4C Model description

The process-based model 4C (FORESEE: forest ecosystems in a changing environment) is a forest dynamics model (Lasch et al. 2005), developed at PIK to investigate long-term forest behaviour under changing environmental conditions (Bugmann et al. 1997).

Running the model, it needs to be initialized by a forest stand description (dimensions of trees or seedlings) and information about the physical and chemical parameters of the soil profile and subsequently to be driven by weather data (temperature, precipitation, air vapour pressure, relative humidity, solar radiation and wind speed) at daily resolution.

The model uses tree and stand-level variables to simulate the composition of tree species, forest structure, as well as carbon and water balances of the ecosystem. The development of a forest stand is described by the reproduction, growth and mortality of tree cohorts, which are classes of trees with identical dimensions, foliage, sapwood, heartwood and fine root biomass, species type and age. Tree cohorts compete for light, water and nutrients available in the soil.

Tree cohorts compete for light by means of crown height and crown area, and for water and nutrients available in the soil. The latter competition is modeled via absorption of water and nitrogen by fine roots in proportion to the fine root mass of the individual cohorts in the soil layers. A multi-layered soil module is further needed in 4C to calculate the transport of heat and water, as well as the dynamics of nitrogen and carbon based on the decomposition and mineralisation of organic matter (Kartschall et al. 1990; Grote et al. 1998). The inherent processes of the model are described as follows:

Light absorption
The share of any cohort in the total stand's net photosynthetic assimilation of carbon is proportional to its share of the absorbed photosynthetically active radiation. The total fraction of photosynthetically active radiation absorbed by each cohort is calculated each time stand phenology changes, based on the Lambert-Beer law. Four models exist to calculate light transmission and absorption through the canopy (LM1, LM2, LM3, LM4). LM1 is based on the classical gap model approach that each tree covers the whole patch with its canopy, this simplistic view is refined in LM2 by attributing each cohort/tree a specific projected crown coverage area depending on its dbh (diameter at breast height). LM2 and LM3 differ in the way the light is transmitted through the canopy and LM4 additionally introduces an average growing season sun inclination angle. Every time phenology changes within the stand, e.g. a species bud bursts or leaves are shed, the light transmission through the canopy and accordingly light absorption changes.

Interception
The total interception storage of the canopy is given by a special weighted mean of the species specific interception capacity depending on the leaf area index. This storage is filled by the precipitation and emptied by water evaporation, according to the potential evapotranspiration (Jansson, 1991).

Evapotranspiration
The potential evapotranspiration is calculated on two ways depending on the air temperature (Dyck, 1989): At $T \geq 5°C$ it is calculated from air temperature and global radiation by an equation of TURC

with a modification factor on relative humidity. At $T < 5°C$ it is calculated according to IVANOV using air temperature and relative humidity. To derive at the potential transpiration of each cohort the potential evapotranspiration is first reduced by the interception evaporation and then divided among the cohorts considering the cohort-specific relative conductance.

Net primary production (NPP)

The photosynthesis module (Haxeltine & Prentice, 1996) is based on the mechanistic photosynthesis model of Farquhar et al. (1980) as simplified by Collatz et al. (1991). It describes net daily photosynthesis depending on absorbed photosynthetically active radiation. As this approach assumes abundant water and nutrient supply, the calculated NPP is further reduced by a drought related factor that is determined upon cohort-specific demand and supply.

Soil model

The soil is divided into different layers with optional thickness following the horizons of the soil profile. Each layer, the humus layer and the deeper mineral layers, is regarded as homogeneous concerning its physical and chemical parameters. Water content, soil temperature, carbon and nitrogen turnover of each soil layer are estimated as functions of the soil parameters, air temperature, stand precipitation and deposition. The time step of the soil model is one day due to the high dynamics of the water processes.

Soil water

The soil water content is balanced by a simple percolation model. The input into the first layer is the net precipitation after canopy interception. For each other layer, the input is equal to the percolation water from the above layer. The output is estimated from the percolation water into the next layer, the soil evaporation (up to a certain depth), and the water uptake by roots. If the water content of a layer is greater then the field capacity the percolation water is calculated according to a special water conductivity parameter which depends on the soil texture (Glugla, 1969;Koitzsch, 1977). If air temperature is below freezing (0°C), the precipitation is stored as a water equivalent in a pool of snow, which is emptied as a function of temperature. The melt-water will then be added to the uppermost soil layer. In the case of frozen soil no percolation occurs.

Root uptake is limited by the transpiration demand of all trees of the cohort and the plant available water. It is assumed that optimal conditions for water uptake exist only when the water content does not vary by more than 10 percent from field capacity, otherwise there is a linear reduction of the plant available water (Chen, 1993) . The water uptake of each cohort is calculated based on the cohort's relative share of fine roots on the total amount of fine roots.

Soil temperature

The dynamics of soil temperature are described by a one-dimensional heat conduction equation with spatial and time depending heat capacity and thermal conductivity (Suckow, 1989). The thermal capacity of the soil layer is calculated from the specific heat capacity of the solid soil components, the bulk density and the heat capacity. The thermal conductivity depends on the bulk density and the water content of the soil layer. The upper boundary condition is the surface temperature which is estimated from the air temperature of the last three days. Furthermore, the initialisation of the soil temperature distribution is calculated from the annual temperature wave. The solution of the heat conduction equation with the aid of a non-negative-containing, conservative finite-difference method provides the soil temperature in each soil layer (Suckow, 1986).

Soil carbon and nitrogen

Yearly production of foliage litter, dead branches and dead fine roots are added to the pool of soil organic matter. Carbon and nitrogen mineralisation of this soil organic matter is calculated dependent on soil water content, soil temperature, soil pH value and substrate-specific turnover rates (Franko, 1990; Kartschall, et al., 1990; Running and Gower, 1991). This process leads to the release of carbon, nitrogen and CO_2 (Goto, et al., 1994). The released products (1) are fed back to the pool of soil organic matter, (2) are absorbed by plant uptake (nitrogen), (3) are translocated to lower soil layers due to soil water dynamics (mineralized nitrogen) and (4) are released to the atmosphere (CO_2).

Allocation and assimilation

The allocation submodel is based on the framework of Mäkelä (1990):
(1) Carbon-balance: net growth is the difference between gross growth and the three factors senescence, growth respiration and maintainance respiration (and relations between these factors)
(2) Functional balance (Davidson 1969), which states that the shoot-root ratios are adjusted so as to maintain a balanced carbon-nitrogen ratio in the plant.
(3) Pipe model theory (Shinozaki et al. 1964), which reasons that each unit of foliage requires a unit pipeline of wood to conduct water from the roots (both the latter are seen as evolutionary adaptations)
(4) Principle of mass conservation
(5) A height growth strategy that maximises survival
Allocation is performed on a yearly time step and contains the compartments foliage, sapwood, and fine roots.

Phenology

The phenological approach in 4C is based on the interaction of inhibitory and promotory agents that are assumed to control the developmental status of a plant. The agents are driven by temperature and photoperiod, which play the most prominent role in phenology. Using these simple but basic principles a model for the abundance or concentration of an inhibitory and a promotory compound made of a system of two difference equations is used (Schaber and Badeck, 2003).

Mortality and regeneration

The mortality module of 4C consists the following two kinds of mortality. The so called 'age related' mortality based on life span corresponds to the intrinsic mortality developed by Botkin (1993) and the response of trees to growth suppression, described by a carbon-based stress mortality.
The regeneration module describes the processes of seed supply (Rogers and Johnson, 1998), seed germination (Jorritsma et al, 1999), growth and mortality of seedlings, and the recruitment of seedlings into the tree cohorts. Furthermore, the growth and mortality of planted saplings is implemented. Growth of each seedling or sapling cohort is updated annually. Net primary production and phenology are simulated similarly to those of older tree cohorts, using radiation, temperature, CO_2 concentration, water and nutrient availability as inputs. When the simulated height of the seedlings exceeds an arbitrary threshold value, the entire cohort is then transformed into a regular tree cohort.

Management

With 4C management of mono- and mixed species forests can be simulated. For this purpose, a number of thinning and harvesting options and regeneration strategies (natural regeneration, planting, short rotation coppice) are implemented (Lasch et al. 2005).

Timber grading / Wood processing model / Socio-economic analysis

Timber grades are calculated regarding standing and harvested biomass. For this purpose a variety of diameter, height and volume calculations are carried out to assort a stem into different types of wood (stems, segments, industrial wood, fuel wood).

The Wood Processing Model (WPM) estimates the carbon content of timber products and carbon pools (such as soil, landfill, atmosphere). Pools are initialized by a spinup run and harvested wood is sorted into timber product groups, defined by certain life spans. Then the product group carbon flow is calculated along the simulation period. Removals of product groups are partly recycled and return into the timber cycle. Finally all products end up in landfills (or atmosphere) and thus, stored carbon is subsequently released to the atmosphere (Eggers, 2002).

The Socio Economic Analysis (SEA) allows analysing a harvest timber and standing stock due to the aspects of costs, revenues and subsidies in a given time frame. SEA uses the 4C information about the harvested wood, standing stock and silvicultural operations of a simulated area, sorts the input analog to WPM into different timber grades and computes the costs, assets and subsidies per year. Unlike the WPM it analyses also the standing stock in respect to its financial value (Fürstenau e.al. 2007).

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