Austrian Journal of Forest Science

Centralblatt für das gesamte Forstwesen

Geleitet von
P. Mayer und H. Hasenauer
Gegründet 1875

129. Jahrgang ◆ Heft 1 ◆ 2012
Seite 1–65

Austrian Journal of Forest Science

Centralblatt für das gesamte Forstwesen

Gegründet im Jahre 1875
von den Forstinstituten der Universität für Bodenkultur (BOKU) und des Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft (BFW)

Ziel: Das Centralblatt für das gesamte Forstwesen veröffentlicht wissenschaftliche Arbeiten aus den Bereichen Wald- und Holzwissenschaften, Umwelt und Naturschutz, sowie der Waldökosystemforschung. Die Zeitschrift versteht sich als Bindeglied von Wissenschaftlern, Forstleuten und politischen Entscheidungsträgern. Daher sind wir auch gerne bereit, Überblicksbeiträge sowie Ergebnisse von Fallbeispielen sowie Sonderausgaben zu bestimmten aktuellen Themen zu veröffentlichen. Englische Beiträge sind grundsätzlich erwünscht. Jeder Beitrag geht durch ein international übliches Begutachtungsverfahren.

Aims and scope: The Austrian Journal of Forest Science publishes scientific papers related to forest- and wood science, environmental science, natural protections as well as forest ecosystem research. An important scope of the journal is to bridge the gap between scientists, forest managers and policy decision makers. We are also interested in discussion papers, results of specific field studies and the publishing of special issues dealing with specific subjects. We are pleased to accept papers in both German and English. Every published article is peer-reviewed.

Gründungsherausgeber: Rudolf Micklitz, 1875

Herausgeber:

Dipl.-Ing. Dr. Peter Mayer
Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft (BFW)
Seckendorff-Gudent-Weg 8
A-1131 Wien

Univ.-Prof. Dr. Hubert Hasenauer
Institut für Waldbau
Universität für Bodenkultur
Peter-Jordan-Straße 82
A-1190 Wien

Internet: http://www.boku.ac.at/cbl
Gedruckt mit der Förderung des Bundesministeriums für Bildung, Wissenschaft und Kultur in Wien.

Austrian Journal of Forest Science

CENTRALBLATT
FÜR DAS GESAMTE
FORSTWESEN

ORGAN DES DEPARTMENTS FÜR WALD- UND BODENWISSENSCHAFTEN DER UNIVERSITÄT FÜR BODENKULTUR UND DES BUNDESAMT UND FORSCHUNGSZENTRUM FÜR WALD

Begründet 1875

129. JAHRGANG HEFT 1 Jänner bis März 2012 Seite 1–65

INHALT DIESES HEFTES

ÖSTERREICHISCHER AGRARVERLAG WIEN

Erscheinungsweise: jährlich 4 Hefte,
Jahresbezugspreise inkl. Postgebühr und 10% Mehrwertsteuer im Inland € 259,10, Einzelheft € 64,80; im Ausland € 264,20 (exkl. 10% Ust.). Das Abonnement gilt für ein weiteres Jahr als erneuert, falls nicht 8 Wochen vor Ende des Bezugszeitraumes eine schriftliche Kündigung beim Verlag eintrifft. Printed in Austria. Die Herausgabe dieser Zeitschrift erfolgt mit Förderung durch das Bundesministerium für Wissenschaft und Forschung.

Medieninhaber und Herausgeber:
Österreichischer Agrarverlag, Druck- und Verlagsges.m.b.H. Nfg. KG, Sturzgasse 1a, 1140 Wien.
DVR-Nr. 0024449, HRB-Nr.: FN 150499 y; UID-Nr.: ATU 41409203, ARA: 9890.
Abonnement-Verwaltung: Sturzgasse 1a, 1140 Wien,
Tel. +43 (0) 1/981 77-0, Fax +43 (0)1/981 77-130.
Internet: http://www.agrarverlag.at. Layout: DI Anton Sprenger
Hersteller: AV+Astoria Druckzentrum GmbH, Faradaygasse 6, A-1030 Wien.

129. Jahrgang (2012), Heft 1, S. 1–21

Austrian Journal of Forest Science
Centralblatt für das gesamte Forstwesen

Assessing the Carbon Flux Dynamics within Virgin Forests: The Case Study ‘Babia hora’ in Slovakia

Die Kohlenstoffkreislaufdynamik des Urwaldes \`Babia Hora´ in der Slowakei

Katarína Merganicová[1, 2], Jan Merganic[1, 2], Hubert Hasenauer[3]

Keywords: Virgin forest, spatial interpolation, Mortality, carbon cycle

Schlagworte: Urwald, Interpolation, Mortalität, Kohlenstoffkreislauf

Abstract

Virgin forests provide unique information about natural conditions and forest ecosystem succession dynamics. Such information is needed to assess the carbon sink and source potential of our forests and to evaluate the ’self initialization procedures‘ within large scale ecosystem models. In this paper we use inventory data from the Babia hora virgin forest in Slovakia to assess the carbon flux dynamics of virgin or old growth Norway spruce (Picea abies L Karst) ecosystems. The species-specific version of the biogeochemical-mechanistic ecosystem model BIOME-BGC is applied to assess the flux dynamics of this ecosystem. The comparison of simulated versus observed data is based on the error analysis of the carbon pools. The results confirm previous

---

[1] Forest research, inventory and monitoring (FORIM), Huta 14, 962 34 Železná Breznica, Slovakia
[2] Czech University of Life Sciences in Prague, Faculty of Forestry, Wildlife and Wood Sciences, Department of Forest Management, Kamýcká 129, 165 21 Praha 6 – Suchdol, Czech Republic
[3] Institute of Silviculture, University of Natural Resources and Life Sciences Vienna, Peter Jordan Straße 82, A-1190 Wien, Austria

findings within old growth forest ecosystems suggesting that for modeling purposes a "dynamic mortality" model is required to mimic the carbon flux dynamics of such forests correctly.

Kurzfassung

Die wenigen in Europa verbliebenen Urwälder zeigen die Waldentwicklung ohne menschlichen Einfluss. Damit sind Urwälder wichtige Referenzflächen für die Abschätzung der Kohlenstoffkreislaufes (Senken und Quellenpotentiale) von unbewirtschafteten Waldökosystemen. Weiters sind Urwälder eine wichtige Referenzfläche für die Evaluierung von sogenannter `Selbinistialsierungen´ von Ökosystemmodellen, wie dies für die Generierung von Startwerten für die Modellierung üblich ist. In dieser Arbeit werden mit Hilfe von Daten aus dem Urwald Babiha Hora in der Slowakei die im Ökosystem Model BIOME-BGC implementierte dynamische Mortalitätsmodell evaluiert. Abschließend werden die Kohlenstoffsenken und Kohlenstoffquellen für einen Sukzessionszyklus im Urwald Babiah Hora mit Hilfe des Modells dargestellt. Ergebnis der Studie ist, dass für die richtige Abschätzung der Stoffflüsse im Urwald Babiha Hora ein dynamisches Mortalitätsmodell verwendet werden muss. Diese bestätigt frühere Untersuchung im Urwald Rothwald in Österreich, wo man zu ähnlichen Ergebnissen kam.

1. Introduction

Greenhouse gas emissions including atmospheric carbon dioxide (CO_2) have steadily increased since pre-industrial times, contributing to temperature increases in many parts of the world (IPCC 1996). A continuation of this trend is expected to cause significant changes to global ecosystems. Forests are an important part of the global carbon cycle and forest management for sequestering carbon is of increasing interest (Percy et al. 2003). European forest ecosystems have experienced a long management history resulting in substantial changes to species distributions and severe soil degradation effects affecting the nitrogen and carbon pools (Pietsch and Hasenauer 2002). Among real world ecosystems, virgin forests provide the best representation of natural conditions and give insights into the conceptual long-term potential dynamics of the carbon cycle (carbon sinks versus carbon sources in forests) without any management-related impacts (Pietsch and Hasenauer 2006, Field and Kaduk 2004).

Carbon exchange dynamics within larger virgin forest areas are poorly understood (Suchanek et al. 2004). Traditionally, old-growth forests have been assumed to be in equilibrium (Odum 1953), where the carbon uptake equals the amount of carbon released by respiration and decomposition (Križová et al. 1992), i.e. their long-term net ecosystem production is zero (Odum 1969). Hence, such forests are characterized by a long-term average volume of growing stock (Vacek 2003). However, on a smaller scale given virgin forests exhibit periods in which they act as net carbon sinks, as carbon neutral stands and as net carbon sources. Such source-sink transitions are a part of natural ecosystem dynamics.

This conceptual idea of an ecosystem in equilibrium has been widely used within ecosystem modeling to initialize starting conditions for model applications. While typical gap or patch models (Bugamann 2001) simulate the potential vegetation as tree populations or mixtures as they evolve over time, large scale ecosystem carbon flux models such as BIOME-BGC (Thornton 1998) or LPJ-BGC (Lund Potsdam Jena Model – Sitch et al. 2003) use this equilibrium concept to run self-initialization or spinup procedures to derive the carbon and nitrogen pools as they may depend on site and climatic conditions for given biome types or tree species (see Pietsch and Hasenauer 2006). During this procedure the model gradually accumulates carbon in the ecosystem until a steady state. The steady state reached at the end of self initialization is interpreted as the "temporally averaged state of an undisturbed ecosystem for a region large enough to encompass all its natural development stages" (Law et al. 2001). This situation is also described as the "dynamic equilibrium in net ecosystem carbon exchange with variable ecosystem age classes" (Bachelet et al. 2004). Although this interpretation is theoretically reasonable, practical evaluations versus observed field data representing such undisturbed ecosystems are still very limited.

Examples of such an evaluation are presented in the studies performed by Merganicová (2004), Pietsch and Hasenauer (2006) for mixed beech/spruce forests using data from the Rothwald old-growth forest in Austria. The main result of these studies was that the fluctuation of mortality rates in virgin forests across the developmental stages should be accounted for in the simulations. Self-initialization procedures of large scale ecosystem models that ignore these changes in mortality by assuming constant biomass mortality rates of managed forests (e.g. 0.5%/J of vegetation biomass) may lead to an overestimation of the ecosystem carbon content of up to 400% (see Pietsch and Hasenauer 2006), depending how and if potential disturbance regimes (fire, wind) are addressed. Such overestimation of the carbon content leads to ill-defined starting conditions for ecosystem modeling and may also overestimate the carbon storage of real world forest ecosystems.

The objective of this study is to apply the conceptual outline of the dynamic mortality model proposed by Pietsch and Hasenauer (2006) to the old growth Norway spruce forests in Babia hora, Slovakia. We are specifically interested in answering two questions:

1. Does the dynamic mortality model implemented in the BIOME-BGC model (Pietsch and Hasenauer 2006) also properly mimic the succession dynamics of the old growth forest Babia hora in Slovakia?
2. What adjustments may be needed to analyse the temporal performance of carbon fluxes of the virgin forest Babia hora versus the mixed beech/spruce virgin forest at Rothwald in Austria?

2. Methods

2.1. Ecosystem Model

In this study we use an extension of BIOME-BGC (see Pietsch et al. 2003, 2005), a biogeochemical model that simulates daily cycling of energy, water, carbon and nitrogen within an ecosystem (Thornton 1998). The extensions address species-specific parameters, a groundwater routine for the hydrological conditions in floodplain forests and the dynamic mortality rate applicable to unmanaged virgin forests (see next section for details).

The model requires input information about climate (daily values of minimum and maximum temperature, daily sum of precipitation, incident solar radiation, and vapor pressure deficit), site (aspect, elevation, soil depth, and soil texture), nitrogen deposition and fixation, and the prevailing tree species. The original model BIOME-BGC (Thornton 1998) accounted for fire and regular mortality (i.e. mortality caused by senescence and competition), and presumed that mortality takes place annually as a constant predefined ratio of the vegetation biomass. The regular mortality rate in the original version is set to 0.5% of vegetation biomass per year (White et al. 2000).

2.2. The dynamic mortality model

Previous studies (Merganičová 2004; Hasenauer et al. 2005; Pietsch and Hasenauer 2006) found that in virgin forests a dynamic mortality model is needed to mimic the developmental cycles of such forests. In the following section we will shortly outline the key principles of this mortality model as it is relevant for this study. A more detailed discussion is available in Pietsch and Hasenauer (2006).

The dynamic mortality model assumes a U-shaped mortality development from juvenile to senescent stands. Pietsch and Hasenauer (2006) constructed an elliptic trajectory for mortality, consisting of two half ellipses, of which each is given by

(1) $$\frac{(x-c_x)^2}{a^2}+\frac{(y-c_y)^2}{b^2}=1$$

where x is the time and y is the mortality rate, c_x, c_y are the x- and y coordinates of the centre of the ellipse, and a, and b are the two semi axes. Solving this quadratic equation for the mortality rate y gives

(2) $$y=c_y \pm \frac{b}{a}\sqrt{a^2-x^2+2xc_x-c_x^2}$$

The semi axes a, b and the centre coordinates c_x, c_y of the ellipse can be expressed as

(3) $$a=c_x=\frac{L}{2}$$

(4) $$b=\frac{mort_{\max}-mort_{\min}}{2}$$

(5) $$c_y=b+mort_{\min}=\frac{mort_{\max}+mort_{\min}}{2}$$

with L the length of the low or high mortality phase, $mort_{max}$ and $mort_{min}$ the maximum and minimum mortality rates. After substituting equations (3), (4) and (5) into equation (2) one finds:

(6) $$y=\frac{mort_{\max}+mort_{\min}}{2}\pm\frac{mort_{\max}-mort_{\min}}{L}\cdot\sqrt{L\cdot x-x^2}$$

In equation (6) the first right hand side term represents the mean annual mortality rate. The second right hand side term governs the changes along the mortality cycle. The vector of their subtraction gives the trajectory of the low mortality phase and addition the trajectory of the high mortality phase.

In the model implementation the parameters representing minimum and maximum mortality rates and the length of the low and high mortality phases are added to the model parameter set, which allows the flexible scaling of low and high mortality phases as they may differ by ecosystem.

3. Data

The data used for this study come from the nature reserve Babia hora situated in the northern part of Slovakia. Babia hora is an isolated mountain massif belonging to the outer Western Carpathian mountain range. Thiss massif is built of tertiary flysch rocks, mainly sandstones, marl, clay stones, slate and conglomerates. The soil types that occur in the area are raw soils, andosols and most frequently podsols. The mean annual precipitation is 1,600 mm, and the mean annual temperature 2°C. The forest stands are almost entirely composed of Norway spruce (Picea abies L./Karst.) with a small admixture of rowan (Sorbus aucuparia L.) and silver fir (Abies alba Mill.).

In 1926 a nature reserve was established to preserve natural mountainous spruce forest ecosystems in this region. Originally the nature reserve encompassed 117.6 ha, but in 1974 the reserve was enlarged and currently its area is 503.94 ha (Korpec 1995), and comprises not only forests, but also dwarf mountain pine stands and sub-alpine meadows.

Within the forested area of the nature reserve 57 permanent circular sample plots were established in 2002 (Merganic et al. 2003), each with an area of 500 m² (i.e. radius = 12.62 m). The plots are located at an elevation ranging from 1,173 m to 1,503 m above sea level, the latter representing the upper timber line in this region (Figure 1).

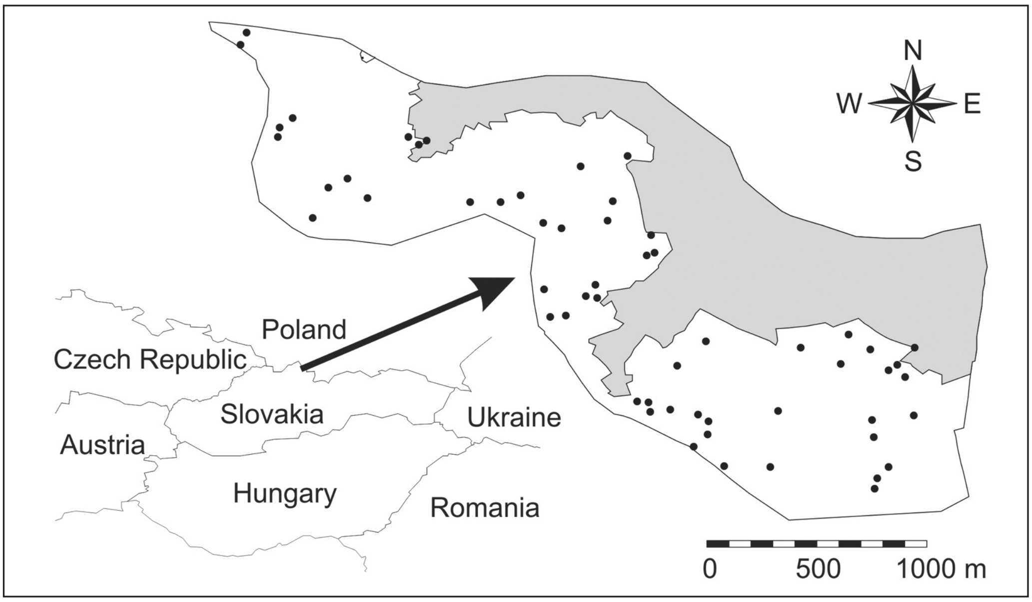

Fig. 1: Location of sample plots in the Nature Reserve Babia hora. Legend:
▨ *alpine meadows and stands of mountain dwarf pine,* □ *forest, • sample plots*

In all plots, mensurational information was collected on living trees and dead wood with a diameter above 7 cm. For living trees and standing dead trees, tree height and diameter at breast height were determined. In the case of lying dead wood (lying stems and naturally formed stumps), total length and diameter at the midpoint was measured, whereas for stumps only the diameter at 0.3 m height was determined. The decay class was assessed using the 8-degree scale as proposed by Holeksa (2001). The collected information was used for calculating the volume of living woody mass and dead woody mass per hectare. The volume of standing trees was calculated using an integral equation based on the models of stem shape derived by Petráš (1986, 1989, 1990). The simplified form for calculating the volume of stem inside bark is as follows:

(7) $$v = \frac{\pi}{40{,}000} \times \int_0^{hR} d\left(h_i, hM, d_{1.3}, \vec{a}, sp\right)^2 dh$$

where:

v – volume of stem inside bark in m^3,

hR – actual (measured) tree height in m,

hM – simulated tree height in m (estimated from the diameter-height curves derived from the undamaged trees, Merganic et al. 2003),

$d_{1.3}$ – tree diameter at 1.3 m height in cm,

d – tree diameter at i tree height (h_i) in cm,

a – vector of tree-species specific parameters in the model of stem shape,

sp – tree species.

The volume of lying deadwood was calculated using Huber´s formula, while the volume of stumps was estimated as the volume of a cylinder with the height equal to 0.3 m.

To compare the field observations with the simulation output, the observed stand volume of living and dead wood was recalculated to carbon amount per hectare using the conversion formula:

(8) $$CC = V * \rho * C\%/100$$

where CC is carbon content in kgC.ha^{-1}, V is stand wood volume in m^3.ha^{-1}, ρ is basic wood density in kg.m^{-3}, and $C\%$ is the fraction of carbon in woody mass in %. The carbon fraction was assumed as 50.1 % of the dry mass as reported by Weiss et al. (2000) for Norway spruce in Central Europe. Basic wood density of living trees was set to 430 kg.m^{-3} as a mean of published values (Bütler *et al*. 2007, Morelli *et al*. 2007, Weiss *et al*. 2000). Hence, 1 m^3 of living wood can be transferred in carbon content by multiplying 430 kg.m^{-3} (basic wood density of living trees) with 0.501 (carbon fraction of the dry mass). Applied basic wood densities of deadwood for individual decay classes were derived by Merganicová and Merganic (2010), and are given in Table 1.

Table 1: Basic wood density of Norway spruce coarse woody debris per decay class (derived by Merganicová and Merganic 2010) according to the scale of Holeksa (2001). The decay classes are characterized on the basis of the presence or absence of bark, twigs and branches, log shape, texture, and position with respect to the ground. Decay class 1 represents the least decayed dead wood with intact bark, present twigs and branches, round shape, smooth surface, intact texture, and the position elevated on support points. As the decay process proceeds, the twigs, parts of branches and bark degrade from traces to absent. In decay class 4, only stubs of branches of diameter greater than 4–5 cm are present, a knife can slide up to 3 cm into a log, and crevices up to 0.5 cm deep are present. In the next decay classes, bark and branches are absent, wood becomes softer and fragmented, and the round shape becomes elliptical. Decay class 8 represents the most decomposed dead wood, when the log is on the ground overgrown by mosses and vascular plants.

Basic wood density (g.cm^{-3})	Decay class according to the scale of Holeksa (2001)							
	1	2	3	4	5	6	7	8
	0.394	0.357	0.321	0.284	0.248	0.211	0.175	0.138

Forest litter and soil samples were collected in one third of the inventory plots (19 plots). The plots for soil sampling were selected to ensure that the full elevation range was covered. In each selected plot, four litter cores were extracted from the four corners of a 5 x 5 m square plot situated in the middle of the inventory plot. Round litter augers 50 mm in diameter were used for litter collection. Soil samples were originally planned to be extracted from the same points using the soil auger (diameter 70 mm, length 50 cm). However, due to a high proportion of rock fragments which exceeded the diameter of the soil auger, this technique could be applied only on 10 inventory plots. On the remaining 9 plots soil pits each minimum 50 cm deep were dug inside the area of the inventory plot. The four litter cores extracted from each inventory plot were mixed and analyzed as one sample. Soil samples were divided into genetic horizons, and each horizon was analyzed separately. Organic carbon content in one gram of litter or soil was determined from the oven-dried mass (ÖNORM L 1080) by the combustion in O_2-flow and consequent measurement of CO_2 using the infrared-spectrometer (LECO S/C 444). Summary statistics of stand and soil data are given in Table 2.

Table 2: Basic stand and soil characteristics of the virgin forest Babia hora, where Spruce% represents spruce proportion in tree species composition, h is the mean tree height, DBH the mean quadratic diameter at breast height, V the stand volume per hectare, N the number of trees per hectare, SDI the stand density index according to Reineke (1933), V_{CWD} and C_{CWD} the volume and the mass of carbon in coarse woody debris, and C_{soil} carbon amount in soil.

Stand characteristics	Number of observations	Mean value	Minimum	Maximum
Spruce %	57	99.38	91.26	100
h [m]	57	16.99	3.07	30.10
DBH [cm]	57	27.71	5.21	53.15
V [$m^3 \cdot ha^{-1}$]	57	313	18.65	1,014
N [ha^{-1}]	57	1,253	80	8,874
SDI	57	755	219	1,748
V_{CWD} [$m^3 \cdot ha^{-1}$]	57	145	0	714
C_{CWD} [$tC \cdot ha^{-1}$]	57	20.31	0	100.1
C_{soil} [$tC \cdot ha^{-1}$]	19	68.40	31.85	142.04

Daily climate data for running the model BIOME-BGC were extrapolated with MT-CLIM (Running et al. 1987) from daily weather records from the climate station Rabca located at the southern foot of the massif Babia hora at an elevation of 642 m above sea level. The daily weather data covered daily minimum, maximum, and average temperature, and daily precipitation from 1961 and 2002.

4. Analysis and Results

The concept of a 'mosaic cycle' (Remmert 1991) assumes a steady state at the landscape level with disequilibria at the local level due to vegetation dynamics. A virgin forest such as Babia hora may be seen as a mosaic of different stages which shift over time, while their abundance at the landscape level remains constant. Hence, the data from a virgin forest, which cover the full range of successional variability, represent the mosaic cycle and the mean value of all different stages represents the steady state or the equilibrium at the landscape level. This landscape equilibrium represents the modelled steady state reached at the end of the self initialisation process, which is used in large scale ecosystem models but also provides an insight into the carbon dynamics of unmanged forest ecosystems. From previous studies in the Rothwald virgin forest in Austria (Merganicová 2004, Pietsch and Hasenauer 2006) we know that the correct assessment of the successional differences in the biomass mortality rates are crucial, suggesting the need for a dynamic mortality concept for undisturbed virgin forest ecosystems. This dynamic mortality model requires the specification of the length of the developmental cycle, the length of the high mortality phase and the minimum and maximum mortality rates.

4.1. Calibration of the mortality model

We started our analysis with the assessment of a potential age structure to define the length and the range of the dynamic mortality cycle. The data analysis from Babia hora and the literature review from the region (Korpel' 1995) suggested that the same length of the developmental cycle as well as of high and low mortality phases as used for the Rothwald virgin forest (Pietsch and Hasenauer 2006) are applicable: (i) length of the developmental cycle equals 300 years, (ii) the low mortality phase is 225 years and (iii) the high mortality phase is 75 years.

Next the minimum and maximum annual mortality rates within the defined developmental cycle have to be calibrated. For this step multidimensional spatial error analysis was applied using the following three core variables: (i) stem carbon content, (ii) carbon content in coarse woody debris, and (ii) soil carbon. In principle the model calibration follows the method applied by Pietsch and Hasenauer (2006) with some improvements related to the fact that a larger number of independent field observations were available (57 plots in Babia hora versus 18 plots in Rothwald). Pietsch and Hasenauer (2006) analyzed the differences between predicted versus observed data using the medians, percentiles and the relative differences between predicted versus observed stem carbon content, coarse woody debris, and soil carbon. In this study we use the mean values, standard errors, and mean differences between predicted and observed values of the same variables (stem carbon, carbon in coarse woody debris, and soil carbon) to search for an unbiased (using paired t-statistics) solution. The advantage in our study is that the greater number of independent observations gives us a typical normal distribution in the error structure justifying the applicability of rigorous statistical methods.

The search for suitable minimum and maximum annual mortality rates was performed through the following steps:

1. First, the simulations were performed with all 57 plots using a constant plant biomass mortality rate of 0.5 % per year for a full successional cycle of 300 years. Based on these simulation results, we selected the two plots with the lowest and highest simulated total carbon content.
2. These two plots were used for calibrating the minimum and maximum mortality rates. This was done by testing an array of different combinations of minimum and maximum mortality rates, while the range of minimum mortality was 0.1 – 2.5 % and the interval of maximum mortality rates was from 0.5 to 15 %. This gives us in total 807 different combinations of minimum and maximum mortality, while the length of the mortality cycle was predefined and remained constant at 300 years (low mortality phase = 225, high mortality phase = 75 years).
3. For each mortality combination, the simulation of each of the two selected plots (plots with the lowest and the highest simulated amount of carbon in step 1) was repeated 30 times using Monte Carlo technique, while the length of each simulation was chosen randomly. Hence, each mortality combination was simulated 60 times (2 plots x 30 Monte-Carlo simulations). This resulted in total 48,420 performed simulations (= 807 mortality combinations, 30 Monte-Carlo simulations, and the 2 simulated plots).

For the Babia hora data the number of mortality combinations tested were 7 times higher than for Rothwald (807 versus 160). For Babia hora the range of minimum mortality was a little larger (0.1 – 2.5 %) compared to Rothwald with minimum mortality ranging from 0.5 to 2.5 % (Pietsch and Hasenauer 2006), while the interval of maximum mortality rates was identical with a range from 0.5 to 15 %.

In the study by Pietsch and Hasenauer (2006) the median and 0.1 and 0.9 percentiles for all mortality combinations were determined and compared with observations obtained from the Rothwald virgin forest. They expressed the differences of the three tested variables ((i) stem carbon, (ii) coarse woody debris, and (iii) soil carbon content) as relative values between the model predictions versus field observations regardless of the sign, and grouped them into categories with a 33 % step (i.e. predictions and observations differ by less than 33 %, 67 %, 100 %, etc.). The results were overlaid and all the graphs of calculated differences between the model predictions and observations had to differ by less than 33 %. The best solution was found with a minimum and maximum mortality rate of 0.9 % and 6.0 %, suggesting that for Rothwald these mortality settings produce unbiased and consistent results (Pietsch and Hasenauer 2006).

In this study we applied a classical statistical approach based on frequency probability techniques by calculating the mean and the variance of the predictions of modeled variables (stem carbon content, coarse woody debris, and soil carbon content) for the different mortality variants. The mean simulated results were compared with the mean of the observations derived from all 57 inventory plots of the Babia hora forest. Thus, we obtained mean differences (modeled versus observed means) and their standard error.

The calculated differences and their variability were interpolated using spatial interpolation techniques across the range of the minimum and maximum mortality rates. Nearest neighbor techniques were applied, which take into account a specific number of nearest points. In our case, the number of the nearest neighbors was set to 6 and the power, i.e. the exponent of the distance that controls the significance of the influence of surrounding points on the value given to the cell that is being analyzed, was set to 3.

Error graphs for all of the examined parameters were produced and the differences between the simulated and the observed mean values were tested using a paired t-test to specify the areas where differences are not significant at 95 % confidence level (Figure 2).

The graphs of the individual parameters (Figures 2A to 2C) provide the areas where the examined parameters (i) stem carbon, (ii) coarse woody debris, and (iii) soil carbon, at a given range of minimum and maximum mortality exhibited no significant difference between predicted versus observed values (Figure 3). The black areas in Figure 3 exhibit the range in which the calibrated mortality model produces unbiased and consistent estimates of stem carbon, coarse woody debris and soil carbon content.

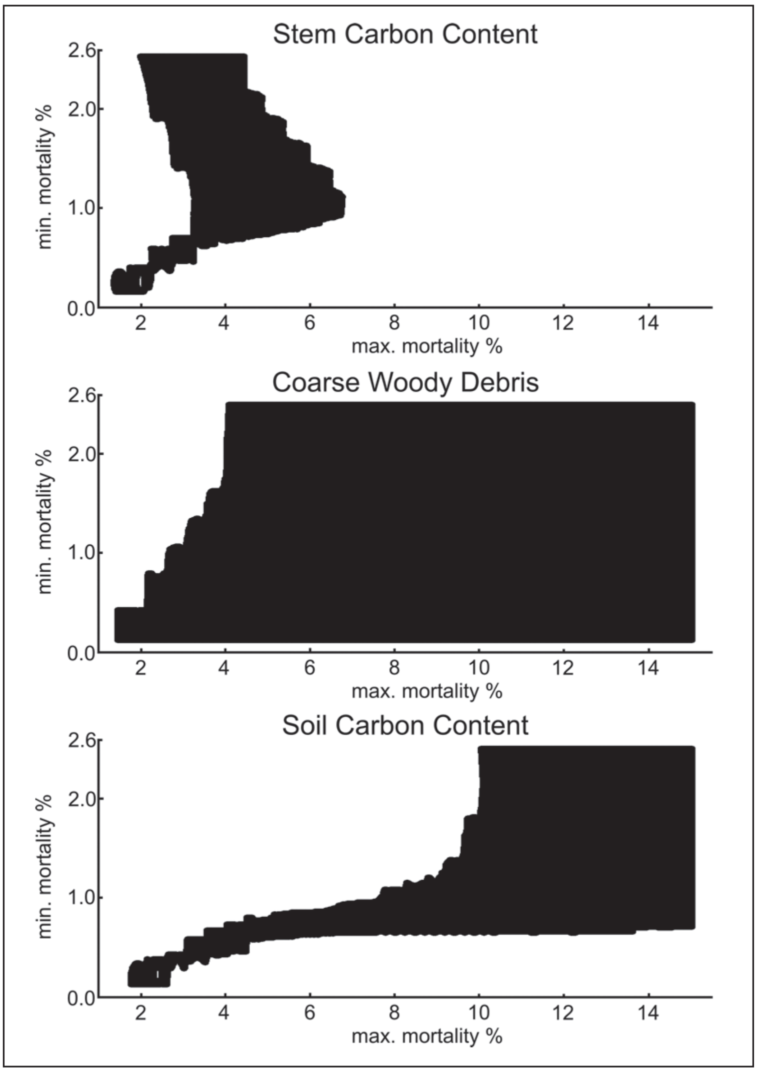

Figure 2: Examination of model performance over the range of examined combinations of minimum and maximum mortality rates. Black areas represent differences not significant at CI 95% between simulated and observed values of carbon content in three different carbon pools (stem, coarse woody debris, soil).

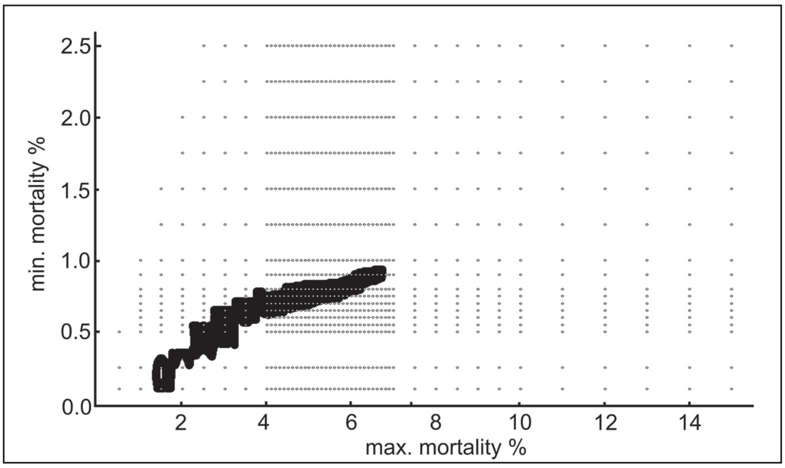

Figure 3: Specification of the area where the simulated results of all assessed carbon pools were not significantly different from observations (CI 95%). Black area represents the overlap of the insignificant areas of all assessed carbon pools (carbon in stem, coarse woody debris, and soil). The circles represent the combinations of minimum and maximum mortality, which were simulated with the model.

Table 3: Validation results of the mortality module in BIOME-BGC for the virgin forest of Babia hora. Differences represent the deviations of the model from the observations. N is the number of simulations for each mortality combination (57 plots x 30 Monte Carlo simulations per plot).

Annual mortality rate %		N	Carbon in stem [kg.m-2]		Carbon in deadwood [kg.m^{-2}]		Carbon in soil [kg.m^{-2}]	
Max.	Min.		Mean difference	Standard error	Mean difference	Standard error	Mean difference	Standard error
4.8	0.7	1710	1.18	0.22 **	-0.05	0.11	-0.25	0.12 **
5.9	0.75	1710	0.79	0.22 **	0.07	0.11	0.16	0.11 *
6	0.75	1710	0.73	0.22 **	0.06	0.11	0.13	0.11 *
5.8	0.75	1710	0.86	0.22 **	0.08	0.11	0.19	0.11 *
5.9	0.73	1710	0.59	0.22 **	-0.03	0.11	-0.19	0.11 *
5.9	0.74	1710	0.48	0.23 **	0.02	0.11	-0.02	0.11
6	**0.74**	**1710**	**0.42**	**0.23 ****	**0.01**	**0.11**	**-0.05**	**0.11**

4.2. Model evaluation

While for model calibration only two plots were used (the plot with the highest and the plot with the lowest carbon content accumulated in vegetation), we next evaluated the mortality model settings using all 57 plots by applying all valid mortality variants specified in the calibration process. Similarly as in the calibration process, the plots were simulated using the Monte Carlo approach, i.e. each plot was simulated 30 times with a random start within the 300-year cycle. This resulted in 1,710 simulations for each mortality combination (57 plots x 30 Monte Carlo simulations per plot).

The simulated results covering the stem carbon, coarse woody debris, and soil carbon component were compared with the corresponding observations. The results revealed that only a small number of mortality variants produced unbiased (non-significant differences between predicted and observed values) and consistent estimates.

Figure 4:

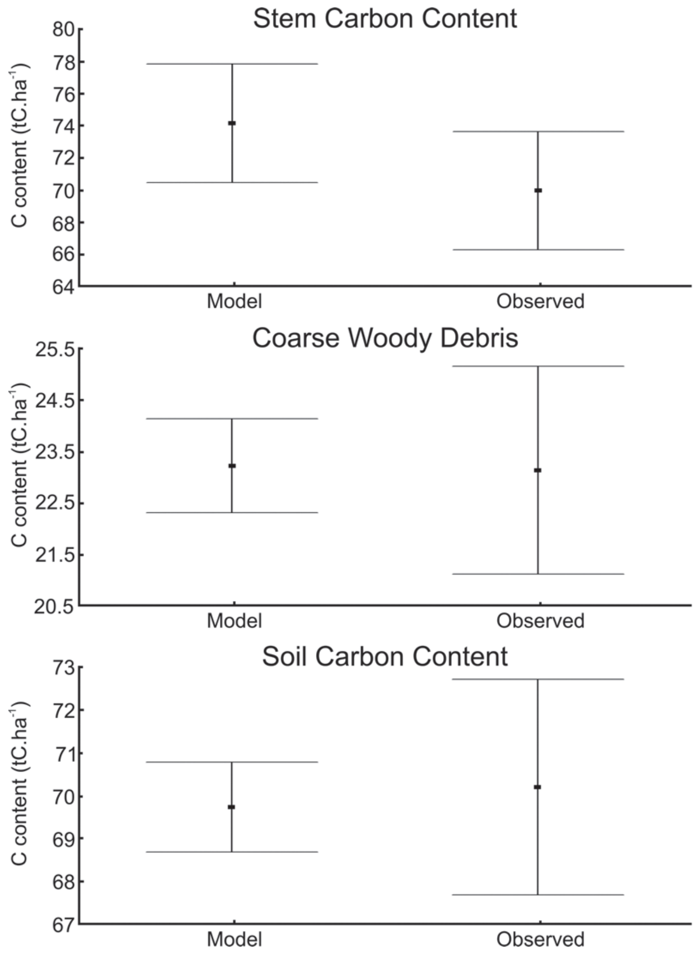

Figure 4: Simulated and observed carbon content in stem biomass, coarse woody debris and soil in tC.ha-1. Simulated carbon content represents model results obtained with the dynamic mortality cycle 300 years long, 225 years of low mortality phase, minimum and maximum annual whole-plant mortality rates 0.74% and 6.0%, respectively. Average and variability of simulated results were obtained from all plots, while each plot was simulated 30-times with random end within one developmental cycle.

The variant with minimum and maximum mortality rates equal to 0.74 % and 6.0 % per year, respectively, (Table 3, Figure 4) exhibited the best results for all three considered parameters: (i) stem carbon, (ii) carbon in coarse woody debris and (iii) soil carbon. Consequently this variant was taken as the correct combination for addressing the mosaic different stages of the Babia hora virgin forest.

4.3. The carbon flux dynamics of the Babia hora virgin forest

Based on our previous findings the ecosystem model BIOME-BGC allows us to conceptually mimic the carbon flux dynamics. Thus we were next interested in examining the carbon fluxes for the virgin forest Babia hora across the whole successional cycle. Figure 5 gives the mean development of the (i) stem carbon content, (ii) the coarse woody debris, and (iii) soil together with (iv) annual natural mortality rate, plus (v) net primary production (NPP), (vi) heterotrophic respiration (Rh), and (vii) the net ecosystem exchange (NEE) using the minimum mortality rate of 0.74 % and the maximum mortality of 6.0 %.

Carbon content in stems may be seen as an equivalent to "stand volume". At the beginning of the developmental cycle, it increases steadily indicating that a large proportion of NPP is allocated to stem growth. The stem carbon reaches its maximum when NPP equals heterotrophic respiration, i.e. when NEE is zero (Figure 5). After this point, the stem carbon content decreases until the second transition point. The second transition point of the stem carbon cycle is given when NPP again equals Rh (heterotrophic respiration) (see Figure 5). In the period between the first and the second transition, i.e. for about 100 years, the stand acts as carbon source, because Rh exceeds NPP, while in the remaining part of the developmental cycle the forest acts as carbon sink (Figure 5).

5. Discussion

Our analysis revealed that for Babia hora virgin forest the only appropriate variant producing insignificant differences between predictions and observations for the three analysed variables, i.e. carbon content in stems, coarse woody debris, and soil is the combination of 0.74 % minimum and 6.0% maximum mortality rates. The maximum mortality rate is the same as that found for the Rothwald virgin forest in Austria (Pietsch and Hasenauer 2006). Minimum mortality rates differ between the two regions; in Rothwald 0.9 % was found to be the suitable value versus 0.74 % in Babia hora. We presume that the difference in minimum mortality rates is due to the differences in tree species composition in the two regions. While Babia hora is a pure spruce forest, Rothwald is a mixed forest with a predominance of beech, for which the model was parameterised. Hence, beech seems to have a higher minimum mortality rate than spruce.

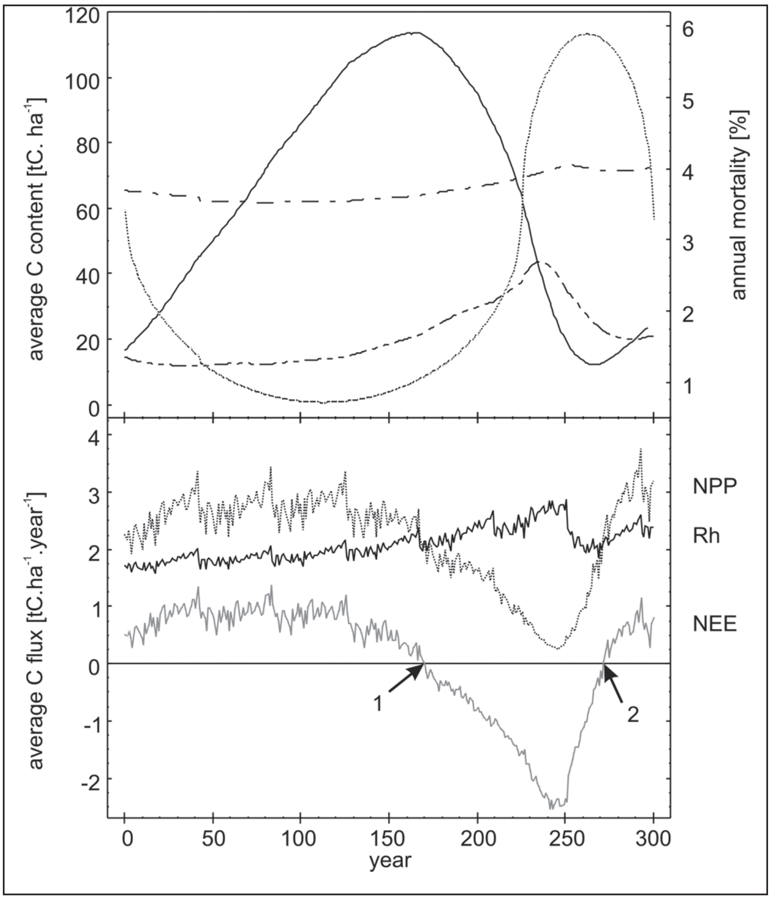

Figure 5: Temporal development of simulated output over the whole developmental cycle Top: carbon content in stem (——), coarse woody debris (— - —), soil (— - - —), and annual regular mortality rate (--------). Bottom: Net primary production (NPP), heterotrophic respiration (Rh), net ecosystem exchange (NEE), numbers 1 and 2 indicate 1st and 2nd transition points, respectively. Dynamic mortality cycle settings: cycle length 300 years, 225 years of low mortality phase, minimum and maximum annual whole-plant mortality rates 0.74 % and 6.0 %, respectively.

Our work showed that multidimensional spatial error analysis supported by GIS tools as applied here is an appropriate tool for model calibration. It is an objective approach based on statistical testing of differences between the model and observations. Here we applied the tests of the significance of sample means of differences between the predictions and observations, which are known to have a normal frequency distribution (Snedecor and Cochran 1980). As Maronna et al. (2006) points out, in the case the assumption of normality holds, classical statistics has a better statistical performance than robust statistics..

While model evaluation revealed only one appropriate variant of mortality rates for Babia hora (Table 3), the results of the model calibration detected more possible combinations of minimum and maximum mortality rates (Figure 3). This is in contrast to Pietsch and Hasenauer (2006) who found only one appropriate variant of mortality when calibrating the model for Rothwald forest. This might result from a different approach of analysing the differences between the model and the observations, when Pietsch and Hasenauer (2006) pre-defined the categories of relative differences (33, 67, 100, 133 %, etc.), while here we applied statistical t-test to examine the significance of the differences between the model and the observations.

The assessment of the simulated developmental cycle was based on the temporal performance of carbon pools and fluxes over the whole cycle (Figure 5). The carbon fluxes of the examined parameters followed a biological pattern over the whole cycle. The performance of carbon content in stem, which is an equivalent to stand volume, coincides with the curves of stand volume hypothesised and presented by e.g. Korpel' (1995) for virgin forests of Central Europe following a small developmental cycle. From Figure 5 we can see that a mountainous spruce forests acts as a carbon sink during two thirds of its developmental cycle, and only in one third it acts as a carbon source.

The comparison of the modeled results of the two virgin forests revealed that all analysed carbon pools and fluxes follow the same trajectory in both virgin forests. The curves of carbon content in stem, coarse woody debris and soil are shifted upwards in Rothwald in comparison to Babia hora, because Rothwald forest is more productive than Babia hora (stand volume is 559 $m^3.ha^{-1}$ versus 313 $m^3.ha^{-1}$). This is also documented by the performance of NPP, NEE and Rh (Figure 5), which reach greater maximum values in Rothwald than in Babia hora. The differences in absolute values of the examined variables reflect the differences in species composition as well as in site conditions of the two forests. Babia hora is situated further on the north at higher elevations and has a cooler climate. The soils in Babia hora are shallower with a greater proportion of sand.

6. Conclusion

The self-initialisation procedure with the dynamic mortality model incorporated in the species specific version of BIOME-BGC (Pietsch et al.2005, Pietsch and Hasenauer 2006) produces unbiased and consistent estimates of an equilibrium that can be observed in virgin forestsope. Multidimensional spatial error analysis based on the assessment variables covering a large range of input criteria is an appropriate approach for calibrating the dynamic mortality model which is required to mimic the successional dynamics of old growth forest ecosystems. The assessment of the temporal performance of carbon fluxes across a full developmental cycle revealed that the BGC model is capable of simulating the dynamic developmental cycle of virgin forests in Central Europe.

Acknowledgements:

This work was performed during the Short Term Scientific Mission 04966 of COST Action FP0603 at University of Natural Resources and Applied Life Sciences (BOKU) Vienna, Austria. We thank the Slovak Hydrometeorological Institute for providing us with climate data, Stephan Pietsch and Chris Eastaugh for their helpful comments.

References

Bugmann, H. 2001. A review of forest gap models. Climate Change. 51: 259-305.

Bütler, R., Patty, L., Le Bayon, R.-C., Guenat, C., and R. Schlaepfer. 2007. Log decay of Picea abies in the Swiss Jura Mountains of central Europe. Forest Ecology and Management 242: 791–799.

Field, C. B., and J. Kaduk. 2004. The carbon balance of an old-growth forest: building across approaches. Ecosystems 7: 525-533.

Hasenauer, H., Merganicová, K., and S.A. Pietsch. 2005. Modeling biogeochemical cycles within old-growth forest ecosystems. Forest Snow Landscape Research 79 (1/2): 81-90.

Holeksa, J. 2001. Coarse woody debris in a Carpathian subalpine spruce forest. Forstwissenschaftliches Centralblatt 120: 256-270.

IPCC. 1996. Technical Summary. In: Houghton J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and K. Maskell (eds.): Climate change 1995 – the science of climate change: contribution of the working group I to the second assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge. pp. 9-50.

Korpel', Š. 1995. Die Urwälder der Westkarpaten. G. Fischer, Stuttgart. 310pp.

Križová, E., Kropil, R., Caboun, V., and R. Midriak. 1992. Všeobecná ekológia. TU Zvolen. 180pp.

Maronna, R. A., Martin, R. D., and V. J. Yohai. 2006. Robust Statistics: Theory and Methods. John Wiley & Sons, Ltd. 403pp.

Merganic, J., Vorcák, J., Merganicová, K., Durský, J., Miková, A., Škvarenina, J., Tucek, J., and J. Mind'áš. 2003. Diversity monitoring in mountain forests of Eastern Orava. EFRA, Tvrdošín: 200pp. (in Slovak). Available at http://www.forim.sk/index_soubory/Merganic_Vorcak_Merganicova_Dursky_Mikova_Skvarenina_Tucek_Mindas_2003.pdf (Accessed June 20, 2011)

Merganicová, K. 2004. Modelling forest dynamics in virgin and managed forest stands, PhD. thesis, University of Natural Resources and Applied Life Sciences Vienna: 155pp.

Merganicová, K., and J. Merganic. 2010. Coarse woody debris carbon stocks in natural Spruce forests of Babia hora. Journal of Forest Science, 56 (9): 397-405.

Morelli, S., Paletto, A., and V. Tosi. 2007. Deadwood in forest stands: assessment of wood basic density in some tree species, Trentino, Italy.Forest@ 4(4): 395-406.

Odum, E. P. 1953. Fundamentals of ecology. Philadelphia: Saunders 384pp.

Odum, E. P. 1969. The strategy of ecosystem development. Science 164: 262-270.

Percy, K. E., Jandl, R., Hall, J. P., and M. Lavigne. 2003. The role of forests in carbon cycles, sequestration, and storage. Forests and the global carbon cycle: Sources and sinks. IUFRO Task Force on "The Role of Forests in Carbon Cycles, Sequestration and Storage". Issue 1: 5pp. Available at: www.iufro.org/download/file/1626/3754/issue1_march31.pdf (Accessed June 20, 2011)

Petráš, R. 1986. Mathematical model of stem shape. Lesnícky casopis 32(3): 223-236 (in Slovak).

Petráš, R. 1989. Mathematical model of stem shape of coniferous tree species. Lesnictví, 35(10): 867-878 (in Slovak).

Petráš, R. 1990. Mathematical model of stem shape of broadleaved tree species. Lesnícky casopis, 36(3): 231-241 (in Slovak).

Pietsch, S. A., and H. Hasenauer. 2002. Using mechanistic modeling within forest ecosystem restoration. Forest Ecol. and Manage. 159: 111-131.

Pietsch, S. A., Hasenauer H., and P.E. Thornton. 2005. BGC-model parameter sets for central European forest stands. Forest Ecology and Management 211: 264-295.

Pietsch, S. A., Hasenauer H., Kucera J., and J. Cermák. 2003. Modelling effects of hydrological changes on the carbon and nitrogen balance of oak in floodplains. Tree Physiology 23: 735-746.

Pietsch, S.A., and H. Hasenauer. 2006. Evaluating the self-initialisation procedure of large scale ecosystem models. Global Change Biology 12: 1658-1669.

Remmert, H. 1991. The mosaic-cycle concept of ecosystems. Springer Verlag, Berlin. Ecological Studies 85.

Running, S.W., Nemani, R.R., and R.D. Hungerford. 1987. Extrapolation of synoptic meteorological data in mountainous terrain and itsuse for simulating forest evapotranspiration and photosynthesis. Can. J. For. Res. 17: 472-483.

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan J, Levis S, Lucht W, Sykes M, Thonicke K, Venevski S (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model. Global Change Biology 9: 161-185.

Snedecor, G. W., and W. G. Cochran. 1980. Statistical methods. 7th edition. The Iowa State University Press, Ames, Iowa. 507pp.

Suchanek, T. H., Mooney, H. A., Franklin, J. F., Gucinski, H., and S. L. Ustin. 2004. Carbon dynamics of an old-growth forest. Ecosystems 7: 421-426.

Thornton, P.E. 1998. Description of a numerical simulation model for predicting the dynamics of energy, water, carbon and nitrogen in a terrestrial ecosystem. PhD. thesis. University of Montana, Missoula, MT. 280pp.

Vacek, S. 2003. Minimum area of forests left to spontaneous development in protected areas. Journal of Forest Science 49(8): 349-358.

Weiss, P., Schieler, K., Schadauer, K., Radunsky, K., and M. Englisch. 2000. Die Kohlenstoffbilanz des österreichischen Waldes und Betrachtungen zum Kyoto-Protokol. Federal Environment Agency, Wien, Monographie 106: 94pp.

White, M.A., Thornton, P.E., Running, S.W., and R.R. Nemani. 2000. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: Net primary production controls. Earth Interactions 4 (3): 1-85.