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Modeling Afforestation and the Underlying Uncertainties

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Abstract A dynamic model of the carbon budget of an oak forest ecosystem that takes into account forest stand age was developed. A numerical experiment was designed to simulate the afforestation process, and a Monte Carlo simulation was performed to determine how parameter uncertainties and environmental variability influence the result. It was found that while the total amount of carbon stored in the ecosystem increases from 1.9 kg C/m^2 to 4.4 kg C/m^2 over the following 20 years, the relative standard deviation increases from 9 to 21%. The contribution of varying climate and carbon dioxide parameters to total uncertainty is substantial; for example, the standard deviation at the 10th modeling year for phytomass doubles and the uncertainties of the soil pool and total accumulated carbon increase by a factor of nearly 1.4, while the uncertainty of the litter pool stays almost at the same level.

Keywords afforestation · mathematical model · Monte Carlo simulation · uncertainty estimation

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1 Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change commits most developed countries to reducing their greenhouse gas emissions. The Protocol also defines some "legal" means that can be used by countries to reach the required emission levels, one of these being afforestation (the planting of forests on land where forests have not grown for the last 50 years); afforestation is a "natural" way of trapping the atmospheric carbon dioxide (CO_2) in long-living phytomass, detritus, and humus. Countries can use the carbon credits accumulated through afforestation activities (1) to fulfill their obligations under the Kyoto Protocol; and (2) to participate in the market-based mechanisms created under the Protocol (i.e., international emissions trading, joint implementation, and the clean development mechanism).

The uncertainty regarding emission estimates plays an important role in emissions trading (see, in particular, Bartoszczuk & Horabik, 2007; Monni, Syri, Pipatti, & Savolainen, 2007; Nahorski, Horabik, & Jonas, 2007). While, in emissions trading between EU15 members, land use change and forestry do not influence total uncertainty (Monni et al., 2007), for some countries the effects of afforestation, reforestation, and deforestation can be considerable.

When developing an afforestation project, it is important to estimate the amount of carbon that can be accumulated in the ecosystem during a given period

of time, bearing in mind the uncertainty of the estimates and the risk of not achieving the desired result. The point is that the forest will grow in a changing environment. Prognostic modeling can help in obtaining a first guess as to the values of accumulated carbon and will demonstrate not only the uncertainties and risks but also the influence of environmental variability.

To account for forest stand age, we propose the use of a dynamic mathematical model of the carbon budget of an oak forest ecosystem (discussed in Gusti, Bun, Dachuk, & Shpakivska, 2004), which incorporates growth functions (Shvidenko, Venevsky, Raile, & Nilsson, 1996) and regression expressions (Lakida, Nilsson, & Shvidenko, 1996). To describe phenology, a function of the monthly mean temperature is developed. To estimate the available water in the ecosystem, a simple mathematical model, which accounts for the effects of frozen water accumulation in winter and the thawing of ice in spring, is elaborated. The uncertainties of the model parameters (including temperature, precipitation, and atmospheric carbon dioxide) are modeled with random generators.

The study is illustrative, as information about the model parameters is incomplete; thus, uncertainty classes of 10% and 20% of the relative standard deviation, as well as assumptions on probability distribution types (normal or uniform), were introduced. However, many other factors influencing the forest carbon budget (e.g., insects and fires) were not taken into account.

2 Description of the Model and Experiment

2.1 Description of the Model

In the mathematical model of the carbon budget of an oak forest the following carbon pools are considered: phytomass (leaves, distinguished using a regression expression), litter (five reservoirs: foliage, stems, branches, coarse roots, and fine roots), and soil organic matter. The following carbon flows are also considered: atmosphere–phytomass, phytomass–litter (litter sorted into five types using regression expressions), litter–atmosphere, litter–soil, soil–atmosphere, and phytomass–boundary of the ecosystem (harvested phytomass).

The mathematical model of the carbon budget is presented in the form of a system of ordinary differential equations of the first order:

$$\frac{dX_{ph}}{dt} = v_{ap} - \left(v_{plf} + v_{pls} + v_{plb} + v_{plcr} + v_{plfr} + v_{ph}\right),$$
$$\frac{dX_{lf}}{dt} = v_{plf} + v_{hlf} - \left(v_{lfa} + v_{lfs}\right),$$
$$\frac{dX_{ls}}{dt} = v_{pls} + v_{hlb} - \left(v_{lsa} + v_{lss}\right),$$
$$\frac{dX_{lb}}{dt} = v_{pbl} + v_{hlb} - \left(v_{lba} + v_{lbs}\right),$$
$$\frac{dX_{lcr}}{dt} = v_{plcr} + v_{hlcr} - \left(v_{lcra} + v_{lcrs}\right),$$
$$\frac{dX_{lfr}}{dt} = v_{plfr} + v_{hlfr} - \left(v_{lfra} + v_{lfrs}\right),$$
$$\frac{dX_{s}}{dt} = v_{lfs} + v_{lss} + v_{lbs} + v_{lcrs} + v_{lfrs} - \left(v_{sa} + v_{saq}\right),$$

where X with subscripts denotes carbon pools (kg C/m^2; *ph* is phytomass, *lf* is foliage litter, *ls* is stem and branch litter (diameter >10 cm), *lb* is branch litter (diameter <10 cm), *lcr* is coarse root litter, *lfr* is fine root litter), and v with subscripts denotes carbon flows between corresponding reservoirs (kg C/(m^{2}year)), for example, *ap* is atmosphere–phytomass, *plf* is phytomass–foliage litter, *ph* is phytomass–harvested phytomass, and *saq* is soil–aquatic system.

Intensity of net photosynthesis (the v_{ap} flow) is presented with a complex function:

$$v_{ap} = \alpha_{ap} {*} F_l {*} \min\left\{F_f, F_c, F_w\right\},$$

where α_{ap} is the calibration coefficient, F_l is the function of the mass of leaves, which, in turn, is a function of forest stand age (A, years), F_T is dependence on the monthly air temperature (T, °C), F_c is dependence on the monthly concentration of atmospheric CO_2 (C, ppmv), and F_w is dependence on the monthly amount of available water (W_a, kg/m^2).

Let us now consider the main functions. The mass of leaves (denoted as *f*) is defined with a regression equation (see Equation for R below), but the time at which leaves appear in oak forests is controlled by the air temperature (T_{lg}, °C). The process is described with the expression:

$$F_l = \frac{1}{1 + \exp\left(0.9{*}\left(-T + T_{\lg}\right)\right)} {*} \frac{R_f {*} X_{ph}}{R_{tot}}.$$

The functions F_T, F_c, and F_w are defined in Gusti (2002). The optimal temperature for photosynthesis is chosen to