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Comparison of carbon estimation methods for European forests

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ABSTRACT

National and international carbon reporting systems require information on carbon stocks of forests. For this purpose, terrestrial assessment systems such as forest inventory data in combination with carbon estimation methods are often used. In this study we analyze and compare terrestrial carbon estimation methods from 12 European countries. The country-specific methods are applied to five European tree species (*Fagus sylvatica* L., *Quercus robur* L., *Betula pendula* Roth, *Picea abies* (L.) Karst. and *Pinus sylvestris* L.), using a standardized theoretically-generated tree dataset. We avoid any bias due to data collection and/or sample design by using this approach. We are then able to demonstrate the conceptual differences in the resulting carbon estimates with regard to the applied country-specific method. In our study we analyze (i) allometric biomass functions, (ii) biomass expansion factors in combination with volume functions and (iii) a combination of both. The results of the analysis show discrepancies in the resulting estimates for total tree carbon and for single tree compartments across the countries analyzed of up to 140 t carbon/ha. After grouping the country-specific approaches by European Forest regions, the deviation within the results in each region is smaller but still remains. This indicates that part of the observed differences can be attributed to varying growing conditions and tree properties throughout Europe. However, the large remaining error is caused by differences in the conceptual approach, different tree allometry, the sample material used for developing the biomass estimation models and the definition of the tree compartments. These issues are currently not addressed and require consideration for reliable and consistent carbon estimates throughout Europe.

1. Introduction

Forests play an integral role in the global carbon cycle. According to the Food and Agriculture Organization (FAO, 2013), forests cover about 31% of the land surface area. Forests store about 2.4 Pg of carbon per year (Pan et al., 2011) and sequester about 30% of the current global CO_2 emissions, thus reducing the atmospheric CO_2 concentration by almost a third (Canadell et al., 2007). In the past the production of timber and fuel wood was the primary objective of forest management (FOREST EUROPE, UNECE, FAO, 2011). Today non timber forest ecosystem services such as clean

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air and water, protection against natural hazards, and biodiversity are of increasing interest (EUROSTAT, 2012). Following the Kyoto Protocol the forest's ability to store carbon and produce renewable energy in the form of biomass became a focal point in natural resource management. Within Europe (EU-27), 18.3% of the energy is generated from renewable sources, with 67.7% of that consisting of biomass (including renewable waste; EUROSTAT, 2012).

The increasing demand on European forests and their services requires consistency in forest information and monitoring. The primary source of forest information is produced by National Forest Inventories (NFIs), which often vary in terms of their conceptual approaches, sampling designs and data collection systems (Tomppo et al., 2010). Aside from more traditional applications such as monitoring forest resources and the sustainability of forestry, NFI data are of increasing interest for assessing the role of forests in the carbon cycle (e.g., for Kyoto reporting or future climate-related treaties such as the REDD+ Programme; Mohren et al., 2012).

Forest inventories record tree data which are, in turn, used for estimating standing timber volume in m^3/ha. The same tree measures can be used to derive total biomass or carbon content of forest ecosystems in t/ha. Biomass is the dry weight of wood estimated for constant conditions (i.e., oven dried wood samples until a constant weight is reached; Bartelink, 1996; Repola, 2008, 2009 or Cienciala et al., 2006). Carbon accounts for approximately half of this oven dried biomass, which consists mainly of polysaccharides such as cellulose, lignin and hemicellulose (Lamlom and Savidge, 2003; McGroddy et al., 2004).

Two conceptually different approaches are used to assess carbon stocks of forests: (i) the biogeochemical-mechanistic approach, and (ii) the statistical empirical approach. The biogeochemical-mechanistic approach is based on physiological principles of carbon uptake through photosynthesis and carbon loss due to the respiration and decomposition processes. This approach uses energy, water, and nutrient cycles to determine the carbon fluxes of an ecosystem. This method is implemented in large scale carbon cycle models and requires soil data, daily climate information and ecophysiological parameters for the given vegetation or forest ecosystem.

Carbon related outputs include GPP (Gross Primary production), NPP (Net Primary production) as well as stem, root or leaf carbon. Any comparison with terrestrial data such as forest inventory data requires a transfer function (Eastaugh et al., 2013), i.e., converting the model output carbon into tree volume (usually biomass expansion factors). These principles have been implemented in large scale carbon cycle models to circumvent the problem of missing terrestrial data and to provide methodologically consistent carbon cycle information for large regions, continents or even for the whole globe (VEMAP Members, 1995). Examples of models that use such an approach are BIOME BGC (Thornton, 1998; Thornton et al., 2002; Pietsch et al., 2005), CLM (Lawrence et al., 2011) and C-FIX (Veroustraete et al., 2002). A related product, known as the MOD17 product, implements key components of BIOME BGC with additional use of satellite data and provides GPP and NPP estimates on a $0.0083° \times 0.0083°$ resolution (approx. 1×1 km) for the whole globe (Running et al., 2004; Zhao and Running, 2010).

The statistical empirical approach is probably more commonly used in forestry, since it was developed earlier than the biogeochemical approach and requires terrestrial data such as forest inventory data (Tomppo et al., 2010). With this approach, biomass and carbon are estimated by applying (i) allometric biomass functions and/or (ii) biomass expansion factors.

Allometric biomass functions use tree variables such as diameter at breast height and/or tree height for estimating tree biomass. The share of carbon is then estimated using tree carbon fraction factors. In contrast, when using biomass expansion factors, conversion factors are used to transform tree volume into biomass. Volume functions must be used before the application of the expansion factors.

These statistical principles in deriving terrestrial biomass and carbon are also implemented in tree population models such as succession or gap models and typical tree growth models. Predicted volume or tree dimensions such as diameter or height serve as input parameters to apply either biomass functions or biomass expansion factors for calculating the terrestrial biomass in t/ha. Typical examples are succession models like PICUS (Lexer and Hoenninger, 2001; Seidl et al., 2005), LANDCARB (Mitchell et al., 2012), the matrix model EFISCEN (Nabuurs et al., 2000) or tree growth models such as MOSES (Hasenauer, 1994), PROGNAUS (Sterba and Monserud, 1997), SILVA (Pretzsch et al., 2002) or BWINPro (Nagel, 1999).

Allometric biomass and volume functions as well as biomass expansion factors are derived empirically from tree sampling. Destructive sampling, extensive field and lab work are needed to obtain biomass data for the different tree compartments – stem, branches, roots and foliage. Based on these sample data, generalized statistical functions for the different tree compartments or expansion factors are developed and applied to inventory data. Every region or country has different resulting functions and factors (e.g. for Austria Pollanschütz, 1974; for Romania Giurgiu et al., 1972; for Sweden Marklund, 1988; for Finland Repola, 2008, 2009 or for France Vallet et al., 2006). Examples for biomass functions developed for larger regions are Wirth et al. (2004), Muukkonen (2007) or Wutzler et al. (2008). The resulting biomass and carbon estimates strongly depend on the samples, but also on the chosen conceptual approach (i.e., whether biomass functions or biomass expansion factors are used).

Previous studies have shown that throughout many parts of the world, the calculation methods have a large impact on the results for biomass and carbon, both for trees and for tree compartments (Araújo et al., 1999 for Brazil; Westfall, 2012 and MacLean et al., 2014 for Northeastern United States; Guo et al., 2010 for China; Jalkanen et al., 2005 for Sweden, or Thurnher et al., 2013 for Austria). This supports the necessity for a similar study for Europe; however such a study was not done until now.

In Europe, National Forest Inventory data is commonly used for country reporting for international statistics and programs such as the Forest Resource Assessment Program for the Food and Agriculture Organization (FAO), or the Land Use, Land-Use Change and Forestry (LULUCF) report for the United Nations Framework Convention on Climate Change (UNFCCC; Tomppo et al., 2010). However, consistent calculation methods are required to be able to integrate and assess data from various countries for the purpose of assessing climate change mitigation or carbon sequestration potential in European forests (McRoberts et al., 2009; Ståhl et al., 2012).

The purpose of this study is to analyze the different carbon estimation methods covering 12 different countries across Europe and assess the impact of the methodological differences in deriving biomass estimates. Five important tree species in Europe are selected for comparison (*Fagus sylvatica, Quercus robur, Betula pendula, Picea abies* and *Pinus sylvestris*). We are specifically interested in

(i) compiling and assessing country-specific calculation methods for deriving biomass and carbon from NFI data; and
(ii) quantifying the effect of the various calculation methods on resulting biomass and carbon estimates using a standardized theoretical data set.

2. Methods

Europe's forests consist of a variety of ecological and climatic conditions covering different tree species. For our study we select