ASSESSMENT OF FOREST PRODUCTIVITY USING AN ECOSYSTEM PROCESS MODEL, REMOTELY SENSED LAI MAPS AND FIELD DATA

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ABSTRACT

The process-level ecosystem simulation model Biome-BGC was run aspatially for a highly managed forest, the Idarwald. The area (49°45'N, 7°10'E) is climatically dominated by oceanic influences and mainly consists of managed stands of Norway spruce *(Picea abies)*. Biome-BGC was run for 90 years using model parameters adapted to the local environmental conditions. The parameters include meteorological input data (1988-2002) from nearby Morbach weather station, ecophysiological constants for Picea abies and initialisation variables from Running & Gower (1991). Annual whole-plant mortality (AMT) fraction was adapted to the situation of a managed forest, where biomass is removed during thinning and logging measures in developing stands. AMT was calculated to a value of 0.017 yr^{-1}. Fire mortality fraction was set to zero. Model outputs were compared to remotely sensed leaf area index (LAI) and field measured variables (stem volume and radial stem growth). Airborne imaging spectrometer (HyMap) data had been used to derive an LAI Map of Idarwald forest (cross-validated RMSE = 0.54 m^2 m^{-2}). Age courses of modelled and remotely sensed LAI both had a maximum of 5 m^2 m^{-2} at about stand age 15 and decreased to 3 m^2 m^{-2} at age 80. Measurements of stem volume [m^3 ha^{-1}] were converted to stem carbon (SC) [kgC m^{-2}] and compared to modelled values. At age 35, Biome-BGC overestimated SC by factor 2. From age 55 to 75 modelled SC was in good agreement with measured SC. Radial stem increment (RSI) data [mm yr^{-1}] was available for the period 1990-2002 for a test plot located nearby Idarwald forest. Model outputs of "C pool to total stem C" [kg m^{-2} d^{-1}] were converted to RSI. Modelled and measured values of RSI agree for most of the years. The RMSE between modelled and measured RSI (n=9) was relatively low (0.10 mm yr^{-1}). In a summary, model outputs of Biome-BGC did relatively well agree with measured data. Obviously, Biome-BGC reasonably simulated ecosystem processes in a managed forest.

Keywords: Ecosystem simulation model, Biome-BGC, Forest, Leaf Area Index, Stem biomass, Remote Sensing

1 INTRODUCTION

Most of the forests located in the midlatitudes of the Northern Hemisphere act as a carbon sink, however, with considerable spatial and temporal variations and uncertainties (Valentini et al., 2000; Schimel et al., 2000; Canadell et al., 2000). Quantifying the strength of the carbon sink for present or future times can be achieved through ecosystem simulation models (e.g., Biome-BGC) together with remotely sensed estimates of biophysical variables, such as leaf area index (LAI) (Wicks & Curran, 2003). Biome-BGC (biogeochemical cycles) is a process-level ecosystem simulation model that calculates the cycling of carbon, water, and nitrogen through, e.g., forest ecosystems (Running & Coughlan, 1988). The model has been developed for North-American growth conditions. Though it has been applied to other forested regions of the world, it is not clear to what extent Biome-BGC can reasonably simulate ecosystem processes in highly managed forests of Western Europe.

The coupling of remote sensing with ecosystem simulation models can be achieved through three basic approaches: Initialisation, incorporation, and validation. Validating model predictions of forest growth has been the least utilised application of remotely sensed imagery (Coops & White, 2003). In the present study, the validation approach was applied. We used Biome-BGC to predict LAI (and other variables). The predictions of LAI were then compared to LAI as estimated from HyMap remote sensing data. Other variables (stem carbon, C pool to stem C) were compared to field measured data.

2 MATERIAL AND METHODS

2.1 STUDY AREA

Idarwald test site (49°45'N, 7°10'E) is located on the north-western slopes of a mountain ridge (Hunsrück). Maximum elevation is about 770 m above mean sea level (a. s. l.). Climatically the area is dominated by oceanic influences with mean annual precipitation of 800-1000 mm and mean annual air temperature of 6.5° C. Geologically the area is underlain by Devonian quartzite and Devonian shale. The forest mainly consists of managed stands of Norway spruce *(Picea abies)*.

2.2 REMOTELY SENSED LAI MAP

Airborne imaging spectrometer (HyMap) data was used to derive leaf area index (LAI) of Idarwald forest. The HyMap (Integrated Spectronics, Australia) was flown over the Idarwald at 17th July 1999. HyMap data was radiometrically and geometrically corrected (Hill & Mehl, 2003). Field measurements were carried out in 1999 and 2000 contemporary to the HyMap overflight. 42 spruce stands were identified at the study area. Within each stand, a square 0.09 ha plot was established. At each plot measurements of forest LAI were carried out with a Li-Cor LAI-2000 instrument.

Table 1: Summary statistics for Leaf Area Index (LAI) in five age classes

Stand age [years]	n	Leaf Area Index [$m^2\ m^{-2}$]			
		Mean	Standard deviation	Minimum	Maximum
< 10	1	5.3	0.0	5.3	5.3
10-30	24	5.2	0.7	3.3	6.8
30-50	46	3.7	0.9	1.9	6.7
50-80	41	3.1	0.6	2.2	4.6
> 80	45	2.6	0.4	1.7	3.9

A perpendicular vegetation index (PVI) based on HyMap wavebands at 1088 nm and 1148 nm was linearly related to LAI. LAI was estimated with a cross-validated R^2 of 0.77 and a cross-validated RMSE of $0.54m^2m^{-2}$ (17 percent of the mean) between estimated and measured LAI (Schlerf et al., 2004). From the resulting LAI map and the existing Forest Geographic Information System, average values of LAI were computed for five age classes based on 157 forest stands (Table 1).

2.3 FIELD DATA

Two types of field data were available from test sites located at Idarwald or nearby: a) Stem volume [m^3 ha^{-1}] and b) radial stem increment [mm yr^{-1}]. Stem volume data has been measured at three plots of *Picea abies* at Idarwald between 1961 until 2000 every five or six years. For each year the three single measurements were averaged. Radial stem increment (RSI_{mes}) was measured annually between 1990 and 2002 nearby Idarwald at Leisel test site (650 m a. s. l.).

2.4 BIOME-BGC SIMULATIONS

2.4.1 Model parameterisation

Biome-BGC was run for 90 years using model parameters adapted to the local environmental conditions. The model requires meteorological input data, ecophysiological constants and initialisation variables. Climatic variables, such as temperature and precipitation are used to drive the model. Meteorological input data for the period 1988-2002 was available from the nearby Morbach weather station operated by the Forest Research Institute Rheinland-Pfalz. The meteorological variables that were measured at the station were daily maximum, minimum and average air temperature [°C] and daily precipitation [cm]. MTCLIM (version 4.3) was used to derive other meteorological variables required by the model, such as the daylight average water vapor pressure deficit [Pa], the daylight average shortwave radiant flux density [W m^{-2}] and the daylength [s].

The ecophysiological constants define certain characteristics of the vegetation type being simulated. When available from the literature (White et al. 2000), ecophysiological parameters specific to Norway spruce *(Picea abies)* were chosen. In case of several values of a certain parameter for *Picea abies* listed in White et al. (2000), the mean was taken. Table 2 presents selected variables used for the simulations with Biome-BGC. Without reference in literature, default values were used.

Table 2: Selected ecophysiological parameters used for the model simulations

Parameter	Value	Source
Annual leaf and fine root turnover fraction [yr^{-1}]	0.23	White et al. 2000
Annual whole-plant mortality fraction [yr^{-1}]	0.016	Own calculation
Annual fire mortality fraction [yr^{-1}]	0.000	Assumption
New fine root carbon to new leaf carbon (ratio)	1	Default value
New stem carbon to new leaf carbon allocation (ratio)	2.3	White et al. 2000
Coarse root carbon to stem carbon allocation (ratio)	0.19	White et al. 2000
Specific leaf area [m^2 kgC^{-1}]	7.8	White et al. 2000
Fraction of leaf N in rubisco	0.04	Default value
Canopy water interception coefficient [LAI^{-1} d^{-1}]	0.012	Solling Project

Mortality, the fraction of the carbon pool that dies or is consumed each year, was adapted to the situation of a managed forest. Fire mortality fraction was set to zero as forest fires almost never occur or become quickly extinguished. For the annual whole-plant mortality fraction (AMF), Biome-BGC requires a proportion of the stand that dies each year in mature (not developing) stands (White et al., 2000). Despite of this demand, AMF was adapted to the situation of a managed forest, where biomass is removed during thinning and logging measures in developing stands. AMF was calculated according to

$$\mathrm{n_t} = \mathrm{n_0} \cdot (1 - AMF)^{\mathrm{t}} \qquad (1)$$

where n_0 is the number of individuals at time $t=0$, n_t is the number of individuals after time intervall t and t is the time interval in years. At Idarwald, average stem density of 15 year old stands was measured to 1839 stems ha^{-1} (n=4) and of 100 year old stands to 420 stems ha^{-1} (n=4) from a total dataset of 42 stands (Schlerf et al., 2004). With n_0 assumed to be 1839 trees per ha at the year 15 of stand development, n_t of 420 trees per ha at a stand age of 100 years and a value of 85 years for t, equation (1) was solved for AMF = 0.017 yr^{-1}.

The canopy water interception coefficient (CWI) determines the amount of precipitation intercepted by the canopy and controls the amount of precipitation entering the soil water pool. As values of CWI were not available for *Picea abies* from White et al. (2000), we took an appropriate value for CWI of 0.012 LAI^{-1} d^{-1} from the documentation of the Solling project (www.forstweg.de/port/CO2solling.pdf).

The initialisation variables were taken from Running & Gower (1991). For instance, leaf carbon was initialised for all runs at 0.12 kgC m^{-2} representing the leaf area index of a "sapling" (Table 3).

2.4.2 Model runs

Two types of simulations were run: i) long-term and ii) short-term simulations. Long-term simulations used one single-year climate file, 1988, that was repeated for 90 years. The 1988 climate data was considered to be representative for the whole period. Long-term simulations intended to compare modelled long-term stand development with two types of measured data: a) a remotely sensed map of LAI (section 2.2) and b) stem volume measurements (section 2.3). The LAI map was a single-year map. Forest in the map ranged from young to old stands (10-100 years) in five age classes (Table 1). We treated the LAI map as if originated from a temporal process and compared remotely sensed LAI (LAI_{mes}) to modelled LAI (LAI_{mod}).

Stem volume measurements comprised a period of 40 years, from a stand age of 35 until 75 years. Stem volume, measured in units of m^3 ha^{-1}, was converted to stem carbon (SC_{mes}) [kgC m^{-2}] using 0.47 g cm^{-3} for the density of wood at 12-15% moisture content (Sedlmayer, 2004) and 0.45 for the fraction of carbon in dry wood (Kreeb, 1983). The modelled output variables "Life stem C" and "Dead stem C" were added to "Total stem C" (SC_{mod}) [kgC m^{-2}]. SC_{mod} were then compared to SC_{mes} (Section 3.1).

Short-term simulations used climate data of the period 1988-2002. The modelled output variables "C pool to life stem C" and "C pool to dead stem C" were added to "C pool to total stem C" (C2C) and converted from unit kg m^{-2} d^{-1} (Carbon) to the variable "Radial stem increment" (RSI_{mod}) of unit mm yr^{-1} (fresh wood):

$$RSI_{\mathrm{mod}} = \sqrt{\frac{C2C \cdot 365 \cdot 10000 \cdot 1000000 \cdot 4\pi}{SD \cdot \rho \cdot c \cdot H}} - PBH \tag{2}$$

where SD is the stem density [ha^{-1}], ρ is the density of fresh wood [g cm^{-3}], c is the fraction of carbon in dry wood, H is the average tree height [mm] and PBH is the average perimeter at breast height [mm]. The following values were measured in Norway spruce stand of approximately 60 years at Idarwald forest (n=8): SD = 499 stems per hectare, H = 26963 mm and PBH = 1060 mm. The other parameters were taken from literature: ρ = 0.47 g cm^{-3} at 12-15% moisture content (Sedlmayer, 2004), c = 0.45 (Kreeb, 1983). After the conversion, RSI_{mod} were then compared to RSI_{mes} (Section 3.3).

Table 3: Initialisation variables as specified by Running & Gower (1991)

Parameter	Value	Unit
First-year maximum leaf carbon	0.12	(kgC m^{-2})
First-year maximum stem carbon	1.00	(kgC m^{-2})
Coarse woody debris carbon	0.10	(kgC m^{-2})
Litter carbon, labile pool	0.30	(kgC m^{-2})
Litter carbon, unshielded cellulose pool	0.10	(kgC m^{-2})
Litter carbon, shielded cellulose pool	0.10	(kgC m^{-2})
Litter carbon, lignin pool	0.10	(kgC m^{-2})
Soil carbon, fast microbial recycling pool	0.1125	(kgC m^{-2})
Soil carbon, medium microbial recycling pool	0.1506	(kgC m^{-2})
Soil carbon, slow microbial recycling pool	0.4890	(kgC m^{-2})
Soil carbon, recalcitrant SOM (slowest)	9.0279	(kgC m^{-2})
Litter nitrogen, labile pool	0.200	(kgN m^{-2})
Soil nitrogen, mineral pool	0.002	(kgN m^{-2})

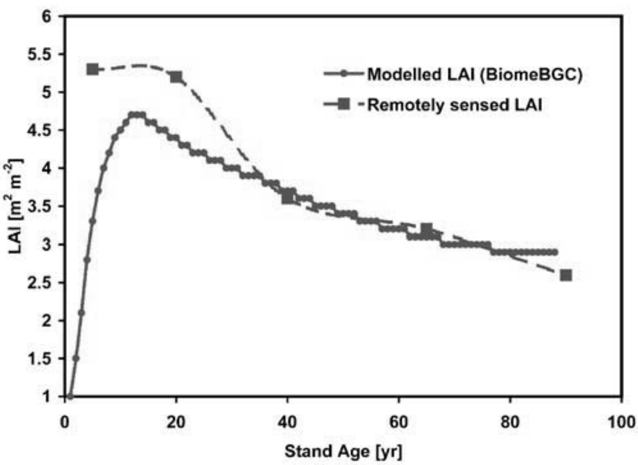

Figure 1: Age courses of modelled and remotely sensed leaf area index. Step-like appearance of the modelled LAI curve is caused by the format of Biome-BGC's annual text output file. This file contains values rounded to the first decimal place.

3 RESULTS AND DISCUSSION

3.1 LEAF AREA INDEX (LAI)

LAI_{mod} (Biome-BGC) was compared to LAI_{mes} (Remote Sensing). A decrease with stand age was observed for both modelled and measured LAI. The inverse relation between LAI and stand age seems to be related to the fact that during stand development, crowns of individual trees expand and increase utilization of available growing space. The point at which crowns of different trees begin to interact is considered as being the peak LAI after which a rapid decrease takes place due to competition between the individual trees (Vose et al. 1994). In Figure 1, a peak LAI can be assumed at an age of 15. From an age of 15 onwards, a gradual decline in LAI up to age 90 is evident. An additional decrease of LAI is caused by gaps related to thinning and logging measures.

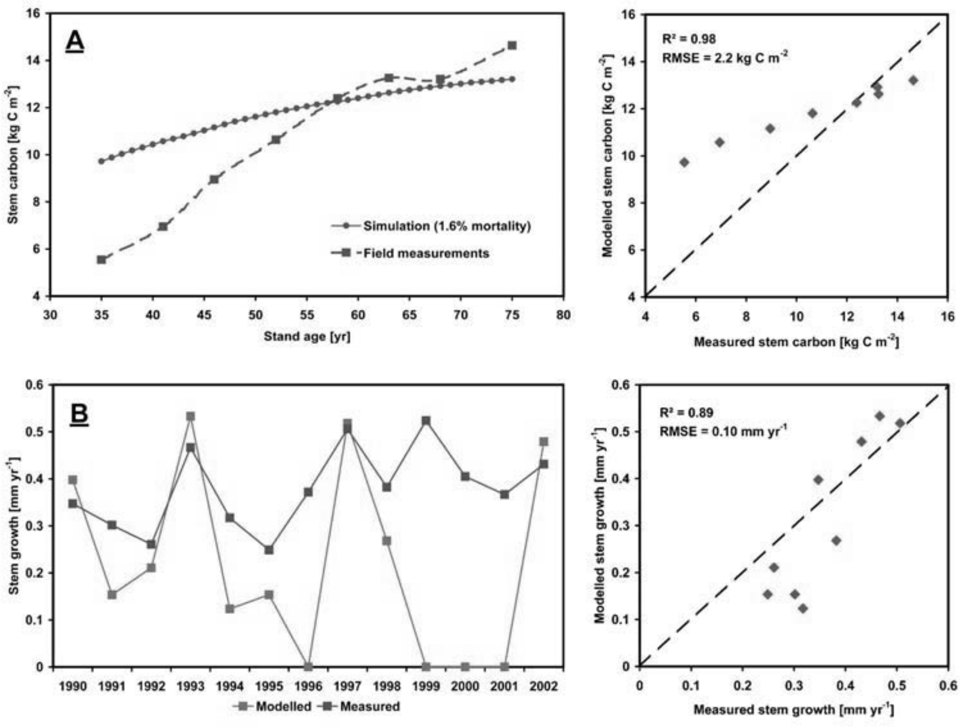

Figure 2: A) Left: Age course of modelled and measured stem carbon, right: scatter plot. B) Left: Age courses of modelled and measured radial stem increment (stem growth), right: scatter plot showing nine of thirteen measurements (four years were left out where modeled values of stem growth were zero).

There are two reasons for the difference between modelled and remotely sensed LAI in young stands. First, the underestimation of LAI by Biome-BGC may be caused by the use of equal ecophysiological parameters for young and mature stands. In reality, physiological activities and allocation differ between young and mature trees. Second, the determination of remotely sensed LAI was validated only for stands of age 10 and older. Therefore, no information was available for the age course of LAI in the first ten years of stand development. For mature stands (40-100 years old) the differences between modelled and remotely sensed LAI were small.

3.2 STEM CARBON (SC)

SC_{mod} (Biome-BGC) was compared to SC_{mes} (field data). At age 35, Biome-BGC overestimated SC by factor 2 (Figure 2A). From age 55 to 75 modelled SC was in good agreement with measured SC.

The overestimation of SC_{mod} at stand ages from 35 to 50 years may also be caused by unique ecophysiological parameterisation over the whole tree life. Carbon allocation changes during tree life which may cause the overestimation of stem carbon allocation in younger stands.

3.3 RADIAL STEM INCREMENT (RSI)

Modelled radial stem increment (RSI_{mod}) amounted to 0.1 - 0.6 mm yr^{-1}. Modelled and measured values of RSI agreed for most of the years (Figure 2B). However, in 4 out of 13 years, Biome-BGC simulated RSI values of zero. More investigations have to be done to explain this model behaviour. When these four years are left out, the RMSE between modelled and measured RSI is relatively low (0.10 mm yr^{-1}).

4 CONCLUSIONS

The following conclusion could be drawn from the research:

Model outputs of Biome-BGC did relatively well agree with measured long-term and short-term data

Annual whole-plant mortality fraction was adapted to the situation of a highly managed forest

Age courses of modelled and remotely sensed leaf area index both had a maximum of 5 m^2 m^{-2} at about stand age 15 and decreased to 3 m^2 m^{-2} at age 80.

Stem carbon was reliably simulated for stand age 55-75, but not for stand age 35-55

Radial stem increment showed good agreement for 9 out of 13 years (RMSE = 0.10 mm yr^{-1})

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