply the existing biomass of the particular component multiplied by a decay –or turnover- constant.

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 module (see the section on products below). During conventional forest logging, the mortality of the remaining trees also increases due to perturbations and damage. 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 zero 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).

3.2 Carbon stored in soil organic matter

At this stage, the estimation of flows and stocks of carbon in soil organic matter in the CO2fix model is done through the YASSO model, developed at the European Forest Institute (Liski et al, in prep). YASSO was chosen because this soil model uses a one year time interval as CO2FIX, provides more information on dynamics in different soil pools than the previous soil model, and is not too data intensive. The YASSO model is mainly suitable for non waterlogged mineral soils, and was tested for temperate and boreal circumstances with a distinct growing season.

YASSO consists of three litter compartments describing physical fractionation of litter and five compartments in the mineral soil describing the decomposition and humification processes. Litter compartments are stem litter, branches/coarse root litter, and foliage/fine root litter. The five other compartments are soluble, holocellulose, and lignin-like compounds of litter, and two humus pools. The soil model requires data on mean annual temperature (MAT, °C), precipitation in the growing season (Prec, mm), and Potential Evapotranspiration in the growing season (May to September for the Northern Hemisphere, Pet, mm) for study site. For tropical circumstances the year-round precipitation (Prec, mm), and the year-round Potential Evapotranspiration (Pet, mm) may be used.

3.3 Carbon stored in wood products

The products module is a carbon accounting sub-model 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 and used before by Karjalainen et al. (1994) for modelling the carbon budget in the Finnish forest sector. A more detailed version of the model has been applied for the European forest sector (Karjalainen et al. 2001, Eggers 2001).

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. This last pool can either remain in the field and thus entering the soil pool, or can be used for energy. Manufacturing includes various categories of production lines, such as sawn wood, board and panels, pulp and paper, firewood. Products (also broader categories) are distributed to usage categories according to expected usage time. Finally, products can be disposed to landfills, used for energy generation or recycled. Carbon is released to the atmosphere when by products are set aside and decompose in the manufacturing phase (i.e., in mill site dumps) , when firewood is burned and when products decompose in landfills.

CO2fix v.2 provides the opportunity to the user to choose either default parameters for even-aged, agroforestry or primary tropical forestry systems, or to modify those parameters based on own data. Default parameters are provided for pioneer, intermediate and climax species. In addition, minimum and maximum values for the parameters are provided to show the range for these parameters and user can modify default parameters within this range based on own data.

4. Application to Selected Case Studies

The model has been tested initially in 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) Tropical rainforest in Costa Rica; and e) Multistrata Agroforestry System in Costa Rica. See Masera et al. (2001) and Nabuurs et al. (2001) for more details about each of the management systems, as well as the parameters used in the simulations.

Selected output tables are presented in Figures 4 to 7 that illustrate the model versatility and usefulness at handling diverse forest management situations. Specifically, the model allows for examining simultaneously multiple cohorts (Fig.4), conduct a precise analysis of the carbon stored in wood products with different life-spans (Fig. 5), study the carbon dynamics associated to the harvesting of tropical forests using three generic cohorts –pioneers, intermediate and climax species- (Fig. 6), and examining the way the diverse components of living biomass (foliage, branches, stems and roots) contribute to total carbon biomass through time (Fig. 7).

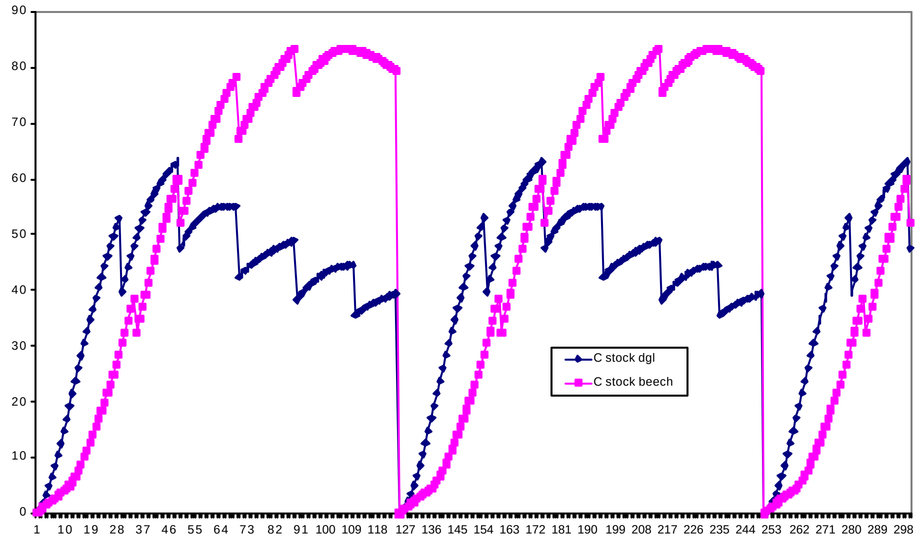

Figure 4. Carbon stocks in forest biomass in the mixed Douglas-fir beech forest ecosystem with competition.

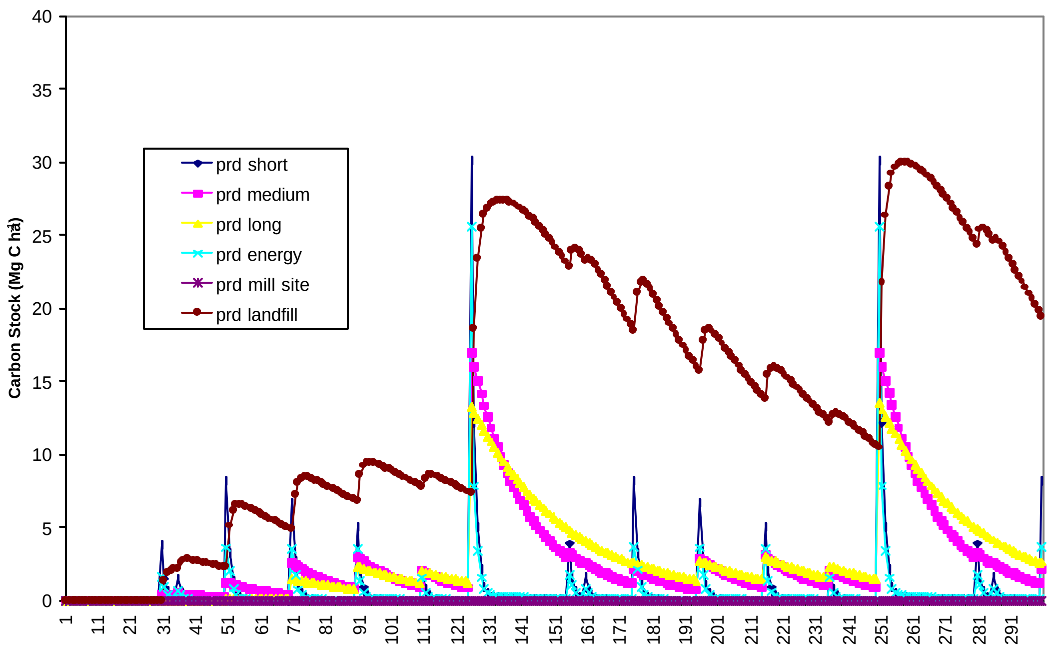

Figure 5. Carbon stocks in the wood products module including land fills.

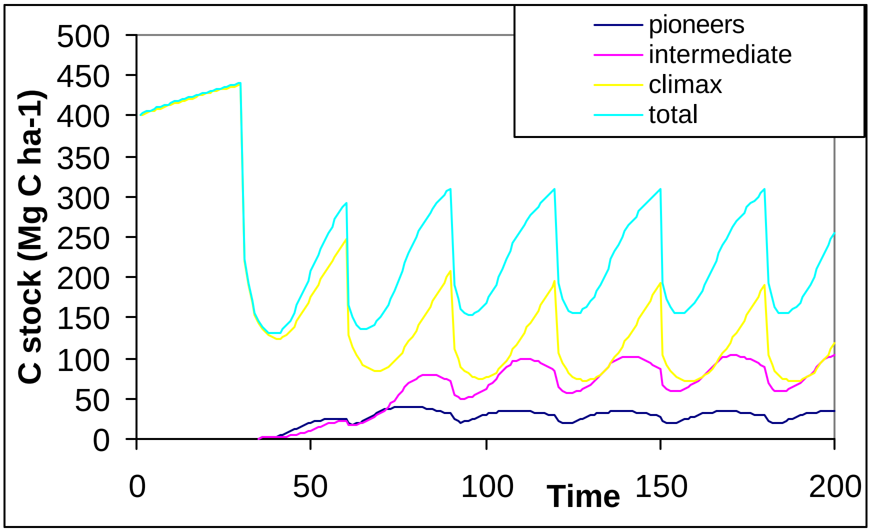

Figure 6. Carbon stocks in forest biomass in a selective logging system in tropical rainforest. The simulation starts in the primary forest.

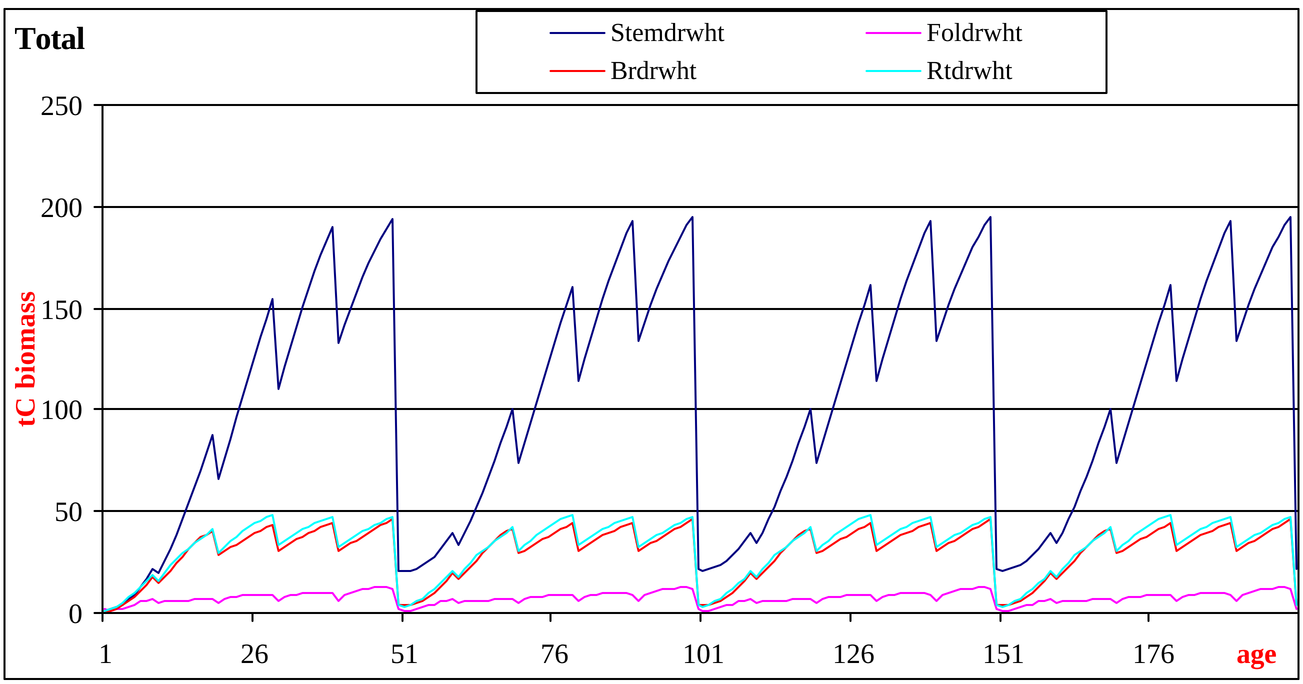

Figure 7. Carbon stocks in forest biomass in a selective logging system in temperate mixed Pine-Oak native forests of Central Mexico.

5. 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 ecosystems 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.

Currently, feedback from users is needed to better calibrate and 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's support group and a case study database, with validated parameters for the most common systems around the world. The model will also be upscaled to the landscape level will be integrated it into a geographic information system (GIS). The current version of the model can be downloaded from the site www.efi.fi/projects/casfor.

6. Acknowledgments

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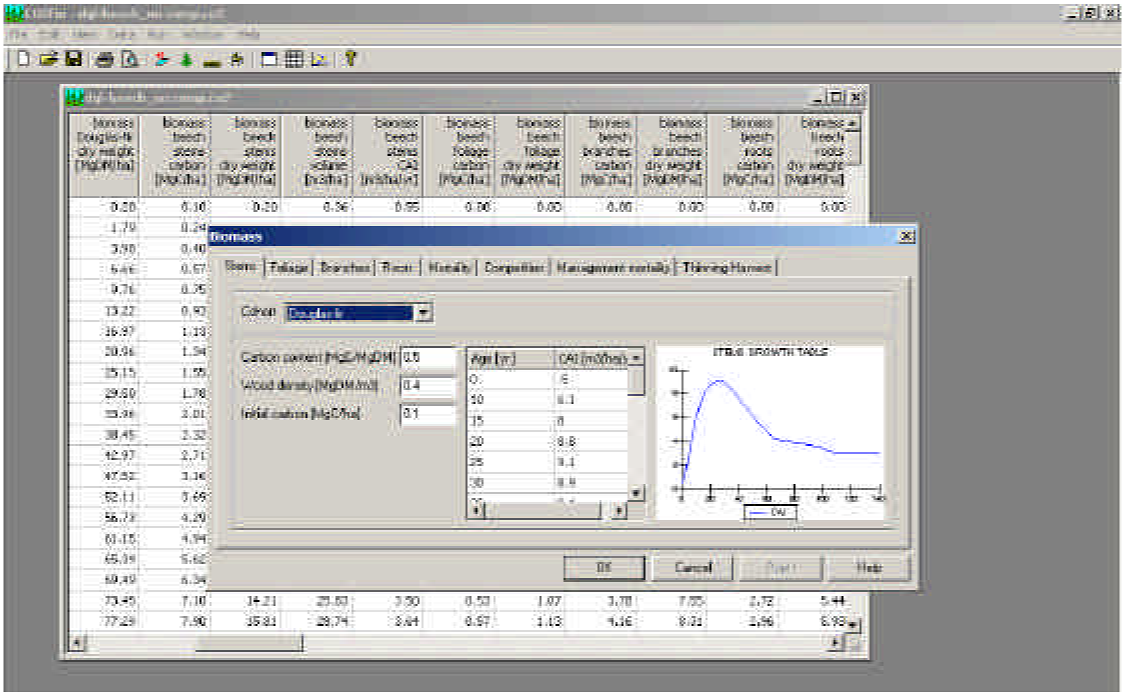

Figure. A view at the windows based CO2FIX V 2.0

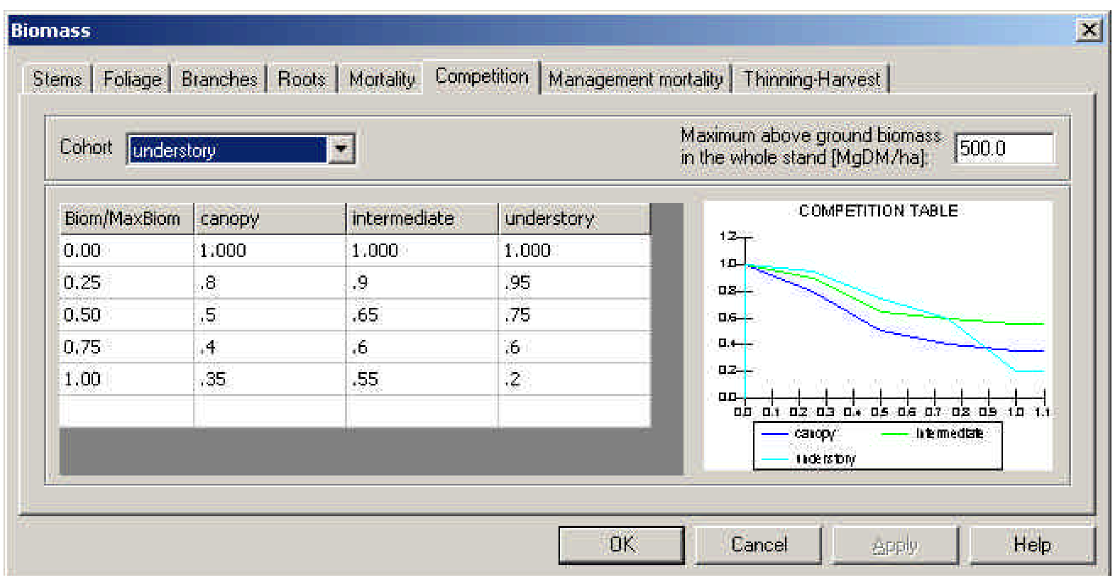

Figure. Competition between cohorts