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Toward consistent measurements of carbon accumulation: A multi-site assessment of biomass and basal area increment across Europe

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ABSTRACT

The use of tree-ring data in carbon cycle research has so far been limited because traditional study designs are not geared toward quantifying forest carbon accumulation. Existing studies that assessed biomass increment from tree rings were often confined to individual sites and used inconsistent sampling schemes. We applied a consistent biomass-oriented sampling design at five managed forest sites located in different climate zones to assess the annual carbon accumulation in above-ground woody tissues (i.e. stems and branches) and its climate response. Radial growth and biometric measurements were combined to reconstruct the annual biomass increment in individual trees and upscaled to the site level. In addition to this, we estimated that 32–60 trees are required at these five sites to robustly quantify carbon accumulation rates. Tree dimensions and growth rates varied considerably among sites as a function of differing stand density, climatic limitations, and management interventions. Accordingly, mean site-level carbon accumulation rates between 65 g C m^{-2} y^{-1} and 225 g C m^{-2} y^{-1} were reconstructed for the 1970–2009 period. A comparison of biomass increment with the widely used basal area increment (BAI) revealed very similar growth trends but emphasized the merits of biomass assessments due to species-specific BAI/biomass relationship. Our study illustrates the benefits and challenges of combining tree-ring data with biometric measurements and promotes the consistent application of a standardized sampling protocol across large spatial scales. It is thus viewed as a conceptual basis for future use of tree-ring data to approach research questions related to forest productivity and the terrestrial carbon balance.

Introduction

Annual growth variability derived from tree-ring measurements ranks among the primary tools used to assess historical forest growth dynamics on decadal to millennial time-scales. Dendrochronological records have been used for countless purposes ranging from climate reconstructions (Jones et al., 2009; Trouet et al., 2009; Frank et al., 2010), forest ecology studies (Neuwirth et al., 2004; Esper et al., 2007; Krause et al., 2012), dating archeological remains (Haneca et al., 2009), to reconstructions of geomorphic activity (Gärtner et al., 2004). The vast number and wide geographic coverage of available tree-ring chronologies has allowed for the establishment of continental to hemispheric networks (Briffa et al., 2002; Lloyd and Bunn, 2007; Wettstein et al., 2011; Babst et al., 2013) that have promoted dendrochronology as a tool to assess large-scale spatiotemporal patterns in forest growth variability in the context of global change (e.g. Gedalof and Berg, 2010). Projected shifts in environmental forcing are expected to heavily affect the magnitude of the forest carbon sink (Nemani et al., 2003; Beer et al., 2010) through alterations in the balance of photosynthetic gain and heterotrophic and autotrophic respiration losses (Schwalm et al., 2010) as well as increased disturbances (Kurz et al., 2008). Tree-ring data can contribute to resolving these issues because they are a direct measure of radial stem growth, which is closely linked to annual wood formation

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and related carbon accumulation (Bouriaud et al., 2005). So far, however, tree rings have found little appreciation in carbon cycle research because most existing archives are not suitable for forest biomass and productivity quantification.

Traditional dendrochronological study designs are not geared toward measuring carbon accumulation and the collected metadata is often limited in this respect (Babst et al., 2013), although recent efforts have been invested to improve metadata archiving (e.g. Brewer et al., 2010). In addition to this, sampling schemes tend to focus on the oldest and/or most climatically stressed stands in a region, thus making them a biased representation of forested ecosystems. Standard field procedures for sample collection typically involve researcher-specific decisions about how many trees (often < 20), of which canopy class (usually dominant), covering which area (often undefined), and with which associated metadata (usually excluding key variables such as tree height and maybe even tree diameter). These approaches do not allow upscaling to stand biomass because (i) stand density is rarely quantified or computable from the collected metadata, (ii) possible biases related to collecting dominant individuals may be subtle in origin but profound in their consequences for inferred growth trends (Melvin, 2004), (iii) the number of sampled trees varies, and (iv) the sampling area is typically poorly defined.

Recognizing the need to assess and reconstruct annual biomass increment and the related carbon accumulation, some efforts have been invested to combine tree-ring data with measures of tree dimensions and/or allometric biomass functions (Zianis et al., 2005; Tabacchi et al., 2011). Existing studies have used this methodological framework to address research questions related to climate-induced changes in productivity (Graumlich et al., 1989; Knorre et al., 2006), quantifications of the local forest carbon budget (Chiesi et al., 2005; Babst et al., 2014), or assessments of changes in carbon sequestration after different forest management interventions (Davis et al., 2009). Results of these studies are hopefully, but not necessarily comparable, because sampling schemes varied from coring 20–30 trees (Chiesi et al., 2005; Knorre et al., 2006) to establishing a number of circular plots with a fixed diameter (e.g. 10 m in Davis et al., 2009). While the optimal number of trees or plots has been investigated (Mérian et al., 2012), the sampling scheme itself has received little attention. Furthermore, biomass was inferred from radial growth in different ways including either biomass functions or a combination of tree volume with text book derived or measured wood density. The above examples illustrate the potential of tree-ring based biomass estimates to empirically quantify changes in forest carbon stocks and at the same time they emphasize the need to apply consistent sampling strategies to harmonize quantification across large spatial scales.

Existing large-scale estimates of ecosystem productivity mostly rely on forest inventory data (Pan et al., 2011), dynamic global vegetation models (DGVMs; Friedlingstein et al., 2006), as well as combinations thereof with remote sensing products (Jung et al., 2007; Zhao and Running, 2010) or in situ eddy-covariance (EC) measurements (Beer et al., 2010). All of these methods have their advantages and limitations. For example, DVGM estimates contain uncertainties in the simulated climate response of forests (Babst et al., 2013) and in assumptions about the strength of CO_2 and nitrogen fertilization (Piao et al., 2012). Validations of forest productivity simulations with extensive and annually resolved biometric biomass inventories are thus expected to significantly increase the reliability of projected changes in the forest carbon sink (Kaplan et al., 2012).

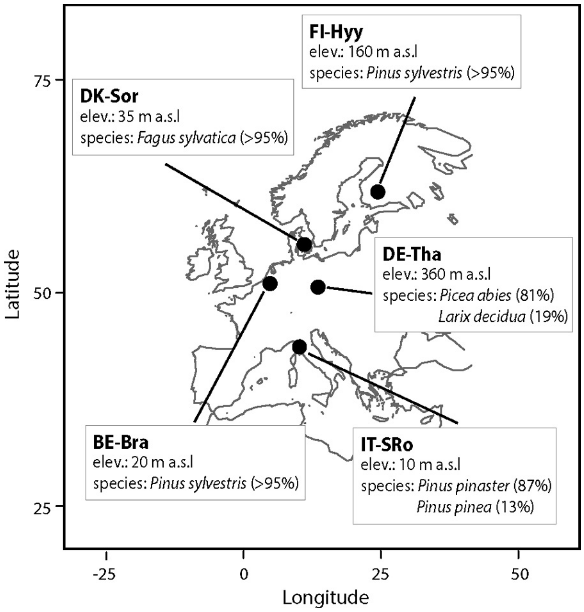

Fig. 1. Location and species composition of the five study sites.

Here, we perform a sampling and analysis campaign with the aim to derive annually resolved estimates of above-ground annual woody biomass increment and related carbon accumulation from tree-rings. This study involves consistent radial growth measurements and biometric data collection at five managed forest sites across Europe characterized by different species compositions, climate, and stand histories. Annual to decadal trends in biomass increment are compared to growth trends inferred from the more commonly applied basal area increment as well as to monthly and seasonal climate variability. We also provide some estimates for the number of trees necessary to quantify carbon accumulation of a stand to a certain fidelity.

Materials and methods

Site description

Primary study sites were established at the forest research stations in Hyytiälä (FI-Hyy), Soroe (DK-Sor), San Rossore (IT-SRo), Tharandt (DE-Tha) and Braschaat (BE-Bra; see Fig. 1 for locations). These sites together include all major European tree species except oak and reflect growth conditions of the three principal climate zones (i.e. boreal, temperate, and Mediterranean). Sites are characterized by a more or less homogeneous species and age distribution (details regarding climate conditions and stand characteristics are summarized in Table 1). The canopy-forming trees contain the

Table 1
Description of the study sites with specifics on plot and tree (mean DBH) dimensions, as well as annual climate. For further specifics please refer to the citations provided.

Site	Nr. trees	Nr. (radius) of plots	DBH (cm)	Annual *T* (°C) 1970–2009	Annual *P* (mm) 1970–2009	References
FI-Hyy	100	2 (10/12 m)	15.2	4.07	551	Rannik et al. (2002)
DK-Sor	41	1 (20 m)	37.6	8.81	545	Pilegaard et al. (2011)
IT-SRo	97	2 (15/15 m)	29.6	15.5	856	Chiesi et al. (2005)
DE-Tha	82	2 (20/20 m)	35.3	8.2	586	Grünwald and Bernhofer (2007)
BE-Bra	48	1(22.5 m)	30.9	10.5	792	Carrara et al. (2003)