



Carbon pools in a montane old-growth Norway spruce ecosystem in Bohemian Forest: Effects of stand age and elevation



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ABSTRACT

Good understanding of forest productivity and carbon (C) storage capacity is essential for better understanding of C dynamics and climate modeling. Studies of old-growth forest C dynamics from central and eastern Europe are rare and the few remaining pristine forests represent a unique opportunity to study natural forest dynamics in an otherwise managed landscape. We studied protected old-growth Norway spruce (*Picea abies* L.) stands in the Bohemian Forest, Czech Republic, to explore total ecosystem C pool (live and dead biomass and soil) variability in forest ecosystem as a function of stand age and elevation. These old-growth forest ecosystems store very high amounts of C, up to 570 t C ha⁻¹, and 393 t C ha⁻¹ on average. Live biomass is the dominant C pool followed by mineral soil, forest floor and dead biomass. We found that total C significantly decreased with increasing elevation (1025–1338 m a.s.l.) from 456 to 294 t C ha⁻¹, predominantly driven by decreases in live biomass and forest floor C pools. Significant changes take place in individual pools based on age and elevation gradients, but total C was not significantly different between stands age 116–145 years. Contrary to some recent findings that old-growth forest ecosystems continue to sequester C long after maturity, our data supports the hypothesis that old-growth forests reach a steady state and become C neutral. They accumulate same amount of C through photosynthesis than is lost by decay and leaching. This study provides a detailed overview of C pools of old-growth Bohemian Forests and highlights the importance of including all major C pools in forest ecosystem C studies.

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1. Introduction

Forest ecosystems are well-known for their large carbon (C) storage capacity and they play an important role in global carbon (C) cycle (Pregitzer and Euskirchen, 2004; Yang et al., 2011). Estimates of forest C stocks provide valuable data to improve characterization of forest C dynamics (Keith et al., 2009) and assist in the parameterization and validation of C accounting models for modeling C fluxes through soil–vegetation–atmosphere systems. Such models represent a valuable tool used to predict atmosphere–biosphere interactions and CO₂ effects on climate (Krinner et al., 2005; Kull et al., 2011). However, data from some forest ecosystems is rare, hampering accurate modeling. For example, only a few C stock estimations exist from central and eastern European natural montane forest ecosystems (Etzold et al., 2011; Jacob et al., 2013).

A central focus in forest ecology research is the productivity of old-growth forests (Luyssaert et al., 2008), particularly whether

old-growth forests sequester C and what factors influence forest ecosystem productivity. This knowledge is highly relevant in terms of identifying climate change mitigation potential of forest ecosystems. Historically it was thought that after reaching a maximum, forest productivity declines (Kira and Shidei, 1967; Odum, 1969). However, recent evidence from different forest ecosystems suggests that forests continue to accumulate C for centuries (Kashian et al., 2013; Luyssaert et al., 2008; Tan et al., 2011). Controversially, some recent studies have found a declining productivity in old-growth forests (Taylor et al., 2014). It is evident that more data is required to better understand old-growth forest productivity and C storage potential, particularly because different forest ecosystems have inherently different productivity dynamics and a common trend between forest ecosystems might not exist.

Due to a long history of human land use, natural forest ecosystems are rare and continually threatened in central and eastern Europe (Gibson et al., 2011; Knorn et al., 2013). The few remaining areas of protected forests provide a unique opportunity to study the dynamics and functioning of a natural old-growth forest. Knowledge of old-growth forest dynamics is useful because it

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provides the possibility to estimate the state of managed forest relative to un-managed natural forests. Based on old-growth forest studies, good close-to-nature management practices can be developed.

Elevation gradients provide a good opportunity to study the effects of changing environmental conditions on forest ecosystems (Körner, 2007). Physical changes linked to elevation (e.g. temperature and atmospheric pressure) and changing environmental conditions that are not generally due to elevation (e.g. moisture, wind, hours of sunshine) influence process rates and forest dynamics (Körner, 2007). Forest growth generally slows, vegetation biomass declines and dead biomass increases with increasing elevation as environmental conditions change (e.g. Barrera et al., 2000). This also results in a decline in forest productivity (Körner, 2003).

Much emphasis in forest disturbance research has been given to stand replacing disturbances (Magnani et al., 2007). Knowledge of moderate severity disturbances (e.g. non stand replacing windthrow and beetle outbreaks), that are very common in montane forests of the temperate zone, is limited (Svoboda et al., 2012). These forests have a diverse age and stand structure compared to more even age stands originating from stand replacing disturbances (e.g. fire and clearcuts). Understanding of forest ecosystem C dynamics in moderate severity disturbance regimes is limited.

Carbon in forest ecosystems is distributed between four distinct pools: live biomass, dead biomass, forest floor, and mineral soil (Seedre et al., 2011). The dynamics of each C pool differs during forest development stages and subsequently their share of total ecosystem C varies. Although many studies focus on C pool dynamics, often not all relevant C pools are studied. Although live tree roots are commonly measured, mass of roots of dead trees are rarely estimated. Also, soil C is typically measured to a fixed depth (e.g. 30 or 60 cm) (Jacob et al., 2013; Prietzel and Christophel, 2014) introducing a large uncertainty, particularly as soil C pool is highly dependent on soil depth (Harrison et al., 2011; Jobbager and Jackson, 2000; Zabowski et al., 2011). Overall, studies that include estimations of total ecosystem C are rare forcing forest C modelers to guess C values in some pools, possibly leading to large prediction errors.

We established 54 sample plots in the Čertovo Lake catchment area in the Bohemian Forest (Czech Republic) to study the C pools of natural old-growth Norway spruce (*Picea abies* (L.) Karst) forest. Our central aim was to (i) estimate variability in total (live and dead biomass and soil) ecosystem C pools as a function of stand age and elevation and (ii) to contribute to the question of old-growth forest productivity and (iii) advance understanding about moderate severity disturbance effects on C dynamics.

2. Material and methods

2.1. Study site

The study was carried out in the catchment of Čertovo Lake (49°10'N, 13°12'E) at 1027–1343 m above sea level (a.s.l.) in the Bohemian Forest, Czech Republic (Appendix A). The catchment consists mostly of steep slopes that are south-east oriented and reaches a plateau above 1200 m. The total area is 86.9 ha (including the lake of 10.7 ha) and is dominated by Norway spruce stands, with a minor component of European beech (*Fagus sylvatica* L.). The area is a strictly protected reserve since 1933. The current forest was established after a severe disturbance that occurred between 1860 and 1870 and there has been no severe disturbance since (Čada et al., 2013), except for windthrows in 2007 and 2008, which damaged the forest on ~14% of the catchment area (Kopáček et al., 2013). Affected area was not sampled. Climate is harsh with a

mean annual temperature of 4.1 °C at an elevation of 1056 m, an annual precipitation of 840–2200 mm and snow cover usually from late November to May (Kopáček et al., 2011; Turek et al., 2014).

The bedrock of the Čertovo Lake catchment consists of mica-schist (muscovite gneiss), quartzite and a small amount of pegmatite. Dominant soils are ~0.5 m deep dystric cambisol (58%), podsol (21%), and shallow (~0.2 m) leptosol (17%); wetlands and bare rocks cover ~3% and 1% of the catchment, respectively. Average forest floor depth is 10 cm and ranges from 3.3 to 26 cm. Average mineral soil depth is 33 cm and ranges from 1.7 to 65 cm. Fine soil (<2 mm fraction) is sandy (48–81%) with a low (1–4%) content of clay. Soil pH is low, with pH_{CaCl2} values of 2.5–4.5, and pH_{H2O} values about ~0.6 units higher. The mean effective cation exchange capacity of the soils is dominated by exchangeable Al (62%) and protons (29%), while base saturation is 9% (Kopáček et al., 2002).

2.2. Sampling design

Similar to previous studies carried out in relatively small, unmanaged protected areas (e.g. Jacob et al., 2013; Šebková et al., 2011) the study area was limited to a rare and specific forest area. To examine the effects of age and elevation on forest C stocks in old-growth Norway spruce forest, 54 sample plots of 500 m² were established in the summer of 2008. Plots were chosen randomly at an elevation range between 1025 and 1338 m a.s.l to represent the study area and its old-growth forest characteristic within an age range between 116 and 145 years of mean stand age.

To estimate stand age, three randomly chosen canopy trees in each plot were cored at 1 m height, thus, tree age is expressed as recruitment age at 1 m height (Niklasson, 2002). Cores were measured and crossdated to ensure accurate dating. Norway spruce is a shade tolerant species and can persist for decades under a full canopy suggesting germination age might poorly coincide with the timing of past disturbances. To better represent mean plot age, we modeled a diameter age relationship using a power function based on sampled trees to estimate the age of trees that were not cored. Based on ages of all trees, mean stand age was calculated. Elevations of plots were obtained from a digital elevation model using plot coordinates.

2.3. Data collection

2.3.1. Live tree biomass carbon pool

For all trees >7 cm diameter at breast height (dbh), we measured dbh and tree height. Total (above- and below-ground) Norway spruce biomass was calculated using dbh, height and age based on best available models developed by Wirth et al. (2004). European beech above-ground biomass was calculated using dbh and height with equations developed by Cienciala et al. (2005) and below-ground root biomass by using dbh with equations developed by Bolte et al. (2004). The share of other species was very small (<1%). For the other conifer species (Silver fir, *Abies alba*) Norway spruce and for angiosperms (Rowan, *Sorbus aucuparia* and sycamore maple, *Acer pseudoplatanus*) European beech equations were used. Carbon content of 50.8% and 48.8% were used for conifers and angiosperms, respectively (Thomas and Martin, 2012).

2.3.2. Dead biomass carbon pool

Downed dead trees were defined as all lying or leaning (with a zenith angle ≤45°) dead material with mid-length diameter ≥7 cm. Biomass was calculated using measured mid-length diameters, length and decay stages of logs that had their root system located inside the plot. A five class decay classification was used (Sippola and Renvall, 1999): (1) Recently dead or cut

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