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Future carbon cycle in mountain spruce forests of Central Europe: Modelling framework and ecological inferences

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ABSTRACT

Although mountain Norway spruce forests may act as powerful carbon (C) sinks, the complexity of climate change effects on their C cycle remains unclear. In the current study, we combined the simulations produced by the process-based model Biome-BGC and the empirical model SIBYLA in order to predict the future C cycle in the spruce-dominated mountain forest stand in Central Europe. Annual data for tree height and diameter from 1997–2010 were used for models calibration. Observed climate data from 1939–2009 were transiently coupled with four climate change scenarios for the period 2010–2100. For the assessment of climate change effects, stable reference climate data were generated for 2010–2100. Because future forest mortality can follow different trajectories, Biome-BGC was run with three plausible mortality assumptions. Factorial Analysis of Variance based on Generalized Linear Models was used to dissect the total variability of produced estimates and to determine which factors explained most of the variability in the projected C pools and fluxes. Climate change was found to increase the total amount of C accumulated by ca. 3% in 2021–2050 and by 13% in 2071–2100 as compared with the reference climate. While the most likely increase was 12% for aboveground C and 6% for belowground by 2100, deadwood C remained relatively stable during the simulation period. By 2100, net ecosystem exchange was projected to increase by ca. 28%, indicating an increase in the ecosystem's capacity to accumulate C. Substantial proportions of the variability in all pools and fluxes were explained by mortality assumption and model selection but not by climate change scenario. Given the divergent outputs obtained in the current study and in other studies, we argue that C cycle simulations and inferences should not be based on any single model but rather on the integration of multiple models with complex simulation design. The performed variability decomposition stressed the importance of future forest mortality in forest C cycle modelling as well as the fact that climate change-driven scenarios of forest mortality have not been developed and used in C cycle simulations so far. Strong effect of mortality assumptions on the evaluated C cycle underscores the increasing importance of forest protection under climate change as well as the importance of silvicultural interventions to reduce stand susceptibility to damage. Low variability of the simulated values up to stand age 100 years implies that the proposed approach may provide useful support to management decisions mainly in stands where a rotation period up to 100 years is applied.
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1. Introduction

Available observations show that climate change has already affected a range of physical and biological systems around the world (Grimm et al., 2013; Hanewinkel et al., 2012). Our understanding of the effects of climate change on ecosystems, however, is limited for

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Central Europe, even though the forests in this region may be particularly susceptible to climate change because of diverse non-climatic stressors such as the persisting effects of former air pollution (Badea et al., 2004; Hédl et al., 2011), improper management, and man-altered species composition over large areas (Hlásny and Sitková, 2010; Hlásny and Turčáni, 2013). The presence of the xeric distributional limits for several zonal tree species suggests that climate change could result in reduced production and even in the retraction of species distribution (Czúcz et al., 2011; Jump et al., 2009), which has been corroborated by recent observations (Mátyás et al., 2010). Moreover, the lower performance of some transitional economies along with the frequent perception of forests as of sources of quick profit reduce the potential for effective forest adaptation (Hlásny et al., 2014; Merganičová et al., 2013). The climate in Central Europe is projected to change substantially (e.g., Seneviratne et al., 2006; Vautard et al., 2014), with potentially adverse effects on natural resources and societies (e.g. Kirilenko and Sedjo, 2007; Hanewinkel et al., 2012). Although a recent study by Diffenbaugh and Giorgi (2012) did not emphasize this region, Central and Eastern Europe were found to be surrounded by three of the most prominent climate-change hot spots in the world (Giorgi, 2006). These facts imply that Central European forests need to be thought of as highly vulnerable to climate change, though this fact has not received adequate attention so far (but see for example Hlásny et al., 2011a; Tatarinov and Cienciala, 2009).

Recently, a range of modelling exercises has been performed to describe future forest development under projected climate change (Hlásny et al., 2011a; Matala et al., 2005; Ťupek et al., 2010), and these projections have included changes in the forest carbon (C) cycle (Eggers et al., 2008; Rötzer et al., 2009; Tatarinov and Cienciala, 2009; Zierl and Bugmann, 2007). Some modelling studies aimed at understanding how forest management could be altered to optimize C sequestration and forest production (Lindner, 2000; Seidl et al., 2008; Tatarinov et al., 2011). Both empirical and process-based approaches to forest modelling have been broadly used, and evaluation of the performance of various models has been repeatedly addressed (Hanson et al., 2004; Huber et al., 2013). While empirical models provide evidence of statistical association between forest growth and climate, they only hint at possible biological mechanisms (Arbaugh and Peterson, 1989; Foster and LeBlanc, 1993). Process-based models, in contrast, attempt to predict forest development by describing the response of processes to external driving variables and interactions between processes (Landsberg, 2003). Because the models have generated quite divergent results (Draper, 1995; Huber et al., 2013; Pilkey and Pilkey-Jarvis, 2007), multi-model inference, i.e., the assessment of desired quantities using several models, should be recognized as a useful approach in forest modelling. Multi-model inference is a robust method that circumvents the problem of overly optimistic predictive or inferential uncertainty by improving the representation of model structure uncertainty (Valle et al., 2009). However, this approach has seldom been used for supporting the management of forests and other natural resources. Another approach that increases the robustness and accuracy of simulations is model hybridisation (Girardin et al., 2008; Snowdon, 2001), which focuses on the exchange of some quantities, parameters, or algorithms among models to compensate for the weaknesses in some models and to benefit from the strengths in other models. The available studies that have used multiple models, however, have mostly focused on comparing and evaluating models (Hanson et al., 2004; Huber et al., 2013; Matala et al., 2003; Seidl et al., 2008) rather than on producing robust multi-model estimates (but see Wamelink et al., 2009).

The current study focuses on Norway spruce (*Picea abies* L Karst), an important component of European mountain forests with a long tradition of use for timber production and for the maintaining of biological diversity (Gömöry et al., 2011; Svoboda et al., 2010). In contrast to ecosystems at low-to-medium elevations, mountain forests may benefit from the projected increase in air temperature, the prolonged vegetation season, and the reduced period with frozen soil, which are among the main limits for vegetation growth in higher elevations and latitudes (Bonan and Shugart, 1989; Bergh and Linder, 1999; Jarvis and Linder, 2000). These effects can be further amplified by increases in atmospheric CO_2, which stimulate growth and biomass increment (Leakey et al., 2009); processes related to species acclimation to increasing CO_2 level, however, have not yet been sufficiently explored (Chen and Zhuang, 2013; Smith and Dukes, 2013). At the same time, climate change may also result in an increased rate of heterotrophic respiration and thus increased C emission from dead biomass, litter, and soil (Burke et al., 2003; Conant et al., 2011) as well as more frequent episodic releases of C due to forest disturbances (e.g. Kurz et al., 2008). Such complex responses indicate that an assessment of the future forest C cycle should use ecosystem models featuring diverse nonlinear relationships and feedback effects (Kurbatova et al., 2008).

In view of the importance of European forests in the global C cycle (Kauppi et al., 1992; Nabuurs et al., 1997, 2013), we strive to develop a dependable modelling framework that is suitable for the temperate Central European forests, a region for which little is known about how climate change is likely to affect the forest C cycle (but see Hlásny et al., 2011a; Tatarinov et al., 2011; Tatarinov and Cienciala, 2009). We demonstrate the utility of the proposed approach by describing the future development of the main C pools and fluxes of the Norway spruce stand in the mountains of Central Europe. Finally, we consider the benefits and limits of such an approach for forest management.

In this study, we set out to test the hypotheses (i) that sequestration capacity of spruce forests will increase in the future and (ii) that an increase in gross primary production of mountain forests will compensate for increased ecosystem respiration rate driven by projected increase in air temperature. We show that the comprehensive modelling design is capable of generating robust and reliable descriptions of future forest C cycle, when compared to single-model and single-scenario-based estimates. The frequent divergence in outputs of the latter type of simulation designs can be found limiting the support to forest management and decision making.

2. Materials and methods

2.1. Investigated forest plot

The simulations were performed on data from a forest plot located in the High Tatras Mts. (plot ID 54-203, name "Jasenie", 48.9253N, 19.4875E, 1222 m a.s.l, 0.25 ha), which has been operated within the European intensive forest monitoring programme since 1997. The plot is located in the present ecological optimum of spruce and is representative of unmanaged mountain spruce forests in Central Europe. Based on data from 1961–1990, the mean annual air temperature at the plot is 3.2 °C, and mean annual precipitation is 870 mm.

The soil type is cambisol (Cambic Umbrisols Humic Endoskeletic, WRB, 2006) with depth of approximately 60 cm. The approximate content of gravel and other coarse fragments is 25% in the topsoil and 45% in the subsoil. The topsoil contains 57% sand, 33% silt, and 10% clay (Pavlenda et al., 2012).

The plot was established in 1939 following a clearcut or windstorm, and in 2012 contained a total of 177 spruce trees with a mean age of 73 years (standard deviation 2.6 years). Maple (*Acer pseudoplatanus* L.) (7 trees), beech (*Fagus sylvatica* L.) (8 trees), fir (*Abies alba* Mill.) (1 tree), and mountain ash (*Sorbus aucuparia* L.) (1 tree) were also growing in the plot in 2012. Because the plot lies in the zone that has been under a high conservation regime since 1949, no management has been applied, and dead trees have been

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