Universität für Bodenkultur Wien

Department of Forest and Soil Sciences

Institute of Silviculture
Head and Supervisor:
Univ.Prof. Dipl.-Ing. Dr.nat.techn. Hubert Hasenauer

ESTIMATING NET PRIMARY PRODUCTION USING REMOTE SENSING AND TERRESTRIAL FOREST INVENTORY DATA

Dissertation
to obtain the doctoral degree
at the University of Natural Resources and Life Sciences, Vienna

Submitted by
Dipl.-Ing. Mathias Neumann

Vienna, August 2016

Preface and list of papers

This work is a cumulative dissertation of three peer-reviewed publications provided in the Appendix 7.1 to 7.3. The formatting of the publications varies due to the requirements of the different journals.

Paper 1: **Neumann, M.**, Zhao, M., Kindermann, G., & Hasenauer, H. (2015). Comparing MODIS Net Primary Production Estimates with Terrestrial National Forest Inventory Data in Austria. Remote Sensing, 7(4), 3878–3906. http://doi.org/10.3390/rs70403878

Paper 2: **Neumann, M.,** Moreno, A., Mues, V., Härkönen, S., Mura, M., Bouriaud, O., Lang, M., Achten, W. M. J., Thivolle-Cazat, A., Bronisz, K., Merganic, J., Decuyper, M., Alberdi, I., Astrup, R., Mohren, F.,Hasenauer, H. (2016). Comparison of carbon estimation methods for European forests. Forest Ecology and Management, 361, 397–420. http://doi.org/10.1016/j.foreco.2015.11.016

Paper 3: **Neumann, M.,** Moreno, A., Thurnher, C., Mues, V., Härkönen, S., Mura, M., Bouriaud, O., Lang, M., Cardellini, G., Thivolle-Cazat, A., Bronisz, K., Merganic, J., Alberdi, I., Astrup, R., Mohren, F., Zhao, M., & Hasenauer, H. (2016). Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests. Remote Sensing, 8(554), 1–18. http://doi.org/10.3390/rs8070554

Citations to this work should refer to Neumann, M., 2016. Estimating Net Primary Production using remote sensing and terrestrial forest inventory data, Ph.D. thesis, University of Natural Resources and Life Sciences, Vienna, p.119 or by reference to the individual papers.

Acknowledgements

The work leading to this thesis was supported by the project MOTI (Comparing MODIS Satellite versus Terrestrial Inventory driven Carbon Estimates for Austrian Forests) funded by the Climate and Energy Fund of Austria managed by Kommunalkredit Public Consulting GmbH under contract number K10AC1K00050 and the project FORMIT (Forest management strategies to enhance the mitigation potential of European forests, contract number 311970) funded by the European Commission.

I want to acknowledge the open data policy that made this work possible in the first place. E-OBS climate data was provided by the European Climate Assessment & Dataset project (ECA&D) and the various MODIS products (land cover, Leaf Area Index, Fraction Absorbed radiation) by NASA and the MODIS land product science team. Special thanks and respect go to all the field crews throughout Europe collecting the forest inventory data used in this study. I owe my gratitude also to the people responsible for maintaining the inventory databases that helped me in accessing and analyzing this data.

Thanks to the R Core Team, the R Foundation for Statistical computing, and the R community worldwide for creating and maintaining this unique open source project. This allowed me to make sense out of all the information I present here and all of the data I analyzed but did not end up using.

I am grateful to my colleagues at BOKU. Thanks to Adam Moreno MSc, my office mate and friend, paramount in English editing and usually my first, challenging but most appreciated reviewer! Many thanks to Dr. Christopher Thurnher, programing hero and IT-genius, without your help I would be still reading manuals. I am also thankful to the support of Assoc. Prof. Dipl.-Ing. Dr. Rupert Seidl, Dipl.-Ing. Dominik Thom, Dipl.-Ing. Dr. Elisabeth Pötzelsberger, Mag. Eva Lanz, and all other colleagues at the Institute of Silviculture.

My thanks go to my colleagues from the FORMIT project, in particular our coordinator Prof.Dr.ir. Frits Mohren and the colleagues that helped in processing the forest inventory data: Dr. Volker Mues, Sanna Härkönen PhD, Matteo Mura PhD, Olivier Bouriaud PhD, Mait Lang PhD, Giuseppe Cardellini MSc, Wouter Achten PhD, Alain Thivolle-Cazat PhD, Karol Bronisz PhD, Jan and Katarina Merganicova, Iciar Alberdi PhD and Rasmus Astrup PhD.

I want to acknowledge Prof. Dr. Steve W. Running and Maosheng Zhao PhD for their support in working with the MOD17 algorithm, for all the fruitful discussions and their critical but amicable evaluation of my work.

Special thanks go to my supervisor Univ.Prof. Dipl.-Ing. Dr. Hubert Hasenauer. Thank you for believing in my potential and hiring a Diplom-Ingenieur in the field of Natural Hazards working at the Viennese administration of parks and garden to work on forest inventory and remote sensing projects. Without his constant mentoring and care I would not be at this point.

Finally I want to thank my family, my mother Josefine, my father Markus and my brother Lukas, who shaped me more than they know and layed the corner stone for my ever-searching and skeptical mind. Special thanks to Kati, my partner in crime and light of my life. You make me see the sun, when the night is dark.

Mathias Neumann Vienna, August 2016

„Die Wissenschaft fängt eigentlich erst da an, interessant zu werden, wo sie aufhört.“
(„Chemische Briefe“, Justus von Liebig)

Abstract

Forests provide important ecosystem services worldwide such as material for timber and fiber industries, food and biodiversity, clean water and air and protection against natural hazards. They are also increasingly important due to their prominent role in the global carbon cycle and their ability in both storing large amounts of carbon under ongoing climate change and providing the raw material for an emerging bio-economy. The physiology and growth of forests are strongly influenced by environmental conditions such as climate, soil and disturbances, both natural and anthropogenic. Thus understanding the response and feedbacks of forest towards environmental change requires a consistent large scale model framework incorporating the biogeochemical processes between vegetation and the atmosphere. Large scale forest information is provided amongst others by satellites in the Earth's orbit. The MOD17 algorithm combines satellite remotely sensed vegetation data and daily climate data with a biogeochemical model logic and provides global productivity measures on a 1-km resolution. In this study, a new regional dataset on Net Primary Production (NPP) "MODIS_EURO" was derived by rerunning MOD17 with local European climate data. It was evaluated with NPP from 13 European National Forest inventories and provides pan-European NPP (EU-27 including Norway, Switzerland and the Balkan). MODIS EURO shows a better agreement with the terrestrial reference NPP from forest inventory data, than the MODIS NPP driven by global climate data across scales and gradients. Differences in stand density and the employed tree carbon estimation methods are important for understanding discrepancies between MODIS EURO and terrestrial data. This novel dataset allows for spatial and temporal analysis of the impacts of ongoing climate change on vegetative ecosystems across Europe and their feedbacks to the global carbon cycle.

Kurzfassung

Wälder versorgen uns mit einer Vielzahl an Ökosystemdienstleistungen weltweit, wie Rohmaterial für verschiedene Industriezweige, Nahrung und Biodiversität, sauberes Wasser und Luft sowie Schutz vor Naturgefahren. Weitere Bedeutung erhalten sie durch ihre bedeutende Rolle im globalen Kohlenstoffkreislauf, deren Fähigkeit große Menge Kohlenstoff zu binden sowie als Ressourcenquelle für die aufstrebende Bioökonomie. Physiologie und Wachstum von Bäumen wird in großem Maße beeinflusst durch Umweltbedingungen wie Klima, Boden und Störungen, natürlichen wie menschlichen Ursprungs. Für das Verständnis der Reaktionen und Wechselwirkungen von Wäldern auf solche Veränderungen sind groß-skalige konsistente Informationen essentiell, um die biogeochemischen Zusammenhänge zwischen Vegetation und Atmosphäre abzubilden. Der biogeochemische MOD17 Algorithmus berechnet aus Satelliten-basierten Vegetationsdaten und Klimadaten Netto Primär Produktion (NPP) weltweit mit 1 km Auflösung. In dieser Arbeit wurde NPP mit MOD17 und lokalen Europäischen Klimadaten berechnet und mit NPP aus terrestrischen Waldinventurdaten 13 Europäischer Länder evaluiert. Mit diesem neuen Datensatz „MODIS EURO“ sind durchgehend räumliche explizite NPP Daten für Europa verfügbar (EU-27 inklusive Schweiz, Norwegen und Balkanländer). Über verschiedenen Skalen und Gradienten, MODIS EURO zeigt bessere Übereinstimmung mit NPP aus Waldinventurdaten als MODIS NPP errechnet mit globalen Klimadaten. Unterschieden in Bestandesdichte sowie der verwendeten Kohlenstoffschätzmethoden sind wichtig um Abweichungen zwischen MODIS EURO und der terrestrischen NPP zu erklären. MODIS EURO ermöglicht eine zeitlich und räumlich explizite Analyse der Auswirkungen und Wechselwirkungen des Klimawandels auf den Europäischen Wald.

Table of content

1 Introduction

Forests cover about 38% of Europe's land area (160.9 Mio. ha in the EU-27 (FOREST EUROPE, 2015), provide key ecosystem services such as timber supply, carbon sequestration (Pan et al., 2011), biodiversity (Thom and Seidl, 2015), and protection against erosion or flooding (Brang, 2001). However, forests are increasingly affected by climate change (Zhao and Running, 2010), natural disturbances (Seidl et al., 2014) and anthropogenic exploitation (Hansen et al., 2013). Since tree growth is strongly affected by environmental conditions such as solar radiation, water availability or CO_2 concentration a reliable tool for studying forest productivity should consider such effects as well as the vegetation's response on its environment (Thornton, 1998; Waring and Running, 2007).

Biogeochemical mechanistic flux models were developed to understand land-atmosphere interactions by incorporating various ecosystem processes that mimic a host of biogeochemical cycles (e.g., carbon, energy, water, nutrients). Biome BGC is a widely used biogeochemical model (Cienciala and Tatarinov, 2006; Hasenauer et al., 2003; Pietsch et al., 2005; Pötzelsberger et al., 2015; Thornton, 1998; White et al., 2000). Since most of Europe's forests are managed, Biome-BGC needs management routines to provide meaningful results in Europe (Petritsch et al., 2007; Thurnher et al., 2014). However, such management routines are not yet available across Europe. The MOD17 algorithm (Running et al., 2004) does not need such information and captures the vegetative development and response to environmental conditions with temporally and spatially explicit Leaf Area Index and Fraction Absorbed radiation. MOD17 integrates key components of Biome-BGC's model logic with remote-sensing products from the satellite-mounted sensor MODIS and provides annual Gross Primary Production and Net Primary Production (GPP and NPP) worldwide on 1-km resolution since the year 2000 (Zhao and Running, 2010). A key strength of biogeochemical models and the MOD17 algorithm is their climate-sensitivity (Zhao et al., 2006).

Another source of forest productivity information is terrestrial forest growth data such as long-term research plots (Hasenauer et al., 2012; Phillips et al., 1998) or national forest inventory data sets (Tomppo et al., 2010). Carbon accumulation by forests, a fundamental component of NPP (Malhi et al., 2011; Olson et al., 2001), is obtained using terrestrial forest growth data from the change in tree carbon stocks using consecutive measurements. Since tree carbon is estimated using local biomass functions and measurements of tree diameter and/or height, terrestrial NPP estimates capture variations in tree allometries, stand density and local effects such as soil limitations. They represent an independent source for productivity assessments alongside MOD17. Drawbacks are that inventory assessments are carried out every 5 to 10 years and that a certain number of plots have to be aggregated across a region to derive reliable results. Currently there is no consistent large-scale forest inventory dataset available in Europe such as the FIA data (Forest Inventory and Analysis) from the United States (Bechtold and Patterson, 2005). This lack of availability in forest inventory data is due to differences in country-specific methodology, sample designs and country specific legal restrictions in data availability (Tomppo et al., 2010).

Large-scale, consistent and reliable NPP estimates would allow for carbon balance assessments (Quegan et al., 2011), monitoring terrestrial carbon fluxes (Potter et al., 2012), assessing species richness (Phillips et al., 2008), and estimating available biomass for bioenergy and a bio-based economy (McCormick and Kautto, 2013; Smith et al., 2012). Another application could be in carbon emissions assessments such as LULUCF (Land use, land-use change and forestry), that traditionally used terrestrial field data (IPCC, 2006).

Evaluation with independent data is important to verify the reliability of any model results. While GPP from MOD17 can be validated with eddy covariance data from flux towers (Heinsch et al., 2006), NPP using terrestrial field assessments are currently the only independent data source for validating MOD17 NPP (Turner et al., 2006). There have been hypotheses on drivers for discrepancies between terrestrial and remotely sensed NPP, but have yet to be examined in Europe on the continental-scale. This include differences in stand density (Hasenauer et al., 2012), the impact of the sampling design (Hasenauer and Eastaugh, 2012) and the effect of terrestrial estimation methods (Thurnher et al., 2013).

2 Vision and objectives

This thesis aims to create and validate a consistent pan-European Net Primary Production (NPP) dataset, which was not available before this study. Two independent methodologies for estimating NPP are employed, the MOD17 algorithm and terrestrial forest inventory data. MOD17 provides continuous coverage of NPP using MODIS satellite data and the forest inventory data are obtained to evaluate and understand the results of MOD17.

This thesis has the following objectives:

- Test suitability of forest inventory data for linking with MOD17 NPP to understand the conceptual limitations on country scale,
- collate and harmonize forest inventory data and tree carbon estimation methods for 13 European countries,
- create pan-European MODIS NPP using new daily European climate data set ("MODIS EURO") evaluated with terrestrial NPP using forest inventory and harmonized carbon estimation methods across Europe, and
- analyze conceptual discrepancies between the two NPP data sets and explore future applications of the consistent, continuous temporal and spatial explicit NPP dataset MODIS EURO.

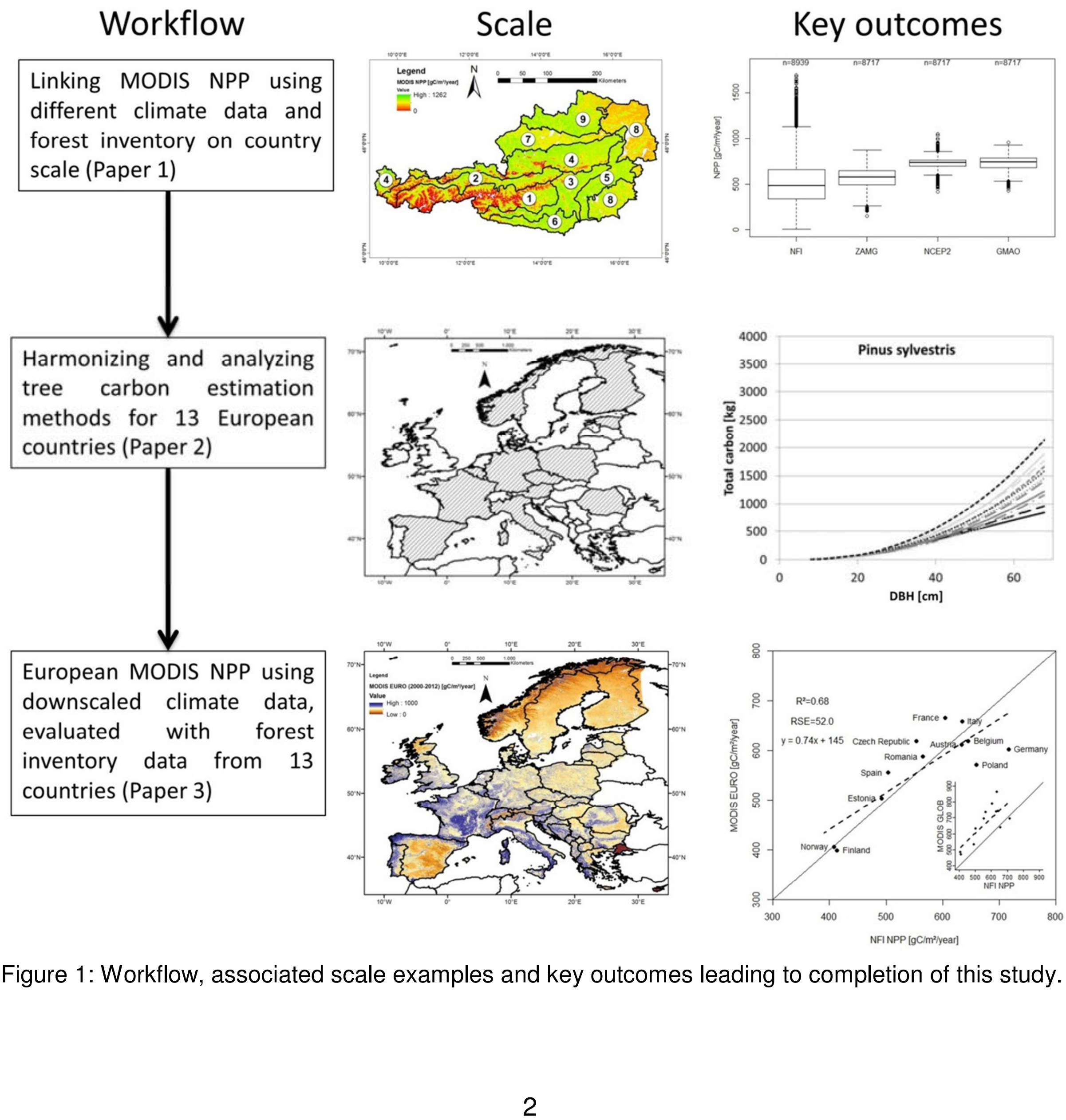

Figure 1: Workflow, associated scale examples and key outcomes leading to completion of this study.

3 Net Primary Production using remote sensing and forest inventory data

The publications supporting this thesis followed several steps along a gradient in scale and cover my first three objectives (Figure 1). A local pilot study in Austria compares for the first time forest inventory data with NPP from MOD17 (Paper 1 provided in Appendix 7.1). A pan-European compilation of tree carbon estimation methods provides the means to compute forest inventory NPP across Europe (Paper 2 provided in Appendix 7.2). Forest inventory NPP across Europe is used to evaluate a newly created regional MODIS NPP dataset (the “MODIS EURO” dataset, covering EU-27 including Norway, Switzerland and the Balkan) at different scales and gradients (Paper 3 provided in Appendix 7.3). I refer to the Appendices for a detailed description of the used data and methodology and the deduced results.

The last objective I elaborate here by describing the conceptual differences between NPP using MOD17 and forest inventory data using selected topics relevant across the three papers and the genesis of this thesis. Such conceptual drivers have an impact irrespective of the location of the study, the used input data or the spatial scale.

3.1 Two conceptually different methods for estimating NPP

Net Primary Production (NPP) is the net carbon uptake by vegetation that is converted into plant biomass (Running et al., 2004). While it is largely impossible to directly measure NPP due to the complexity of the associated processes (Clark et al., 2001), NPP can be estimated using two different and independent methods on the country-scale (Austria) in Paper 1 and on the continental-scale (Europe) in Paper 3. Prior to that, Paper 2 compiled the tree carbon estimation methods used in Europe. To understand discrepancies, it is important to understand the conceptual differences between the two methods.

On the one hand, NPP can be estimated as the difference of Gross Primary Production (GPP, the amount of chemical energy produced via photosynthesis) minus maintenance respiration (energy for supporting and maintaining living biomass) minus growth respiration (additional energy needed for creating new plant biomass). This approach derives NPP from its physiological potential by accounting the energy plants have to spend for maintaining their metabolism and body. The MOD17 algorithm (Running et al., 2004; Zhao and Running, 2010) follows this logic.

On the other hand, NPP can also be estimated by adding up the carbon invested into produced plant compartments (Malhi et al., 2011). Most important compartments are the photosynthetic active parts carrying chlorophyll (needles, leaves), the belowground system for collecting water and nutrients (fine roots) and the respective supporting structures (stem, branches and coarse roots) (Olson et al., 2001; Thornton, 1998). The first two have little share in forest carbon stocks (Friedlingstein et al., 1999; Helmisaari et al., 2002), but account for substantial carbon allocation by frequent annual turnover (Finér et al., 2011; Liu et al., 2004). Deriving NPP from the sum of carbon built into plant compartments is employed when using terrestrial observations of plant growth (Olson et al., 2001; Scurlock and Olson, 2002).

MOD17 follows the first approach and using forest inventory data (NFI) the second. Ideally both methods should come up with the same results. However, discrepancies have to be expected because the two approaches are conceptually very different and use varying input to derive NPP (Figure 2). A gap between the NPP results was found both in Paper 1 for Austria on the country-scale (Figure 2 of Paper 1 in Appendix 7.1) and for Europe on continental-scale (Table 2 of Paper 3 in Appendix 7.3).

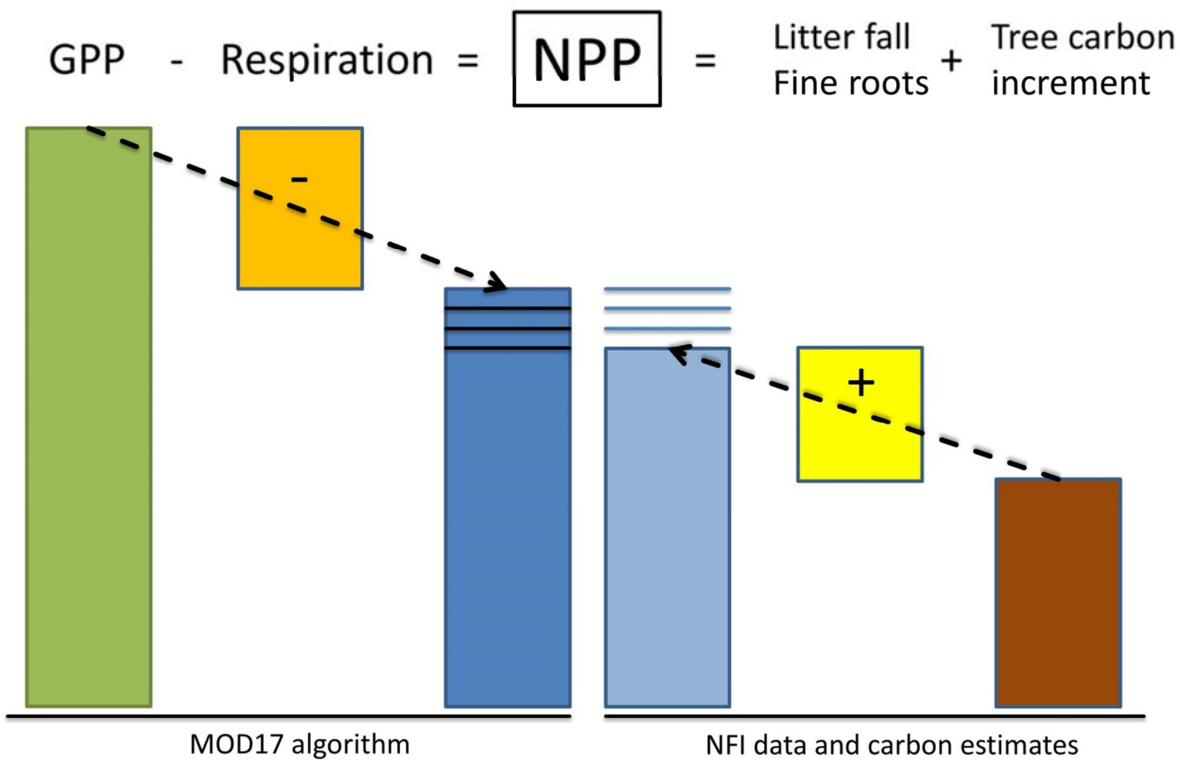

Figure 2: Conceptual illustration of estimating NPP using MOD17 algorithm (left) and using Terrestrial forest inventory NFI data and carbon estimation methods (right).

3.2 Representation of trees in the two model frameworks

Errors in each of the four contributing components to NPP (GPP and respiration for MOD17 and carbon increment, litter fall and fine roots for NFI NPP) can lead to discrepancies (Figure 2). A description of the NPP components and how forests and trees are integrated and represented in the two modelling frameworks is helpful to understand discrepancies.

There are conceptual differences how trees are represented and implemented in the two NPP modelling frameworks. Net Primary Production is the net increase in carbon allocated into vegetation. Thus both methods require some information describing vegetation quantity or abundance.

3.2.1 MOD17 algorithm

At first, GPP gets estimated by employing the radiation use efficiency concept (Monteith, 1972) and accounting for limitations due to low temperature and water stress. MOD17 uses biome-specific parameters stored in the Biome-Property-Lookup-Tables (BPLUT) covering 11 biomes, because such effects vary between different biomes (for instance broadleaf forests versus grassland). Next, NPP is deduced from GPP by accounting for respiration (Figure 2). To highlight the variables describing vegetation, spatially and temporally explicit drivers are marked **bold** and biome-specific parameters from the BPLUTs in *italics*.

$$GPP = 0.45 \cdot SW_{rad} \cdot \mathit{LUEmax} \cdot f_{Tmin} \cdot f_{vpd} \cdot \mathbf{FPAR} \tag{1}$$

SWrad is short wave solar radiation load, of which 45% is photosynthetically active, and is calculated using the MT-CLIM model (Thornton and Running, 1999). LUEmax is the maximum light use efficiency, which gets adjusted by multipliers f_{Tmin} and f_{vpd} to account for water stress due to low temperature (Tmin) and vapor pressure deficit (VPD). All three are biome-specific and are from the Biome-Property-Lookup-Tables (BPLUT) indicated by *italic letters.* The BPLUTs were first published in (Zhao and Running, 2010) and are also shown in (Hasenauer et al., 2012). FPAR is the fraction of absorbed photosynthetic active radiation and is the only spatial and temporal explicit variable (indicated by **bold letters)** obtained from remote sensing data in the GPP submodel.

NPP = GPP – leaf_mass · *leaf_mr* · Q10_mr - leaf_mass · *froot_leaf_ratio fineroot_mr* · Q10_mr - leaf_mass · *livewood_leaf_ratio* · *livewood_mr* · Q10_mr – 0.25 · NPP (2)

leaf_mass = **LAI** / *SLA* (3)

NPP is finally the difference of GPP and the maintenance (leaves, live wood and fine roots) and growth respiration. leaf_mass, the biomass of needles and leaves, describes the abundance of vegetation in the MOD17 algorithm and is obtained using remotely sensed Leaf Area Index (LAI) marked **bold** and Specific Leaf Area (SLA), a biome-specific constant from the BPLUTs. Using leaf mass, the alive plant compartments, fine roots and live wood, are deduced using biome-specific allometries, *froot_leaf_ratio* and *livewood_leaf_ratio*. The biome-specific parameters *leaf_mr, fineroot_mr* and *livewood_mr* provide a base respiration rate for the compartments leaf, fine roots and live wood, which are modified by climate. Q10_mr is an exponent shape parameter controlling respiration as a function of temperature. Growth respiration is the energy need for constructing organic compounds and was empirically parametrized with 25% of the NPP (Cannell and Thornley, 2000; Running and Zhao, 2015).

Thus spatial and temporal variation in vegetation properties is captured in MOD17 solely via LAI and FPAR obtained from remote sensing data (Yang et al., 2006) and differences in vegetation types via the biome-specific constants from the Biome-Property-Lookup-Tables.

3.2.2 Forest inventory NPP

Using forest inventory data, carbon increment in forests is estimated using repeated observations of tree carbon stocks. Figure 2 shows, that NPP is the sum of carbon increment of trees, aboveground litter fall and belowground fine root turnover (Olson et al., 2001; Scurlock and Olson, 2002).

NPP = CARB_INC + LF + FR (4)

CARB_INC is the gain of carbon stored in plant biomass and is estimated based on carbon stock estimation between 2 consecutive inventory periods. LF is the litter fall of aboveground compartments such as leaves, needles, but also branches or fruits and FR is the amount of carbon needed for fine-root turnover and their exudates. Both are estimated using the species- and climate-sensitive method proposed by (Liu et al., 2004) and assuming proportionality between above and belowground litter fall (Raich and Nadelhoffer, 1989).

Tree carbon for CARB_INC is derived from tree biomass (approx. 50% of biomass is carbon, Table A.1 in Appendix 7.2). Biomass in turn is estimated with terrestrial tree measurements such as diameter and tree height provided by forest inventory data (NFI) using biomass functions or biomass expansion factors. The employed functions are developed using regression analysis with samples obtained from destructive sampling of trees. Since each country uses their own methodology, Paper 2 in Appendix 7.2 compiles the different methods.

All of the methods of the 13 countries of this study use diameter at breast height (DBH) as an independent variable to predict biomass. For most countries and most species in addition to tree height is used and some countries also use other variables such as tree age, crown ratio or stem volume (Appendix 7.2). Thus each tree is described by at least tree species and diameter and depending on the countries methodology different carbon results are obtained even when using the same input data (Figure 3).

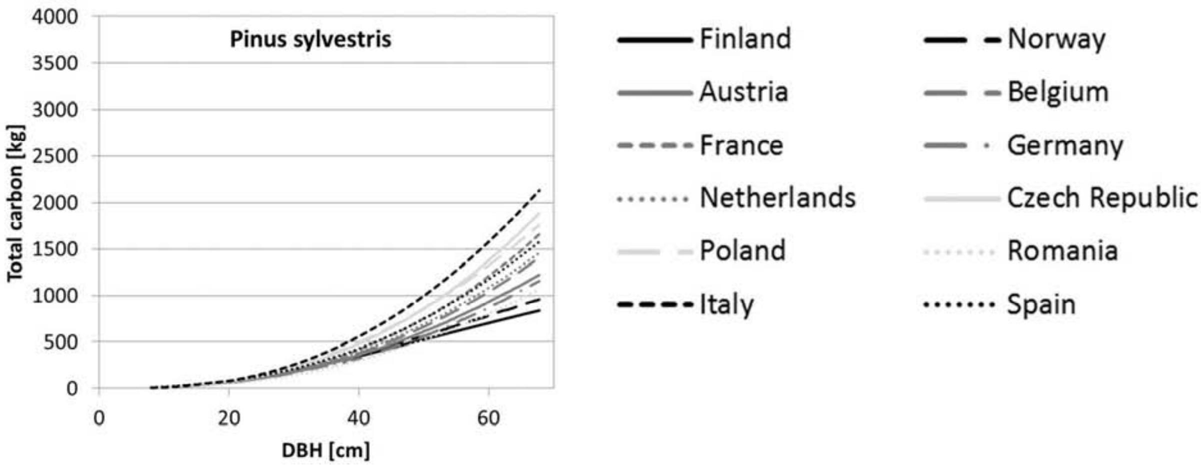

Figure 3: The tree carbon for *Pinus sylvestris* using one consistent input dataset and the estimation methods from different countries. Within countries there is no variation besides by tree diameter (DBH), since tree height is calculated using DBH. The figure is modified from Appendix 7.2

The carbon content of a single tree increases by diameter, since trees accumulate carbon over time via photosynthesis. The carbon content of a forest is the sum of carbon of the trees of an NFI plot and thus driven by their abundance, species, diameter, tree height, etc. Carbon increment is calculated as the difference of two carbon stocks accounting for mortality and new trees (Eq. 4 in Appendix 7.1).

In forest inventory data, forests are represented by the properties of single trees assessed on an inventory plot and NFI NPP change by using different carbon estimation methods. MOD17 observes each forested pixel as one homogenous canopy layer with a certain biome type, LAI and FPAR, and provide consistent results across countries. Interpreting discrepancies between MOD17 and NFI NPP (Figure 2; Appendix 7.1 and 7.3) needs consideration of the outlined conceptual differences. For instance, German will modify their estimation procedure to derive tree carbon in future reportings on their forest inventory. This will results in an reduction of the estimated tree carbon stocks by 4.3 % (Kändler and Bösch, 2013) as compared to the current method used in Paper 2 (Appendix 7.2) and thus will change also the German NFI NPP.

3.3 Climate-sensitivity

The effect of climate is a primary driver in NPP estimates using the MOD17 algorithm. Climate affects and regulates plant growth (Thornton, 1998; White et al., 2000) and a key strength of MOD17 is the climate-sensitivity incorporating into its submodules, such as the temperature-dependent modifier of light-use efficiency (Eq. 1). Previous research showed that inaccuracies in the climate data driving MOD17 can have a substantial effect on the agreement of predicted GPP and NPP with reference data (Heinsch et al., 2006; Zhao et al., 2005). For the global MOD17 dataset the NCEP climate data is used, current version NCEP-DOE Reanalysis 2 (Kanamitsu et al., 2002), which is constantly updated and freely available worldwide.

For this study, a new NPP dataset ("MODIS EURO") was derived by rerunning the MOD17 algorithm after replacing the global NCEP data with European focused daily climate data on a 1-km resolution (Moreno and Hasenauer, 2015). The same vegetation information (Land cover map and LAI/FPAR datasets) was used for MODIS EURO as was used for the original global MODIS NPP estimates. MODIS EURO (average NPP 577 grams carbon m^{-2} $year^{-1}$) is comparable with NFI NPP (average NPP 539 gC m^{-2} $year^{-1}$) across countries, while global

MOD17 NPP (average NPP 680 gC m^{-2} $year^{-1}$) shows a systematic overestimation (Figure 4). Using new and more accurate climate input in MOD17 results in lower NPP across Europe (minus 103 gC m^{-2} $year^{-1}$ or minus 15 % for Europe; Table 2 in Appendix 7.3). The same effect (minus 159 gC m^{-2} $year^{-1}$ or 22 %) was also observed in the pilot study in Austria (Paper 1 in Appendix 7.1) by rerunning MOD17 using an DAYMET interpolation (Hasenauer et al., 2003) of national weather stations from Austria. An interpolation on a European scale was not possible due to insufficient availability of raw weather station data.

MODIS EURO and NFI NPP show agreement not only on country-scale but also across gradients such as elevation, tree age or dominant species (Figures S6 to S9 in Appendix 7.3). Thus, using high-resolution reliable climate data in MOD17 provides consistent, pan-European NPP across different scales and gradients. This NPP dataset accounts for the climatic effects to forest growth over time and also the response of vegetation to changing climate via reaction in LAI and FPAR.

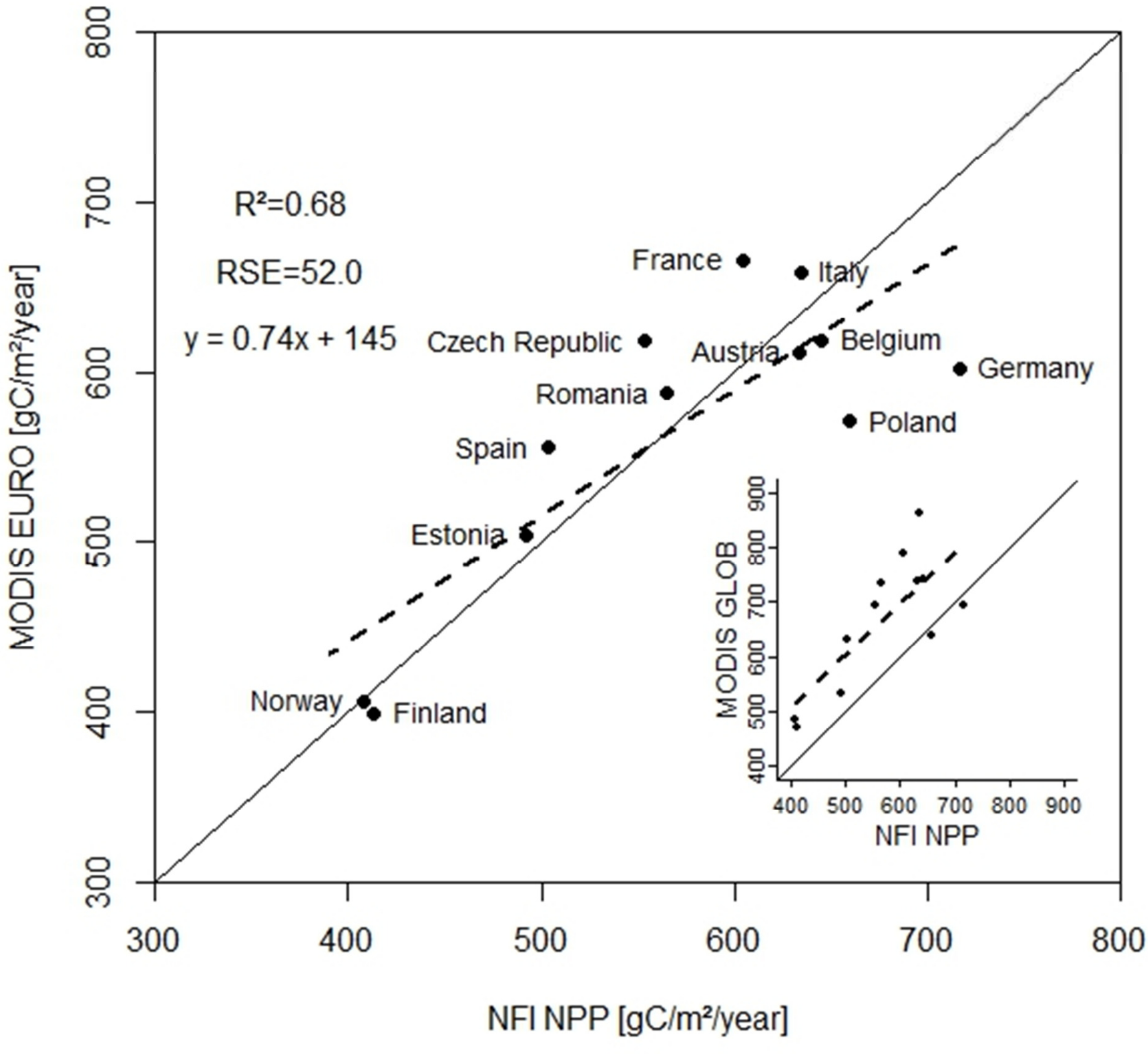

Figure 4: Comparison of MODIS EURO vs. NFI NPP on the country-scale. Bottom-right corner compares NFI NPP with the global MODIS NPP product. The figure is taken from Appendix 7.3

3.4 Forest stand density effects

The density of forests affects the growth rates of single trees and their allocation patterns (Assmann, 1970) via changes on the increment of diameter and height, both of which are inputs to carbon estimation methods (Paper 2 in Appendix 7.2). In addition, a forest with sparse canopy cover could have gaps with trees below diameter threshold (Table S1 in Appendix 7.3), which are not captured by NFI data and do not contribute to NFI NPP. On the other hand, LAI and FPAR, which are the key inputs of MOD17 to describe vegetation, capture all vegetation independent of diameter by assuming full coverage. MOD17 does not integrate variability such as density effects, unless LAI and FPAR across a 1 km² pixel are substantially changed. Previous research in Austria illustrates the importance of stand density to understand discrepancies between MODIS NPP and NPP using terrestrial forest information (Hasenauer et al., 2012).

The Stand Density Index (SDI) was used in this study as a measure for competition between trees (Reineke, 1933). Across scales, stand density showed a substantial effect on the discrepancies between MOD17 results and forest inventory NFI NPP (Appendix 7.1 and 7.3). Plotting ΔNPP (discrepancy between MODIS EURO using European climate data and NFI NPP) by SDI reveals a significant ($p < 0.001$, $\alpha = 0.05$) negative trend. This pattern is also apparent on the country-scale (Figure 7 in Appendix 7.3) or using alternative measures for stand density such as CCF, the Crown Competition Factor (Krajicek et al., 1961) in Figure 3 in Appendix 7.1.

MODIS EURO overestimates NFI NPP by 12% of the average European NPP equal 70 gC m^{-2} $year^{-1}$ (ΔNPP median for SDI < 200; Figure 5). Such a difference could be explained by gaps in the canopy cover with small trees, grass or shrubs not measured by forest inventory data. The discrepancy gets smaller with increasing density and at SDI from 400 to 600 both NPP estimates agree. At large stand density, ΔNPP gets negative and thus NFI NPP exceeds MODIS EURO (-19% of average NPP equal -107 g m^{-2} $year^{-1}$; ΔNPP median for SDI > 1000). Such high SDI values could indicate very dense but small-scale forest areas with understory and suppressed trees under the canopy that are rare on a landscape scale. MOD17 covers 1 km² pixels and cannot capture such small-scale features. The pattern of ΔNPP is in fact caused by NFI NPP, while MODIS EURO does not change with SDI (Figure S10 in Appendix 7.3).

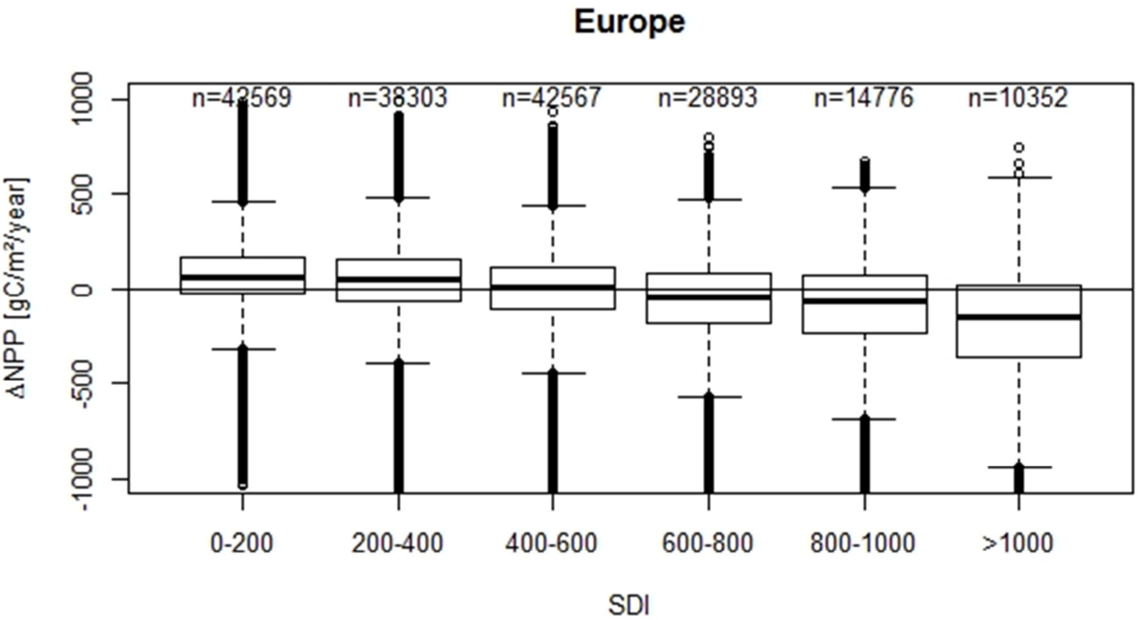

Figure 5: NPP difference ΔNPP between MODIS EURO using MOD17 with local climate data and NFI NPP from 13 European countries grouped by classes of Stand Density Index (Reineke, 1933). The figure is taken from Appendix 7.3

This study suggests that stand density is a key variable to explain discrepancies between MODIS EURO and NFI NPP, as opposed to other gradients such as tree age, elevation, water balance deficite, dominant species or tree height (Figure 6 in Appendix 7.1 and Figure 5 and Figures S6 to S9 in Appendix 7.3).

The agreement of MODIS EURO and NFI NPP at average stand density in Figure 5 (Mean SDI across Europe is 469; Appendix 7.3) can also be related to the calibration of the Biome-Property-Lookup-tables (BPLUTs) of MOD17 (Zhao et al., 2005). For calibrating the BPLUTs, terrestrial NPP from research plots across the globe were used (Olson et al., 2001; Roy et al., 2001; Scurlock and Olson, 2002) and parameters such as specific leaf area or the ratio of live wood to foliage (Eqs. 2 and 3) were calibrated to match the median (Zhao et al., 2005). Thus MODIS NPP represents average conditions and might have difficulties in capturing very high and low stand densities. Unfortunately the literature on the terrestrial calibration data do not provide information on density and it is not possible to compare the density of the calibration dataset with European conditions.

3.5 Scales and coverage with data

There are also key differences between MODIS NPP driven by remote sensing data and terrestrial NPP from forest inventory data in terms of their scale and coverage. MOD17 is driven by data from the MODerate-resolution Imaging Spectroradiometer (MODIS) mounted on the satellites Terra and Aqua operated by National Aeronautics and Space Administration (NASA). The spatial resolution of the data products used in the MOD17 algorithm, MCD15, is currently 1 km or 0.0083° at the equator.

Forest inventory data (NFI) is collected on systematic grids using sample plots (Tomppo et al., 2010). The grid spacing of the NFI data from the 13 countries used in this work varies between 0.5 to 11 km, mostly between 2 and 4 km (Table S1 in Appendix 7.3). At the grid points, there are either single plots or a cluster of multiple plots (6 countries with clusters and 7 with single plots). Consequently, the number of plots varies according to the grid design but also the number of plots at each grid intersection. Figure 6 depicts the conceptual spatial differences in scale between MODIS data and two forest inventory systems covering a hypothetical area of 10 by 10 km.

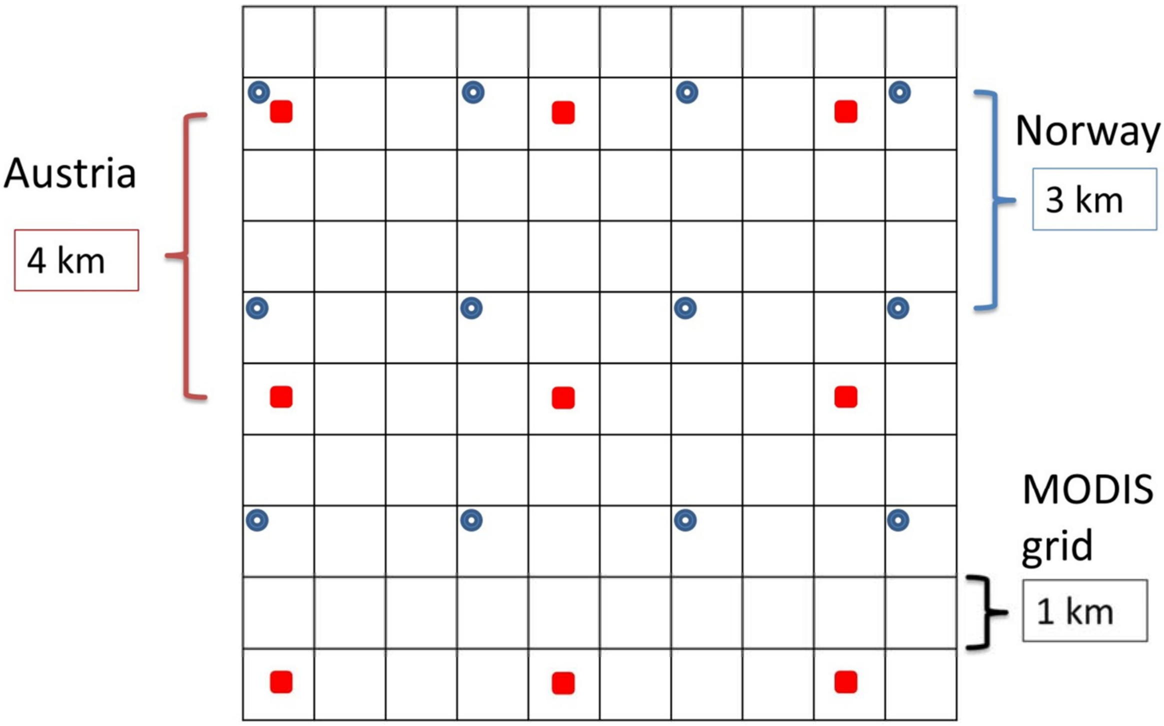

Figure 6: Comparison of MODIS data (1 km grid) with two NFI systems: Austria – cluster of 4 plots every 4 km (red squares), and Norway – single plots every 3 km (blue circles), sizes of squares and circles are not true to scale.

A region of 10 by 10 km (100 km²) is covered by 100 MODIS pixels. A forest inventory using the system of Austria would have in total 36 plots (9 grid points each with 4 plots) and using the Norwegian system would result in 12 plots (information on other countries in Table S1 in Appendix 7.3). Thus the number of samples is very different not only between MOD17 and forest inventory in general, but also between the single forest inventories. The error structure and variation of the two NPP results is thus different (Moreno et al., 2016) and explains the high variation of NFI NPP as compared to MOD17 NPP (Appendix 7.1 and 7.3).

The NFI data also differs in terms of the procedure to select sample trees for tree measurements. The two sampling techniques commonly used are fixed area plots and angle count sampling (Bitterlich, 1948). Out of the 13 countries with available NFI data, 3 countries use angle count sampling (Finland, Austria and Germany). For fixed area plots, which are usually circular, only the distance from the tree to the center of the plot is relevant. For angle count sampling, the ratio of diameter and distance to plot center determines the selection of sample trees. Angle count sampling overestimates volume as compared to fixed area plots, particularly in conditions with low volume and small diameters (Hasenauer and Eastaugh, 2012).

The data sources differ also on the temporal scale. The MOD17 results are usually aggregated to annual values and provide since 2000 annual NPP. The NFI data was selected to match the temporal coverage with MODIS data. However the time of the inventory measurements differ by country (re-measurements every 5 to 10 years, details in Appendix 7.3). Thus the NFI data cover different time periods. For instance, Norwegian NFI used in this study was collected in 2000 to 2004 with re-measurements in 2005 to 2009. Thus Norwegian NFI NPP represents a 5-year mean for the period 2000 to 2009. The NFI from Austria provide data for 2000 to 2002 and 2007 to 2009, resulting in 7-year means for 2000 to 2009.

3.6 Litter fall and fine root turnover

As shown at the beginning of this section, NPP includes all biomass compartments of a tree both above and below ground (Figure 2). Aboveground litter fall (Berg and Meentemeyer, 2001) and fine root turnover (Finér et al., 2011) account for a substantial share of forest NPP. Average NPP of European forests is approx. 1154 grams dry biomass m^{-2} $year^{-1}$ (assuming 50% carbon; MODIS EURO from Appendix 7.3). Litter fall measurements of European coniferous forests result in 347 ± 15 g m^{-2} $year^{-1}$ (mean ± standard error) and in broadleaf forests 442 ± 21 g m^{-2} $year^{-1}$ (Liu et al., 2004). Fine root production in temperate forests is 337 ± 36 g m^{-2} $year^{-1}$ (Finér et al., 2011).

Estimating aboveground litter fall for NFI NPP was done using a climate-sensitive model developed for Eurasian forests (Liu et al., 2004). Belowground fine root turnover was assumed to be proportional to aboveground litter fall (Raich and Nadelhoffer, 1989). This method of estimating fine-root turnover as a proportion of litter fall is often done if empirical data is missing (Olson et al., 2001; Scurlock and Olson, 2002).

The litter fall estimates from this study equal fine root turnover and are 364 ± 0.15 g m^{-2} $year^{-1}$ (Median 345 g m^{-2} $year^{-1}$, Standard deviation 64 g m^{-2} $year^{-1}$) and are in similar range with literature (Finér et al., 2011; Liu et al., 2004) but with a much smaller variation (Figure 7). Note that these values represent dry biomass, which differ from NPP results representing carbon (carbon is approx. 50% of biomass).

A substantial share of NPP in Europe is litter fall and fine root turnover with 33% of NPP each and only 34% of NPP get allocated into long-lived tree biomass (CARB INC covering mostly stem, branches and coarse roots; Figure 7). Similar patterns were also observed by a study in tropical forests with litter fall 34 ± 6% and fine roots 27 ± 11% versus allocation into wood of 39 ± 10% (Malhi et al., 2011).

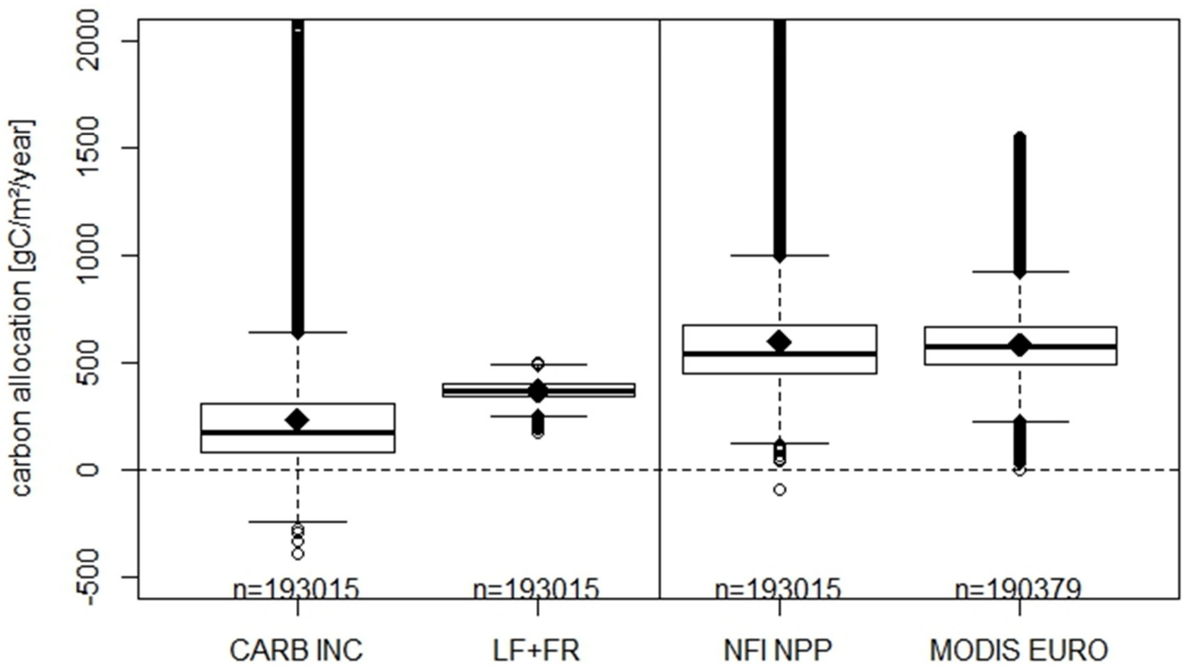

Figure 7: Components of Terrestrial NFI NPP - tree carbon increment CARB INC and litter fall and fine root turnover LF+FR. MODIS EURO is NPP using MOD17 algorithm and local climate data. The box represents the Median, the 25th and 75th percentile, the diamond the arithmetic mean, the whiskers extend to 1.5 of the interquartile range, values outside this range are indicated by circles, on the bottom the number of observations are given. To enhance the interpretability, CARB INC and NFI NPP larger 2100 gC m^{-2} $year^{-1}$ are not shown, but included in the boxplots.

4 Discussion and Conclusion

By re-running the MOD17 algorithm with local European climate data, this study provides a spatial and temporal explicit (annually 2000 to 2012, 1-km resolution) pan-European Net Primary Production dataset (“MODIS EURO”). Forest inventory data from 13 European countries were collated and harmonized to obtain a terrestrial NFI NPP dataset, which is independent from “MODIS EURO”. These two NPP sources are comparable across scales and gradients (Appendix 7.3), while the MOD17 NPP using the global climate driver shows a systematic overestimation compared to NFI NPP for most European countries. This suggests that the newly created MODIS EURO dataset is able to capture the specific conditions of European forests and is useful for large-scale spatially explicit assessments of carbon sequestration or the response of forests to climate change.

The papers and their key findings summarized in this study highlight the respective strengths and weaknesses of the two employed methodologies. This study also identified Key conceptual differences between the two methods, which will help to interpret potential discrepancies detected in future studies. Combining both methods will utilize their respective advantages.

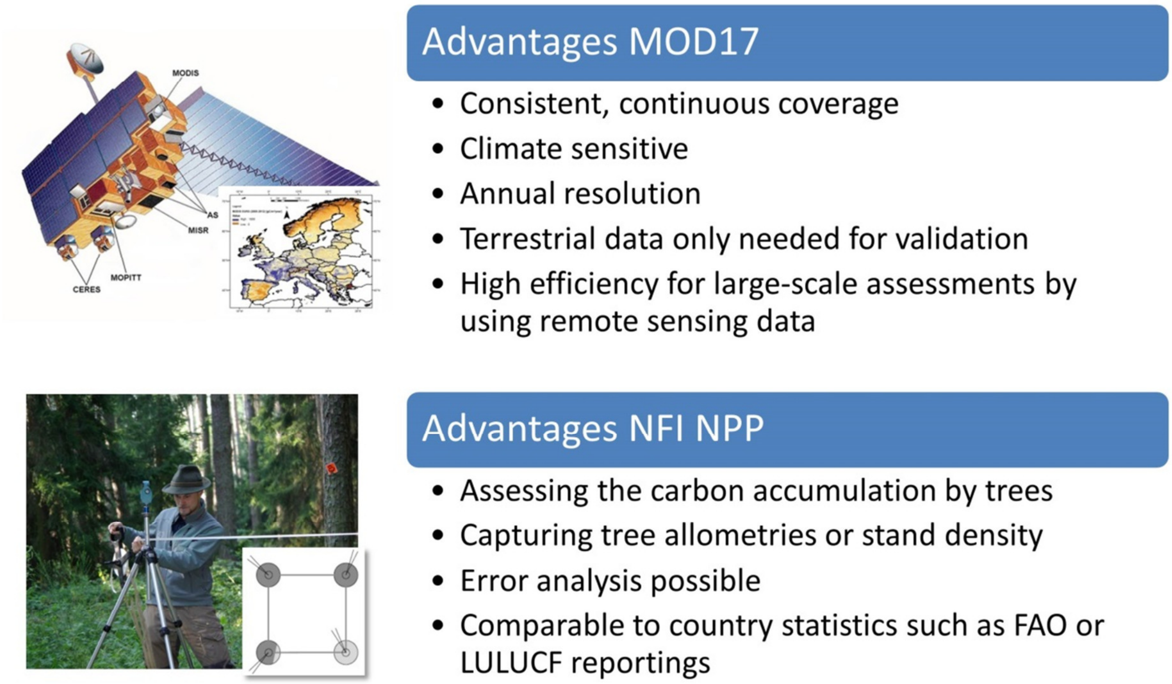

Figure 8: Advantages of MOD17 versus NFI NPP, FAO is the Food and Agriculture Organization of the United Nations and LULUCF stands for land use, land-use change and forestry. Pictures used with courtesy from NASA (top) and Bundesamt und Forschungszentrum für Wald (bottom)

The MOD17 algorithm exhibits the unique advantage in providing spatially explicit NPP with annual resolution using a consistent methodology. While the primary 8-day estimates are usually aggregated to annual values, it is also possible to compute inter-annual, seasonal NPP. The algorithm is sensitive to climate and incorporates the response of vegetation due to changes in the environment via the remotely sensed LAI and FPAR maps. Terrestrial data is only needed to validate the input data and the NPP results. Field data could also potentially be used to recalibrate the parameters of the Biome-property-lookup-tables. By using satellite remote sensing data and climate data, large-scale information can be obtained in a highly cost-efficient way.

An important feature, which makes NPP using terrestrial NFI data unique, is its ability to assess the actual carbon accumulation by trees on the ground. This permits evaluating

MOD17 results and quantifying the amount of carbon allocated into trees considering local differences in wood density or biomass allometries (Appendix 7.2). Additionally, field assessments are able to describe the forest structure. Error analysis is possible to quantify the reliability of the estimations (mean ± standard error), since NFI data is collected using sample plots on a systematic grid. Forest inventory systems were established to monitor forest resources such as tree carbon stocks (Tomppo et al., 2010). National country statistics and reports for FAO, Kyoto or LULUCF (Land use Land-use Change and forestry) traditionally use carbon accumulation assessed from NFI data. Thus carbon increment from NFI data is conceptually comparable with such statistics. Although collecting field data is labor-intensive especially due to travel costs between inventory plots, the procedure of collecting information on the ground is rather simple such as diameter and tree height measurements.

The new dataset MODIS EURO can be used to study NPP and its components across Europe in more detail. Each of the components of NPP, carbon increment, litter fall and fine root activity, account each for approximately a third of total NPP. With forest inventory data we can analyze carbon increment, but further research and other data sources are needed to understand the importance and variation of litter fall and fine root turnover. The model employed in this study (Liu et al., 2004) is not able to fully explain the observed variation in litter fall because the litter fall estimations of this study have a substantially lower variation than observations of litter fall. A more mechanistic, process-oriented or biological-constrained approach could be useful in this context, for instance by using remote-sensing Leaf Area Index (He et al., 2012) or foliage biomass (Härkönen et al., 2011; Ťupek et al., 2015), which has to be validated with independent observations.

MOD17 can be used with other current available or upcoming data products as well, such as more accurate climate data, Leaf Area Index or land cover maps. This is especially important, since it is unknown how long data from the MODIS sensor will be available. The satellites carrying the MODIS sensor were launched in 1999 (Terra) and 2001 (Aqua) and their design life time and planned mission duration was 6 years (Parkinson, 2003). Besides ensuring continuous coverage with data, using new data could also enhance the MOD17 predictions, for instance through the higher spatial resolution of Landsat 8 and its sensor Operational Land Image (OLI) or the Sentinel satellites from the Copernicus Programme.

The MODIS EURO dataset can be used for climate impact studies both on forest and not-forest vegetation such as crops or shrub-lands. Analysis of NPP anomalies will deepen the understanding of spatial patterns in environmental stress and mortality, as outlined by a global study on drought impacts (Zhao and Running, 2010). Consistent NPP information is useful when linking remote sensing and terrestrial data (Moreno et al., 2016) for instance to obtain large-scale forest information such as growing stock or tree carbon. Such information can in turn be used for assessing the potential biomass supply for the bio-based economy (McCormick and Kautto, 2013). Understanding and combining remotely sensed satellite data with terrestrial field data could push forward and revolutionize our insights in the processes of our planet.

5 References

Assmann, E., 1970. The Principles of Forest Yield Study. Pergamon Press: New York, USA.

Bechtold, W.A., Patterson, P.L. (eds), 2005. The Enhanced Forest Inventory and Analysis Program — National Sampling Design and Estimation Procedures. Gen. Tech. Rep. SRS-80, 85.

Berg, B., Meentemeyer, V., 2001. Litter fall in some European coniferous forests as dependent on climate: a synthesis. Can. J. For. Res. 31, 292–301. doi:10.1139/cjfr-31-2-292

Bitterlich, W., 1948. Die Winkelzaehlprobe. Allg. Forst- und Holzwirtschaftliche Zeitung 59, 4–5.

Brang, P., 2001. Resistance and elasticity: promising concepts for the management of protection forests in the European Alps. For. Ecol. Manage. 145, 107–119. doi:10.1016/S0378-1127(00)00578-8

Cannell, M., Thornley, J., 2000. Modelling the Components of Plant Respiration: Some Guiding Principles. Ann. Bot. 85, 45–54. doi:10.1006/anbo.1999.0996

Cienciala, E., Tatarinov, F.A., 2006. Application of BIOME-BGC model to managed forests. For. Ecol. Manage. 237, 252–266. doi:10.1016/j.foreco.2006.09.086

Clark, D., Brown, S., Kicklighter, D.W., Chambers, J.Q., Thomlinson, J.R., Ni, J., 2001. Measuring Net Primary Production in Forests: Concepts and Field Methods. Ecol. Appl. 11, 356. doi:10.2307/3060894

Finér, L., Ohashi, M., Noguchi, K., Hirano, Y., 2011. Fine root production and turnover in forest ecosystems in relation to stand and environmental characteristics. For. Ecol. Manage. 262, 2008–2023. doi:10.1016/j.foreco.2011.08.042

FOREST EUROPE, 2015. State of Europe's Forests 2015 314.

Friedlingstein, P., Joel, G., Field, C.B., Fung, I.Y., 1999. Toward an allocation scheme for global terrestrial carbon models. Glob. Chang. Biol. 5, 755–770. doi:10.1046/j.1365-2486.1999.00269.x

Hansen, M., Potapov, P., Moore, R., 2013. High-resolution global maps of 21st-century forest cover change. Science (80-.). 134, 850–854. doi:10.1126/science.1244693

Härkönen, S., Lehtonen, A., Eerikäinen, K., Peltoniemi, M., Mäkelä, A., 2011. Estimating forest carbon fluxes for large regions based on process-based modelling, NFI data and Landsat satellite images. For. Ecol. Manage. 262, 2364–2377. doi:10.1016/j.foreco.2011.08.035

Hasenauer, H., Eastaugh, C.S., 2012. Assessing Forest Production Using Terrestrial Monitoring Data. Int. J. For. Res. 1–8. doi:10.1155/2012/961576

Hasenauer, H., Merganicova, K., Petritsch, R., Pietsch, S.A., Thornton, P.E., 2003. Validating daily climate interpolations over complex terrain in Austria. Agric. For. Meteorol. 119, 87–107. doi:10.1016/S0168-1923(03)00114-X

Hasenauer, H., Petritsch, R., Zhao, M., Boisvenue, C., Running, S.W., 2012. Reconciling satellite with ground data to estimate forest productivity at national scales. For. Ecol. Manage. 276, 196–208. doi:10.1016/j.foreco.2012.03.022

He, L., Chen, J.M., Pan, Y., Birdsey, R., Kattge, J., 2012. Relationships between net primary productivity and forest stand age in U.S. forests. Global Biogeochem. Cycles 26, 1–19. doi:10.1029/2010GB003942

Heinsch, F.A., Running, S.W., Kimball, J.S., Nemani, R.R., Davis, K.J., Bolstad, P.V., Cook, B.D., Desai, A.R., Ricciuto, D.M., Law, B.E., Oechel, W.C., Wofsy, S.C., Dunn, A.L., Munger, J.W., Baldocchi, D.D., Hollinger, D.Y., Richardson, A.D., Stoy, P.C., Siqueira, M.B.S., Monson, R.K., Burns, S.P., Flanagan, L.B., 2006. Evaluation of remote sensing based terrestrial productivity from MODIS using regional tower eddy flux network observations. IEEE Trans. Geosci. Remote Sens. 44, 1908–1925. doi:10.1109/TGRS.2005.853936

Helmisaari, H.-S., Makkonen, K., Kellomäki, S., Valtonen, E., Mälkönen, E., 2002. Below- and above-ground biomass, production and nitrogen use in Scots pine stands in eastern Finland. For. Ecol. Manage. 165, 317–326. doi:10.1016/S0378-1127(01)00648-X

IPCC, 2006. Good Practice Guidance for Land Use, Land-Use Change and Forestry, CHAPTER 4 FOREST, in: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds.). IGES, Japan, p. 83.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J.J., Fiorino, M., Potter, G.L., 2002. NCEP–DOE AMIP-II Reanalysis (R-2). Bull. Am. Meteorol. Soc. 83, 1631–1643. doi:10.1175/BAMS-83-11-1631

Kändler, G., Bösch, B., 2013. Methodenentwicklung für die 3. Bundeswaldinventur: Modul 3 Überprüfung und Neukonzeption einer Biomassefunktion - Abschlussbericht. Tech. Rep. FVA-BW 1–72.

Krajicek, J., Brinkham, K., Gingrich, S., 1961. Crown Competition - A Measure of Density. For. Sci. 7, 35–42.

Liu, C., Westman, C.J., Berg, B., Kutsch, W., Wang, G.Z., Man, R., Ilvesniemi, H., 2004. Variation in litterfall-climate relationships between coniferous and broadleaf forests in Eurasia. Glob. Ecol. Biogeogr. 13, 105–114. doi:10.1111/j.1466-882X.2004.00072.x

Malhi, Y., Doughty, C., Galbraith, D., 2011. The allocation of ecosystem net primary productivity in tropical forests. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 366, 3225–45. doi:10.1098/rstb.2011.0062

McCormick, K., Kautto, N., 2013. The Bioeconomy in Europe: An Overview. Sustainability 5, 2589–2608. doi:10.3390/su5062589

Monteith, J., 1972. Solar Radiation and Productivity in Tropical Ecosystems. J. Appl. Ecol. 9, 747–766.

Moreno, A., Hasenauer, H., 2015. Spatial downscaling of European climate data. Int. J. Climatol. doi:10.1002/joc.4436

Moreno, A., Neumann, M., Hasenauer, H., 2016. Optimal resolution for linking remotely sensed and forest inventory data in Europe. Remote Sens. Environ. 183, 109–119. doi:10.1016/j.rse.2016.05.021

Olson, R.J., Johnson, K.R., Zheng, D.L., Scurlock, J.M.O., 2001. Global and Regional Ecosystem Modeling: Databases of Model Drivers and Validation Measurements. ORNL/TM-2001/196.

Pan, Y., Birdsey, R., Fang, J., Houghton, R., Kauppi, P., Kurz, W., Phillips, O., Lewis, S., Canadell, J., Ciais, P., Jackson, R., Pacala, S., McGuire, D., Piao, S., Rautainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the World's forests. Science (80-.). 333, 988–992.

Parkinson, C.L., 2003. Aqua: an earth-observing satellite mission to examine water and other climate variables. IEEE Trans. Geosci. Remote Sens. 41, 173–183. doi:10.1109/TGRS.2002.808319

Petritsch, R., Hasenauer, H., Pietsch, S.A., 2007. Incorporating forest growth response to thinning within biome-BGC. For. Ecol. Manage. 242, 324–336. doi:10.1016/j.foreco.2007.01.050

Phillips, O., Hansen, A., Flather, C., 2008. Evaluating the species energy relationship with the newest measures of ecosystem energy: NDVI versus MODIS primary production. Remote Sens. Environ. 112, 4381–4392. doi:10.1016/j.rse.2008.08.002

Phillips, O., Malhi, Y., Higuchi, N., Laurance, W., Nunez, P., Vasquez, R., Laurance, S., Ferreira, L., Stern, M., Brown, S., Grace, J., 1998. Changes in the Carbon Balance of Tropical Forests: Evidence from Long-Term Plots. Science (80-.). 282, 439–442. doi:10.1126/science.282.5388.439

Pietsch, S.A., Hasenauer, H., Thornton, P.E., 2005. BGC-model parameters for tree species growing in central European forests. For. Ecol. Manage. 211, 264–295. doi:10.1016/j.foreco.2005.02.046

Potter, C., Klooster, S., Genovese, V., Hiatt, C., Boriah, S., Kumar, V., Mithal, V., Garg, A., 2012. Terrestrial Ecosystem Carbon Fluxes Predicted from MODIS Satellite Data and Large-Scale Disturbance Modeling. Int. J. Geosci. 03, 469–479. doi:10.4236/ijg.2012.33050

Pötzelsberger, E., Wolfslehner, B., Hasenauer, H., 2015. Climate change impacts on key forest functions of the Vienna Woods. Eur. J. For. Res. 134, 481–496. doi:10.1007/s10342-015-0866-2

Quegan, S., Beer, C., Shvidenko, A., Mccallum, I., Handoh, I.C., Peylin, P., Rödenbeck, C., Lucht, W., Nilsson, S., Schmullius, C., 2011. Estimating the carbon balance of central Siberia using a landscape-ecosystem approach, atmospheric inversion and Dynamic Global Vegetation Models. Glob. Chang. Biol. 17, 351–365. doi:10.1111/j.1365-2486.2010.02275.x

Raich, J., Nadelhoffer, K., 1989. Belowground carbon allocation in forest ecosystems: global trends. Ecology 70, 1346–1354.

Reineke, L., 1933. Perfecting a stand-density index for even-aged forests. J. Agric. Res. 46, 627–638.

Roy, J., Saugier, B., Mooney, H., 2001. Terrestrial global productivity. San Diego, CA: Academic Press.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M., Hashimoto, H., 2004. A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. Bioscience 54, 547. doi:10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2

Running, S.W., Zhao, M., 2015. User 's Guide Daily GPP and Annual NPP (MOD17A2/A3) Products NASA Earth Observing System MODIS Land Algorithm Version 3.0, 10/7/2015 28.

Scurlock, J.M., Olson, R.J., 2002. Terrestrial net primary productivity A brief history and a new worldwide database. Environ. Rev. 10, 91–109. doi:10.1139/a02-002

Seidl, R., Schelhaas, M.-J., Rammer, W., Verkerk, P.J., 2014. Increasing forest disturbances in Europe and their impact on carbon storage. Nat. Clim. Chang. 4, 806–810. doi:10.1038/nclimate2318

Smith, W.K., Zhao, M., Running, S.W., 2012. Global Bioenergy Capacity as Constrained by Observed Biospheric Productivity Rates. Bioscience 62, 911–922. doi:10.1525/bio.2012.62.10.11

Thom, D., Seidl, R., 2015. Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. Biol. Rev. 1–22. doi:10.1111/brv.12193

Thornton, P.E., 1998. Description of a numerical simulation model for predicting the dynamics of energy, water, carbon and nitrogen in a terrestrial ecosystem. Ph.D. thesis, University of Montana, Missoula.

Thornton, P.E., Running, S.W., 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. Agric. For. Meteorol. 93, 211–228. doi:10.1016/S0168-1923(98)00126-9

Thurnher, C., Eastaugh, C.S., Hasenauer, H., 2014. A thinning routine for large-scale biogeochemical mechanistic ecosystem models. For. Ecol. Manage. 320, 56–69. doi:10.1016/j.foreco.2014.02.028

Thurnher, C., Gerritzen, T., Maroschek, M., Lexer, M.J., Hasenauer, H., 2013. Analysing different carbon estimation methods for Austrian forests. Austrian J. For. Sci. 130, 141–166.

Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R., 2010. National Forest Inventories: Pathways for common reporting. Springer, Berlin, Germany.

Ťupek, B., Mäkipää, R., Heikkinen, J., Peltoniemi, M., Ukonmaanaho, L., Hokkanen, T., Nöja, P., Nevalainen, S., Lindgren, M., Lehtonen, A., 2015. Foliar turnover rates in Finland — comparing estimates from needle-cohort and litterfall-biomass methods. Boreal Environ. Res. 20, 283–304.

Turner, D.P., Ritts, W.D., Cohen, W.B., Gower, S.T., Running, S.W., Zhao, M., Costa, M.H., Kirschbaum, A. a., Ham, J.M., Saleska, S.R., Ahl, D.E., 2006. Evaluation of MODIS NPP and GPP products across multiple biomes. Remote Sens. Environ. 102, 282–292. doi:10.1016/j.rse.2006.02.017

Waring, R., Running, S.W., 2007. Forest Ecosystems: Analysis at Multiple Scales. Academic Press, San Diego.

White, M.A., Thornton, P.E., Running, S.W., Nemani, R.R., 2000. Parameterization and Sensitivity Analysis of the BIOME–BGC Terrestrial Ecosystem Model: Net Primary Production Controls. Earth Interact. 4, 1–85. doi:10.1175/1087-3562(2000)004<0003:PASAOT>2.0.CO;2

Yang, W., Tan, B., Huang, D., Rautiainen, M., Shabanov, N.V., Wang, Y., Privette, J.L., Huemmrich, K.F., Fensholt, R., Sandholt, I., Weiss, M., Ahl, D.E., Gower, S.T., Nemani, R.R., Knyazikhin, Y., Myneni, R.B., 2006. MODIS leaf area index products: from validation to algorithm improvement. IEEE Trans. Geosci. Remote Sens. 44, 1885–1898. doi:10.1109/TGRS.2006.871215

Zhao, M., Heinsch, F.A., Nemani, R.R., Running, S.W., 2005. Improvements of the MODIS terrestrial gross and net primary production global data set. Remote Sens. Environ. 95, 164–176. doi:10.1016/j.rse.2004.12.011

Zhao, M., Running, S.W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329, 940–943. doi:10.1126/science.1192666

Zhao, M., Running, S.W., Nemani, R.R., 2006. Sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. J. Geophys. Res. 111, G01002. doi:10.1029/2004JG000004

6 List of figures

7 Appendix

7.1 Paper 1

Neumann, M., Zhao, M., Kindermann, G., & Hasenauer, H. (2015). Comparing MODIS Net Primary Production Estimates with Terrestrial National Forest Inventory Data in Austria. Remote Sensing, 7(4), 3878–3906. http://doi.org/10.3390/rs70403878

Remote Sens. **2015**, *7*, 3878-3906; doi:10.3390/rs70403878

OPEN ACCESS

remote sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Article

Comparing MODIS Net Primary Production Estimates with Terrestrial National Forest Inventory Data in Austria

Mathias Neumann [1,*], Maosheng Zhao [2], Georg Kindermann [3] and Hubert Hasenauer [1]

[1] Institute of Silviculture, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Vienna, Peter-Jordan-Str. 82, A-1190 Vienna, Austria; E-Mail: hubert.hasenauer@boku.ac.at

[2] Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA; E-Mail: zhaoms@umd.edu

[3] Natural Hazards and Landscape, Department of Forest Growth and Silviculture, Federal Research and Training Centre for Forests, Vienna, Seckendorff-Gudent-Weg 8, A-1130 Vienna, Austria; E-Mail: georg.kindermann@bfw.gv.at

* Author to whom correspondence should be addressed; E-Mail: mathias.neumann@boku.ac.at; Tel.: +43-1-47654-4078; Fax: +43-1-47654-4092.

Academic Editors: Randolph H. Wynne and Prasad S. Thenkabail

Received: 11 December 2014 / Accepted: 17 March 2015 / Published: 1 April 2015

Abstract: The mission of this study is to compare Net Primary Productivity (NPP) estimates using (i) forest inventory data and (ii) spatio-temporally continuous MODIS (MODerate resolution Imaging Spectroradiometer) remote sensing data for Austria. While forest inventories assess the change in forest growth based on repeated individual tree measurements (DBH, height *etc.*), the MODIS NPP estimates are based on ecophysiological processes such as photosynthesis, respiration and carbon allocation. We obtained repeated national forest inventory data from Austria, calculated a "ground-based" NPP estimate and compared the results with "space-based" MODIS NPP estimates using different daily climate data. The MODIS NPP estimates using local Austrian climate data exhibited better compliance with the forest inventory driven NPP estimates than the MODIS NPP predictions using global climate data sets. Stand density plays a key role in addressing the differences between MODIS driven NPP estimates *versus* terrestrial driven inventory NPP estimates. After addressing stand density, both results are comparable across different scales. As forest management changes stand density, these findings suggest that management issues are important in understanding the observed discrepancies between MODIS and terrestrial NPP.

Keywords: forest; NPP; management; inventory; MODIS; Austria

1. Introduction

Productivity estimates are important measures to characterize the mass budget of a forest ecosystem. In this context, the carbon balance and carbon storage of the earth's ecosystems and their spatial and temporal development is important. A measure for the carbon flux is Net Primary Production (NPP) which describes the carbon uptake by vegetation through photosynthesis. In principle, large scale carbon measures are currently provided by National Forest Inventories, flux towers and remotely sensed methods, such as the MODIS (MODerate resolution Imaging Spectroradiometer) NPP algorithm.

Researchers in previous studies have compared MODIS satellite-driven NPP with NPP estimates derived using terrestrial data [1–3]. Shvidenko *et al.* [1] found that for Russia the two estimates comply on average. Pan *et al.* [2] observed deviations between MODIS and terrestrial NPP using inventory data from the mid-Atlantic region of the USA and suggest that differences in water availability explain this variation. Hasenauer *et al.* [3] also found similar deviations and concluded that the different data sources for predicting NPP compare well after addressing forest management impacts. The authors further suggest that a combination of "ground-based" forest data with "space-based" forest productivity estimates would utilize the advantages of both methods.

National forest inventories are established for a continuous monitoring of the forest situation across countries. They are often based on a systematic permanent grid design. For each sample plot, a limited number of trees compared to the total forest area [4] is recorded to provide information on the standing growing stock, increment, species composition and other information needs relevant for forest management [5,6]. Such forest inventories are usually repeated every five to 10 years. Examples for national long term forest inventories can be found in countries such as Austria, Norway, Finland, Germany, *etc.* [4].

The MODIS NPP algorithm is based on remote sensing techniques and was developed for estimating large-scale forest productivity [7,8]. MODIS is a satellite-mounted sensor operated by the National Aeronautics and Space Administration of the United States (NASA) that provides large-scale information on global dynamics and processes. The MODIS algorithm MOD17 uses satellite data, climate data and biophysical properties of various cover types to derive eight-day GPP (Gross Primary Production) and NPP estimates on a 1 × 1 km pixel resolution. This data source may be seen as a "space-based" approach and provides continuous coverage across the global land area to assess forest productivity.

The differences of the two approaches are as follows:

(i) The MODIS satellite-driven NPP is based on the principles of carbon uptake following light use efficiency logic [9] using a simplification of the NPP algorithms implemented in BIOME-BGC [10]. According to the hypothesis put forth by Hasenauer *et al.* [3] the MODIS NPP algorithm assumes a fully stocked forest for a given vegetation class or biome type and provides eight-day results NPP estimates on a 1 × 1 km grid.

(ii) NPP estimates derived from terrestrial forest growth data (permanent sampling plots or forest inventory data) employ biomass expansion factors or biomass functions based on repeated observations such as breast height diameter (*dbh*) and/or tree height (*h*). Depending on the measurement interval the derived increment results represent a mean periodic average. Since this method is based on individual tree observations (e.g., *dbh*, *h*), potential changes in tree growth due to stand age, stand density or environmental effects such as weather patterns or CO_2 concentration are included as they affect *dbh* and *h* development.

Several studies have compared satellite to terrestrial inventory data [1,2,11–16], however, no analysis has compared forest inventory data to MODIS NPP in Central Europe.

The mission of this paper is to compare space-based MODIS satellite-driven NPP data to ground-based inventory data driven NPP estimates using the Austrian National Forest Inventory Data. This Forest Inventory is based on a systematic permanent grid design with repeated observations [5,17]. The objectives of our study are:

(i) obtain MODIS NPP estimates (using different climate data) for comparing the results with terrestrial-driven NPP estimates
(ii) examine the potential effects of stand density, MODIS land cover types, stand age, species composition, ecoregion and elevation on NPP estimates by method.

2. Methods

2.1. MODIS NPP—"Space Based" Approach

We use the algorithms for the MODIS products MOD17A2 and MOD17A3, which provide global Gross and Net Primary Production (GPP, NPP) estimates for a 1 × 1 km pixel on an eight-day time-step [7,8]. The algorithm calculates *GPP* as

$$GPP = LUE_{\max} \times 0.45 \times SWrad \times FPAR \times f_{VPD} \times f_{Tmin} \quad (1)$$

where LUE_{max} is the maximum light use efficiency, *SWrad* is the short wave solar radiation load at the surface of which 45% is photosynthetically active, *FPAR* the fraction of absorbed PAR (Photosynthetic Active Radiation) from the MOD15 product, and f_{VPD} and f_{Tmin}, which are multipliers between 0 and 1 addressing water stress due to vapor pressure deficit (*VPD*) and low temperature limits (T_{min}, daily minimum temperature). Values that determine the LUE_{max} and the T_{min} and *VPD* multipliers limits are stored in the Biome Property Type Look Up Tables (BPLUT) and cover five forest biome types: (i) ENF—Evergreen Needleleaf Forest, EBF—Evergreen Broadleaf Forest, DNF—Deciduous Needleleaf forest, DBF—Deciduous Broadleaf Forest, and MF—Mixed Forests ([3] for the model coefficients).

Annual Net Primary Production (*NPP*) is calculated from Gross Primary Production (*GPP)* by subtracting the autotrophic respiration components (i) maintenance respiration R_m and (ii) growth respiration R_g and summing up over a year to get annual values:

$$NPP = \sum_{i=1}^{365} GPP - R_m - R_g \quad (2)$$

With 366 days for leap years, R_m and R_g are calculated using leaf area index (*LAI*) from the MOD15 product, climate data, and parameters from the BPLUTs. For further details, please refer to the original literature [7,8].

2.2. Terrestrial NPP—"Ground Based" Approach

NPP can be calculated as the sum of biomass increment, mortality, and turnover of foliage and fine roots [18]. We employ volume and biomass functions along with repeated observations to get increment and mortality. Turnover of foliage, including mortality of other plant components, is represented by a climate-sensitive litterfall model [19]. The advantage of this model is the requirement of little input data and assumptions compared to calculating litterfall using biomass and turnover rates [18]. We lack a reliable model for fine root turnover in Austria and we assume that carbon uptake of fine roots is already incorporated in litterfall and coarse root increment.

2.2.1. Increment Estimation

Originally forest growth data was intended to provide volume increment in m^3/ha per growth period [6]. The growth period varies depending on the temporal measurement interval of terrestrial sample plots. We develop a consistent and comparable terrestrial productivity data set by deriving NPP estimates using forest inventory data starting with:

$$NPP = inc_{plot} + C_{Litter} \tag{3}$$

where C_{Litter} is the flow of dry carbon into litter [gC/m^2/year] as defined in Equation (9), inc_{plot} is the dry carbon increment of trees (above and below ground biomass) [gC/m^2/year] resulting from repeated plot observations taken at the end C_{Forest_2} minus those observations taken at the beginning C_{Forest_1} of the growth period

$$inc_{plot} = C_{Forest\_2} - C_{Forest\_1} \tag{4}$$

Equation (4) gives the common way to calculate increment for repeated observations and terrestrial plot data, the carbon values (C_{Forest_1} and C_{Forest_2}) being the sum of the tree carbon estimates calculated from repeatedly measured diameters at breast height (*dbh*) and tree heights (*h*) for a given tree. The National Forest Inventory of Austria use a combined recording system with (i) fixed area plots for trees ranging in *dbh* from 5 cm to 10.4 cm and (ii) an angle count sampling system [20] for all trees with a *dbh*>10.4 cm. In angle count sampling the stem number represented by a sample tree changes by diameter and thus the represented tree population changes too, which differs from fixed-area plots (e.g., used in the National Forest Inventory system of Norway [4] or permanent research plots like the "Austrian Waldboden-Zustandsinventur" [21]). This affects volume or biomass stocks as well as periodic increment and thus the results from fixed area plot sampling are quite different compared to angle count sampling [6].

In principle, three different approaches in estimating increment form angle count sample data exist: (i) the starting value method; (ii) the end value method and (iii) the difference method.

For details we refer to Schieler [22] and Hasenauer and Eastaugh [6]. All three methods are statistically sound and deliver unbiased results [23,24].

For our study, we use the starting value method, which is also used by the Austrian National Forest Inventory:

$$inc_{plot} = \Sigma inc_{survivors} + \Sigma inc_{ingrowth} \tag{5}$$

where inc_{plot} is the periodic increment on each plot resulting from $\sum inc_{survivors}$ the "survivor trees", which were also sampled in the last measurement, and $\sum inc_{ingrowth}$ the "ingrowth trees" or trees, which have reached the threshold during the re-measurement period and are thus selected [6,22,25]. The carbon increments of the "survivor trees" are calculated as

$$\Sigma inc_{survivors} = \Sigma((C_2 - C_1) \times nrep_1) \tag{6}$$

and the carbon increments of the "ingrowth trees" are

$$\Sigma inc_{ingrowth} = \Sigma(C_2 \times nrep_2) \tag{7}$$

$nrep_i$ is the "represented" stem number per hectare at time 1 or time 2 and depends on the basal area factor k and the individual tree basal area g (for trees with dbh >10.4 cm $nrep_i = k/g$ and for trees with dbh 5–10.4 cm $nrep_i$ = 10,000/(2.6^{2}π) = 470.9). C_i are the carbon estimates for this "representative" tree at time 1 or time 2.

2.2.2. Carbon Estimation

The carbon increment calculation requires carbon estimates for each tree on a given inventory plot. For our study, we use the same method as applied by the Institute of Forest Inventory, Federal Research Centre for Forest, the agency responsible for the National Forest Inventory in Austria. The total dry carbon tree estimates of a single tree, C_i, can be calculated as follows:

$$C_i = CC \times (dsm + dbm + dfm + drm) \tag{8}$$

where CC is the carbon content and considered to be 0.5 for all species [26], dsm is the dry stem mass including bark, dbm the dry branch mass, dfm the dry foliage mass and drm the dry root mass with a diameter >2 mm.

The calculation of tree biomass is done using volume and biomass functions developed and used in Austria (see Appendix).

2.2.3. Litterfall Estimation

The last compartment for estimating NPP from terrestrial data in Equation (3) is the carbon flow into litter (C_{Litter}). We select the method proposed by Liu *et al.* [19], which calculates the forest litter fall including all aboveground plant compartments according to Equations (9) and (10):

$$C_{Litter} = CC \times LF \tag{9}$$

$$\ln(LF) = 2.296 + 0.741 \times \ln(T + 10) + 0.214 \times \ln(P) \tag{10}$$

C_{Litter} is the carbon in litterfall [gC/m^2/year], CC carbon content equal 0.5 [26], LF total litter fall [g·dry·biomass/m^2/year], T the mean annual temperature 2000–2010 [°C], P mean annual precipitation 2000–2010 [mm].

2.2.4. Stand Density Calculation

Forest management reduces stand density, stand density affects individual tree growth and thus the "ground-based" terrestrial NPP predictions [3]. For characterizing the stand density variation on the inventory plots we select the following two commonly used competition measures: *CCF* the crown competition factor [27] with Equation (11) and *SDI* the stand density index [28] with Equation (14):

$$CCF = \frac{\sum PCA_i \times nrep_i}{A} \times 100\% \quad (11)$$

Where PCA_i the species-specific potential crown area [m^2] according to Equations (12) and (13)

$$PCA_i = (\frac{CW_i}{2})^2 \times \pi \quad (12)$$

$$CW_i = e^{c_0 + c_1 \times \ln(dbh)} \quad (13)$$

with $nrep_i$ as the representative stem number [ha^{-1}] and A the observed area. CW_i is the potential crown width [m] and *dbh* the diameter at breast height [cm]. The PCA_i defines the crown area of a tree assuming open-grown conditions (the tree never experienced competition). Coefficients c_0 and c_1 in Equation (13) are derived from open-grown tree dimensions [29] and are given in Table A6 in the Appendix.

The Stand Density Index (*SDI*) is calculated according to Reinecke [28]:

$$SDI = N\left(\frac{dg}{25}\right)^{1.605} \quad (14)$$

where N is the number of trees per unit area [ha^{-1}], *dg* is the quadratic mean stand diameter at breast height [cm], 25 is a reference *dg* and 1.605 is the slope parameter for the maximum carrying capacity. The SDI has been proven to be site and age independent and SDImax defines an estimate for the carrying capacity of a given forest type [30].

2.2.5. Determining the Dominant Tree Species and the Ecoregions

One important aspect of our study is to assess potential effects of tree species on the MODIS and the NFI-driven productivity estimates. A grouping of the dominant tree species is done according to the main relative proportion of the basal area at a given inventory plot. The Norway Spruce (*Picea abies* (L.) Karst) and the Silver Fir (*Abies alba* Mill.), as relatively shade-tolerant species, are combined in one group. The Scots Pine (*Pinus sylvestris* (L.) Karst.) and the European Larch (*Larix decidua* Mill.) are light-demanding pioneer species and are also combined in one group. The two main broadleaf species groups are the Common Beech (*Fagus sylvatica* (L.)) and the Oak (*Quercus spp.*). These four groups cover 89% of the inventory plots. The remaining 11% are dominated by tree species which are aggregated into two groups: other coniferous trees and other broadleaf trees.

Austria has some very distinct biogeographic growth conditions due to the east-west aligned Alps. According to Kilian *et al.* [31], these differences lead to typical ecoregions (see Figure 1) and are characterized by similar environmental, macro-climatic as well as geological conditions leading to differences in potential vegetation. To assess the potential effect of these drivers, we assign the ecoregions to each inventory plot according to the plot location as outlined in Figure 1. With the ecoregions, we then can also examine the effect of geographical location on the results.

3. Data

3.1. Climate Data

Climate data is required as input to the MOD17 algorithms that derive MODIS NPP and for estimating the carbon content in the litterfall with Equations (9) and (10). Daily records of minimum and maximum temperature, precipitation, vapor pressure deficit and incident short wave radiation are interpolated from weather station data using DAYMET, a climate interpolation model [10] adapted and validated for Austrian conditions [32,33]. DAYMET interpolates daily precipitation and minimum and maximum temperatures from surrounding permanent climate stations. Based on the resulting climate data, daily solar radiation and vapor pressure data are calculated [34]. The current version of DAYMET [35] requires longitude, latitude, elevation, slope, aspect and the horizon angle facing east and west for each given plot. The meteorological data for running DAYMET were provided by the Austrian National Weather Center (ZAMG) in Vienna and include daily weather records from 250 stations across Austria since 1961. For our analysis, we generate daily weather data at a 1 × 1 km grid across the country.

For the MODIS NPP calculations we also use two additional climate data sets called "GMAO" and "NCEP2", which are described in the next chapter.

3.2. MODIS Data

The storage system of MODIS data consists of 286 vegetated land tiles covering the whole globe. Each tile covers an area of 1200 × 1200 km or 1.44 million pixels. The MOD17 algorithm provides an eight-day GPP/NPP estimate for each 1 × 1 km pixel. We sum eight-day values to annual. We use the MODIS NPP product developed by Zhao *et al.* [36].

Previous studies showed that the direct use of 1 × 1 km MODIS pixel for validation may be inappropriate [37–39]. Reported reasons are (i) mismatch between MODIS gridded pixels and observations caused by gridding artifacts [38]; (ii) problems in the mixed land cover and surface reflectance information and (iii) uncertainties in the information provided for building the look-up tables [38]. We follow previous studies [3,37–39] and obtain the mean MODIS NPP of a 3 × 3 pixel patch (nine 1 x 1 km pixels) for each inventory plot. Within these 9 pixels we select only forest pixels according to the MOD12Q1 product [8] and the classification system of Friedl *et al.* [40]. Pixels with any other land cover type are ignored. For each of the forest pixels, we take the mean value of the MODIS NPP estimates according to three different climate input data sets provided by:

(1) the NASA Global Modeling and Assimilation Offices (GMAO) at NASA Goddard Space Flight Center with a spatial resolution of 0.5 × 0.67° [41]. MODIS NPP derived from this data set will be referred to as "GMAO".
(2) the daily climate data set called NCEP_DOE_II with a spatial resolution of approx. 1.875 × 1.875° [42,43], referred to as "NCEP2".

(3) Austrian local daily climate data interpolated with DAYMET (see previous chapter) on 1 × 1 km (approx. 0.0083 × 0.0083°) resolution with station data provided by the Austrian National Weather Centre: "ZAMG".

The difference between the MODIS NPP driven by GMAO and NCEP2 is caused by the different global daily climatology drivers and correspondingly modified BPLUT file [44]. The first two data sets are maintained by the Numerical Terra Dynamic Simulation Group (NTSG) at the University of Montana, while the Austrian local climate data are maintained by the Institute of Silviculture at The University of Natural Resources and Life Science, Vienna (BOKU).

From 1 January 2000 to 31 December 2011 for 11 full years all three variants of MODIS NPP estimates are computed. Until February 2000, missing MODIS data is considered negligible. Although the data is available annually, we use the periodic mean annual NPP for these 11 years to have a consistent and comparable temporal scaling with the forest inventory data. The variation between annual and periodic mean MODIS NPP is small (mean standard deviation 37.1 gC/m^2/year) and shows no trend across Austria. The lack of trend and the low variation supports the use of the temporal aggregation.

Figure 1 gives the periodic mean annual MODIS driven NPP (2000–2011) estimates across the country and demonstrates the special feature of a "space-based" satellite-driven approach, providing continuous cover in productivity estimates for every km^2 across Austria.

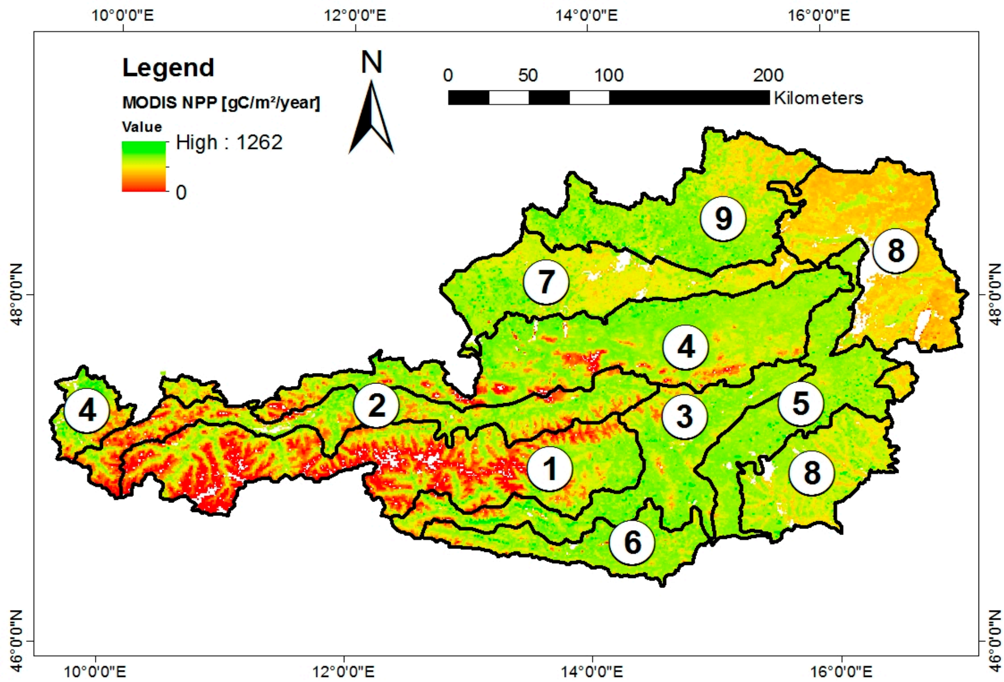

Figure 1. MODIS NPP for Austria calculated with NCEP2-climate data, black lines delineate forest ecoregions [31] used in the analysis.

3.3. Forest Inventory Data

The National Austrian Forest Inventory is based on a systematic permanent grid design of 3.889 × 3.889 km over Austria with a cluster of four inventory plots at each grid point (approx. 22,000 plots and 5500 clusters). One cluster is a square with 200 m length on each side and a plot in each corner. The permanent plots were established during 1981–1985, where each year every 5th cluster was established. The inventory uses a hidden plot design where the center of each plot is marked with a hidden iron stick to eliminate research plot bias [45]. This is important because this procedure ensures that the Forest Inventory is representative for the growing conditions and forest management throughout Austria. The condition of the forest is measured on each plot with an angle count sample plot [20] using a basal area factor of 4 m^2/ha for trees with *dbh* ≥10.4 cm and with a fixed area plot (r = 2.6 m, A = 21.2 m^2) for trees with *dbh* ranging from 5.0 to 10.4 cm.

For details on the plot and sampling design, see Schadauer *et al.* [5] and Gabler and Schadauer [17]. For details on the applied sample methodology and its advantages and constraints, see literature [6,20,22,24,46].

We obtain the two most recent inventory measurements for our study: NFI 6, plot data recorded from 2000 to 2002, and NFI 7, plot data recorded from 2007 to 2009 resulting in a re-measurement interval of seven years [17]. We calculate periodic mean annual increment inc_{plot} with Equations (3)–(5).

Measurements of diameter at breast height (1.3 m) were taken for all sample trees. In NFI 6, tree height and height to the live crown base were only recorded for a subsample of trees on each plot. The missing estimates were estimated by applying dbh-dependent models. In NFI 7, tree height, height to the live crown base and dbh were recorded for every tree [17]. Data are available for approximately 9000 plots. Table 1 shows the summary statistics of the data available from the inventory plots for our analysis.

4. Results and Analysis

For the presented results and figures, the median is used which is less affected by outliers and skewed distributions. In the text the arithmetic mean is given, however, any comparison based on mean values assumes a symmetric distribution of the results and a balanced age class distribution of forests.

4.1. MODIS NPP versus *Terrestrial NPP*

Since three different daily climate data sets are available for deriving MODIS NPP across Austria, we explore the impact of different daily climate data on the resulting MODIS NPP computations. We compute the MOD17 NPP estimates for the years 2000–2011 using three different daily climate data sets: (i) GMAO; (ii) NCEP2 and (iii) ZAMG. For all three settings, the improved method for estimating NPP according to Zhao *et al.* [44] is used.

The mean values for the NPP results using the local climate data set (ZAMG) 568.0 gC/m^2/year (median 579.8 gC/m^2/year, standard deviation 113.6 gC/m^2/year), using the climate data of NCEP2 728.6 gC/m^2/year (median 738.9 gC/m^2/year, standard deviation 59.6 gC/m^2/year) and of GMAO 731.5 gC/m^2/year (median 742.3 gC/m^2/year, standard deviation 79.2 gC/m^2/year) (Figure 2). The NPP estimates result from the computations according to Equations (1) and (2) and the cited references. The varying NPP computation results are due to the differences in the daily climate data sets [44], as all other input parameters were kept constant.

For the same forest inventory plots we calculate the terrestrial NPP according to Equations (3)–(10) and the information given in the Appendix. Note that due to the inventory design the results cover all trees with a *dbh* ≥5 cm. The terrestrial NPP results (NFI) are also presented in Figure 2 and show a mean of 525.2 gC/m^2/year (median 486.3 gC/m^2/year, standard deviation 251.4 gC/m^2/year). The numbers above the boxplots give the sample size. The difference between NFI and MODIS of 222 are the inventory plots, where MODIS classify a land cover other than forest. The root mean square error (RMSE) between MODIS and terrestrial NPP is for ZAMG 276.1 gC/m^2/year, for NCEP2 335.5 gC/m^2/year and for GMAO 340.3 gC/m^2/year.

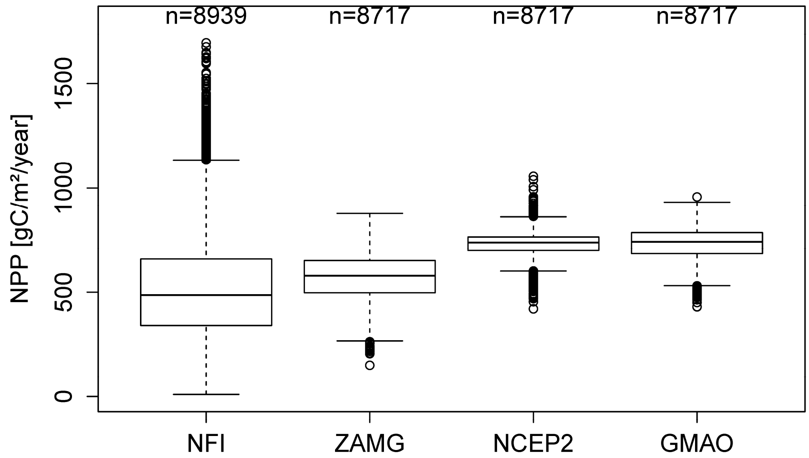

Figure 2. Comparisons of the NPP estimates where (1) *NFI*—the terrestrial NPP; (2) *ZAMG*—MODIS NPP estimates using the daily weather data from the Austrian National Weather Centre; (3) *NCEP2*—MODIS NPP estimates using the daily weather data of the so called NCEP_DOE_II [42], and (4) *GMAO*—MODIS NPP using the daily climate data from NASA Global Modeling and Assimilation Office [41]. The box represents the Median and the 25th and 75th quartile, the whiskers extend to 1.5 of the interquartile range, values outside this range are indicated by circles, and on the top the number of values represented by the boxplots is given.

4.2. Stand Density Effects

MODIS NPP estimates vary by climate input data (ZAMG, NCEP2, GMAO) and are in general higher compared to the terrestrial NPP (NFI in Figure 2). The local daily climate data set provided by the Austrian National Weather Service (ZAMG) exhibits the lowest discrepancy *versus* the terrestrial NPP estimates (RMSE 276.1 gC/m^2/year, difference of medians 93.5 gC/m^2/year, difference of means 42.8 gC/m^2/year).

Forest management reduces stand density [47–52]. Hasenauer *et al.* [3] suggested that stand density explains the observed discrepancies between "space-based" MODIS *versus* "ground-based" NPP estimates. Stand density is important considering that forest management operations change the number of trees, which directly effects the calculation of the terrestrial NPP estimates see Equations (5)–(7). In the MODIS NPP algorithm, on the other hand, forest dynamics are characterized by the two input variables FPAR and LAI, as the land cover type is kept constant. Both variables are derived from spectral properties of the vegetation, in particular the spectral signal of the red and near infrared bands [37,39]. Intensity of forest management in Austria is regulated (crown cover after thinnings of at least 60%, while clearcuts bigger than 0.5 ha need special registration and may not exceed 2 ha) [47]. Thus, it can be assumed that forest management in Austria has only a small and temporary influence on FPAR and LAI. The results of the analysis (not shown) support this as MODIS NPP show no correlation with stand density, while terrestrial NPP clearly does, which will be shown shortly.

For assessing the potential management impacts on the results we obtain for each inventory plot two stand density measures: (i) the *CCF*—Crown Competition Factor according to Krajicek *et al.* [27] Equation (11) as well as (ii) the *SDI*—Stand Density Index according to Reinecke [28] in Equation (14). The mean and the variations across all plots are given in Table 1.

Table 1. Summary statistics of the inventory plots for period 2007–2009 by dominant tree species. Given is mean and in brackets the data range (minimum—maximum). *SDI* the Stand Density Index [28], and *CCF* the Crown Competition Factor [27].

Variable	Spruce, Fir	Larch, Pine	Other Coniferous	Beech	Oak	Other Broadleaf	All
Number of plots	5809	1001	140	886	238	864	8939
Age dominant trees (a)	81 (15–175)	95 (15–175)	122 (15–175)	95 (15–175)	80 (15–165)	51 (15–175)	82 (15–175)
Elevation (m)	1019 (220–2110)	914 (245–2066)	1084 (259–2212)	741 (244–1467)	377 (176–971)	544 (129–1685)	880 (129–2212)
Number of trees (ha^{-1})	1029 (3–10084)	859 (4–6205)	741 (5–3544)	890 (8–9394)	692 (6–5934)	1141 (1–8917)	993 (1–10084)
Stem volume (m^3/ha)	361 (2–1672)	304 (2–1205)	268 (13–726)	329 (2–1382)	220 (8–758)	200 (2–1281)	331 (2–1672)
Basal area (m^2/ha)	36 (1–124)	33 (1–104)	35 (4–79)	33 (1–100)	25 (2–76)	25 (1–107)	34 (1–124)
SDI	738 (36–2618)	665 (38–2086)	679 (48–1705)	655 (36–2066)	512 (49–1523)	553 (36–2649)	697 (36–2649)
CCF	204 (7–1308)	206 (10–969)	188 (7–697)	350 (21–1622)	209 (16–625)	315 (11–1699)	229 (7–1699)

Next, we calculate the differences (Δ*NPP*) between the "space-based" MODIS NPP (using the Austrian daily climate data ZAMG) and the "ground-based" NPP using the NFI data set. After grouping the results by *CCF* and *SDI* classes, the median and the first and third quartile of Δ*NPP versus SDI* and *CCF* class for the total data set are plotted. A direct comparison of terrestrial inventory plots with a MODIS pixel requires the assumption that a plot is actually representative for an area, which is discussed and questioned by previous research [48,49]. However, it allows us to track the effect of stand variables, which would be otherwise impossible.

A distinct stand density related trend is visible with an overestimation of the terrestrial NPP by MODIS NPP at low stand density and an underestimation at high stand density, which is consistent whether using *SDI* or *CCF* (Figure 3).

The MODIS NPP algorithm uses information on the land cover or vegetation type provided by the classification system of the University of Maryland (MODIS Collection 5 global land cover) [8,40]. In total, there are 14 land cover classes, of which five deal with forests and characterize the biophysical properties expressed by the parameters of the Biome Property Look-Up-Tables (BPLUT) [7,8]. These land cover types represent different tree species groups [40] and, due to different coefficients in the BPLUT, affect the MODIS NPP results [8]. Thus, next we are interested if the observed stand density related trends (Figure 3) may differ to MODIS land cover types.

Austria consists of a fragmented landscape, varying forest ownership and distinct historical management impacts. Consequently, many of our 3 × 3 km areas (nine pixels) include several forest land cover classes. To avoid any impact of this "mixture effect" we select only plots which feature nine pixels with only one MODIS land cover type. The land cover types "deciduous needleleaf forest" and "evergreen broadleaf forest" are excluded as there are very few pixel patches that have this land cover type exclusively (one for deciduous needleleaf forest, two for evergreen broadleaf forest).

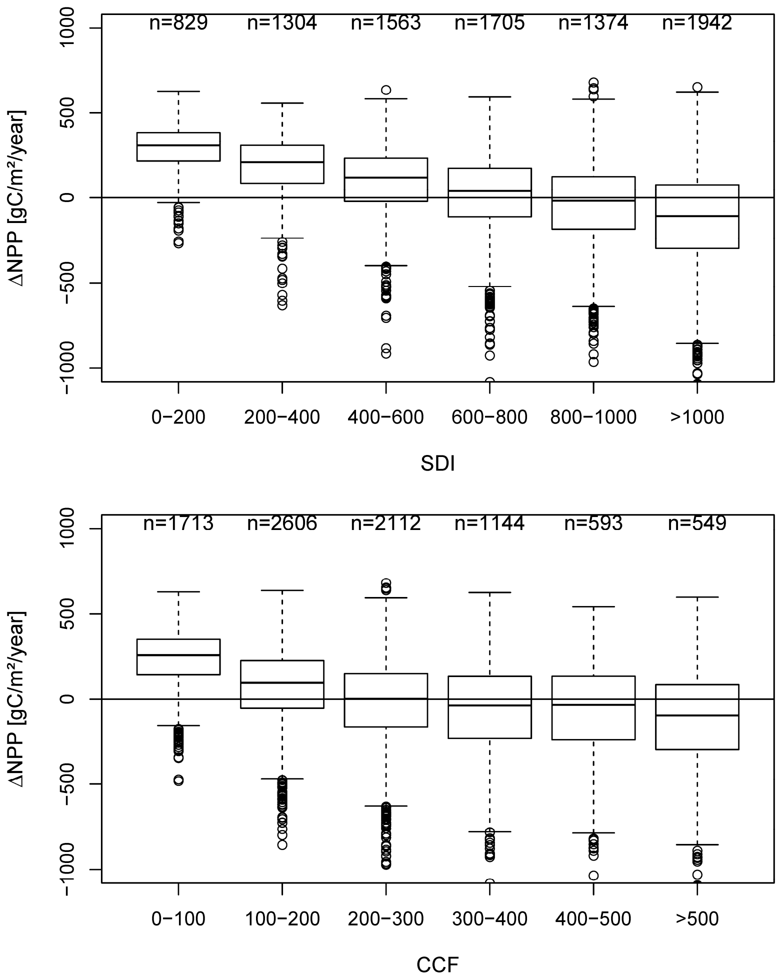

Figure 3. Difference between MODIS NPP and NFI NPP (MODIS minus NFI) grouped by stand density measures: SDI (**top**); CCF (**bottom**). Properties of illustration analogous to Figure 2.

The results for the "deciduous broadleaf forest" (not shown) are similar. To summarize, the results using plots with only one biome type exhibit the same trend when using all data (Figure 3): overestimation of terrestrial NPP by MODIS NPP at low stand density and underestimation at high stand density, which is consistent for both stand density measures (Figure 4).

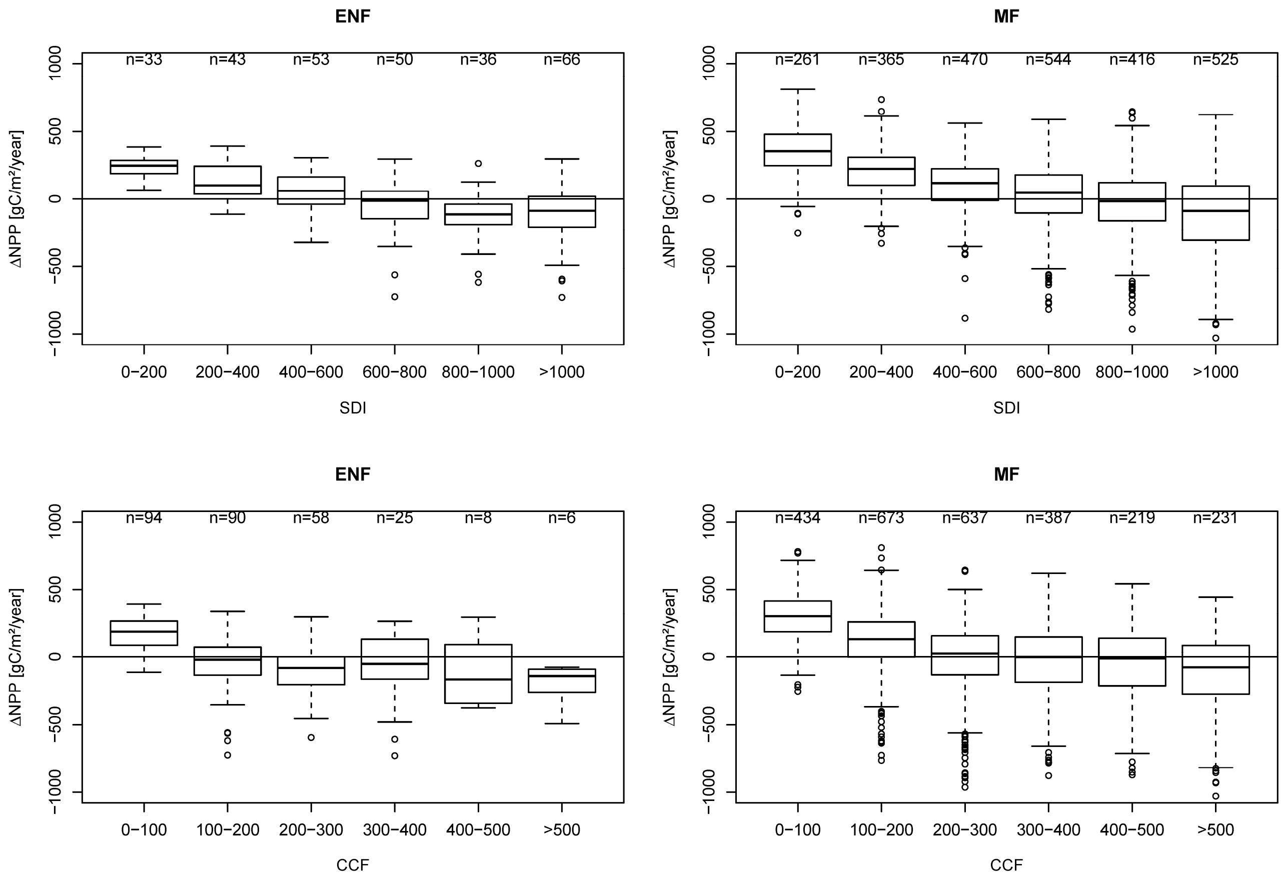

Figure 4. Difference between MODIS NPP and NFI NPP (MODIS minus NFI) grouped by MODIS land cover types (ENF = evergreen needleleaf forest, MF = mixed forest) and stand density measures: SDI (**top**); CCF (**bottom**). Properties of illustration analogous to Figure 2.

4.3. Addressing Stand Density Effects

The results in Figures 3 and 4 show a clear stand density related trend. We apply a logarithmic trend curve to correct for stand density effects similar to Hasenauer *et al.* [3]:

$$\Delta NPP = a + b \times \ln(SDI) \pm \varepsilon \tag{15}$$

$$\Delta NPP = a + b \times \ln(CCF) \pm \varepsilon \tag{16}$$

a and *b* are the corresponding coefficient estimates and ε the remaining error and all other variables as previously defined. We apply Equations (15) and (16) to all data and again separately for the three MODIS forest land cover types relevant for Austrian forests ("evergreen needleleaf forest", "mixed forest" and "deciduous broadleaf forest". Note that the stand density measures *SDI* and *CCF* are calculated based on the stand situation at the end of the growth period. Plotting the results of the fitted trend curves show that all exhibit the same pattern whether they are grouped according to *SDI* or *CCF* (left images in Figure 5). The regression results are given in Table 2.

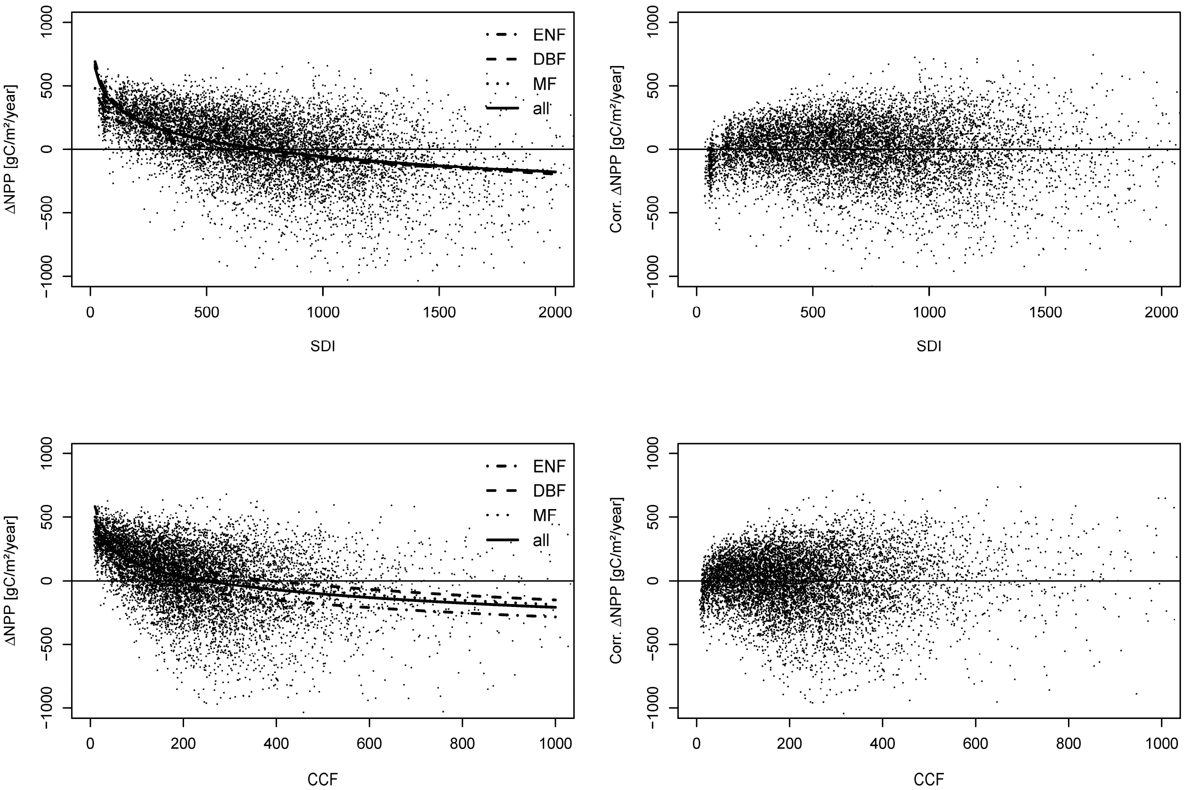

Figure 5. Scatterplots of NPP difference (ΔNPP) and stand density dependent trend curves using SDI (**top left**) and CCF (**bottom left**), the trend curves are calculated for MODIS forest land cover types separately (ENF = evergreen needleleaf forest, DBF = deciduous broadleaf forest, MF = mixed forest) and for all land cover types together (all). The images on the right side (Corr. ΔNPP) show the NPP difference after correcting for stand density given by the trend lines using all plots (all).

Table 2. Coefficients and statistics of trend curves displayed in Figure 5 a,b coefficients for Equations (15) and (16), SE standard error of coefficients, r^2 coefficient of determination, n degrees of freedom.

Depending Variable		**a**	**SE a**	**b**	**SE b**	**r^2**	**n**
SDI	ENF	908.3	83.0	−143.0	13.1	0.30	277
	DBF	1265.8	194.7	−192.2	31.6	0.34	71
	MF	1203.3	38.1	−181.3	6.0	0.26	2516
	all	1181.0	19.4	−178.7	3.0	0.28	8716
CCF	ENF	694.8	60.0	−141.3	12.2	0.33	277
	DBF	951.3	145.1	−159.5	26.5	0.34	71
	MF	841.9	30.1	−148.8	30.1	0.21	2516
	all	812.4	15.1	−147.6	2.9	0.22	8716

A variance analysis reveal no significant differences in the parameter estimates *a* and *b* given in Table 2 between the major forest biome types represented by the MODIS land cover types. This suggests that for Austrian forests no biome type specific parameters are needed (Figure 5).

We remove the stand density bias from MODIS NPP using Equation (15), where *a* equals 1181.0 and *b* −178.7, and Equation (16), where *a* equals 812.4 and *b* −147.6 (Table 2). The detrended MODIS NPP features a mean of 515.5 gC/m^2/year, standard deviation 181.7 gC/m^2/year and compared to terrestrial NPP a RMSE of 227.8 gC/m^2/year. After removing the stand density related trend, the difference between the two NPP assessment methods do not exhibit a bias as shown in the right-hand images in Figure 5 ($SDI\ r^2 \leq 0.01$, $CCF\ r^2 \leq 0.01$) than when using the original MODIS NPP results on the left side of Figure 5.

4.4. Consistency of the NPP Estimates across Scales

From the distinct stand density related trend in Figures 4 and 5, we learn that stand density needs to be taken into consideration to provide consistent and comparable results across scales. To ensure that our findings are also consistent across the heterogeneity of the forests across Austria, we test our data for potential variations according to key forest site and stand parameters: (i) ecoregion; (ii) dominant tree species; (iii) mean stand age and (iv) elevation of a given forest inventory plot.

Austria has very distinct biogeographic growth conditions due to the east-west alignment of the Alps. According to Kilian *et al.* [31], these differences lead to nine typical ecoregions (see Figure 1), which are characterized by similar environmental, macro-climatic and geological conditions leading to differences in the potential vegetation.

Ecoregions strongly affect the species distribution. Thus, we next group our data by dominant tree species according to the main relative proportion of the basal area at a given inventory plot (see data section). Norway Spruce and Silver Fir, as more shade-tolerant species, are combined in one group (*PA* + *AA*). The light demanding tree species Scots Pine and European Larch form the group (*PS* + *LD*) and the group "*other C*" combines all other coniferous trees. The broadleaf species groups are the Common Beech (*FS*), the Oak (*QS*) and *other B*, which summarizes all other broadleaf species. The left images in Figure 6 show the difference between MODIS and terrestrial NPP estimates grouped by ecoregion. The differences are in general positive, both for ecoregions and tree species, before correcting for stand density. The right images show that correcting for stand density reduces this (Figure 6).

Austrian forests grow across a large gradient in elevation, which affects species and growing conditions. Again, we also group all our data by the following elevation classes: (i) <500 m; (ii) 500–1000 m; (iii) 1000–1500 m; (iv) 1500–2000 m and (v) >2000 m in elevation. The same procedure is applied for the mean stand age at a given inventory plot to assess if any age related influences of our findings exist. The six age classes across all data are: (i) <30 years; (ii) 30–60; (iii) 60–90; (iv) 90–120; (v) 120–150; and (vi) >150 years. The same pattern as in the previous Figure 6 is apparent in Figure 7 as well.

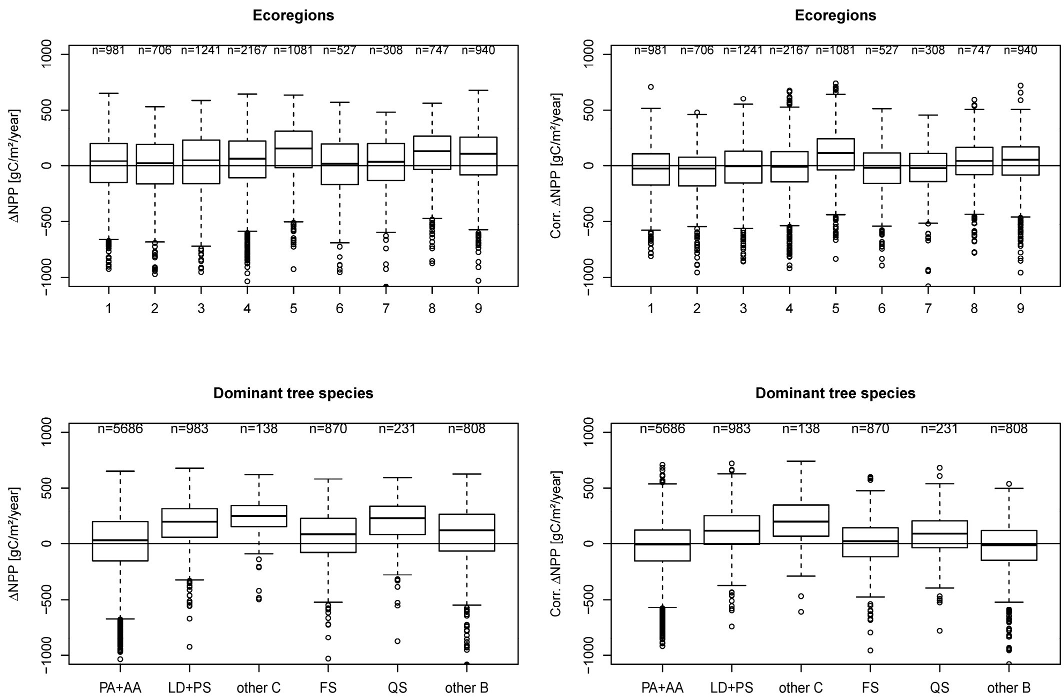

Figure 6. Difference between MODIS NPP and NFI NPP (MODIS minus NFI) grouped by ecoregions (**top**) and dominant tree species (**bottom**). Left original MODIS NPP (ΔNPP) is used, right the detrended MODIS NPP (Corr. ΔNPP) is used. Properties of illustration analogous to Figure 2.

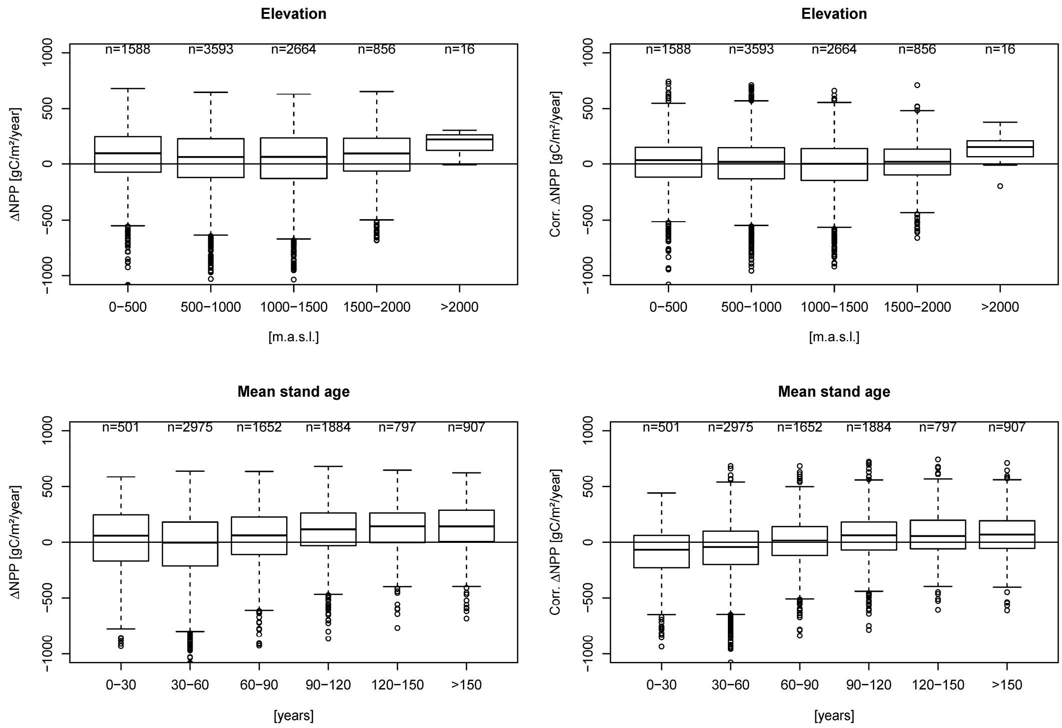

Figure 7. Difference between MODIS NPP and NFI NPP (MODIS minus NFI) grouped by elevation (**top**) and mean stand age (**bottom**). Left original MODIS NPP (ΔNPP) is used, right the detrended MODIS NPP (Corr. ΔNPP) is used. Properties of illustration analogous to Figure 2.

4.5. Effect of Water Availability

Water availability is an important driver of tree productivity. Within the MODIS NPP calculations [50], this is an integral part because daily climate data are required for predicting both GPP and NPP. In a previous study by Pan *et al.* [2], similar discrepancies in comparing the "space-based" MODIS NPP with "ground-based" terrestrial NPP were reported. Pan *et al.* [2] concluded that water availability may be a limiting factor and proposed an "available soil water index" for improving and/or "correcting" MODIS NPP computations compared to terrestrial data. To test this hypothesis and analyze the effect of the water availability on our data, a water balance deficit index is calculated for each inventory plot as an estimate for water limitation according to the following procedure:

$$WBD = ET0 / P \tag{17}$$

$$ET0 = p \times (0.46 \times T + 8) \times 365 \tag{18}$$

WBD is the water balance deficit index which is the ratio of *ET0* potential evapotranspiration and *P* precipitation with *ET0* [mm] of the period 2000–2010 estimated with the method of Blaney-Criddle [51] and *P* the mean annual precipitation 2000–2010 [mm]. *p* is a function of latitude ($p = 0.2729$ for a latitude of 47.5° N) and *T* the mean annual temperature between 2000 and 2010 [°C]. Values of *WBD* less than 1 indicate a lack in available water, while values higher 1 exhibit water availability greater than evapotranspiration. All data are grouped into five *WBD*-classes: (i) <0.5; (ii) 0.5–1.0; (iii) 1.0–1.5; (iv) 1.5 – 2.0 and (v) <2.0.

Figure 8 shows a consisted overestimation of terrestrial NPP by MODIS NPP throughout the different *WBD*-classes when using the original MODIS NPP. The right image in Figure 8 shows that addressing stand density effects reduces this overestimation substantially.

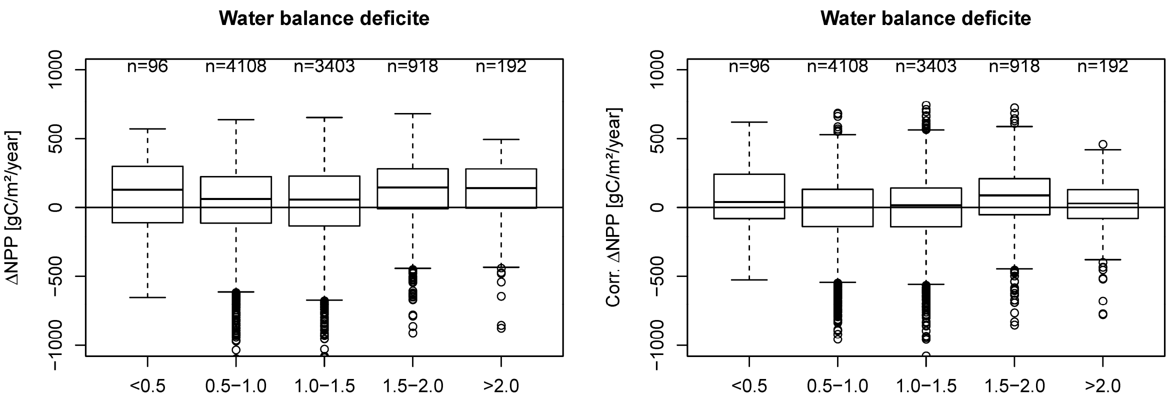

Figure 8. Difference between MODIS NPP and NFI NPP (MODIS minus NFI) grouped by Water balance deficit. Left original MODIS NPP (ΔNPP) is used, right the detrended MODIS NPP (Corr. ΔNPP) is used. Properties of illustration analogous to Figure 2.

5. Discussion

Obtaining daily local climate data (Austrian National Weather Centre ZAMG) for running the MOD17 algorithm reflects the heterogenity of the Austrian landscape more realistically and thus improves the resulting predictions [15]. The ZAMG data set uses more than 200 daily weather stations across Austria while the NCEP2 (NCEP_DOE_II) [42] and GMAO (NASA Global Modeling and Assimilation Offices) [41] include less than 40 stations. In addition, the spatial resolution of the ZAMG data set is at 0.0083 × 0.0083° (approx. 1 × 1 km). This resolution is more detailed than the two global climate data sets GMAO (0.5 × 0.67°), and NCEP2 (1.875 × 1.875°). This is an additional explanation for the higher accuracy in the local data set. Since the NPP is strongly driven by daily climate data [44] the variation of the resulting predictions using the Austrian local climate data set (ZAMG) is higher but better reflects the existing growing conditions (Figure 2).

The NPP estimates derived from 8939 plots of the National Austrian Forest Inventory (NFI) exhibit an Austrian average of 486.3 gC/m^2/year (standard deviation 244.3 gC/m^2/year). Applying the MODIS NPP algorithm using the local Austrian climate data (ZAMG) result in an average of 579.8 gC/m^2/year (standard deviation 113.4 gC/m^2/year). This is a difference between the means of 93.5 gC/m^2/year.

Such differences may have several reasons. For instance, the BPLUTs might not be appropriate for European forest conditions. The difference could also be explained by inconsistency in the definition of NPP (inventory data represent trees with dbh > 5 cm, MODIS LAI all vegetation on a 1 × 1 km pixel). Other issues could be missing fineroot turnover rates in terrestrial NPP calculations, missing carbon increment of trees that died between the inventory measurements or differences in the spatial resolution of the two products. The terrestrial NPP estimates, *SDI* and *CCF*, are calculated based on the stem numbers in Equations (5)–(7). Thus, any variation in *SDI* or *CCF* directly reflects differences in the coverage of the forest area with trees. In our study of Austrian forests, we assume that the detected differences in MODIS *versus* terrestrial NPP (see Figures 3 and 4) estimates are mainly caused by forest management. However, other events also result in changes to stand density (e.g., wind, drought stress, *etc.*). The observed trend by *SDI* [26] and *CCF* [27] (Figures 3 and 4) and the fact that no other analyzed variable (Figures 6–8) can explain the detected apparent deviations of the two NPP estimates supports the hypothesis of Hasenauer *et al.* [3]. Our results thus coincide with Hasenauer *et al.* [3], that MODIS NPP estimates provide the productivity of fully stocked forests, which are represented only by forest areas without recent changes in stand density.

Forest management, such as thinning operations, instantly reduces volume increment per unit area but concentrates the remaining volume increment to fewer trees [52]. Stand density therefore strongly affects tree diameter development. Terrestrial NPP estimates based on diameter or height data are directly affected by any changes in stand density, while the NPP estimates provided by the MODIS NPP algorithm are not. As long as interventions do not strongly reduce the spectral signal of red and near infrared—the two bands used to derive the MODIS inputs FPAR and LAI—forest management is not well detected by satellite-driven NPP estimates (see Figure 3).

The stand density pattern is also consistent when plotting only the results for each of the major vegetation or biome types represented by the MODIS land cover types (Figure 4). In this study, regression analysis and exponential trend curves are used to quantify the stand density related trend similar to Hasenauer *et al.* [3]. The resulting regression curves fitted using *SDI* and *CCF* in Equations (15) and (16) exhibit a consistent trend, no matter whether fitted by biome type or for all available plots. No clustering effect by biome type is evident, suggesting that one density-driven correction function adjusts for the bias in the NPP predictions across scales (Table 2, Figure 5).

Both competition measures (*SDI* and *CCF*) show a very similar behavior (see Figures 3–5). However, for this dataset, *SDI* gives a slightly higher coefficient of determination (Table 2) and seems to better address the recorded competition that exists within Austrian National Forest inventory plots. As shown in Figures 6 and 7, ignoring stand density effects will cause overestimation by MODIS NPP estimates by ecoregions and dominant tree species (see Figure 6), elevation and mean stand age (see Figure 7). Applying the correction function leads to a substantial improvement in the consistency of the different NPP results, and consistent and unbiased results across multiple scales can be expected.

The fact that terrestrial NPP overestimates MODIS NPP at high stand densities (SDI > 1000 or CCF > 500) can be explained with the variable “plot size” of the inventory plots according to the breast height diameter of the trees on a given plot [20]. Thus, the terrestrial NPP estimates based on angle count sample data may have a large random variation and this differs substantially from the terrestrial plot data for deriving NPP as outlined in Hasenauer *et al.* [3] who used fixed area research plots with an area of 2500 m^2.

Pan *et al.* [2] also observed differences between MODIS and terrestrial NPP. They hypothesized that soil water constraints may be a limiting factor and proposed an “available soil water index” for adjusting MODIS NPP computations compared to terrestrial data. Our results of growth conditions in Austrian forests, however, suggest that stand density explains the observed discrepancy as the results grouped by water balance index show a systematic overestimation of terrestrial NPP by MODIS NPP (Figure 8). Correcting for stand density results in a better agreement of MODIS and terrestrial NPP across different “available soil water indices”.

One important concern of our study was if large-scale disturbances like bark beetle outbreaks or windthrow [53,54] may have had an impact on our productivity results by method. Disturbances reduce the stand density of forests in a similar manner to management. In our available data from the Austrian Forest inventory, disturbances can be detected with a recorded variable explaining the reason for sample tree death or removal [17]. There are 484 plots (5% of all plots) where, between 2007 and 2009, at least one tree with “random removal” was recorded and, thus, were affected by the disturbances between 2000 and 2002 and between 2007 and 2009. These plots have a median NPP of 464.7 gC/m^2/year, which is only slightly lower than the median NPP of all 8939 plots (486.3 gC/m^2/year). While disturbances might have big impacts on small scales like forest stands or single inventory plots, they only have a limited and insignificant effect as compared to the forest productivity of Austria.

6. Conclusions

The MODIS NPP model represents all forest vegetation within a 1 × 1 km resolution, assumes fully stocked forest stands and cannot effectively detect management influence in FPAR and LAI. Thus, the effect of forest management, which changes the carbon allocation patterns and, as a consequence, the tree dimensions, is not well represented by MODIS driven NPP estimates. Terrestrial NPP, on the other hand, represents only NPP of trees bigger than the diameter threshold and captures the response of trees to management and, thus, the actual carbon allocation.

Using daily local climate data with high spatial resolution improves the agreement between MODIS NPP and terrestrial NPP.

Correcting the observed stand density related bias in MODIS NPP and thus combining the “space-based” MODIS productivity estimates and “ground-based” national forest inventory data provide consistent and continuous forest productivity estimates. The corrected MODIS NPP has more agreement with forest inventory data. A better agreement of MODIS and terrestrial NPP estimates allows using MODIS for large-scale forest resource estimates in areas with forest management.

Forest productivity across large scales is of increasing interest as more demands are made on forest resources [55] as well as in the context of REDD (Reducing Emissions from Deforestation and Forest Degradation) [56]. This is of particular importance for areas where no or little terrestrial information on forest productivity is available. With this paper, we provide a conceptual outline of how realistic forest productivity estimates can be derived by combining satellite-driven NPP estimates, such as results from the MODIS NPP algorithm, with stand density estimates (using terrestrial or remote-sensing data) in order to enhance forest productivity predictions across multiple scales.

Acknowledgments

This work is part of the project "*Comparing satellite versus ground driven carbon estimates for Austrian Forests*" (MOTI). We are grateful for the financial support provided by the Energy Fund of the Federal State of Austria—managed by Kommunalkredit Public Consulting GmbH under contract number K10AC1K00050. MT. The NTSG work is funded by NASA Earth Observing System MODIS project (grant NNH09ZDA001N-TERRA-AQUA). We thank the editors and the anonymous reviewers for their helpful comments, which substantially improved the quality of this work. We further want to thank Adam Moreno for proof reading the manuscript.

Author Contributions

Mathias Neumann did the comparative analysis of the results, prepared images and tables and wrote the manuscript. Maosheng Zhao did the calculation of MODIS NPP using different climate data and revised the chapters on the MODIS NPP calculations. Georg Kindermann provided the tree carbon results using the Austrian forest inventory data and revised the chapters on forest inventory data and carbon estimation method. Hubert Hasenauer provided the climate data for Austria and revised the whole manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix

Carbon estimation and calculation of crown width using NFI data

The carbon increment calculation require carbon estimates for each tree on a given inventory plot. For our study, we use the same method as applied by the Institute of Forest Inventory, Federal Research Centre for Forest, the agency responsible for the National Forest Inventory in Austria. The total dry carbon tree estimate of a single tree, C_i, is calculated as follows:

$$C_i = CC \times (dsm + dbm + dfm + drm) \tag{A1}$$

where *CC* is the carbon content and considered to be 0.5 for all species [26], *dsm* is the dry stem mass, *dbm* the dry branch mass, *dfm* the dry foliage mass and *drm* the dry root mass.

Dry stem biomass (*dsm*) is calculated using stem volume and species-specific conversion factors. Stem volume (V_{tree}) is derived from the tree measurements diameter at breast height (*dbh*), total tree height *(h*) and the species-specific form factor (*FF*). The calculated volume represents the stem excluding aboveground part of the stump and the branches [17,57,58].

$$dsm = V_{tree} \times wd \times \frac{100 - sf}{100} \tag{A2}$$

$$V_{tree} = \left(\frac{dbh}{200}\right)^2 \times \pi \times h \times FF \tag{A3}$$

where V_{tree} is the stem volume of a single tree [m³], *wd* is the dry wood density [t BM/m³], *sf* the shrinkage factor by tree species [%], *dbh* the diameter at breast height (1.3 m), *h* the tree height, *d*03 the diameter at 30% of tree height and *hc* the crown height (height to the crown base). The form factor (*FF*) reduces the volume of the cylinder to the actual tree form. The Austrian Forest Inventory uses two different form factor functions: one for the trees with *dbh* ranging from 5–10.4 cm with the following form,

$$FF = c_1 + c_2 \times \ln^2(dbh) + c_3 // h + ?c_4 / dbh + c_5 / dbh? + c_6 \quad dbh \quad h + c_7 \quad dbh \quad h \tag{A4}$$

and a second one for all trees with a *dbh*≥10.4 cm:

$$FF = c_0 + c_1 \times d03 / dbh + c_2 \times (d03 / h)^2 + c_3 \times h / dbh + c_4 \times h / dbh? + c_5 / dbh + c_6 \times hc / h \tag{A5}$$

c_i are species-specific parameter estimates for calculating stem volume used by the Austrian Forest Inventory given in Tables A1 and A2 [17,57,59]. The conversion factors *wd* and *sf* according to Wagenführ and Scheiber [60] are given in Table A3. Note that for Equation (A3) *dbh* [cm] and *h* [m], while in Equations (A4,A5) the *d*03, *dbh*, *hc* and *h* [dm].

Table A1. Coefficients used in models for volume for trees with dbh 5.0–10.4 cm (Schieler [59] cited in Gabler and Schadauer [17]).

Species Name	c1	c2	c3	c4	c5	c6	c7
Picea abies, other coniferous	0.5634	−0.1273	−8.5502	0	0	7.6331	0
Abies alba	0.5607	0.1547	−0.6558	0.0332	0	0	0
Larix decidua	0.4873	0	−2.0429	0	0	5.9995	0
Pinus sylvestris, Pinus strobus	0.4359	−0.0149	5.2109	0	0.0287	0	0
Pinus nigra	0.5344	−0.0076	0	0	0	0	2.2414
Pinus cembra	0.5257	−0.0335	7.3894	−0.1065	0	0	3.3448
Fagus sylvatica, other broadleaf	0.5173	0	−13.6214	0	0	9.9888	0
Quercus sp.	0.4171	0.2194	13.3259	0	0	0	0
Carpinus betulus	0.3247	0.0243	0	0.2397	0	−9.9388	0
Fraxinus sp., Sorbus sp., Prunus sp.	0.4812	−0.0149	−10.831	0	0	9.3936	0
Acer sp.	0.5010	−0.0352	−8.0718	0	0.0352	0	0
Ulmus sp.	0.4422	−0.0245	0	0	0	0	2.8771
Betula sp.	0.4283	−0.0664	0	0	0	8.4307	0
Alnus sp.	0.3874	0	7.1712	0.0441	0	0	0

Table A1. *Cont.*

Species Name	c1	c2	c3	c4	c5	c6	c7
Populus sp.	0.3664	0	1.1332	0.1306	0	0	0
Salix sp.	0.5401	−0.0272	−25.1145	0.0833	0	9.3988	0

Table A2. Coefficients used in models for volume for trees with dbh≥10.4 cm (Braun [57] cited in Gabler and Schadauer [17]).

Species Name	c0	c1	c2	c3	c4	c5	c6
Picea abies, other coniferous	−0.2436	0.8271	0	2.91E-04	0	0.0287	0
Abies alba	0.0991	0	0.5126	4.46E-04	0	0.0160	0
Larix decidua	−0.2198	0.8028	0	3.24E-04	0	0.0184	0
Pinus sylvestris	−0.2099	0.8140	0	1.96E-04	0	0.0317	0
Pinus nigra, Pinus strobus	−0.1929	0.8479	0	2.04E-04	0	0.0069	0
Pinus cembra	0.0501	0.4676	0	1.57E-04	0	0.0761	0
Fagus sylvatica, other	−0.1309	0.6743	0	0	1.67E-04	0	0.0668
Quercus sp.	0.1852	0	0.3501	0	4.77E-04	0	0.0657
Carpinus betulus	0.0421	0.4226	0	0	4.21E-04	0	0.0770
Fraxinus sp.	−0.0198	0.5124	0	0	4.70E-04	0	0.0535
Acer sp.	−0.0286	0.5655	0	0	2.37E-04	0	0.0083
Ulmus sp.	−0.1390	0.6950	0	0	3.18E-04	0	0.0166
Betula sp.	−0.0778	0.5682	0	0	5.54E-04	0	0.0517
Alnus sp.	−0.1646	0.7038	0	0	2.59E-04	0	0.0589
Populus tremula	−0.1456	0.6657	0	0	4.18E-04	0	0.0589
Populus alba	−0.1438	0.6487	0	0	5.62E-04	0	0.0812
Populus nigra	−0.0843	0.5928	0	0	6.47E-04	0	0.0227
Salix sp.	−0.1376	0.6944	0	0	4.59E-04	0	0.0128

Table A3. Conversion factors for stem biomass [60].

Species Name	wd	sf
Picea sp.	0.41	11.80
Abies sp.	0.41	11.85
Larix sp.	0.55	13.20
Pinus sylvestris, other Pinus	0.51	11.80
Pinus nigra	0.56	11.80
Pinus cembra	0.40	9.00
Pinus strobus	0.37	9.00
Pseudotsuga menziesii	0.47	12.00
Taxus baccata	0.64	8.80
Fagus sylvatica, other hardwood broadleaf	0.68	17.50
Carpinus betulus	0.67	13.60
Quercus sp.	0.75	18.80
Fraxinus sp.	0.67	13.20
Acer sp.	0.59	11.65
Ulmus sp.	0.64	12.80
Castanea sativa	0.56	11.45
Robinia pseudacacia	0.73	11.80

Table A3. *Cont.*

Species Name	wd	sf
Prunus sp., Sorbus sp.	0.57	13.85
Sorbus domestica	0.71	17.15
Sorbus aucuparia	0.62	18.60
Betula sp.	0.64	13.95
Alnus sp.	0.49	13.40
Tilia sp., other softwood broadleaf	0.52	14.65
Populus sp.	0.45	11.90
Populus nigra	0.41	12.50
Salix sp.	0.52	9.60
Juglans regia	0.64	13.70
Juglans nigra	0.56	12.65
Ostrya carpinifolia	0.75	18.80
Malus, Pyrus	0.70	14.40

For the remaining biomass components (*dbm, dfm, drm*), we use allometric biomass functions developed for Austrian forest conditions, which are also used by the Austrian National Forest Inventory.

The dry branch biomass *dbm* [kg] for *Pinus sp.* is calculated with a *dbh* [cm] and *h* [m] dependent equation [61],

$$dbm = 1.0366 \cdot e^{(-2.8762+2.04516 \cdot \ln(dbh) - 0.07025 \cdot \ln(h))} \tag{A6}$$

We use equations from Ledermann and Neumann [62] for all other tree species. If height to the life crown measurements (*hc)* are available, models using *dbh*, *h* and *hc* as input variables are used according to Equation (A8). If *hc* is missing, models with *dbh* and *h* are used according to Equation (A7) [62]:

$$dbm = l2 \cdot e^{b_{20}+b_{21} \cdot \ln(dbh)+b_{22} \cdot \frac{h}{dbh})} \tag{A7}$$

$$dbm = l3 \cdot e^{b_{30}+b_{31} \cdot \ln(dbh)+b_{32} \cdot \frac{h}{dbh}+b_{33} \cdot \ln(CR)} \tag{A8}$$

$$CR = \frac{h-hc}{h} \tag{A9}$$

where *CR* is the crown ratio and all other variables as previously defined. The species-specific parameters b_i, *l2* and *l3* are given in Table A4**.**

Table A4. Coefficients used in models for biomass in branches [62].

Species Name	b20	b21	b22	l2	b30	b31	b32	b33	l3
Picea abies, other	-	1.7459	-	1.102	-	2.0252	0.1451	0.9154	1.051
Abies alba	-	2.0429	-	1.105	-	2.2066	0	0.4384	1.087
Fagus sylvatica, other BL	-	2.3930	-	1.251	-	2.5568	-	0.6002	1.212
Quercus sp.	1.8554	0.9332	-	1.334	-	1.9445	0	1.2137	1.280
Carpinus betulus	-	2.8913	-	1.181	-	2.8281	0	0.9318	1.130

For coniferous trees, the foliage biomass (*dfm*) is included in the branch biomass calculations (*dbm*) as outlined above. For the deciduous trees, *dfm* [kg] is calculated using allometric functions according to *dbh*. These functions are based on measurements collected by Burger [63,64] and are modified after Lexer and Hönninger [65].

$$dfm = a_0 \times dbh^{a_1} \tag{A10}$$

The species-specific parameters a_i are given in Table A5.

The root biomass (*drm*) in [kg] is defined as roots with a minimum diameter of 2 mm including the root stump. For *Pinus sylvestris* and *Pinus nigra* the allometric function of Offenthaler and Hochbichler [66] is used:

$$drm = 0.038872 \times dbh^{2.066783} \tag{A11}$$

For all other species, the following dbh and age-dependent model is applied [67,68]:

$$drm = c_0 \cdot e^{c_1 + c_2 \cdot \ln(dbh) + c_3 \cdot \ln^2(dbh) + c_4 \cdot \ln(age)} \tag{A12}$$

dbh in [cm], *age* is the tree age [a], c_i are species-specific parameter according to [67,68].

The species-specific parameters c_i are given along with the parameters for foliage biomass in the Table A5.

Table A5. Coefficients c_i used in models for biomass in roots ([67] for "Coniferous (except Pinus sp.)", [68] for "Fagus sylvatica, other broadleaf", [66] for "Quercus sp." and "Carpinus betulus") and *a0* and *a1* for biomass in foliage [63–65].

Name	c0	c1	c2	c3	c4	a0	a1
Coniferous (except Pinus sp.)	1.041	−8.350	4.568	−0.330	0.281	-	-
Fagus sylvatica, other broadleaf	1.080	−4.000	2.320	0	0	0.022	2.300
Quercus sp.	1.051	−3.975	2.523	0	0	0.135	1.811
Carpinus betulus	1.052	−3.848	2.488	0	0	0.022	2.300

Equation (A13) estimates maximum crown width of a tree assuming open-grown conditions for calculating *CCF* [27]. The species-specific parameters to calculate maximum crown width are given in Table A6.

$$CW_i = e^{c_0 + c_1 \cdot \ln(dbh)} \tag{A13}$$

Table A6. Coefficients used for maximum crown width [29].

Name	c0	c1
Picea abies, other coniferous	−0.3232	0.6441
Abies alba	0.0920	0.5380
Larix decidua	−0.3396	0.6823
Pinus sylvestris, other Pinus sp.	−0.1797	0.6267
Pinus nigra	−0.1570	0.6310
Pinus cembra	−1.3154	0.8288
Fagus sylvatica, other broadleaf	0.2662	0.6072
Quercus sp., Castanea sativa	−0.3973	0.7328
Acer sp., Betula sp., Alnus sp., Populus sp., Salix sp., Ulmus sp.	0.4180	0.5285

Table A6. *Cont.*

Name	c0	c1
Fraxinus sp., Robinia, sp. Prunus sp. Sorbus sp.	0.1366	0.6183
Tilia sp.	0.1783	0.5665

References

1. Shvidenko, A.; Schepaschenko, D.; McCallum, I.; Santoro, M.; Schmullius, C. Use of remote sensing products in a terrestrial ecosystems verified full carbon account: Experiences from Russia. In Proceedings of the International Institute for Applied Systems Analysis: Earth Observation for Land-Atmosphere Interaction Science, Frascati, Italy, 3–5 November 2010.
2. Pan, Y.; Birdsey, R.; Hom, J.; McCullough K.; Clark, K. Improved estimates of net primary productivity from MODIS satellite data at regional and local scales. *Ecol. Appl.* **2006**, *16*, 125–132.
3. Hasenauer, H.; Petritsch, R.; Zhao, M.; Boisvenus, C.; Running, S.W. Reconciling satellite with ground data to estimate forest productivity at national scales. *For. Ecol. Manag.* **2012**, *276*, 196–208.
4. Tomppo, E.; Gschwantner, T.; Lawrence, M.; McRoberts, R.E. *National Forest Inventories: Pathways for Common Reporting*; Springer: Berlin, Germany, 2010; p. 610.
5. Schadauer, K.; Gschwantner, T.; Gabler, K. Austrian National Forest Inventory: Caught in the Past and Heading toward the Future. In Proceedings of the Seventh Annual Forest Inventory and Analysis Symposium, Washington, DC, USA, 3–6 October 2005; pp. 47–53.
6. Hasenauer, H.; Eastaugh, C.S. Assessing forest production using terrestrial monitoring data. *Int. J. For. Res.* **2012**, doi:10.1155/2012/961576.
7. Running, S.; Nemani, R.; Heinsch, F.; Zhao, M.; Reeves, M.; Hashimoto, H. A continuous satellite-derived measure of global terrestrial primary production. *BioScience* **2004**, *54*, 547–560.
8. Zhao M.; Running S.W. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* **2010**, *329*, 940–943.
9. Monteith, J. Solar radiation and productivity in tropical ecosystems. *J. Appl. Ecol.* **1972**, *9*, 747–766.
10. Thornton, P.E.; Running, S.; White, M. Generating surfaces of daily meteorological variables over large regions of complex terrain. *J. Hydrol.* **1997**, *190*, 214–251.
11. Van Tuyl, S.; Law, B.E.; Turner, D.P.; Gitelman, A.I. Variability in net primary production and carbon storage in biomass across Oregon forests—An assessment integrating data from forest inventories, intensive sites, and remote sensing. *For. Ecol. Manag.* **2005**, *209*, 273–291.
12. Waring, R.H.; Milner, K.S.; Jolly, W.M.; Phillips, L.; McWethy, D. Assessment of site index and forest growth capacity across the Pacific and Inland Northwest USA with MODIS satellite-derived vegetation index. *For. Ecol. Manag.* **2006**, *228*, 285–291.
13. Muukkonen, P.; Heiskanen, J. Biomass estimation over a large area based on standwise forest inventory data and ASTER and MODIS satellite data: A possibility to verify carbon inventories. *Remote Sens. Environ.* **2007**, *107*, 617–624.

14. Härkönen, S.; Lehtonen, A.; Eerikäinen, K.; Mäkelä, A. Estimating forest carbon fluxes for large regions based on process-based modelling, NFI data and Landsat satellite images. *For. Ecol. Manag.* **2011**, *262*, 2364–2377.
15. Eenmäe, A.; Nilson, T.; Lang, M. A note on meteorological variables related trends in the MODIS NPP product for Estonia. *For. Stud./Metsanduslikud. Uurim.* **2011**, *55*, 60–63.
16. Fang, H.; Wei, S.; Liang, S. Validation of MODIS and CYCLOPES LAI products using global field measurement data. *Remote Sens. Environ.* **2012**, *119*, 43–54.
17. Gabler, K.; Schadauer, K. Methods of the Austrian forest inventory 2000/02 origins, approaches, design, sampling, data models, evaluation and calculation of standard error. Available online: http://bfw.ac.at/rz/bfwcms.web?dok=7518 (accessed on 30 March 2015).
18. He, L.; Chen, J.M.; Pan, Y.; Birdsey, R.; Kattge, J. Relationships between net primary productivity and forest stand age in U.S. forests. *Glob. Biogeochem. Cycles* **2012**, *26*, 1–19.
19. Liu, C.; Westman, C.; Berg, B.; Kutsch, W.; Wang, G.Z.; Man, R.; Ilvesniemi, H. Variation in litterfall-climate relationships between coniferous and broadleaf forests in Eurasia. *Glob. Ecol. Biogeogr*. **2004**, *13*, 105–115.
20. Bitterlich, W. Die Winkelzaehlprobe. *Allg. For. Holzwirtsch. Ztg.* **1948**, *59,* 4–5.
21. Englisch, M.; Karrer, G.; Mutsch, F. Österreichische Waldboden-Zustandsinventur. Teil 1: Methodische Grundlagen. *Mitt. Forstichen Bundesver. Wien.* **1992**, *168*, 5–22.
22. Schieler, K. Methode der Zuwachsberechnung der Oesterreichischen Waldinventur. Ph.D. Thesis, University of Natural Resources and Applied Life Sciences, Institute of Forest Growth, Vienna, Austria, 1997; p. 92.
23. Van Deusen, P.C.; Dell, T.R.; Thomas, C.E. Volume Growth Estimation from Permanent Horizontal Points. *For. Sci.* **1986**, *32*, 415–422.
24. Eastaugh, C.S.; Hasenauer, H. Biases in Volume Increment Estimates Derived from Successive Angle Count Sampling. *For. Sci.* **2013**, *59*, 1–14.
25. Martin, G.L. A method for estimating ingrowth on permanent horizontal sample points. *For. Sci.* **1982**, *28*, 110–114.
26. *Intergovernmental Panel on Climate Change, Good Practice Guidance for Land Use, Land-Use Change and Forestry*; Institute for Global Environmental Strategies (IGES): Hayama, Japan, 2003; p. 590.
27. Krajicek, J.E.; Brinkman, K.A.; Gingrich, S.F. Crown competition—A measure of density. *For. Sci.* **1961**, *1*, 35–42.
28. Reinecke, L.H. Prefecting a stand density index for even-aged forest. *J. Agric. Res.* **1933**, *46*, 627–638.
29. Hasenauer, H. Dimensional relationships of open-grown trees in Austria. *For. Ecol. Manag.* **1997**, *96*, 197–206.
30. Hasenauer, H.; Burkhart, H.; Sterba, H. Variation in potential volume yield of loblolly pine plantations. *For. Sci.* **1994**, *40*, 162–176.
31. Kilian, W.; Müller, F.; Starlinger, F. Die forstlichen Wuchsgebiete Österreichs—Eine Naturraumgliederung nach waldökologischen Gesichtspunkten. Available online: http://bfw.ac.at/030/2377.html (accessed on 27 March 2015).

32. Hasenauer, H.; Merganičová, K.; Petritsch, R.; Pietsch, S.A.; Thornton, P.E. Validating daily climate interpolations over complex terrain in Austria. *Agric. For. Meteorol.* **2003**, *119*, 87–107.
33. Eastaugh, C.S.; Petritsch, R.; Hasenauer, H. Climate characteristics across the Austrian forest estate from 1960 to 2008. *Aust. J. For. Sci.* **2010**, *127*, 133–146.
34. Thornton, P.E.; Hasenauer, H.; White, M.A. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: An application over complex terrain in Austria. *Agric. For. Meteorol.* **2000**, *104*, 255–271.
35. Petritsch, R.; Hasenauer H. Climate input parameters for real-time online risk assessment. *Nat. Hazards* **2011**, *59*, 1–14.
36. Zhao, M.; Heinsch, F.A.; Nemani, R.R.; Running, S.W. Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sens. Environ.* **2005**, *95*, 164–175.
37. Wang, Y.; Woodcock, C.E.; Buermann, W.; Stenberg, P.; Voipio, P.; Smolander, H.; Hame, T.; Tian, Y.; Hu, J.; Knyazikhin, Y.; Myneni, R.B. Evaluation of the MODIS LAI algorithm at a coniferous forest site in Finland. *Remote Sens. Environ.* **2004**, *91*, 114–127.
38. Tan, B.; Woodcock, C.; Hu, J.; Zhang, P.; Ozdogan, M.; Huang, D.; Yang, W.; Knyazikhin, Y.; Myneni, R. The impact of gridding artifacts on the local spatial properties of MODIS data: Implications for validation, compositing, and band–to–band registration across resolutions. *Remote Sens. Environ.* **2006**, *105*, 98–114.
39. Yang, W.; Tan, B.; Huang, D.; Rautiainen, M.; Shabanov, N.V.; Wang, Y.; Privette, J.L.; Hummerich, K.F.; Fensholt, R.; Sandolt, I.; *et al.* MODIS leaf area index products: From validation to algorithm improvement. *IEEE Trans. Geosci. Remote Sens.* **2006**, *44*, 1885–1898.
40. Friedl, M.; Sulla-Menashe, D.; Tan, B.; Schneider, A.; Ramankutty, N.; Sibley, A.; Huang, X. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sens. Environ.* **2010**, *114*, 168–182.
41. Ma, L.; Zhang, T.; Li, Q.; Frauenfeld, O.W.; Qin, D. Evaluation of ERA-40, NCEP-1, and NCEP-2 reanalysis air temperatures with ground-based measurements in China. *J. Geophys. Res.* **2008**, *113*, 1–15.
42. Kanamitsu, M.; Ebisuzaki, W.; Woollen, J.; Yang, S.K.; Hnilo, J.J.; Fiorino, M.; Potter, G.L. NCEP-DOE AMIP-II reanalysis (R-2). *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1631–1643.
43. Weng, Q. *Global Urban Monitoring and Assessment through Earth Observation*; CRC Press: Boca Raton, FL, USA, 2014; p. 440.
44. Zhao, M.; Running, S.W.; Nemani, R.R. Sensitivity of moderate resolution imaging spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. *J. Geophys. Res.* **2006**, *111*, 1–13.
45. Bruce, D. Yield Differences between Research Plots and Managed Forests. *J. For.* **1977**, *75*, 14–17.
46. Hradetzky, J. Concerning the precision of growth estimation using permanent horizontal point samples. *For. Ecol. Manag.* **1995**, *71*, 203–210.
47. Austrian Forest Act (Österreichisches Forstgesetz). Available online: https://www.ris.bka.gv.at/ (accessed on 4 February 2015).
48. Eastaugh, C.; Hasenauer, H. Improved estimates of per-plot basal area from angle count inventories. *Forests* **2014**, *7*, 178–185.

49. Seidl, R.; Eastaugh, C.S.; Kramer, K.; Maroschek, M.; Reyer, C.; Socha, J.; Vacchiano, G.; Zlatanov, T.; Hasenauer, H. Scaling issues in forest ecosystem management and how to address them with models. *Eur. J. For. Res.* **2013**, *132*, 653–666.
50. Zhang, K.; Kimball, J.S.; Mu, Q.; Jones, L.A.; Goetz, S.J.; Running, S.W. Satellite based analysis of northern ET trends and associated changes in the regional water balance from 1983 to 2005. *J. Hydrol.* **2009**, *379*, 92–110.
51. Blaney, H.F.; Criddle, W.D. *Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data*; Technical Paper; United States Department of Agriculture: Washington, WA, USA, 1950 ; Volume 96, p. 44.
52. Assmann, E. *The Principles of Forest Yield Study*; Pergamon Press: New York, NY, USA, 1970; p. 506.
53. Seidl, R.; Rammer, R.; Jäger, D.; Lexer, M.J. Impact of bark beetle (*Ips. typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. *For. Ecol. Manag.* **2008**, *256*, 209–220.
54. Seidl, R.; Fernandes, P.M.; Fonseca, T.F.; Gillet, F.; Jönsson, A.M.; Merganicova, K.; Netherer, S.; Arpaci, A.; Bontemps, J.D.; Bugmann, H.; *et al.* Modelling natural disturbances in forest ecosystems: A review. *Ecol. Model.* **2010**, *222*, 903–924.
55. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Lewis, S.L.; Canadell, J.G.; Ciais, P.; *et al.* A large and persistent carbon sink in the world's forests. *Science* **2011**, *333*, 988–992.
56. Angelsen, A. *Realising REDD+ National Strategy and Policy Options*; CIFOR: Bogor, Indonesia, 2009; p. 390.
57. Braun, R. Österreichische Forstinventur. Methodik der Auswertung und Standardfehler-Berechnung. *Mitt. Forstl. Bundesver. Wien.* **1969**, *84*, 1–60.
58. Pollanschütz, J. Formzahlfunktionen der Hauptbaumarten Österreichs. *Inf. Forstl. Bundesver. Wien.* **1974**, *153*, 341–343.
59. Schieler, K. Methodische Fragen in Zusammenhang mit der österreichischen Forstinventur. Master Thesis, University of Natural Resources and Applied Life Sciences, Institute of Forest Growth, Vienna, Austria, 1988; p. 99.
60. Wagenführ, R.; Scheiber, C. *Holzatlas*, 2nd Ed.; VEB Fachbuchverlag: Leibzig, Germany, 1985; p. 690.
61. Hochbichler, E.; Bellos, P.; Lick, E. Biomass functions for estimating needle and branch biomass of spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) and branch biomass of beech (*Fagus sylvatica*) and oak (*Quercus robur* and *petrea*). *Aust. J. For. Sci.* **2006**, *123*, 35–46.
62. Ledermann, T.; Neumann, M. Biomass equations from data of old long-term experimental plots. *Aust. J. For. Sci.* **2006**, *123*, 47–64.
63. Burger, H. Holz, Blattmenge und Zuwachs. VIII. Mitteilung. Die Eiche. *Mitt. Schweiz. Anst. Forstl. Vers.* **1947**, *25*, 211–279.
64. Burger, H. Holz, Blattmenge und Zuwachs. X. Mitteilung. Die Buche. *Mitt. Schweiz. Anst. Forstl. Vers.* **1949**, *26*, 419–468.
65. Lexer, M.J.; Hoenninger, K. A modified 3D-patch model for spatially explicit simulation of vegetation composition in heterogeneous landscapes. *For. Ecol. Manag.* **2001**, *144*, 43–65.

66. Offenthaler, I.; Hochbichler, E. Estimation of root biomass of Austrian forest tree species. *Aust. J. For. Sci.* **2006**, *123*, 65–86.
67. Wirth, C.; Schumacher J.; Schulze E.D. Generic biomass functions for Norway spruce in Central Europe—A meta-analysis approach toward prediction and uncertainty estimation. *Tree Physiol.* **2004**, *24*, 121–139.
68. Bolte, A.; Rahmann, T.; Kuhr, M.; Pogoda, P.; Murach, D.; von Gadow, K. Relationships between tree dimension and coarse root biomass in mixed stands of European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies*[L.] Karst.). *Plant Soil* **2004**, *264*, 1–11.

7.2 Paper 2

Neumann, M., Moreno, A., Mues, V., Härkönen, S., Mura, M., Bouriaud, O., Lang, M., Achten, W. M. J., Thivolle-Cazat, A., Bronisz, K., Merganic, J., Decuyper, M., Alberdi, I., Astrup, R., Mohren, F.,Hasenauer, H. (2016). Comparison of carbon estimation methods for European forests. Forest Ecology and Management, 361, 397–420. http://doi.org/10.1016/j.foreco.2015.11.016

Forest Ecology and Management 361 (2016) 397–420

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Comparison of carbon estimation methods for European forests

Mathias Neumann [a,*], Adam Moreno [a], Volker Mues [b], Sanna Härkönen [c], Matteo Mura [d], Olivier Bouriaud [e], Mait Lang [f], Wouter M.J. Achten [g,o], Alain Thivolle-Cazat [h], Karol Bronisz [i], Ján Merganič [j], Mathieu Decuyper [k,n], Iciar Alberdi [l], Rasmus Astrup [m], Frits Mohren [n], Hubert Hasenauer [a]

[a] Institute of Silviculture, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Vienna, Peter-Jordan-Str. 82, A-1190 Wien, Austria
[b] University Hamburg, Centre for Wood Science, World Forestry Leuschnerstr. 91, D-21031 Hamburg, Germany
[c] Finnish Forest Research Institute, Yliopistokatu 6, BOX 68, FI-80101 Joensuu, Finland
[d] Department of Bioscience and Territory, University of Molise, Contrada Fonte Lappone snc, 86090 Pesche (IS), Italy
[e] Universitatea Stefan del Mare, Suceava, Str. Universitatii, nr. 13, cod postal 720229, Suceava, Romania
[f] Tartu Observatory, 61602 Tõravere, Estonia
[g] KU Leuven – University of Leuven, Division Forest, Nature and Landscape, Celestijnenlaan 200E – 2411, BE-3001 Leuven, Belgium
[h] Technological Institute, Furniture, Environment, Economy, Primary processing and supply (FCBA), 10 rue Galilée, 77420 Champs sur Marne, France
[i] Department of Dendrometry and Forest Productivity, Faculty of Forestry, Warsaw University of Life Sciences, Nowoursynowska 159, 02-787 Warsaw, Poland
[j] Czech University of Life Sciences, Faculty of Forestry and Wood Sciences, Kamycka 1176, 16521 Prague 6, Czech Republic
[k] Wageningen University, Laboratory of Geo-Information Science and Remote Sensing, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[l] INIA-CIFOR, Departamento de Selvicultura y Gestión de los Sistemas Forestales, Ctra. A Coruña, km 7,5, 28040 Madrid, Spain
[m] Norwegian Forest and Landscape Institute, Høgskoleveien 8, Postboks 115, 1431 Ås, Norway
[n] Wageningen University, Forest Ecology and Forest Management Group, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[o] Université Libre de Bruxelles (ULB), Institute for Environmental Management and Land Use Planning (IGEAT), Avenue Franklin D. Roosevelt 50 CP 130/02, B-1050 Brussels, Belgium

ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form 30 September 2015
Accepted 7 November 2015

Keywords:
Biomass
Carbon
Forest inventory
Allometric biomass functions
Biomass expansion factors
Europe

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

* Corresponding author.
E-mail address: mathias.neumann@boku.ac.at (M. Neumann).

http://dx.doi.org/10.1016/j.foreco.2015.11.016
0378-1127/

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

5 species considered to be important European tree species because they have a large distributional range and a high ecological and economic value. The selected deciduous tree species are (i) *F. sylvatica* L. (European beech), (ii) *Q. robur* L. (Pedunculate oak) and (iii) *B. pendula* Roth (Silver birch) and the two coniferous species, (iv) *P. abies* (L.) Karst. (Norway spruce) and (v) *P. sylvestris* L. (Scots pine).

Q. robur also includes *Quercus petraea* L. and *B. pendula* includes *Betula pubescens* Ehrh., since these species are similar in terms of genetics, shape and properties and thus are usually not distinguished from one another by NFI systems or biomass studies (e.g., Muukkonen, 2007; Repola, 2009; Giurgiu et al., 1972; Ledermann and Neumann, 2006).

Within Europe, each country has its own statistical empirical approach for deriving carbon estimates from National Forest Inventory data (Tomppo et al., 2010). We obtain each of these procedures for our comparative analysis. Below, we describe the methods employed for the 12 countries. For a detailed presentation, by country, we refer to Appendices A–M.

2.1. General carbon calculation approach

Biomass is commonly estimated by separate tree compartments (e.g. Wirth et al., 2004; Seidl et al., 2005; Pietsch et al., 2005; Thurnher et al., 2013). We consider four tree compartments for estimating biomass: (i) stem, (ii) branches, (iii) foliage, and (iv) root (including stump). The general equation for calculating total tree carbon can be expressed as:

$$C_{tree} = CC * (dsm + dbm + dfm + drm) \quad (1)$$

where C_{tree} is the total carbon content of a tree [kg], CC is the carbon fraction [kg/kg] given for each country in Appendix A, dsm is the dry stem biomass [kg], dbm is the dry branch biomass [kg], dfm is the dry foliage biomass [kg] and drm is the dry root biomass [kg]. For each country the species specific carbon calculation methods are compiled (see Appendices A–M).

2.2. Carbon calculations by country

European forests cover a wide range of environmental conditions, as well as large elevation and latitudinal gradients. According to FOREST EUROPE, UNECE, FAO (2011) suggestions to limit the range of these environmental, elevation and latitudinal gradients, we cluster the 12 countries which provide biomass estimation methods for our study into four geographic regions: North Europe, Central-West Europe, Central-East Europe, and South Europe. The underlying assumption is that countries within each region should have similar climatic and biophysical conditions for tree growth and we expect that this will reduce the variation in tree allometry. Table 1 summarizes the 12 country-specific carbon estimation methods and the required tree variables.

All carbon calculation methods use diameter at breast height (DBH) and tree height (H) as input variables. In five countries (Finland, Austria, Germany, the Netherlands, and Romania) additional variables are used: crown ratio (CR), aboveground volume (V), and tree age (A). Six methods use allometric biomass functions, three use biomass expansion factors and four use a combination of both (see Table 1). The carbon calculation method, by country, including the coefficients and the definitions of the tree compartments are given in Appendices A–M. Below, we give a brief summary by region.

2.2.1. Northern Europe

Two countries, Finland and Norway, belong to Northern Europe. In Finland (also representing Estonia) the allometric biomass functions use DBH, tree height, and crown ratio. The models developed for Finland obtain carbon from biomass with a constant carbon fraction of 0.5 (see Appendix B). The carbon estimation approach of Finland is also applied in Estonia since forest biomass functions for Estonia are currently under development (Uri et al., 2010).

The Norwegian methodology uses allometric biomass functions. The method for Norway was developed in Sweden (Marklund, 1988; Petersson and Ståhl, 2006). The models use DBH and tree height as variables (see Appendix C).

F. sylvatica is not native in Finland or Norway, thus it is excluded from the analysis for Northern Europe.

Table 1
Summary on calculation Methods (AF = allometric biomass functions, BEF = biomass expansion factors and volume functions, combi = combination of AF and BEF) and used Variables in the calculations (DBH = diameter at breast height, H = tree height, CR = crown ratio, A = tree age, V = aboveground tree volume), variables in brackets indicate that this variable is only used in some functions.

Region	Country	Method	Variables
North Europe	Finland	AF	DBH, H, (CR)
	Norway	AF	DBH, (H)
Central-West Europe	Austria	combi	DBH, (H, CR, A)
	Belgium	combi	DBH, (H)
	France	BEF	DBH, (H)
	Germany	combi	DBH, H, (V, A)
	Netherlands	BEF	DBH, A, (H)
Central-East Europe	Czech Republic	combi	DBH, (H)
	Poland	AF	DBH, (H)
	Romania	BEF	DBH, H, A
South Europe	Italy	AF	DBH, H
	Spain	AF	DBH, (H)

2.2.2. Central-Western Europe

Five countries, Austria, Belgium, France, Germany and the Netherlands, belong to Central-Western Europe. The biomass calculation in Austria uses a combination of species-specific form factor functions, biomass expansion factors, and allometric biomass functions. The allometric biomass functions for branch biomass use crown ratio as an additional input variable (Ledermann and Neumann, 2006), while the functions for root biomass use tree age (Wirth et al., 2004). The volume and branch biomass functions use data from Austria, while the foliage and root biomass function obtain their data from other Central European countries (see Appendix D).

The Belgian biomass calculation method is a combination of volume estimation, expansion factors, and allometric biomass functions. The volume prediction (Dagnelie et al., 1985) and the biomass functions of *P. abies* depend on DBH and tree height. All other biomass functions use only DBH as input variable. The volume calculation method and most of the biomass functions mainly use data from Belgium. Some biomass functions are obtained from other countries such as Austria, the Czech Republic, Germany, France, and the Netherlands (see Appendix E).

In France, the biomass calculation method combines volume functions with biomass expansion factors derived from samples in France (INRA, 2004). Foliage biomass is assumed to be a constant proportion of total biomass (see Appendix F). For all species in France a carbon fraction of 0.475 is used (see Appendix A), which differs from most other countries.

In Germany, a combination of volume functions, biomass expansion factors and allometric biomass functions is applied. The volume calculation is implemented in the program BDAT 2.0 (Kublin, 2002). The expansion factors for tree volume vary by tree age and the expansion factors for root biomass vary by aboveground biomass (see Appendix A). The models (except foliage biomass) are developed with sample material from Germany (see Appendix G).

The method for the Netherlands uses allometric biomass functions to calculate aboveground tree biomass. Aboveground biomass is then separated into tree compartments with proportional biomass fractions. The biomass fractions are derived from tree age and are calculated based on the allometric biomass functions of the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005). The biomass calculations for aboveground biomass and the fraction coefficients come from sample material across Europe and the European part of Russia (see Appendix H).

2.2.3. Central-Eastern Europe

Three countries, Czech Republic, Poland, and Romania, belong to Central-Eastern Europe. The Czech Republic biomass calculation method is similar to Austria and Belgium, using a combination of volume functions, expansion factors, and allometric biomass functions. The functions were developed based on sample material from the Czech Republic or former Czechoslovakia (see Appendix I).

In Poland, allometric biomass functions are used for aboveground biomass and expansion factors for belowground biomass. The functions are developed with sample data from Poland, Finland and Central Europe (see Appendix J).

The calculation in Romania uses a combination of volume functions, biomass expansion factors and biomass fractions similar to the Netherlands. The volume functions based on data from Romania (Giurgiu et al., 1972) provide tree volume. After applying biomass expansion factors, the biomass of tree compartments is estimated using biomass fractions from the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005) (see Appendix K).

2.2.4. Southern Europe

Two countries, Italy and Spain, belong to Southern Europe. Italy uses allometric biomass functions developed with sample material from Italy for aboveground biomass and expansion factors for root biomass (see Appendix L).

In Spain allometric biomass functions developed with Spanish sample data are used. Similar to France, the carbon fractions in Spain differ from the other countries. Species-specific carbon fractions given by Montero et al. (2005) are used (see Appendix A, and for further details Appendix M).

3. Data

Forests across Europe vary by site conditions, age, and genetics and usually have experienced different forest management. Furthermore, available forest inventory data sets differ according to (i) the sampling design (i.e., fixed area plots vs. angle count sampling), (ii) the measurement methods (i.e., minimum diameter threshold for recording trees) or (iii) the data collection and processing method (i.e., measurement of tree height for every tree vs. applying diameter–height relationships, etc.). These differences in forest data from country to country make a theoretical comparison of the different regional biomass calculation methods difficult (Tomppo et al., 2010).

In order to circumvent this problem we produce a standardized input dataset, which provides all necessary input data for the country-specific models (see Appendices A–M). This ensures that any differences in the results are a consequence of the carbon calculation methods.

3.1. Stand data generation

For creating a standardized data set we use STANDGEN (Kittenberger, 2003), a tool implemented in the framework of the single tree simulation model MOSES (Hasenauer, 1994; Klopf et al., 2011). The STANDGEN tool generates stand data including diameter and location of single trees based on information on diameter distribution (mean and standard deviation), spatial distribution, and aggregation of trees. For each of the five selected tree species, three stands are generated, each with a size of 0.25 hectare (2500 m^2). The three stands differ in mean and standard deviation of tree diameter and represent forest stands at different ages. This takes into account that stand age affects eco-physiological processes such as biomass allocation, stem number, or stocking density. For each species, we generate a young stand (quadratic mean DBH 10 cm with standard deviation 1 cm), a middle-aged stand (30 cm ± 5 cm), and an old stand (50 cm ± 10 cm). Note that we use the quadratic mean DBH to refer to the "average or central tree" representing the tree with the mean basal area. For convenience we consider that a tree with quadratic mean DBH represents a tree with "mean tree biomass". We follow here Eastaugh (2014) showing that the error in this assumption is small. Tree height and age are estimated using species-dependent relationships, crown length is estimated using the DBH-, and height-dependent functions implemented in the MOSES framework (Sterba, 1976; Marschall, 1992; Klopf et al., 2011).

3.2. Stand variables

The generated stands are characterized by the stand variables: mean tree height, height–diameter ratio, crown ratio, stand age, stem number per hectare (N), and basal area per hectare (BA). The two latter variables are calculated as follows.

$$BA = 1/S * \Sigma(DBH^2 * \pi/400) \tag{2}$$

$$N = 1/S * ni \tag{3}$$

where BA is the basal area per hectare [m^2/ha], S is equal to 0.25 ha (the size of the generated stand), DBH is the diameter at breast height (at 1.3 m) [cm], N is the stem number per hectare [trees/ha], and ni is the number of trees per stand. Summary statistics of the generated stand properties available for our study are given in Table 2. Tree height, stand age and basal area increase with increasing DBH, while the height–diameter ratio, crown ratio and stem number decrease, meaning that these stand properties change with age (Table 2).

4. Analysis and results

4.1. Tree carbon estimation

We start our analysis by applying the 12 country specific carbon calculation methods as outlined in Appendices B–M to our standardized tree data set. The data set covers five tree species: (i) *F. sylvatica* L., (ii) *Q. robur* L., (iii) *B. pendula* Roth, (iv) *P. abies* (L.) Karst. and (v) *P. sylvestris* L. (Table 2). We calculate biomass for the tree compartments stem, branch, foliage and roots. The biomass results by compartment are added and multiplied with the carbon fraction (Appendix A) to derive total tree carbon. Since the input data set is identical by species, we ensure that any differences in the results represent (i) differences in the calculation approach, (ii) the statistical coefficients and/or (iii) any additional regional biophysical differences by species. Fig. 1 provides the total carbon in kg per tree versus diameter at breast height (DBH) by

Table 2
Properties of the generated standardized tree dataset separated by stands and species, first column properties of stand with quadratic mean diameter (DBH) of 10 cm, second for DBH of 30 cm, third for DBH 50 cm, Stand age [year] derived from yield tables (see Method section), Stem number is number of trees per hectare [ha^{-1}], Basal area is the area of trees at breast height (1.3 m) per hectare [m^2/ha], Mean height is Lorey's mean height (Lorey, 1878) of all trees in stand [m], Mean H/DBH is the mean height-to-diameter ratio [m/m], Mean CR is mean crown ratio (crown height divided by tree height) [m/m].

	Stand age [year]			Stem number [ha^{-1}]			Basal area [m^2/ha]		
	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
Picea abies	25	70	150	3404	740	304	27	52	65
Pinus sylvestris	35	115	>130	2776	576	240	22	41	50
Fagus sylvatica	40	85	>140	3064	496	188	24	35	37
Quercus robur	35	90	>130	2248	440	212	18	31	39
Betula pendula	17	75	>120	2148	412	160	17	29	31
	Mean height [m]			Mean H/DBH [m/m]			Mean CR [m/m]		
Picea abies	8.5	22.6	30.9	83	75	59	0.73	0.58	0.46
Pinus sylvestris	6.6	18.8	26.6	65	62	52	0.79	0.61	0.48
Fagus sylvatica	8.7	20.8	26.7	87	69	54	0.71	0.59	0.48
Quercus robur	8.4	25.2	31.5	82	84	66	0.73	0.55	0.47
Betula pendula	8.4	25.3	31.9	81	84	65	0.73	0.55	0.46

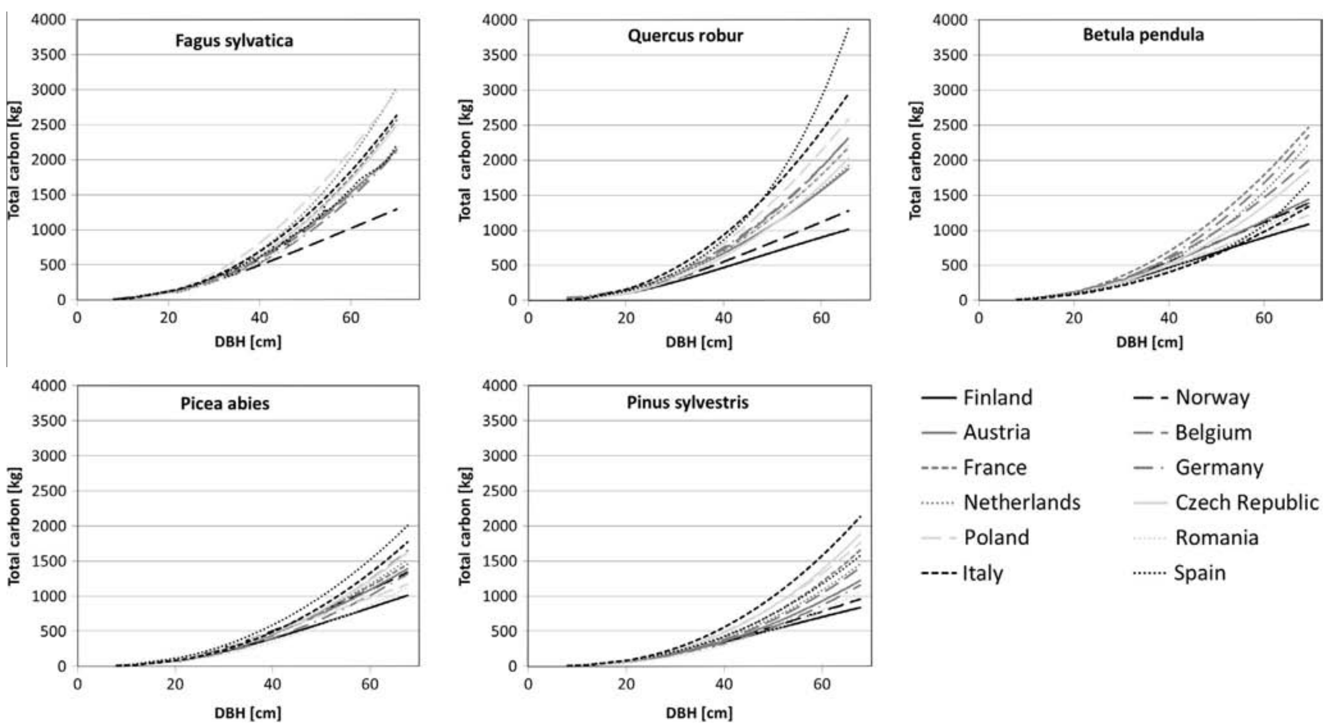

Fig. 1. Tree carbon on tree level [kg/tree] for all countries in this study and for all analyzed tree species, results are grouped by ecoregions (black – North Europe and South Europe, dark gray – Central-West Europe, light gray – Central-East Europe).

species and country. In Fig. 1, and in the following Figs. 2–7, we present curves that originate from the smoothed single tree results.

Strong discrepancies with increasing DBH are evident (Fig. 1) by country. Thus we subsequently group the country-specific results by European forest regions following the definition of the State of Europe's Forests 2011 (FOREST EUROPE, UNECE, FAO, 2011) to address regional biophysical growing conditions resulting from the geographic location, soil and climate conditions, and genetic differences by species across Europe. Country specific biomass estimation methods (Appendices B–M) were developed and calibrated with regional data. Thus the resulting carbon and biomass estimates are expected to capture the different regional biophysical growing conditions. We assign each tree species and country-specific estimation method to each of the four European forest regions. The results for tree carbon in kg per tree versus DBH are ordered by country and grouped by European forest region as shown in Figs. 2–5.

4.2. Tree biomass estimation by compartment

Total tree carbon (Figs. 1–5) is calculated as the sum of the estimated biomass of each compartment (stem, branches, foliage and roots) multiplied by the carbon fraction factor (Eq. (1) and Appendices A–M). Next we evaluate the proportions of the compartment results and their respective discrepancies by species and country across Europe. Since *P. abies* and *F. sylvatica* are the most important coniferous and broadleaf species and cover the vast majority of forest area in Central-East and Central-West Europe, we focus and display here only these two species within these two regions. Fig. 6 presents the trend in the four compartments versus DBH for *P. abies* in Central-West Europe, and Fig. 7 for *F. sylvatica* for Central-East Europe, respectively. We use the identical scaling to show (i) the effect of the different functions by compartment applied and (ii) their contribution to the total tree carbon.

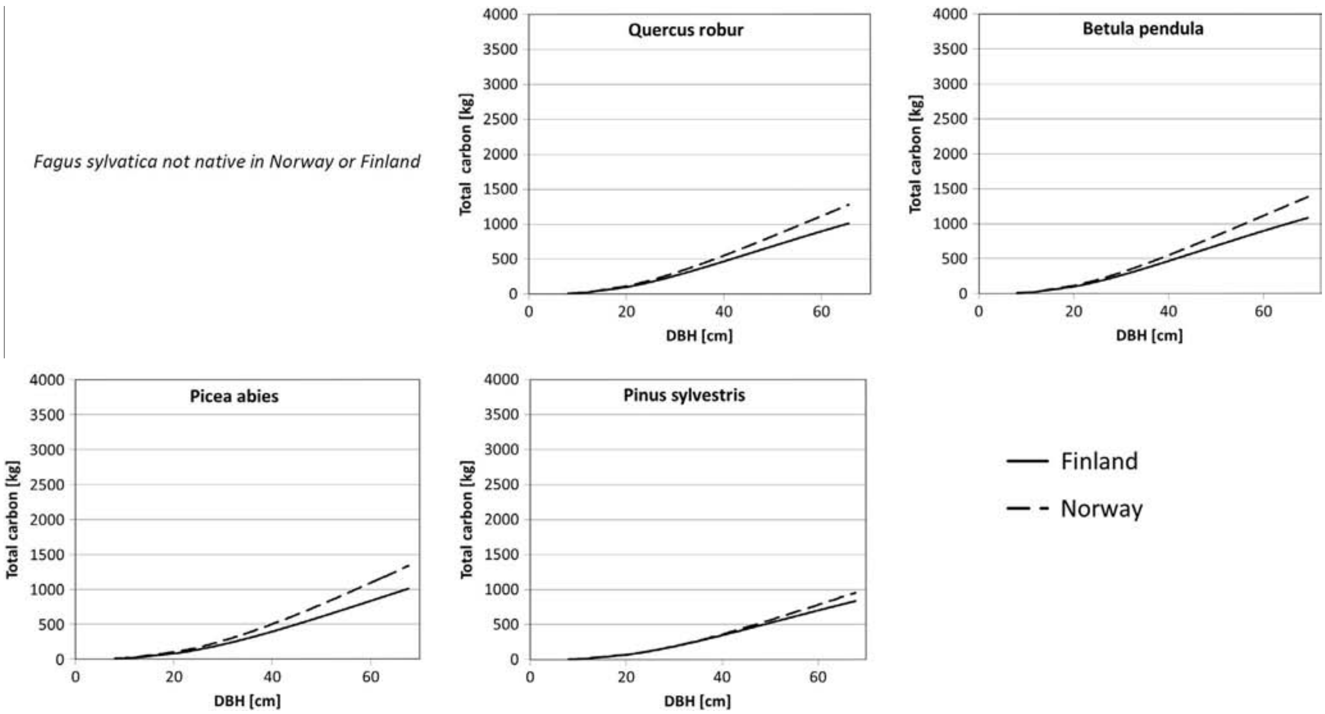

Fig. 2. Tree carbon on tree level [kg/tree] for North Europe and for all analyzed tree species.

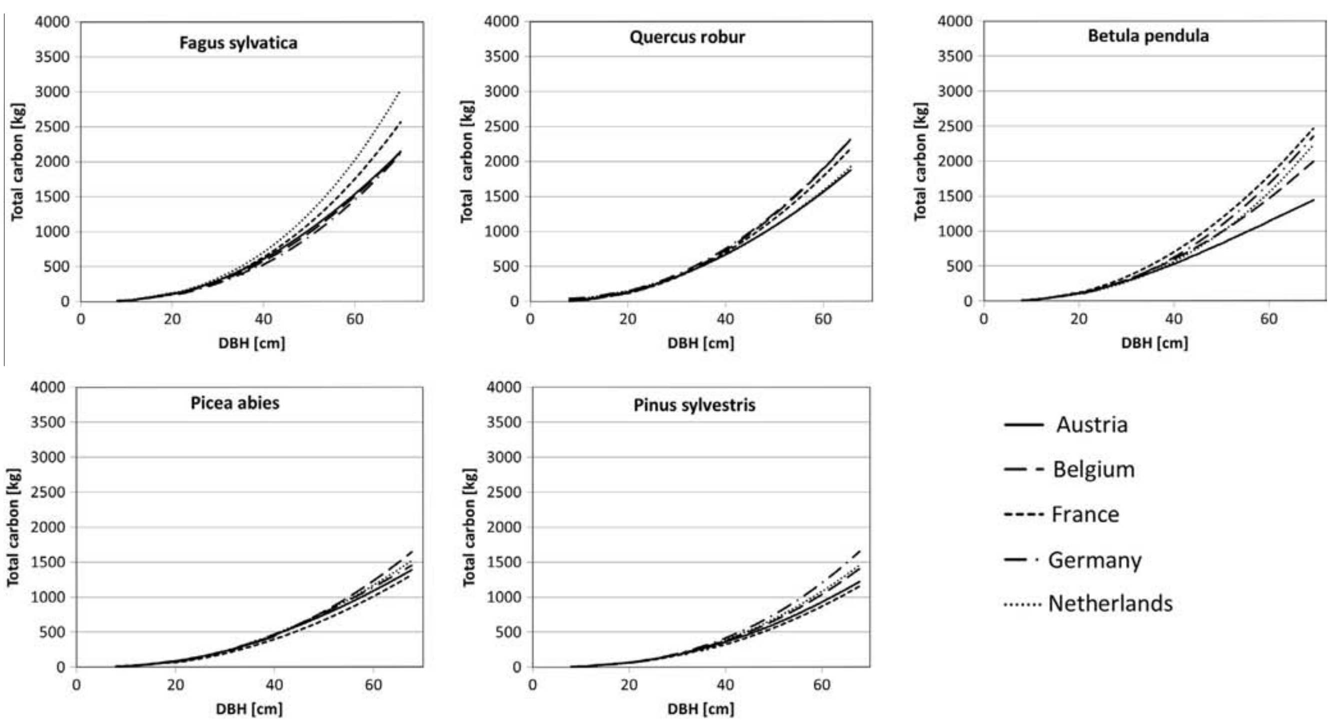

Fig. 3. Tree carbon on tree level [kg/tree] for Central-West Europe and for all analyzed tree species.

4.3. Carbon and biomass of forest stands

The deviations found in the country-specific tree carbon estimates by DBH (see Figs. 1–7) may differ from carbon estimates at the forest stand-level since the number of trees by DBH class varies. In addition, most carbon studies focus on stand level estimates (e.g. t/ha). Therefore, we assess the methodological implications at the forest stand level by country and the species-specific carbon calculation method by deriving forest stand carbon estimates for our generated forest stands. Again, we choose to focus on *P. abies* and *F. sylvatica* and the corresponding three reference stands with a quadratic mean DBH of 10 cm (standard deviation (SD) of DBH distribution 1 cm), 30 cm (SD 5 cm) and 50 cm (SD 10 cm) generated with the tool STANDGEN (see Table 2).

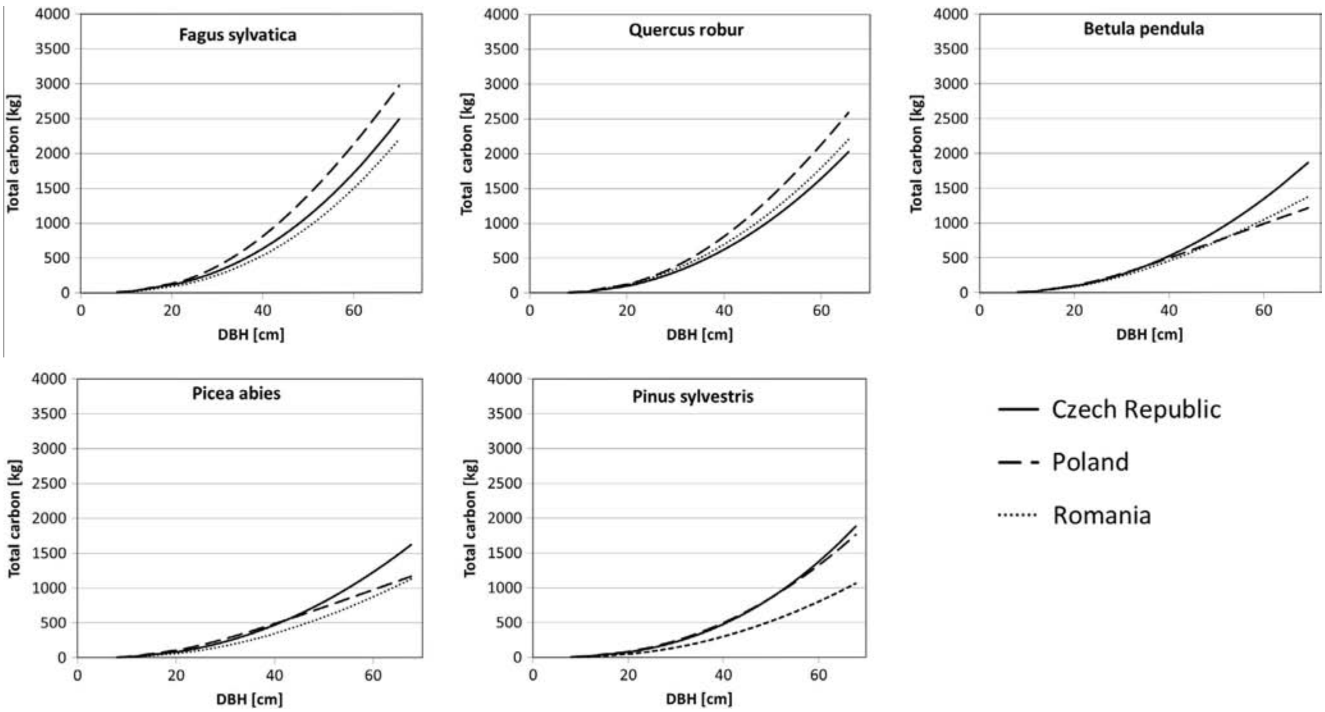

Fig. 4. Tree carbon on tree level [kg/tree] for Central-East Europe and for all analyzed tree species.

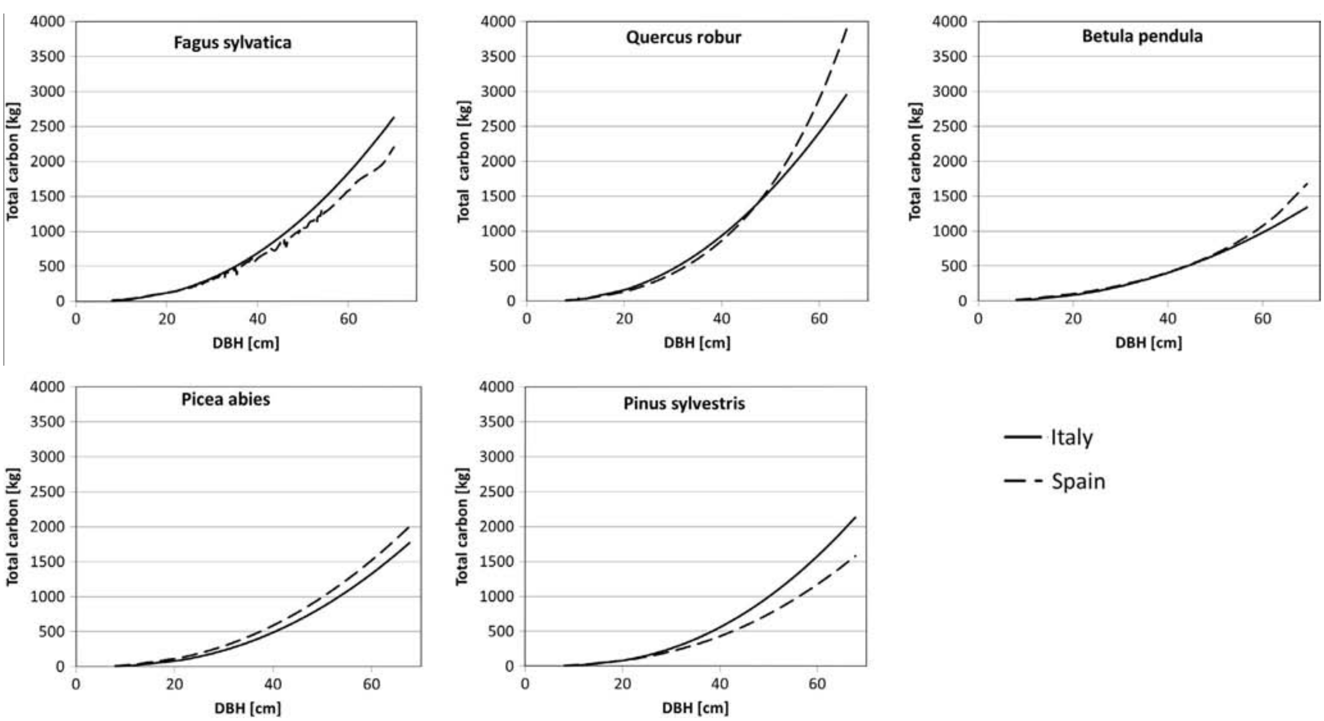

Fig. 5. Tree carbon on tree level [kg/tree] for South Europe and for all analyzed tree species.

For each tree, the biomass and carbon estimation methods are applied. The results for *P. abies* and *F. sylvatica* covering the stem, branch, foliage, root, and total tree biomass plus the tree carbon estimates for each reference stand are given in Tables 3 and 4. Again, we use the quadratic mean DBH representing the tree with mean basal area and mean tree biomass (Eastaugh, 2014). Tables 3 and 4 also provide summary statistics for *P. abies* and *F. sylvatica*. Similar tables for the other species, we provide in Supplementary material (Tables S.1–S.3).

5. Discussion

Carbon estimates by tree species differ substantially by country (see Fig. 1). After grouping the countries by main forest region in Europe (FOREST EUROPE, UNECE, FAO, 2011) to address regional differences, the deviations by species and country within the forest region are found to be smaller, but still evident (Figs. 2–5). The smallest deviations are detected for the North Europe and South

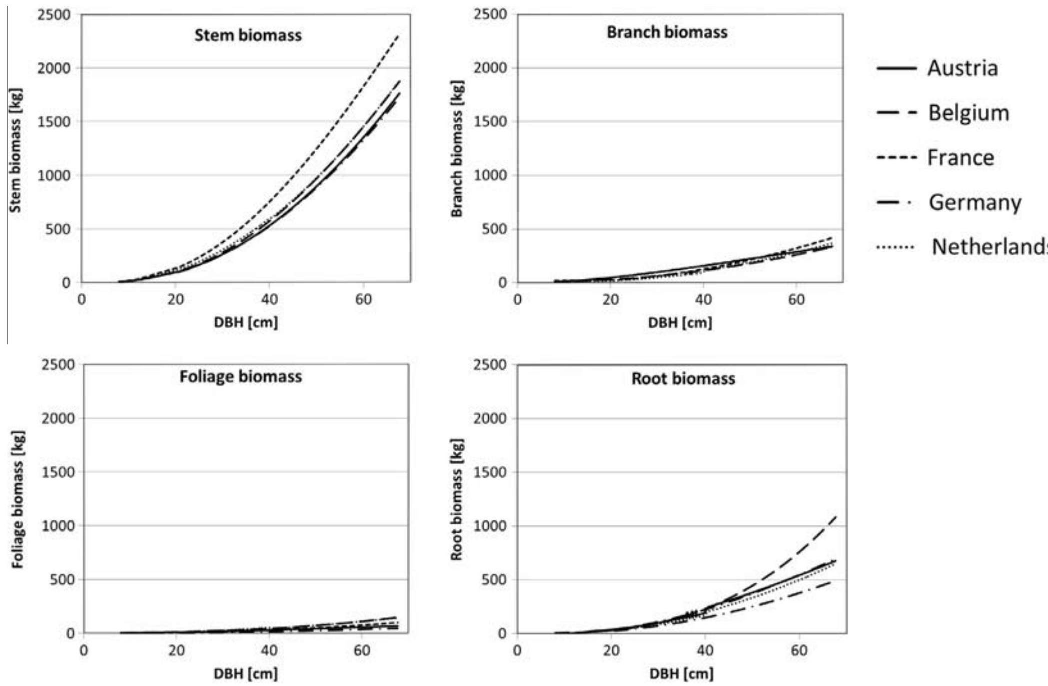

Fig. 6. Biomass in tree compartments on tree level [kg/tree] for *Picea abies* and Central-West Europe.

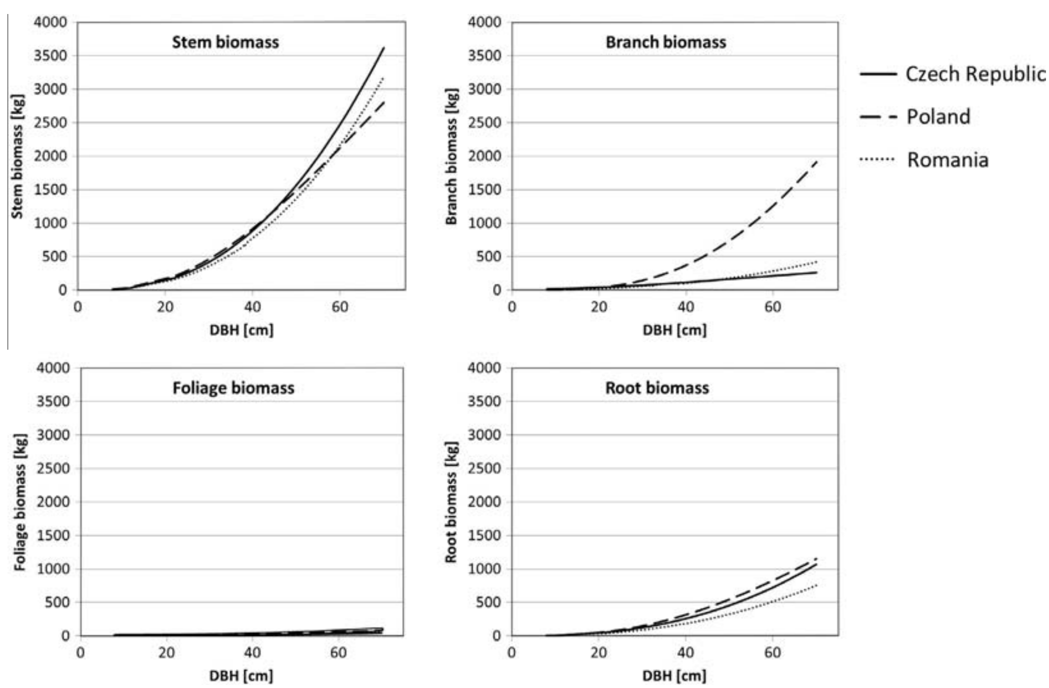

Fig. 7. Biomass in tree compartments on tree level [kg/tree] for *Fagus sylvatica* and Central-East Europe.

Europe regions (Figs. 2 and 5), as compared to Central-West Europe (Fig. 3) and Central-East Europe (Fig. 4). This supports the hypothesis that part of the observed differences can be attributed to environmental growing conditions. The remaining error is caused by the conceptual approach. Stem biomass contributes the largest proportion of total biomass followed by root, branch, and foliage biomass (Figs. 6 and 7). Some unrealistic results are detected, for example in the case of branch biomass for *F. sylvatica* in Poland (Fig. 7).

The results at the stand level (Tables 3 and 4 and Tables S.1–S.3 in Supplementary material) confirm that the differences in tree carbon and biomass in tree compartments at the tree level (Figs. 1–7) can be observed also on the stand level. Tables 3 and 4 further allows quantifying the discrepancies in carbon and biomass observed merely visually in Figs. 1–7. For both *P. abies* and *F. sylvatica,* stem biomass add the largest part to the existing discrepancies in total biomass and carbon followed by branch and root biomass. The average range of stem biomass estimates for all countries and

Table 3
Results for biomass in tree compartments, tree biomass (sum of all compartments) and tree carbon on stand level [t/ha] for *Picea abies*, results arranged according to the 4 Forest regions, first column give the results for the stand with quadratic mean diameter (DBH) of 10 cm, second column for DBH of 30 cm and third column for DBH of 50 cm. At the end of table selected statistics are given for each stand and each biomass and carbon estimate: Mean and Range (Maximum–Minimum) of the country estimates and variation expressed as Range divided by Mean.

Picea abies	Stem biomass [t/ha]			Branch biomass [t/ha]			Foliage biomass [t/ha]			Root biomass [t/ha]			Tree biomass [t/ha]			Tree carbon [t/ha]		
	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
North Europe																		
Finland	49.6	186.3	232.0	17.1	41.7	42.5	12.6	18.0	12.0	29.8	85.7	118.9	109.0	331.6	405.4	48.2	155.9	197.7
Norway	48.2	217.7	316.6	40.1	80.4	80.1	16.3	27.1	25.0	27.4	91.9	113.0	132.1	417.1	534.6	57.9	193.8	256.1
Central-West Europe																		
Austria	45.8	194.3	300.9	45.4	71.4	70.9	11.9	14.1	13.8	13.9	75.3	125.4	117.0	355.0	510.9	52.6	169.7	249.3
Belgium	43.4	206.9	323.5	29.7	47.5	59.8	18.7	18.6	24.6	14.2	76.1	159.1	105.9	349.1	567.1	43.6	164.0	272.6
France	60.2	276.7	412.2	–	–	–	1.2	5.5	8.2	18.1	83.0	123.7	79.5	365.3	544.1	37.8	172.2	259.7
Germany	37.1	192.1	296.2	68.7	46.5	71.7	4.2	11.5	17.0	33.9	54.9	84.6	143.9	304.9	469.5	69.8	145.6	227.4
Netherlands	41.8	224.6	325.7	22.6	36.1	63.7	12.1	20.2	24.6	11.6	64.8	112.3	88.1	345.7	526.3	44.0	171.9	264.1
Central-East Europe																		
Czech Republic	41.1	215.2	346.9	17.5	21.6	26.4	3.5	5.1	6.6	26.7	83.7	133.8	88.8	325.6	513.7	44.4	161.6	258.1
Poland	73.9	278.5	311.2	14.9	32.2	53.0	10.3	15.5	15.5	22.8	75.0	87.3	121.9	401.2	466.9	60.9	199.5	234.6
Romania	29.9	167.0	246.3	16.2	26.8	45.2	8.7	15.0	18.8	8.3	48.2	81.9	63.1	257.0	392.2	31.6	127.6	197.0
South Europe																		
Italy	45.0	210.4	348.5	24.9	60.7	102.6	–	–	–	20.3	78.6	130.8	90.2	349.7	581.9	45.1	173.4	292.4
Spain	55.1	282.8	483.7	60.3	78.9	87.9	4.2	12.3	19.0	34.7	66.9	83.6	154.3	440.9	674.2	77.1	218.8	338.7
Mean [t/ha]	47.6	221.0	328.6	32.5	49.4	64.0	9.4	14.8	16.8	21.8	73.7	112.9	107.8	353.6	515.6	51.1	171.2	254.0
Range [t/ha]	44.0	115.9	251.7	53.8	58.9	76.2	17.5	22.0	18.4	26.4	43.7	77.3	91.2	183.9	282.0	45.6	91.2	141.8
Range/Mean [%]	92	52	77	166	119	119	185	149	109	121	59	68	85	52	55	89	53	56

Table 4
Results for biomass in tree compartments, tree biomass (sum of all compartments) and tree carbon on stand level [t/ha] for *Fagus sylvatica*, for details on the table and the content please see explanations provided for Table 3.

Fagus sylvatica	Stem biomass [t/ha]			Branch biomass [t/ha]			Foliage biomass [t/ha]			Root biomass [t/ha]			Tree biomass [t/ha]			Tree carbon [t/ha]		
	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
North Europe																		
Finland	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Norway	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Central-West Europe																		
Austria	55.9	185.4	241.1	36.0	87.9	110.5	3.3	3.5	3.1	12.7	26.3	32.9	107.8	303.1	387.6	53.9	149.9	195.4
Belgium	48.0	189.8	248.0	19.1	46.9	63.4	3.6	6.5	8.8	21.2	47.7	61.8	91.9	290.8	382.0	45.0	141.0	188.7
France	80.8	247.6	345.6	–	–	–	1.6	5.0	6.9	22.6	69.3	96.8	105.1	321.9	449.2	49.9	151.1	215.2
Germany	43.5	168.9	241.8	29.7	38.7	37.2	3.6	6.5	8.8	31.5	49.8	67.0	108.3	263.9	354.7	54.1	130.2	179.1
Netherlands	79.2	233.1	349.7	13.2	39.7	46.1	5.8	5.4	6.3	34.4	58.6	82.8	132.7	336.8	485.0	66.1	166.4	244.6
Central-East Europe																		
Czech Republic	56.1	209.7	299.5	62.0	36.5	30.6	3.0	3.6	4.0	23.4	62.2	87.2	144.6	312.1	421.2	72.3	154.3	212.3
Poland	80.2	229.7	277.2	14.6	74.7	143.1	3.4	6.4	7.7	23.6	74.6	102.7	121.8	385.3	530.7	60.9	190.4	267.7
Romania	54.1	178.9	262.0	9.0	30.5	34.6	4.0	4.1	4.7	23.5	45.0	62.0	90.6	258.5	363.3	45.3	127.7	183.2
South Europe																		
Italy	63.9	230.2	312.6	21.4	48.8	65.0	–	–	–	17.1	55.8	75.5	102.3	334.8	453.1	51.2	165.5	228.5
Spain	69.3	198.9	260.8	46.5	65.1	76.8	5.0	4.9	4.3	32.4	47.2	50.0	153.2	316.2	391.9	76.6	155.6	198.4
Mean [t/ha]	63.1	207.2	283.8	27.9	52.1	67.5	3.7	5.1	6.1	24.2	53.7	71.9	115.8	312.3	421.9	57.5	153.2	211.3
Range [t/ha]	37.3	78.7	108.6	53.0	57.4	112.5	4.2	3.0	5.6	21.8	48.2	69.8	62.5	126.8	176.1	31.6	62.7	88.6
Range/Mean [%]	59	38	38	190	110	167	114	59	92	90	90	97	54	41	42	55	41	42

stands is 137.2 t/ha for *P. abies* (branch 63.0, root 49.1, and foliage 19.3 t/ha) and 74.8 t/ha for *F. sylvatica* (branch 74.3, root 46.6, and foliage 4.3 t/ha). Although the differences of the root, branch and foliage biomass are smaller in absolute terms, the relative differences are even higher as compared to the stem biomass estimates (Average Range/Mean for stem biomass and all stands for *P. abies* 74% (branch 135%, root 83%, and foliage 148%) and for *F. sylvatica* 45% (branch 156%, root 92%, and foliage 88%) (Tables 3 and 4). Therefor the choice of stem biomass function contributes most to total carbon in absolute terms, but the other compartments have an impact as well, especially in proportion to their results.

Tables 3 and 4 further indicate that these discrepancies differ between the different stands. In the younger forest stands (DBH 10 cm) the ratio of Range and Mean of the tree carbon estimates for *P. abies* is 85% and for *F. sylvatica* of 54% and thus highest as opposed to the two older stands. The same patterns are also visible in the biomass compartments (Tables 3 and 4 and Tables S.1–S.3). This is not detectable from the single tree results (Figs. 1–7) since the scaling hides the results at small DBH. The results for the young trees are very small in absolute values compared to the results of bigger trees (Figs. 1–7). Still the total carbon results of the young stands with DBH 10 cm amount for about a fourth of the results of the old stands with DBH 50 cm (21% for *P. abies* and 28% for *F. sylvatica*; Tables 3 and 4). The large amount of carbon in young stands is caused by the large number of trees per unit area (Table 2), which have an amplifying effect on the single tree results and the differences on forest stand level. Comparing only the carbon of single trees would be misleading because the stem number decreases with age due to competition. Such effects need to be considered if the task is to optimize carbon storage for the purposes of climate change mitigation, such as REDD+ (Canadell et al., 2007; Mohren et al., 2012).

Stand-level results for branch and foliage biomass do not show the same increase based upon DBH as do stem and root biomass. The results show that foliage and branch biomass are constant with a modest increase with stand age. This is consistent with the Pipe Model Theory (Shinozaki et al., 1964a,b) and other research indicating that after canopy closure Leaf Area Index (LAI) is a constant (Waring et al., 1982; He et al., 2012).

Our analysis confirms that the general carbon calculation approach (biomass functions vs. conversion factors) in combination with the specific parameter estimates for deriving biomass functions or conversion factors (Appendices A–M) influences the country-specific results. Differences in carbon estimates across countries are affected by regional conditions. However determining the proportion of the detected deviation that is due to the sampling procedure and methods versus the deviation from environmental conditions (e.g. climate, soil or genetics) or differences in tree allometry remains a key question. Since it is very difficult to know the true biomass amount by compartment and tree species, plausibility checks, such as a careful assessment of the (i) original sample material for calibrating and developing regional biomass estimation methods and the (ii) statistical approach are essential. The empirical sample material for the country-specific estimation methods has large discrepancies (see Tables 5 and 6 for *P. abies* and *F. sylvatica* and Tables S.4–S.6 in the Supplementary material for the remaining species).

Most biomass estimation methods applied in this study use sample data mostly within a DBH range between 10 and 40 cm and lack data from very small or very big trees. Tree heights and ages have similar deficiencies in sample data range (Tables 5 and 6, Tables S.4–S.6 in Supplementary material). This range limitation results in regression functions derived from sample data that may lead to unrealistic estimates if they are extrapolated, particularly for larger, but also smaller tree diameters. Analogously, differences in tree allometry due to forest management or tree genetics can be possible sources of deviation in the carbon and biomass results. Within Europe both management practices (FOREST EUROPE, UNECE, FAO, 2011) and tree genetics vary strongly by tree species (Skrøppa, 2003; Mátyás et al., 2004). This may affect biomass allocation and growth rates (Schmidt-Vogt, 1977; Gruber, 1987; Müller-Starck et al., 1992). Since hardly any references provide information on allometric properties such as crown length, crown width or stem taper or even tree genetics, we cannot examine this in more detail.

The type of estimation method has a large effect on any results and we want to illustrate this for biomass expansion factors versus allometric biomass functions. Biomass expansion factors convert tree volume into biomass by applying a species-specific average conversion factor, independent of age, tree height, etc. Forest management strongly affects the growth rates of stands and thus the tree ring width (Assmann, 1970). Wood density is strongly correlated to tree ring width (MacPeak et al., 1990; Repola, 2006; Ledermann and Neumann, 2006) but also to tree age. It is well known that constant biomass expansion factors tend to overestimate biomass for young trees and underestimate biomass for older trees (Pietsch and Hasenauer, 2002). Allometric biomass functions which derive tree biomass from DBH and/or height were developed to circumvent this problem and include the effect of age in the biomass predictions.

Biomass in tree compartments show higher differences among countries than total biomass estimates (Figs. 6 and 7). Again part of these discrepancies in biomass estimates may be caused by environmental drivers while the rest is an effect of sample material and the estimation methodology. Here it is also important to know the definition of the various tree compartments by country as this also affects the results (Jenkins et al., 2003). For example, the definition of branch or stem biomass for *F. sylvatica* in Poland could be different than in other countries, since the results for total biomass in Poland did not show clear differences in Fig. 4. Unfortunately, in the case of Poland (Muukkonen, 2007) we could not test this hypothesis, since the definition of stem and branch biomass is not given. But there is some evidence in the results of other countries. In France stem biomass includes all branches (Vallet et al., 2006). In most other countries the definition of stem excludes branches as well as the stump (e.g. for Austria Pollanschütz, 1974; for Norway Marklund, 1988). This explains why France has the highest results for stem biomass for *P. abies* (Fig. 6) but only average results for total tree biomass (see Fig. 3 and Table 3).

Similarly, the assigned minimum diameter for root biomass (see Appendices B–M) influences the deviations in root biomass results (Figs. 6 and 7, Tables 3 and 4). For Austria as well as for Norway it is assigned 2 mm (Wirth et al., 2004; Petersson and Ståhl, 2006), while for the Czech Republic or Belgium it is assigned 5 mm (Drexhage and Gruber, 1999; Drexhage and Colin, 2001; Xiao et al., 2003).

All functions in this study use tree diameter to predict the biomass or volume, with many also using tree height (Table 1 and Appendices B–M). Any additional predictor variable decreases the remaining variation and improves the performance of the model (e.g. Ketterings et al., 2001; Ledermann and Neumann, 2006 or Lang et al., 2007). Some models use additional variables such as tree age (Wirth et al., 2004) or tree crown parameters (i.e., crown ratio or crown length; Repola, 2008, 2009; Ledermann and Neumann, 2006). Without tree height or crown height as additional variables the models will assume a constant DBH/height ratio or DBH/crown height ratio. This is an unrealistic assumption since height increment culminates earlier than diameter increment and trees in general modify their crown according to stand density and the light availability (Assmann, 1970). A good example to illustrate the effect of additional variables are root biomass estimates of *P. abies* from Austria and Belgium. Both countries use

Table 5
Properties of the sample material used for volume and biomass functions for *Picea abies* by country and region: if multiple references are used for the compartments in one country, each reference is covered by one row. Given for each reference is DBH (diameter at breast height) and tree height of the sample material, the Origin of the samples (the country where the sample material was collected), the Number of samples, the Age of the sample trees in years as well as the Reference. Boxes with a endash (–) indicate that this information is not given by the reference. For the volume functions used in Czech Republic only the maximum diameter and height of the samples is given (Petráš and Pajtík, 1991).

Forest region	Country	Compartments	DBH [cm]	Height [m]	Origin	No. samples	Age [a]	References
North Europe	Finland	All	1.7–41.7	2.1–35.0	Finland	613	15–164	Repola (2009)
	Norway	Aboveground	0.3–63.4	1.3–35.6	Sweden	551	1–223	Marklund (1988)
		Roots	0.3–63.4	1.3–35.6	Sweden	342	1–223	Petersson and Stahl (2006)
Central-West Europe	Austria	Stem volume	5.0–78.0	10.0–44.0	Austria	9972	–	Pollanschütz (1974)
		Branches	2.4–65.9	2.8–42.6	Austria	3753	35–126	Ledermann and Neumann (2006)
		Foliage	1.8–98.2	2.1–44.8	Switzerland	189	15–270	Burger (1947, 1953)
		Roots	7.6–41.2	6.8–31.7	Temperate Europe	85	16–142	Wirth et al. (2004)
	Belgium	Stem volume	–	–	Belgium	991	–	Dagnelie et al. (1985)
		Branches	2.4–65.9	2.8–42.6	Austria	3753	35–126	Ledermann and Neumann (2006)
		Foliage	4.0–38.0	6.7–25.9	Netherlands	23	9–39	Bartelink (1996)
		Roots	7.6–41.2	6.8–31.7	Temperate Europe	85	16–142	Wirth et al. (2004)
	France	Aboveground	14.3–71.6	–	France	309	–	Vallet et al. (2006)
	Germany	Wood volume	–	–	Germany	–	–	Kublin (2002)
		Foliage	25.0–55.6	22.0–29.8	Germany	7	–	Schwarzmeier (2000)
	Netherlands	Aboveground	0.5–52.0	–	European Russia	222	20–155	Hamburg et al. (1997)
Central-East Europe	Czech Republic	Wood volume	−74.0	−46.0	Czechoslovakia	2111	–	Petráš and Pajtík (1991)
		Foliage, twigs	4.0–92.0	4.0–48.0	Czechoslovakia	265	–	Petráš et al. (1985)
		Roots	5.0–25.0	15 (mean)	N Germany	15	10–40	Drexhage and Gruber (1999)
	Poland	All	0.0–67.5	2.0–42.7	Europe	~1800	–	Muukkonen (2007)
	Romania	Aboveground	–	–	Romania	5403	–	Giurgiu et al. (1972)
South Europe	Italy	All	8.1–81.7	6.0–40.1	NE Italy	93	–	Tabacchi et al. (2011)
	Spain	All (excl. foliage)	9.0–57.5	8.0–29.0	Spain	29 (roots 10)	–	Ruiz-Peinado et al. (2011)
		Foliage	5.3–49.2	7.1–23.8	NW Spain	125	34–44	Diéguez-Aranda et al. (2009)

Table 6
Properties of the sample material used for volume and biomass functions for *Fagus sylvatica* by country and region: for details on the table and the content please see explanations provided for Table 5.

Forest region	Country	Compartments	DBH [cm]	Height [m]	Origin	No. Samples	Age [a]	References
North Europe	Finland	–	–	–	–	–	–	–
	Norway	–	–	–	–	–	–	–
Central-West Europe	Austria	Stem (volume)	–	–	Austria	933	–	Pollanschütz (1974)
		Branches	2.0–67.1	3.6–39.0	Austria	4213	35–125	Ledermann and Neumann (2006)
		Foliage	0.8–57.0	2.6–39.6	Switzerland	91	14–128	Burger (1953)
		Roots	4.0–53.0	7.0–28.0	Germany	27	44–127	Bolte et al. (2004)
	Belgium	Stem (volume)	–	–	Belgium	–	–	Dagnelie et al. (1985)
		Branches	5.7–62.1	9.2–33.9	Czech Republic	20	40–114	Cienciala et al. (2005)
		Foliage	2.0–33.0	3.5–22.5	Netherlands	38	8–59	Bartelink (1997)
		Roots	3.0–38.0	7.0–29.0	Central Europe	48	21–160	Wutzler et al. (2008)
	France	Aboveground	1.6–81.2	–	France	1293	–	Vallet et al. (2006)
	Germany	Wood volume	–	–	Germany	–	–	Kublin (2002)
		Foliage	2.0–33.0	3.5–22.5	Netherlands	38	8–59	Bartelink (1997)
	Netherlands	Aboveground	2.0–33.0	3.5–22.5	Netherlands	38	8–59	Bartelink (1997)
Central-East Europe	Czech Republic	Wood volume	−74.0	−38.0	Czechoslovakia	1886	–	Petráš and Pajtík (1991)
		Foliage, twigs	8.0–84.0	8.0–36.0	Czechoslovakia	285	–	Petráš et al. (1985)
		Roots	3.0–20.0	9.9 (mean)	NE France	16	24–35	Le Goff and Ottorini (2001)
	Poland	All	2.0–64.0	3.5–29.0	Europe	68	–	Muukkonen (2007)
	Romania	Aboveground	–	–	Romania	7070	–	Giurgiu et al. (1972)
South Europe	Italy	All	5.0–60.7	7.2–31.6	Italy	91	–	Tabacchi et al. (2011)
	Spain	All (excl. foliage)	9.5–74.8	9.0–30.9	Spain	72 (roots 14)	–	Ruiz-Peinado et al. (2011)
		Foliage	9.9–21.0	12.6–26.2	NW Spain	16	–	Diéguez-Aranda et al. (2009)

the same reference (Wirth et al., 2004), but Austria use in addition to DBH also the tree age for root biomass prediction. The additional variable has rather little effect for small diameters, while the results for Austria and Belgium strongly deviate after DBH of 40 cm (Fig. 6) and the root biomass of the oldest stand is for Belgium 33.7 t/ha (+27%) higher than for Austria. The choice of biomass or carbon estimation method is restricted to the availability of the input data. If a forest inventory does not provide certain variables (e.g. age or crown height) then more general estimation methods must be used.

Carbon is derived by multiplying biomass with the carbon fraction (Eq. (1)). Research indicated that the carbon fraction in biomass differs by ecoregion (Thomas and Martin, 2012), tree species (Lamlom and Savidge, 2003) or by tree compartment (Lamlom and Savidge, 2006). Besides France, Belgium and Spain, most countries in this study use a carbon fraction of 0.5 as suggested by IPCC (2006) (Appendix A). Considering the literature this is a simplification of the complexity of nature, but necessary since no comprehensive studies exist.

Carbon reporting systems such as the FAO Statistics, the Kyoto protocol or the UNFCCC (United Nations Framework – Convention on Climate Change) are not only concerned with carbon stocks but mainly with changes in carbon stocks (fixation vs. emissions). The effect of the calculation methods presented in this study might be substantially smaller for estimating changes in carbon. Still since the tree results in Figs. 2–5 show different inclination across the DBH range, one can expect that the different methods procure different carbon increment rates for the same change in tree properties like an increase in DBH of 1 cm.

6. Conclusions

We present and compare the official biomass estimation methods from 12 different countries across Europe as they are used for the carbon reporting duties within the Kyoto Protocol under UNFCCC. True tree or stand biomass estimates are impossible to obtain so we compare and assess the country-specific estimation methods to provide a conceptual understanding of the different estimation procedures and how these differences may affect carbon predictions at the European scale. After addressing regional differences by clustering into European forest regions, deviations of single tree carbon and biomass as well as stand-level results decrease but remain throughout Europe (Figs. 2–5, Tables 3 and 4). These discrepancies can be explained with (i) differences in the sample material (Tables 5 and 6), (ii) the variables used in the biomass functions and (iii) the definition of the compartments (Appendices B–M). No additional patterns according to the biomass calculation methods (allometric biomass functions or biomass expansion factors) are evident.

The quality of tree carbon calculations in Europe needs to be improved and systematic quality checks for providing consistent carbon estimation methods are required. These checks must include (i) the definition of the tree compartments, (ii) additional variables to capture differences in site conditions, management impacts, and age effects, (iii) the performance of biomass functions when applied beyond the range of the data set available for parametrization, (iv) representativeness of the functions and the used sample material in terms of covering the tree allometry and specific variability of trees in the region of interest and (v) plausibility checks with local sample material, especially when estimation systems from other regions are applied.

We strengthen the findings of the FPS COST ACTION E43 on "Harmonisation of National Inventories in Europe: Techniques for Common Reporting" (McRoberts et al., 2009; Ståhl et al., 2012) by quantifying the deviation caused by different carbon calculation methods in Europe, which can lead to differences in tree carbon up to 140 t/ha for *P. abies* and 90 t/ha for *F. sylvatica*. We also highlight new issues discovered like the high discrepancies in young stands or the effect of additional tree variables such as crown length or tree age. Choosing and modifying the carbon calculation methodology is the responsibility of each country and NFI organization. However, this is a critical task that should be coordinated across countries because it has such significant ramifications such as its influence on climate change mitigation policy.

Conflict of interests

The authors declare that they have no conflict of interest.

Acknowledgements

This work is part of the project FORMIT ('Enhancing the FORest MITigation potential of European Forests') – financed by DG Research and Innovation within the Seventh Framework Program. The research leading to these results has received funding from the European Union Seventh Framework Programme under grant agreement n° 311970. We further want to acknowledge support from Estonian Ministry of Education and Research (grant n° IUT21-4). The Polish research was supported by funds for science in the years 2013–2016 allocated to an international co-financed project. We thank Loretta Moreno for proofreading the manuscript. We are also thankful to several persons who supported us in preparing the calculation methodology and the manuscript, Isabel Cañellas (Spain), Katarina Merganičová (Czech Republic), Klemens Schadauer, Md. Humain Kabir and Georg Kindermann (Austria). We further want to thank the editor and the anonymous reviewers for their helpful comments that substantially improved the quality of this work.

Appendix A. General details on carbon estimation

Tree carbon gets calculated according to the following general equation.

Table A.1
Carbon fraction (CC) for converting biomass into carbon.

Carbon fraction [/]					
Country	*Picea abies*	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
Austria	0.5	0.5	0.5	0.5	0.5
Belgium	0.5	0.5	0.49	0.5	0.5
Czech Republic	0.5	0.5	0.5	0.5	0.5
Finland	0.5	0.5	0.5	0.5	0.5
France	0.475	0.475	0.475	0.475	0.475
Germany	0.5	0.5	0.5	0.5	0.5
Italy	0.5	0.5	0.5	0.5	0.5
Netherlands	0.5	0.5	0.5	0.5	0.5
Norway	0.5	0.5	0.5	0.5	0.5
Poland	0.5	0.5	0.5	0.5	0.5
Romania	0.5	0.5	0.5	0.5	0.5
Spain	0.506	0.509	0.486	0.484	0.485

Table A.2
Dry wood density (wd) for converting volume into biomass.

Dry wood density [t dry biomass/m^3]					
Country	*Picea abies*	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
Austria	0.362	0.450	0.561	0.579	0.551
Belgium	0.380	0.480	0.560	0.600	0.550
Czech Republic	0.380	0.430	0.570	0.550	0.520
France	0.438	0.438	0.546	0.546	0.546
Germany – branch	0.490	0.490	0.540	0.570	0.540
Germany – stem	0.360	0.360	0.490	0.540	0.490
Romania	0.370	0.420	0.585	0.560	0.525

Table A.3
Root-to-shoot ratio (RS) for deriving root biomass with aboveground biomass (BM).

Root-to-shoot ratio [/]					
Country	*Picea abies*	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
France	0.30	0.30	0.28	0.28	0.28
Germany – BM < 50 t/ha (*Picea, Pinus*), BM < 75 t/ha (*Fagus, Betula*)	0.46	0.46	0.43	0.35	0.43
Germany – BM 50–150 t/ha (*Picea, Pinus*), BM 75–150 t/ha (*Fagus, Betula*)	0.32	0.32	0.26	0.35	0.26
Germany – BM > 150 t/ha	0.23	0.23	0.24	0.35	0.24
Italy	0.29	0.36	0.20	0.20	0.24
Poland	0.23	0.23	0.24	0.24	0.24

$$C_{tree} = CC * (dsm + dbm + dfm + drm) \tag{A.1}$$

where C_{tree} is the total carbon content of a tree [kg], CC is the carbon fraction [/] given for each country in Table A.1, dsm is the dry stem biomass [kg], dbm the dry branch biomass [kg], dfm the dry foliage biomass [kg] and drm the dry root biomass [kg].

If applicable in the country-specific methodology, dry wood density wd to derive biomass using volume estimates are provided in Table A.2 and root-to-shoot ratio RS for deriving root biomass in Table A.3.

Some of the biomass calculation methods consider different compartments than the above mentioned. To get comparable results, the results of these sub-compartments are aggregated to the compartments stem, branch and roots according to the following equations:

$$dsm = dswm + dsbm \tag{A.2}$$

$$dbm = dabm + ddbm \tag{A.3}$$

$$drm = dstm + dcrm + dfrm \tag{A.4}$$

with dsm dry stem biomass, $dswm$ dry stem wood biomass, $dsbm$ dry stem bark biomass, dbm dry branch biomass, $dabm$ dry alive branch biomass, $ddbm$ dry dead branch biomass, drm dry root biomass, $dstm$ dry stump biomass, $dcrm$ dry coarse root biomass, $dfrm$ dry fine root biomass, all quantities in [kg].

The biomass functions of the Czech Republic and Spain separate branches into different diameter classes (e.g. Spain Ruiz-Peinado et al., 2011, 2012; Diéguez-Aranda et al., 2009 and Balboa-Murias et al., 2006a,b; for the Czech Republic Petráš et al., 1985). As foliage biomass is included in the branch biomass, for calculating branch biomass solely foliage biomass get substracted, see Eq. (A.5).

$$dbm = dbm1 + dbm2 + dbm3 + dbm4 + dbm5 - dfm \tag{A.5}$$

With $dbm1$ thick branches with diameter >7 cm, $dbm2$ medium branches with diameter 2–7 cm, $dbm3$ thin branches and twigs with diameter <2 cm, $dbm4$ thin branches with diameter 0.5–2 cm, $dbm5$ twigs with diameter <0.5 cm, dfm foliage biomass.

In the following chapters the biomass calculations are described for each country in detail. Often used variables are DBH diameter at breast height, at 1.3 m above ground, H tree height from ground to tree top, HC crown height from ground to living crown (first living branch), CR crown ratio calculated $CR = (H - HC)/H$, wd dry wood density.

Carbon fraction (CC), dry wood density (wd) and Root-to-shoot ratios (RS) are coefficients most calculation methods use and are therefore presented accumulated for all calculation methods here.

Appendix B. Biomass calculation in Finland

Allometric biomass functions dependent on DBH, tree height and crown length are used for calculating biomass for tree compartments (stem wood, stem bark, living branches, dead branches, foliage (leaves/needles), stump, coarse roots (diameter >1 cm)) (Repola, 2008, 2009) and fine roots (diameter <1 cm) (Härkönen et al., 2011) (see Table B.1).

The chosen methodology is largely identical then the method from the Finnish NIR report. It differs merely in the choice of coefficients used for estimating fine root biomass (Härkönen et al., 2011; Statistics Finland, 2013). It uses allometric biomass functions developed in Finland.

Model type 1:

$$dswm, dsbm, \ldots = cf * exp(c0 + c1 * dk/(dk + c2) + c3 * ln(H) + c4 * H + cf2) \tag{B.1}$$

Model type 2:

$$dswm, dsbm, \ldots = cf * exp(c0 + c1 * dk/(dk + c2) + c3 * H/(H + c4) + c5 * ln(CL) + cf2) \tag{B.2}$$

$$dk = 2 + 1.25 * DBH \tag{B.3}$$

$$dfrm = f_{fr} * dfm \tag{B.4}$$

with dk stump diameter [cm], DBH [cm], H [m], CL crown length [m], CR crown ratio [/], coefficients ci, cf, $cf2$ and f_{fr} are given below. f_{fr} are valid for semi-fertile sites (Härkönen et al., 2011).

For broadleaf trees and dfm CR is used instead $\ln(CL)$. For broadleaf trees and $dabm$ CL instead $\ln(CL)$.

F. sylvatica is not native in Finland. Therefore Finland is excluded from analysis for this tree species.

Table B.1
Coefficients for calculating biomass for Finland (Repola, 2008, 2009).

Coefficients for biomass by compartments for Finland									
Compartment	*c0*	*c1*	*c2*	*c3*	*c4*	*c5*	*cf*	*cf2*	Model type
Picea abies									
dswm	−3.555	8.042	14	0.869	0.015	0	1	0.009	1
dsbm	−4.437	10.071	18	0.261	0	0	1	0.029	1
dabm	−3.023	12.017	14	−5.722	5	1.033	1	0.0425	2
dfm	−0.085	15.222	4	−14.446	1	1.273	1	0.0575	2
ddbm	−5.317	6.384	18	0.982	0	0	1.208	0	1
dstm	−3.964	11.73	26	0	0	0	1	0.0615	1
dcrm	−2.294	10.646	24	0	0	0	1	0.1095	1
Pinus sylvestris									
dswm	−3.721	8.103	14	5.066	12	0	1	0.0055	2
dsbm	−4.695	8.727	12	0.228	0	0	1	0.0355	1
dabm	−5.166	13.085	12	−5.189	8	1.11	1	0.0415	2
dfm	−1.748	14.824	4	−12.684	1	1.209	1	0.0625	2
ddbm	−5.318	10.771	16	0	0	0	0.913	0	1
dstm	−6.753	12.681	12	0	0	0	1	0.027	1
dcrm	−5.55	13.408	15	0	0	0	1	0.0395	1
Betula pendula, Quercus robur									
dswm	−4.879	9.651	12	1.012	0	0	1	0.004035	1
dsbm	−5.433	10.121	12	2.647	20	0	1	0.02739	2
dabm	−5.067	14.614	12	−5.074	12	0.092	1	0.035855	2
dfm	−20.856	22.32	2	0	0	2.819	1	0.027185	2
ddbm	−7.996	11.824	16	0	0	0	2.1491	0	1
dstm	−3.574	11.304	26	0	0	0	1	0.03348	1
dcrm	−3.223	6.497	22	1.033	0	0	1	0.07477	1

Table C.1
Coefficients for calculating biomass for Norway (Marklund, 1988; Petersson and Ståhl, 2006).

Coefficients for biomass by compartment for Norway					
	a0	*a1*	*a2*	*a3*	*a4*
Picea abies					
dswm	−2.3032	7.2309	14	0.0355	0.7030
dsbm	−3.4020	8.3089	15	0.0147	0.2295
dabm	−1.2063	10.9708	13	−0.0124	−0.4923
ddbm	−4.6351	3.6518	18	0.0493	1.0129
dfm	−1.8551	9.7809	12	0	−0.4873
drm	4.58761	10.4404	138	0	0
Pinus sylvestris					
dswm	−2.6864	7.6066	14	0.02	0.8658
dsbm	−3.2765	7.2482	16	0	0.4487
dabm	−2.5413	13.3955	10	0	−1.1955
ddbm	−5.8926	7.1270	10	−0.0465	1.106
dfm	−3.4781	12.1095	7	0.0413	−1.565
drm	3.4428	11.0654	113	0	0
Quercus robur, Betula pendula					
dswm	−3.3045	8.1184	11	0	0.9783
dsbm	−4.0778	8.3019	14	0	0.7433
dabm	−3.3633	10.2806	10	0	0
ddbm	−6.6237	11.2872	30	−0.3081	2.6821
drm	6.1708	10.0111	225	0	0

Appendix C. Biomass calculation in Norway

The methodology is taken from the Norwegian NIR report (Climate and Pollution Agency, 2013; oral communication Rasmus Astrup, 2013). It uses allometric biomass functions developed in Sweden. For aboveground biomass the functions from Marklund (1988) and for belowground biomass (minimum root diameter 2 mm) from Petersson and Ståhl (2006) are used. The functions for alive branches for *P. abies* and *P. sylvestris* also contain the biomass of needles (Marklund, 1988). To compare with other results the foliage biomass is calculated with separate functions.

$$dswm, dsbm, \ldots = exp(a0 + a1 * DBH/(DBH + a2) + a3 * H + c4 * ln(H)) \quad (C.1)$$

For the broad leaf species foliage biomass is assumed to be a constant proportion of stem biomass (de Wit et al., 2006):

$$dfm = dswm * 0.021 \quad (C.2)$$

DBH [cm] (for *drm DBH* [mm]), *H* [m], *drm* [g dry weight], coefficients *a*0–*a*4 are given in Table C.1 (Marklund, 1988; Petersson and Ståhl, 2006).

Appendix D. Biomass calculation in Austria

The presented method corresponds widely with the method for forest carbon calculation used in the Austrian National Inventory report for the Kyoto reporting (Umweltbundesamt, 2013) (see Tables D.1–D.3).

Dry stem biomass (dsm) get calculated using stem volume and species-specific wood density (Gschwantner et al., 2010).

$$dsm = V * wd \tag{D.1}$$

$$V = (DBH/200)^2 * \pi * H * FF \tag{D.2}$$

with DBH [cm] and H [m]

$$FF = c1 + c2 * ln^2(DBH) + c3/H + c4/DBH + c5/DBH^2 + c6/DBH/H + c7/DBH^2/H \tag{D.3}$$

with DBH and H [dm] where V stem volume [m^3], FF form factor, wd dry wood density given in Appendix A [kg dry BM/m^3], which is calculated using wood density and shrinkage factor by tree species from Wagenführ and Scheiber (1985), ci coefficients for form factor calculations (Pollanschütz, 1974; Schieler, 1988; Gabler and Schadauer, 2008) are given below.

Dry branch mass (*dbm*) is calculated for *P. abies* (including foliage biomass), *F. sylvatica, B. pendula* (same function as for *F. sylvatica)* and *Q. robur* using allometric functions from Ledermann and Neumann (2006):

$$dbm = cf * exp(a + b * ln(DBH) + c * H/DBH + d * ln(CR)) \tag{D.4}$$

with DBH [cm], H [m], the species-specific parameters a–d and cf given below in the following table.

For *P. abies dfm* is substracted from *dbm* to get comparable results.

Foliage biomass (*dfm*) is calculated for *P. abies*, *F. sylvatica, B. pendula* and *Q. robur* using allometric functions of Burger (1947, 1949, 1953) modified after Lexer and Hoenninger (2001).

$$dfm = a * DBH^b \tag{D.5}$$

dbm and *dfm* for *P. sylvestris* after Hochbichler et al. (2006):

$$dbm, dfm = cf * exp(a + b * ln(DBH) + c * ln(H)) \tag{D.6}$$

with DBH [cm], H [m], the species-specific parameters $b0$, $b1$, cf and a–d are given below.

Root mass (*drm*) get calculated for *P. abies*, *F. sylvatica, B. pendula* and *Q. robur* using the biomass functions of Wirth et al. (2004), Bolte et al. (2004) and Offenthaler and Hochbichler (2006). Only Bolte et al. (2004) provide the minimum diameter of the samples (2 mm).

$$drm = cf * exp(a + b * ln(DBH) + c * ln^2(DBH) + d * ln(A)) \tag{D.7}$$

And for *P. sylvestris* (Offenthaler and Hochbichler, 2006):

$$drm = 0.038872 * DBH^{2.066783} \tag{D.8}$$

with DBH [cm], A is tree age [a], the species-specific parameters a–d and cf are given below.

Appendix E. Biomass calculation in Belgium

The below presented methodology is the result of a literature review. The volume calculation method is identical in the Belgium NIR report (Flemish Environment Agency, 2013). It is a combination of volume functions, expansion factors and allometric biomass functions from Belgium, Austria, the Czech Republic, Germany, France and Netherlands (see Tables E.1 and E.2).

$$V = b0 + b1 * c_{130} + b2 * c_{130}^2 + b3 * c_{130}^3 + b4 * H + b5 * c_{130}^2 * H \tag{E.1}$$

$$dsm = V * wd \tag{E.2}$$

with V merchantable timber volume [m^3] with a minimal diameter of 7 cm (circumference 22 cm), c_{130} (circumference at 1.3 m height) = $DBH \cdot \cdot \pi$, H [m], $b0$–$b5$ coefficients according to Dagnelie et al. (1985) given below in the following table, wd dry wood density are taken from Vande Walle et al. (2005) are given in Appendix A.

If there are no appropriate biomass functions for Belgium available, the allometric functions from other countries are used. The functions are selected to give realistic results across the DBH and height range of the analysed trees.

For *dbm*, *dfm* and *drm* of *P. sylvestris* (Xiao et al., 2003 cited in Zianis et al., 2005), for *dbm* of *F. sylvatica, B. pendula* and *Q. robur* (Cienciala et al., 2005 cited in Zianis et al., 2005), for *dfm* Bartelink (1997) and for *drm* Wutzler et al. (2008):

$$dbm = b0 * DBH^{b1} \tag{E.3}$$

$$dfm = f0 + f1 * DBH^{b2} \tag{E.4}$$

$$drm = r0 * DBH^{r1} \tag{E.5}$$

The coefficients are given in the following table.

For *P. abies* and *dbm* (including needles) Ledermann and Neumann (2006), for *dfm* (not added to total biomass to avoid double counting) Bartelink (1996), for *drm* Wirth et al. (2004):

$$dbm = b0 * exp(b1 + b2 * ln(DBH) + b3 * H/DBH) \tag{E.6}$$

$$dfm = exp(f0 + f1 * ln(DBH) + f2 * ln(H)) \tag{E.7}$$

$$drm = r0 * exp(r1 + r2 * ln(DBH)) \tag{E.8}$$

with DBH [cm], H [m], coefficients given below.

Minimum diameter for root biomass is only provided by Xiao et al. (2003) and is 5 mm.

Appendix F. Biomass calculation in France

The below presented methodology is selected based on available literature on biomass in forests for France (INRA, 2004). It is largely identical then the method from the French NIR report (CITEPA, 2013). It combines volume functions with expansion factors developed in France (see Table F.1).

$$FF = (a + b * CBH + c * CBH^{0.5}/H) * (1 + d/CBH^2) \tag{F.1}$$

$$V = FF * (\pi/40000) * CBH^2 * H \tag{F.2}$$

$$dsm + dbm = V * wd \tag{F.3}$$

$$dfm = V * wd * 0.02 \tag{F.4}$$

$$drm = RS * (dsm + dbm + dfm) \tag{F.5}$$

Table D.1
Coefficients for calculating form factor for Austria (Pollanschütz, 1974; Schieler, 1988; Gabler and Schadauer, 2008).

Coefficients for form factor for Austria							
	$c1$	$c2$	$c3$	$c4$	$c5$	$c6$	$c7$
Picea abies	0.46818	−0.013919	−28.213	0.37474	−0.28875	28.279	0
Pinus sylvestris	0.435949	−0.014908	5.21091	0	0.028702	0	0
Fagus sylvatica	0.686253	−0.037151	−31.0674	−0.386321	0.219462	49.6163	−22.3719
Quercus robur	0.115631	0	65.9961	1.20321	−0.930406	−215.758	168.477
Betula pendula	0.42831	−0.06643	0	0	0	8.4307	0

Table D.2
Coefficients for calculating branch and foliage biomass for Austria (Ledermann and Neumann, 2006 and Burger, 1947, 1949, 1953 modified after Lexer and Hoenninger, 2001)

Coefficients for branch biomass for Austria						For foliage biomass			
	a	*b*	*c*	*d*	*cf*	*a*	*b*	*c*	*cf*
Picea abies	−1.9576	2.0252	0.1451	0.9154	1.051	0.0956	1.56	–	–
Pinus sylvestris	−3.2856	2.1684	0.1473	–	1.041	−3.8876	1.5904	0.2348	1.0417
Fagus sylvatica, Betula pendula	−3.3205	2.5568	−0.1092	0.6002	1.212	0.0217	1.7	–	–
Quercus robur	−1.2943	1.9445	0	1.2137	1.280	0.0270	1.7	–	–

Table D.3
Coefficients for calculating root biomass for Austria (Wirth et al., 2004; Bolte et al., 2004; Offenthaler and Hochbichler, 2006).

Coefficients for root biomass for Austria					
	a	*b*	*c*	*d*	*cf*
Picea abies	−8.35049	4.56828	−0.33006	0.28074	1.0406
Fagus sylvatica, Betula pendula	−4	2.32	0	0	1.08
Quercus robur	−3.97478	2.52317	0	0	1.0505

Table E.1
Coefficients for calculating stem volume for Belgium (Dagnelie et al., 1985).

Coefficients for stem volume for Belgium						
	*b*0	*b*1	*b*2	*b*3	*b*4	*b*5
Picea abies	−0.01093	0.001395	−9.6E−06	−2.5E−07	−0.00279	4.9E−06
Pinus sylvestris	−0.03984	0.001551	−6.2E−06	4.8E−08	7.4E−05	2.96E−06
Fagus sylvatica	−0.01557	0.000923	−7.1E−06	−7.7E−08	−0.00135	4.04E−06
Quercus robur	−0.00227	0.000124	1.26E−05	−5.9E−08	−0.00167	3.75E−06
Betula pendula	−0.01139	−0.0001	2.83E−05	−1.9E−07	−0.0006	3.08E−06

Table E.2
Coefficients for calculating branch, foliage and root biomass for Belgium (Ledermann and Neumann, 2006; Wirth et al., 2004; Bartelink, 1997; Wutzler et al., 2008; Cienciala et al., 2005; Xiao et al., 2003).

Coefficients for branch biomass					For foliage biomass			For root biomass		
	*b*0	*b*1	*b*2	*b*3	*f*0	*f*1	*f*2	*r*0	*r*1	*r*2
Picea abies	1.102	−1.1635	1.7459	−0.9499	−1.346	3.351	−2.201	1.0554	−5.3789	2.9211
Pinus sylvestris	0.0022	2.9122	0	0	0	0.00445	2.2371	0.3399	1.4728	0
Fagus sylvatica, Quercus robur, Betula pendula	0.021	2.471	0	0	0.375	0.0024	2.517	0.0282	2.39	0

Table F.1
Coefficients for calculating tree volume for France (Vallet et al., 2006).

Coefficients for tree volume for France				
	a	*b*	*c*	*d*
Picea abies	0.631	−0.000946	0	0
Pinus sylvestris	0.297	0.000318	0.384	204
Quercus robur, Betula pendula	0.471	−0.000345	0.377	0
Fagus sylvatica	0.395	0.000266	0.421	45.4

with *FF* Form factor for tree volume estimation, $CBH = DBH \cdot \pi$ (circumference at 1.3 m height), *H* [m], *V* [m^3] aboveground tree volume, *a*–*d* coefficients according to Vallet et al. (2006) given in the following table, *wd* wood density and *RS* root-to-shoot ratio given in Appendix A. Minimum root diameter is not defined.

Foliage biomass *dfm* is considered to be 2% of the total aboveground biomass.

Appendix G. Biomass calculation in Germany

The methodology presented below is identical to the method used in the German NIR report (Federal Environmental Agency, 2012) using the same volume functions as the German Forest Inventory (Bundeswaldinventur) (see Table G.1).

Wood volume, wood density and expansion factors are used to calculate biomass. Raw wood volume (minimum diameter 7 cm) (Kublin, 2002) is calculated with the functions implemented in the program BDAT 2.0 (Kublin, 2002) depending on species, DBH, tree height and *d*7 (diameter at height of 7 m). The estimation of the variable *d*7 is done by the program BDAT 2.0 for trees, as these values are not included in the dataset. Tree wood volume is calculated with raw wood volume and expansion factors (see Table G.1) derived from Grundner and Schwappach (1952) cited in Federal Environmental Agency (2012).

Foliage biomass is included in the estimates for coniferous species. Its share can be estimated with respective biomass functions for foliage, for *P. abies* from Schwarzmeier (2000), for *P. sylvestris* from Xiao et al. (2003), for *B. pendula* from Hytönen et al. (1995), for *F. sylvatica* from Bartelink (1997) and for *Q. robur* from Curiel Yuste et al. (2005). The volume functions are from Germany, the functions for the remaining compartments from other European countries.

$$dsm = V_{RW} * wd\_stem \tag{G.1}$$

$$V_{TW} = a + V_{RW} * b \tag{G.2}$$

$$dbm = (V_{TW} - V_{RW}) * wd\_branch \tag{G.3}$$

$$drm = RS * (dsm + dbm + dfm) \tag{G.4}$$

$$dfm = a + b * DBH^c * H^d \tag{G.5}$$

Table G.1
Coefficients for converting raw wood volume to tree wood volume (Federal Environmental Agency, 2012) and for calculating foliage biomass for Germany (Schwarzmeier, 2000; Xiao et al., 2003; Hytönen et al., 1995; Bartelink, 1997; Curiel Yuste et al., 2005).

	Coefficients for tree wood volume for Germany		Coefficients for foliage biomass			
	a	*b*	*a*	*b*	*c*	*d*
Picea abies, age <60 years	0.036697	1.148143	0	0.0026146	2.6763	0
Picea abies, age >60 years	0	1.177947	0	0.0026146	2.6763	0
Pinus sylvestris, age <60 years	0.009946	1.156659	0	0.112269	2.2371	0
Pinus sylvestris, age >60 years	0.036883	1.076103	0	0.112269	2.2371	0
Betula pendula	0.017493	1.121933	0	0.0003	2	0.9583
Fagus sylvatica, age <60 years	0.011942	1.207371	0.375	0.0024	2.517	0
Fagus sylvatica, age 61–100 years	0.008184	1.196184	0.375	0.0024	2.517	0
Fagus sylvatica, age >100 years	0.030255	1.128104	0.375	0.0024	2.517	0
Quercus robur	0.101879	1.051529	0	0.0024	2.6081	0

with V_{RW} rawwood volume [m^3], V_{TW} total wood volume [m^3], *DBH* [cm], *H* [m], *wd_stem* is wood density stem, *wd_branch* wood density branch (Kollmann, 1982 cited in Federal Environmental Agency, 2012) and *RS* root-to-shoot ratio are given in Appendix A, *a*, *b* coefficients for calculating V_{TW} (Federal Environmental Agency, 2012) and for *dfm* are given in Table G.1. Minimum root diameter is not defined.

Appendix H. Biomass calculation in the Netherlands

The chosen method is a combination of the allometric biomass functions published in Nabuurs et al. (2005) also used in the NIR report of the Netherlands (National Institute for Public Health and the Environment, 2013) and biomass fractions calculated using results from the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005). The allometric biomass functions published in Nabuurs et al. (2005) use publications providing species-dependent allometric biomass functions and conversion factors from Europe and the European part of Russia. For *Q. robur* the allometric function of Hochbichler (2002) is used, for *F. sylvatica* of Bartelink (1997), for *B. pendula* of Johansson (1999), for *P. sylvestris* and *P. abies* of Hamburg et al. (1997) (see Tables H.1 and H.2).

Table H.1
Coefficients for calculating aboveground biomass for the Netherlands (Hochbichler, 2002; Bartelink, 1997; Johansson, 1999 and Hamburg et al., 1997 cited in Nabuurs et al., 2005).

	Coefficients for aboveground biomass for the Netherlands		
	*a*0	*a*1	*a*2
Quercus robur	0.41354	2.14	0
Fagus sylvatica	0.0798	2.601	0
Betula pendula	0.00029	2.50038	0
Pinus sylvestris	0.0217	1.9634	0.9817
Picea abies	0.0533	1.791	0.8955

$$BM_{ABG} = a0 * DBH^{a1} * H^{a2} \tag{H.1}$$
$$BM_{total} = BM_{ABG} * (1 + RS) \tag{H.2}$$

with *DBH* [cm] (for *B. pendula DBH* [mm], *H* [m], BM_{ABG} total aboveground biomass [kg dry weight], BM_{total} total tree biomass [kg dry weight], *RS* age-dependent root-to-shoot ratio calculated using biomass fractions from Vilén et al. (2005) given in the next table. Minimum root diameter is not defined. The species-specific publications given above provide the coefficients for the aboveground biomass (*a*0–*a*2) and are cited in Nabuurs et al. (2005).

Total above ground biomass get divided into tree compartments by multiplying with estimates for biomass fractions.

$$dsm, dbm, \ldots = f\_i * BM_{total} \tag{H.3}$$

f_i are given below.

Biomass fractions were calculated within the EFISCEN project (Schelhaas et al., 1999; Vilén et al., 2005) and are based on the biomass allocation functions. For *P. abies* based on the functions of Wirth et al. (2004) for aboveground biomass and for coarse roots on Lehtonen et al. (2004) for fine roots. For *P. sylvestris* on the

Table H.2
Age-dependent fraction values for calculating biomass in tree compartments for the Netherlands.

Biomass fractions dependent on tree age [years] for the Netherlands											
Picea abies	20	30	40	50	60	70	80	90	100	110	1000
f_stem	0.385	0.474	0.562	0.617	0.642	0.650	0.644	0.639	0.634	0.628	0.619
f_branch	0.349	0.256	0.173	0.130	0.111	0.104	0.106	0.108	0.111	0.115	0.121
f_roots	0.100	0.132	0.166	0.178	0.182	0.188	0.195	0.201	0.205	0.209	0.213
f_foliage	0.167	0.138	0.099	0.077	0.065	0.058	0.055	0.052	0.050	0.048	0.047
RS	0.111	0.152	0.199	0.216	0.223	0.231	0.243	0.251	0.258	0.264	0.271
Pinus sylvestris	30	40	50	60	80	100	120	1000			
f_stem	0.357	0.504	0.583	0.624	0.661	0.679	0.688	0.691			
f_branch	0.368	0.258	0.195	0.163	0.135	0.125	0.123	0.127			
f_roots	0.109	0.138	0.154	0.163	0.169	0.171	0.168	0.165			
f_foliage	0.167	0.101	0.068	0.050	0.035	0.026	0.021	0.018			
RS	0.122	0.160	0.182	0.195	0.204	0.206	0.203	0.197			
Fagus sylvatica, *Quercus robur*, *Betula pendula*	40	60	80	100	120	140	1000				
f_stem	0.600	0.674	0.692	0.693	0.712	0.721	0.721				
f_branch	0.100	0.108	0.118	0.129	0.108	0.095	0.089				
f_roots	0.261	0.191	0.174	0.165	0.167	0.171	0.176				
f_foliage	0.044	0.022	0.016	0.014	0.013	0.013	0.014				
RS	0.350	0.237	0.211	0.198	0.200	0.206	0.214				

functions of Cienciala et al. (2006) for aboveground biomass and on Marklund (1988) for root biomass. For *F. sylvatica*, *B. pendula* and *Q. robur* on Bartelink (1997) and Cienciala et al. (2005) for aboveground biomass and Le Goff and Ottorini (2001) for root biomass.

In the EFISCEN database there are no specific biomass fractions for the Netherlands available. Therefore the conversion factors developed for Germany/Austria were selected as these are probably most comparable with the conditions of forests in the Netherlands.

Appendix I. Biomass calculation in the Czech Republic

The presented method of calculating carbon is developed using volumetric functions applied in volume tables for Czechoslovakia (Petráš and Pajtík, 1991), density of wood and bark of tree species (Klement et al., 2010) and published allometric biomass functions (Drexhage and Colin, 2001; Petráš et al., 1985). It combines volume functions, biomass expansion factors and allometric biomass functions from the Czech Republic (see Tables I.1–I.3).

$$dswm, dsbm, \ldots = V_i * wd * I_i \tag{I.1}$$

$$dfm, drm, dbm5 = b1 * (DBH + b2)^{b3} * H^{b4} * b5 \tag{I.2}$$

where V_i is the volume of a certain compartment [m^3], *wd* is wood density [kg/m^3] given in Appendix A and I_i correction index (if applicable) derived from Požgaj et al. (1993), Chmelař (1992) and Miles and Smith (2009).

Minimum root diameter is 5 mm (Drexhage and Collin, 2001). The correction indices for individual tree species and *b*1–*b*5 coefficients for biomass calculation are given below.

$$dsm = BM_{wood>7cmUB} + dsbm \tag{I.3}$$

$$dbm = BM_{wood<7cmUB} + dbm5 \tag{I.4}$$

where $BM_{wood>7cmUB}$ is the biomass of wood under bark with diameter equal to or above 7 cm [kg dry BM], *dsbm* is biomass of bark [kg dry BM], $BM_{wood<7cmUB}$ is biomass of wood under bark with diameter below 7 cm [kg dry BM], *dbm*5 is biomass of green twigs [kg dry BM] as previously described. The individual biomass parts are calculated as follows:

$$BM_{wood>7cmUB} = V_{wood>7cmUB} * wd \tag{I.5}$$

$$BM_{wood<7cmUB} = V_{wood<7cmUB} * wd * I_{wood<7cm} \tag{I.6}$$

$$dsbm = V_{bark} * wd * I_{bark} \tag{I.7}$$

The volume of individual parts of the tree were calculated using two-parameter regressions applied in volume tables for Czechoslovakia and compiled or modified by Petráš and Pajtík (1991). The volume of the different parts of tree (tree, stem, wood with diameter equal to or above 7 cm under bark, wood with diameter below 7 cm under bark) is calculated using volumetric equations.

The compartment is indicated by the lower index. *OB* indicate volume over bark and *UB* under bark. If this is not stated, the used formula is valid for both *OB* and *UB*.

General equation for all different volumes of *P. abies* is:

$$V_i = a0 * (DBH + a1)^{a2} * H^{a3} - a4 * (DBH + a5)^{a6} * H^{a7} \tag{I.8}$$

For *F. sylvatica*:

$$V_i = FF_i * \pi * DBH^2 * H/40000 \tag{I.9}$$

$$FF_{stem} = a0 + a1 * DBH + a2 * DBH^2 + a3 * DBH^3 + a4 * H + a5 * H * DBH + a6 * DBH^2 * H + a7 * DBH^3 * H \tag{I.10}$$

$$FF_{wood>7cm} = a0 + a1/DBH + a2/DBH^2 + a3/DBH^3 + a4 * H + a5 * H * DBH + a6 * DBH^2 * H + a7 * DBH^3 * H \tag{I.11}$$

$$FF_{treeOB} = a0 + a1/H + a2/H^2 + a3/DBH + a4 * H/DBH + a5 * H^2/DBH + a6/DBH^2 + a7/DBH^2/H + a8/DBH^2/H^2 + a9/DBH^3 + a10/DBH^3 * H + a11/DBH^3 * H^2 \tag{I.12}$$

For *Q. robur*:

$$FF_{stem} = a0 + a1/DBH + a2/DBH^2 + a3/DBH^3 + a4 * H + a5 * H * DBH + a6 * DBH^2 * H + a7 * DBH^3 * H \tag{I.13}$$

$$FF_{wood>7cm}, FF_{treeOB} = a0 + a1/H + a2/H^2 + a3/DBH + a4 * H/DBH + a5 * H^2/DBH + a6/DBH^2 + a7/DBH^2/H + a8/DBH^2/H^2 + a9/DBH^3 + a10/DBH^3 * H + a11/DBH^3 * H^2 \tag{I.14}$$

Table I.1
Correction indices of wood density for the Czech Republic (Požgaj et al., 1993; Chmelař, 1992; Miles and Smith, 2009).

Correction indices of wood density for the Czech republic					
	Picea abies	*Pinus sylvestris*	*Fagus sylvatica*	*Quercus robur*	*Betula pendula*
I bark	1.25	0.95	1.2	1	1.13
I wood <7 cm	1.2	1.1	1.1	1.1	1.1

Table I.2
Coefficients for calculating biomass for the Czech Republic (Drexhage and Colin, 2001; Petráš et al., 1985).

Coefficients for biomass calculations for the Czech republic							
		*b*1	*b*2	*b*3	*b*4	*b*5	Reference
Picea abies	Twigs	0.016	1	1.788	0.679	0.468	Petráš et al. (1985)
Picea abies	Foliage	0.015	1	1.831	0.564	0.426	Petráš et al. (1985)
Picea abies	Roots	0.020	0	2.360	0	1	Drexhage and Colin (2001)
Pinus sylvestris	Twigs	0.236	1	1.842	−0.434	0.457	Petráš et al. (1985)
Pinus sylvestris	Foliage	0.119	1	1.857	−0.360	0.425	Petráš et al. (1985)
Pinus sylvestris	Roots	0.013	0	2.740	0	1	Drexhage and Colin (2001)
Fagus sylvatica, Quercus robur, Betula pendula	Twigs	0.076	1	2.245	−0.559	0.401	Petráš et al. (1985)
Fagus sylvatica, Quercus robur, Betula pendula	Foliage	0.029	1	2.432	−0.600	0.365	Petráš et al. (1985)
Fagus sylvatica, Betula pendula	Roots	0.022	0	2.540	0	1	Drexhage and Colin (2001)
Quercus robur	Roots	0.028	0	2.440	0	1	Drexhage and Colin (2001)

Table I.3
Coefficients for volume calculation for the Czech Republic (Petráš and Pajtík, 1991).

Regression coefficients for volumetric equations for the Czech Republic

	Compartment	*a*0	*a*1	*a*2	*a*3	*a*4	*a*5	*a*6	*a*7	*a*8	*a*9	*a*10	*a*11	*a*12
Fagus sylvatica	stemOB	6.77E−01	−1.43E−02	2.92E−04	−2.11E−06	−3.13E−03	2.67E−04	−5.91E−06	4.19E−08					
Fagus sylvatica	stemUB	5.84E−01	−1.14E−02	2.49E−04	−1.88E−06	−2.77E−03	2.40E−04	−5.40E−06	3.87E−08					
Fagus sylvatica	wood ⩾7cm OB	5.65E−01	−2.33E+00	3.93E+01	−2.34E+02	−1.42E−03	−1.83E−06	6.21E−07	−4.77E−09					
Fagus sylvatica	wood ⩾7cmUB	5.42E−01	−3.12E+00	4.43E+01	−2.36E+02	−1.07E−03	−1.86E−05	8.81E−07	−6.00E−09					
Fagus sylvatica	treeOB	5.99E−01	−2.02E−01	4.49E+00	5.99E+00	−4.41E−01	6.10E−03	−2.97E+00	−1.09E+02	8.99E+01	6.66E+01	−1.09E+01	6.35E−01	
Pinus sylvestris	stemOB	3.03E−05	2.08E+00	−1.25E−02	9.61E−01									
Pinus sylvestris	stemUB	2.26E−05	2.12E+00	−1.27E−02	9.80E−01									
Pinus sylvestris	wood ⩾7cmOB					7.20E−02	−2.12E+00	1.37E+00						
Pinus sylvestris	wood ⩾7cmUB					6.43E−02	−2.12E+00	1.37E+00						
Pinus sylvestris	treeOB					3.60E+01	8.11E−01	1.38E+00	3.03E−05	2.08E+00	−1.25E−02	9.61E−01	1.00E+02	
Betula pendula	stemOB	0.00E+00	1.32E+00	−2.30E−04	6.43E+01	−2.04E+01	8.00E+00	−2.32E−01						
Betula pendula	stemUB								1.00E+00	−1.00E−02	1.73E+01	5.05E−03	1.00E−01	−2.06E+00
Betula pendula	wood ⩾7cmOB	−4.50E+00	1.08E+00	−1.15E−03	3.12E+04	−2.32E+01	5.50E+00	−1.43E−01						
Betula pendula	wood ⩾7cmUB								1.00E+00	−1.00E−02	1.73E+01	5.05E−03	1.00E−01	−2.06E+00
Betula pendula	treeOB	0.00E+00	1.11E+00	−4.80E−04	8.30E+04	−2.60E+01	8.00E+00	−1.50E−01						
Quercus robur	stemOB	4.62E−01	4.31E−01	7.46E−01	−9.06E−01	9.96E−04	−6.73E−06	−9.82E−07	7.75E−09					
Quercus robur	stemUB	3.59E−01	−5.25E−01	3.09E+00	−3.14E+00	3.21E−03	−5.84E−05	2.66E−07	−1.96E−09					
Quercus robur	wood ⩾7cmOB	4.47E−01	5.98E+00	−2.09E+00	−1.49E+01	8.70E−02	1.06E−03	−2.69E+01	1.68E+01	−2.21E−01	2.23E+02	−5.39E+01	−1.01E+00	
Quercus robur	wood ⩾7cmUB	4.53E−01	2.16E+00	9.10E+00	−1.21E+01	1.81E−01	−4.01E−03	−6.83E+00	9.44E+00	−2.44E−02	3.37E+01	−9.10E+00	−2.16E+00	
Quercus robur	treeOB	5.24E−01	4.24E+00	−6.60E+00	−7.81E+00	2.67E−01	−7.01E−03	3.74E+01	−2.14E+00	1.15E−01	−2.95E+01	1.73E+00	−9.29E−02	
Picea abies	stemOB	4.01E−05	1.00E+00	1.82E+00	1.13E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					
Picea abies	stemUB	3.20E−05	1.00E+00	1.85E+00	1.15E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					
Picea abies	wood ⩾7cmOB	4.01E−05	1.00E+00	1.82E+00	1.13E+00	9.29E−03	1.00E+00	−1.02E+00	8.96E−01					
Picea abies	wood ⩾7cmUB	3.20E−05	1.00E+00	1.85E+00	1.15E+00	8.29E−03	1.00E+00	−1.02E+00	8.96E−01					
Picea abies	treeOB	4.45E−05	1.00E+00	1.81E+00	1.13E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					

For *B. pendula*:

$$V_{OB} = (H + a0)^{a1} * (a2 + a3 * exp(a4 * (DBH + a5)^{a6})) \quad (I.15)$$

$$V_{UB} = V_{OB} * (a7 + a8 * (a9 * exp(a10 * (V_{OB} + a11)^{a12}))) \quad (I.16)$$

For *P. sylvestris*:

$$V_{stem} = a0 * (DBH + 1)^{a1+a2*log(DBH+1)} * H^{a3} \quad (I.17)$$

$$V_{wood>7cm} = V_{stem} - a4 * (DBH + 1)^{a5} * H^{a6} \quad (I.18)$$

$$V_{treeOB} = V_{stemOB} + a4 * (DBH + 1)^{a5} / H^{a6} * a7 * (DBH + 1)^{a8+a9*log(DBH+1)} * H^{a10} / a11 \quad (I.19)$$

In case no regression equation was available, the required volume was calculated from the available volumes following the principles below:

$$percent\_bark = max\{V_{wood>7cmOB} - V_{wood>7cmUB}) / V_{wood>7cmOB}; V_{stemOB} - V_{stemUB}) / V_{stemOB}\} \quad (I.20)$$

$$V_{wood<7cmOB} = V_{treeOB} - V_{wood>7cmOB} \quad (I.21)$$

$$V_{wood<7cmUB} = (1 - percent\_bark) * V_{wood<7cmOB} \quad (I.22)$$

$$V_{bark} = V_{treeOB} - V_{wood>7cmUB} - V_{wood<7cmUB} \quad (I.23)$$

In the listed equations, FF_i the form factor for volume estimates [/], V_i volume of tree compartments [m^3], *percent_bark* is proportional content of bark [/], *DBH* is tree diameter at breast height in [cm], and *H* is tree height in [m] and parameters *a*0 to *a*12 are regression coefficients derived for the respective species and listed in the following table.

Appendix J. Biomass calculation in Poland

Allometric biomass functions using tree height and/or diameter are used for estimating aboveground biomass in Poland. For *P. sylvestris* models developed with sample material from 18 Scots pines stands in Bory Lubuskie (western Poland) are used (Zasada et al., 2008). Due to lack of appropriate published biomass functions for *P. abies, F. sylvatica* and *Q. robur* in Poland generalized biomass functions for Europe are applied (Muukkonen, 2007). For *B. pendula* height- and diameter-dependent functions developed in Finland are used (Repola, 2008) (see Table J.1).

For *P. sylvestris*:

$$dswm, dsbm, \ldots = a0 * DBH^{a1} * H^{a2} \quad (J.1)$$

With *DBH* [mm], *H* [m]

For *P. abies, F. sylvatica* and *Q. robur*:

$$dsm, dsbm, \ldots = exp(a0 + a1 * DBH / (DBH + a2)) \quad (J.2)$$

With *DBH* [cm]

For *B. pendula*:

Model type 1:

$$dswm, dsbm, \ldots = cf * exp(a0 + a1 * dk / (dk + a2) + a3 * ln(H) + cf2) \quad (J.3)$$

Model type 2:

$$dswm, dsbm, \ldots = cf * exp(a0 + a1 * dk / (dk + a2) + a3 * H / (H + a4) + cf2) \quad (J.4)$$

$$dk = 2 + 1.25 * DBH \quad (J.5)$$

dk and *DBH* [cm], *H* [m], all parameters are given below.

Root-to-shoot ratios are the official values used in official Polish reportings on changes in carbon stocks of the living biomass under the Kyoto Protocol which are the weighted average of the default coefficients proposed by IPCC (2006).

$$drm = RS * (dswm + dsbm + dfm + dabm + ddbm) \quad (J.6)$$

RS is given in Appendix A. Minimum root diameter is not defined.

Appendix K. Biomass calculation in Romania

Tree biomass is calculated using the volume functions developed in Romania by Giurgiu et al. (1972) used in the Romanian NIR report combined with biomass expansion factors. The

Table J.1
Coefficients for calculating biomass for Poland (Zasada et al., 2008; Repola, 2008; Muukkonen, 2007).

Coefficients for biomass calculation for Poland								
	*a*0	*a*1	*a*2	*a*3	*a*4	*cf*	*cf*2	Model type
Pinus sylvestris								
dswm	0.00041	1.627725	1.390374	–	–	–	–	–
dsbm	0.000192	2.117192	–	–	–	–	–	–
dabm	0.0000038	3.653659	−1.6008	–	–	–	–	–
ddbm	0.0000072	2.433082	–	–	–	–	–	–
dfm	0.000212	2.30978	−0.58099	–	–	–	–	–
Picea abies								
dsm	−3.043	11.784	9.328	–	–	–	–	–
dbm	−0.537	10.093	40.426	–	–	–	–	–
dfm	−1.360	7.308	19.662	–	–	–	–	–
Fagus sylvatica, Quercus robur								
dsm	−0.657	10.730	17.394	–	–	–	–	–
dbm	−2.128	13.295	26.095	–	–	–	–	–
dfm	−2.480	9.511	26.771	–	–	–	–	–
Betula pendula								
dswm	−4.879	9.651	12	1.012	–	1	0.004035	1
dsbm	−5.401	10.061	12	2.657	20	1	0.02743	2
dabm	−4.152	15.874	16	−4.407	10	1	0.051975	2
ddbm	−8.335	12.402	16	–	–	2.0737	0	2
dfm	−29.566	33.372	2	–	–	1	0.0385	2

calculated volume includes above ground tree compartments excluding foliage. Wood density values from the Global wood density database (Zanne et al., 2009; Chave et al., 2009) and biomass fractions calculated using results from the EFISCEN project (Vilén et al., 2005) (see Tables K.1 and K.2).

$$log10(V_{abg}) = a0 + a1 * log10(DBH) + a2 * (log10(DBH))^2 + a3 * log10(H) + a4 * (log10(H))^2 \quad (K.1)$$

$$BM_{ABG} = V_{ABG} * wd \quad (K.2)$$

$$dsm, dbm, \ldots = f\_i * BM_{ABG} \quad (K.3)$$

where V_{ABG} aboveground tree volume [m^3], BM_{ABG} aboveground tree biomass [kg], *DBH* [cm], *H* [m], *wd* dry wood density [kg/m^3] from the Global wood density database (Zanne et al., 2009; Chave et al., 2009) in Appendix A, coefficients $a0$–$a4$ and f_i age-dependent biomass fractions are given below. Minimum root diameter is not defined.

Appendix L. Biomass calculation in Italy

The methodology is a combination of the allometric biomass functions developed with sample material from Italy from Tabacchi et al. (2011) and the conversion parameters from Federici et al. (2008). *dsm* includes stem and branches > 5 cm diameter and *dbm* includes foliage and branches < 5 cm diameter (Tabacchi et al., 2011). The Italian NIR report for the Italian Greenhouse Gas Inventory for the period 1990–2010 (ISPRA, 2013) use growing stock reported by the NFI (MAF-ISAFA, 1988) in combination with biomass expansion factors, wood density and root-shoot ratios citing Federici et al. (2008). Growing stock is calculated with allometric functions, which are developed with a subset of the sample material used for the models used in this work (Tabacchi et al., 2011). Since *Q. robur* and *B. pendula* are not covered in Tabacchi et al. (2011), we use the models from *Quercus pubescens* Willd. for the first and from "Altre latifoglie" (other broadleaves) for the second species from the same reference (see Table L.1).

$$dsm = s0 + s1 * DBH^2 * H + s2 * DBH \quad (L.1)$$

$$dbm = b0 + b1 * DBH^2 * H + b2 * DBH \quad (L.2)$$

$$drm = RS * (dsm + dbm) \quad (L.3)$$

with *DBH* [cm], *H* [m], $s0$–$s2$ and $b0$–$b2$ according to Tabacchi et al. (2011) given in table below, *RS* according to Federici et al. (2008) in Appendix A. Minimum root diameter is not defined.

Appendix M. Biomass calculation in Spain

Until now for international reporting, carbon stock in living biomass was calculated using the method of "Change in Carbon Stocks" described in the GPG-LULUCF (IPCC, 2006). Biomass expansion factors were based on large dataset collected in the Ecological Forest Inventory of Catalonia, Spain (Gracia et al., 2002; Mäkipää et al., 2005). Root biomass is estimated with an expansion factor according to IPCC methodology (IPCC, 2006) (see Table M.1).

In future for international reporting on forest biomass allometric functions are probably used. These functions are developed in Spain and are dependent on DBH and/or tree height (Ruiz-Peinado et al., 2011, 2012; Diéguez-Aranda et al., 2009).

For *P. abies* (functions from *Abies alba*), *P. sylvestris* and *F. sylvatica* the functions from Ruiz-Peinado et al. (2011) and Ruiz-Peinado et al. (2012) are used, for *B. pendula* (functions from *Betula alba*) from Diéguez-Aranda et al. (2009) and for *Q. robur* from Balboa-Murias et al. (2006a, 2006b). The minimum root diameter is not given; the authors state however that fine roots are not captured by their excavation method (Ruiz-Peinado et al., 2011, 2012).

As there are no explicit functions for foliage biomass given in Ruiz-Peinado et al. (2011, 2012), the foliage biomass functions from Diéguez-Aranda et al. (2009) are used. For *P. abies* and for *P. sylvestris* the function from *Pinus pinaster* are used, for *F. sylvatica* the function from *Betula alba* (Diéguez-Aranda et al., 2009).

The general equation for *P. abies* and *P. sylvestris* is:

$$dsm, dbm1, \ldots = a * DBH^b * H^c + d * H \quad (M.1)$$

For *P. sylvestris*, $dbm1 = 0$ for $DBH <= 37.5$ cm, if $DBH > 37.5$ cm:

$$dbm1 = 0.54 * (DBH - 37.5)^2 - 0.0119 * (DBH - 37.5)^2 * H \quad (M.2)$$

The general equation for *F. sylvatica*, *Q. robur* and *B. pendula* is:

$$dsm, dbm1, \ldots = a * DBH^b * H^c + d * DBH^2 + e \quad (M.3)$$

Table K.1
Coefficients for aboveground volume calculation for Romania (Giurgiu et al., 1972).

Coefficients for aboveground volume for Romania					
	a0	*a1*	*a2*	*a3*	*a4*
Picea abies	−4.18161	2.08131	−0.11819	0.70119	0.14818
Pinus sylvestris	−3.84672	1.82103	−0.04107	0.35677	0.33491
Fagus sylvatica	−4.11122	1.30216	0.23636	1.26562	−0.07966
Quercus robur	−4.13329	1.88001	0.04880	0.95371	−0.06364
Betula pendula	−4.16999	2.27038	−0.21540	0.30765	0.36826

Table K.2
Age-dependent biomass fractions for calculating biomass in compartments for Romania.

Biomass fractions dependent on tree age [years] for Romania											
Picea abies	20	30	40	50	60	70	80	90	100	110	1000
Stem	0.525	0.649	0.765	0.826	0.853	0.862	0.859	0.855	0.851	0.845	0.836
Branches	0.475	0.351	0.235	0.174	0.147	0.138	0.141	0.145	0.149	0.155	0.164
Roots	0.136	0.180	0.226	0.238	0.242	0.249	0.260	0.269	0.275	0.281	0.288
Foliage	0.227	0.189	0.135	0.103	0.086	0.077	0.073	0.070	0.067	0.065	0.063
Pinus sylvestris	30	40	50	60	80	100	120	1000			
Stem	0.493	0.661	0.749	0.793	0.830	0.845	0.848	0.845			
Branches	0.507	0.339	0.251	0.207	0.170	0.155	0.152	0.155			
Roots	0.150	0.181	0.198	0.208	0.213	0.213	0.208	0.201			
Foliage	0.230	0.132	0.087	0.063	0.044	0.032	0.026	0.022			
Fagus sylvatica, Quercus robur, Betula pendula	40	60	80	100	120	140	1000				
Stem	0.857	0.862	0.855	0.843	0.869	0.883	0.890				
Branches	0.143	0.138	0.145	0.157	0.131	0.117	0.110				
Roots	0.373	0.244	0.215	0.201	0.204	0.209	0.218				
Foliage	0.063	0.028	0.020	0.017	0.016	0.016	0.017				

Table L.1
Coefficients for calculation biomass for Italy (Tabacchi et al., 2011).

Coefficients for biomass calculations for Italy						
	s0	s1	s2	b0	b1	b2
Picea abies	−5.9426	0.01321	0.78369	5.9459	0.0040669	−0.21054
Pinus sylvestris	0.65786	0.017176	0	2.1336	0.0045864	0
Fagus sylvatica	−0.83814	0.024865	0	2.504	0.0051283	0
Quercus robur	1.0832	0.029634	−0.49794	−8.2101	0.0030396	1.7561
Betula pendula	−9.1098	0.0073484	2.3666	−3.6118	0.004319	0.74127

Table M.1
Coefficients for calculating biomass for Spain (Ruiz-Peinado et al., 2011, 2012; Diéguez-Aranda et al., 2009; Balboa-Murias et al., 2006a, 2006b).

Coefficients for biomass calculation in Spain					
Picea abies	*a*	*b*	*c*	*d*	
dsm	0.0189	2	1	0	
dbm1 + dbm2	0.0584	2	0	0	
dbm3	0.0371	2	0	0.968	
dfm	0.1081	1.51	0	0	
drm	0.101	2	0	0	
Pinus sylvestris					
dsm	0.0154	2	1	0	
dbm2	0.0295	2.742	−0.899	0	
dbm3	0.53	2.199	−1.153	0	
dfm	0.1081	1.51	0	0	
drm	0.13	2	0	0	
Fagus sylvatica	*a*	*b*	*c*	*d*	*e*
dsm	0.0182	2	1	0.0676	0
dbm2	0.0792	2	0	0	0
dbm3	0.00226	2	1	0.093	0
dfm	0.0346	1.645	0	0	0
drm	0.106	2	0	0	0
Quercus robur					
dswm	0.01823	2	1	0	−5.714
dsbm	0.00111	2	1	0.03154	−1.5
dbm1	3.427E−09	4.959	2.31	0	0
dbm2	0.00341	2	1	0	4.268
dbm4	0.03851	1.784	0	0	0
dbm5	0.00012	2	1	0	1.379
dfm	0.0101985	1.667	0.7375	0	0
drm	0.0116	1.949	0.9625	0	0
Betula pendula					
dswm	0.1485	2.2223	0	0	0
dsbm	0.031	2.186	0	0	0
dbm2	0.1374	1.76	0	0	0
dbm4	0.05	1.618	0	0	0
dbm5	0.0372	1.581	0	0	0
dfm	0.0346	1.645	0	0	0
drm	1.042	1.254	0	0	0

For *F. sylvatica* *dbm1* = 0 for *DBH* <= 22.5 cm, if *DBH* > 22.5 cm:

$$dbm1 = 0.83 * (DBH - 22.5)^2 - 0.0248 * (DBH - 22.5)^2 * H \tag{M.4}$$

For *B. pendula*:

$$dbm1 = 1.515 * exp(0.0904 * DBH) \tag{M.5}$$

All functions with biomass in [kg], *DBH* [cm] and *H* [m], coefficients *a*–*e* are given below.

Appendix N. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.11.016.

References

Araújo, T.M., Higuchi, N., Andrade de Carvalho Junior, J., 1999. Comparison of formulae for biomass content determination in a tropical rain forest site in the state of Para, Brazil. For. Ecol. Manage. 117, 43–52.

Assmann, E., 1970. The Principles of Forest Yield Study. Pergamon press, New York, 506 p.

Balboa-Murias, M.A., Rodríguez-Soalleiro, R., Merino, A., Álvarez-González, J.G., 2006a. Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural regimes. For. Ecol. Manage. 237, 29–38.

Balboa-Murias, M.A., Rojo, A., Álvarez, J.G., Merino, A., 2006b. Carbon and nutrient stocks in mature *Quercus robur* L. stands in NW Spain. Ann. Forest Sci. 63 (5), 557–565.

Bartelink, H.H., 1996. Allometric relationships on biomass and needle area of Douglas-fir. For. Ecol. Manage. 86 (1–3), 193–203.

Bartelink, H.H., 1997. Allometric relationships for biomass and leaf area of beech (*Fagus sylvatica* L). Ann. Forest Sci. 54, 39–50.

Bolte, A., Rahmann, T., Kuhr, M., Pogoda, P., Murach, D., Gadow, K.V., 2004. Relationships between tree dimension and coarse root biomass in mixed stands of European beech (Fagus sylvatica L.) and Norway spruce (Picea abies[L.] Karst.). Plant Soil 264, 1–11. http://dx.doi.org/10.1023/B:PLSO.0000047777.23344.a3.

Burger, H., 1947. Holz, Blattmenge und Zuwachs. VIII. Mitteilung. Die Eiche. Mitteilungen der schweizerischen Anstalt für forstliches Versuchswesen 25, 211–279 (in German).

Burger, H., 1949. Holz, Blattmenge und Zuwachs. X. Mitteilung. Die Buche. Mitteilungen der schweizerischen Anstalt für forstliches Versuchswesen 26, 419–468 (in German).

Burger, H., 1953. Holz, Blattmenge und Zuwachs. XIII. Mitteilung. Fichten im gleichaltrigen Hochwald. Mitteilungen der schweizerischen Anstalt für forstliches Versuchswesen 29, 38–130 (in German).

Canadell, J.G., Le Quere, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Canadell, J.G., Que, C. Le, Conway, T.J., Gillett, N.P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. PNAS 104, 18866–18870.

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G., Zanne, A.E., 2009. Towards a worldwide wood economics spectrum. Ecol. Lett. 12, 351–366.

Chmelař, T., 1992. Variability of the conventional wood density of spruce *Picea abies* (L.) Karst branches in dependence on the position of branches in crown. Lesnictvi (Prague) 38 (2), 127–135 (in Czech).

Cienciala, E., Černý, M., Apltauer, J., Exnerová, Z., 2005. Biomass functions applicable to European beech. J. Forest Sci. 51 (4), 147–154.

Cienciala, E., Černý, M., Tatarinov, F., Apltauer, J., Exnerová, Z., 2006. Biomass functions applicable to Scots pine. Trees 20 (4), 483–495.

CITEPA, 2013. Rapport National d'Inventaire pour la France au Titre de la Convention Cadre des Nations Unies sur les Changement Climatiques et du Protocole de Kyoto, partie 1., 713 p. (in French).

Climate and Pollution Agency, 2013. National Inventory Report, Greenhouse Gas Emissions 1990–2011.

Curiel Yuste, J., Konôpka, B., Janssens, I.A., Coenen, K., Xiao, C.W., Ceulemans, R., 2005. Contrasting net primary productivity and carbon distribution between neighboring stands of *Quercus robur* and *Pinus sylvestris*. Tree Physiol. 25 (6), 701–712.

Dagnelie, P., Palm, R., Rondeux, J., et al., 1985. Tables de cubage des arbres et des peuplements forestiers. Les Presses Agronomiques de Gembloux, Gembloux, Belgium (in French).

De Wit, H.A., Palosuo, T., Hylen, G., Liski, J., 2006. A carbon budget of forest biomass and soils in southeast Norway calculated using a widely applicable method. For. Ecol. Manage. 225, 15–26. http://dx.doi.org/10.1016/j.foreco.2005.12.023.

Diéguez-Aranda U, Rojo Alboreca A, Castedo-Dorado F, Álvarez González JG, Barrio-Anta M, Crecente-Campo F, González González JM, Pérez-Cruzado C, Rodríguez Soalleiro R, López-Sánchez CA, Balboa-Murias MA, Gorgoso Varela JJ, Sánchez Rodríguez F, 2009. Herramientas selvícolas para la gestión forestal sostenible en Galicia. Xunta de Galicia. ISBN: 978-84-692-7395-1 (in Spanish).

Drexhage, M., Gruber, F., 1999. Above- and below-stump relationships for *Picea Abies*: estimating root system biomass from breast-height diameters. Scand. J. For. Res. 14, 328–333.

Drexhage, M., Colin, F., 2001. Estimating root system biomass from breast-height diameters. Forestry 74 (5), 491–497.

Eastaugh, C.S., Kangur, A., Korjus, H., Kiviste, A., Zlatanov, T., Velickkov, I., Srdjevic, B., Srdjevic, Z., Hasenauer, H., 2013. Scaling issues and constraints in modelling of forest ecosystems: a review with special focus on user needs. Baltic Forest. 19, 316–330.

Eastaugh, C.S., 2014. Relationships between the mean trees by basal area and by volume: reconciling form factors in the classic Bavarian yield and volume tables for Norway spruce. Eur. J. For. Res. 133, 871–877.

EUROSTAT, 2012. Europe in Figures, Eurostat Yearbook 2012, European Union, 698 p.

FAO, 2013. FAO STATISTICAL YEARBOOK, World Food and Agriculture, Food and Agriculture Organization of the United Nations, Rome, 307 p.

FOREST EUROPE, UNECE, FAO, 2011. State of Europe's Forests 2011. Status and Trends in Sustainable Forest Management in Europe, 344 p.

Federal Environmental Agency, 2012. Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. National Inventory Report for the German Greenhouse Gas Inventory 1990–2011, 885 p.

Federici, S., Vitullo, M., Tulipano, S., De Lauretis, R., Seufert, G., 2008. An approach to estimate carbon stocks change in forest carbon pools under the UNFCCC: the Italian case. iForest – Biogeosciences For. 1, 86–95.

Flemish Environment Agency, 2013. Belgium's Greenhouse Gas Inventory (1990–2011) National Inventory Report submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol.

Gabler, K., Schadauer, K., 2008. Methods of the Austrian Forest Inventory 2000/02 Origins, Approaches, Design, Sampling, Data Models, Evaluation and Calculation of Standard Error, vol. 135. BFW-Berichte; Schriftenreihe des Bundesforschungs- und Ausbildungszentrums für Wald, Naturgefahren und Landschaft, Wien, 132 p.

Giurgiu, V., Decei, I., Armasescu, S., 1972. Biometria arborilor si arboretelor din Romania- Tabele endrometrice. Ed. Ceres, Bucuresti, Romania (in Romanian).

Gracia, C., Sabatè, S., Vayreda, J., Ibáñez, J.J., 2002. Aboveground Biomass Expansion Factors and Biomass Equations of Forests in Catalonia. Presentation at the COST E21 Meeting, Besalu (Spain) July 2002.

Gruber, F., 1987. Das Verzweigungssystem und der Nadelfall der Fichte (*Picea abies* (L.) Karst.) als Grundlage zur Beurteilung von Waldschäden. Ber. Forschungszentrum Waldökosysteme/Waldsterben, Reihe A, 26 (in German).

Grundner, F., Schwappach, A., 1952. Massentafeln zur Bestimmung des Holzgehaltes stehender Waldbäume und Waldbestände. 10. Aufl. Verlag Paul Parey, Berlin, Hamburg, 216 p. (in German).

Gschwantner, T., Gabler, K., Schadauer, K., Weiss, P., 2010. National forest inventory reports, chapter 1: Austria. In: Tomppo, E., Gschwantner, T.H., Lawrence, M., McRoberts, R.E. (Eds.), National Forest Inventories: Pathways for Common Reporting. Springer, Heidelberg, Dordrecht, London, New York, pp. 57–71.

Guo, Z., Fang, J., Pan, Y., Birdsey, R., 2010. Inventory-based estimates of forest biomass carbon stocks in China: a comparison of three methods. For. Ecol. Manage. 259 (7), 1225–1231.

Hamburg, S.P., Zamolodchikov, D.G., Korovin, G.N., Nefedjev, V.V., Utkin, A.I., Gulbe, J.I., Gulbe, T.A., 1997. Eestimating the carbon content of Russian forests; a comparison of Phytomass/Volume and Allometric Projections. Mitig. Adapt. Strat. Glob. Change 2, 247–265.

Härkönen, S., Lehtonen, A., Eerikäinen, K., et al., 2011. Estimating forest carbon fluxes for large regions based on process-based modelling, NFI data and Landsat satellite images. For. Ecol. Manage. 262, 2364–2377.

Hasenauer, H., 1994. Ein Einzelbaumwachstumssimulator für ungleichaltrige Fichten-Kiefern- und Buchen-Fichtenmischbestände. Forstl. Schriftenreihe, Univ. f. Bodenkultur, Wien. Österr. Ges. f. Waldökosystemforschung und experimentelle Baumforschung. 152 p. (in German).

He, L., Chen, J.M., Pan, Y., et al., 2012. Relationships between net primary productivity and forest stand age in U.S. forests. Global Biogeochem. Cycles 26, 1–19.

Hochbichler, E., 2002. Vorläufige Ergebnisse von Biomasseninventuren in Buchen- und Mittelwaldbeständen. In: Dietrich, H.P., Raspe, S., Preuhsler, T. (Eds.), Inventur von Biomasse- und Nährstoffvorräten in Waldbeständen, Forstliche Forschungsberichte, vol. 186. LWF, München, Germany, pp. 37–46 (in German).

Hochbichler, E., Bellos, P., Lick, E., 2006. Biomass functions for estimating needle and branch biomass of spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) and branch biomass of beech (*Fagus sylvatica*) and oak (*Quercus robur* and *petrea*). Aust. J. Forest Sci. 123, 35–46.

Hytönen, J., Saarsalmi, A., Rossi, P., 1995. Biomass production and nutrient uptake of short-rotation plantations. Silva Fennica 29 (2), 117–139.

INRA, 2004. Rapport final du projet CARBOFOR, Sequestration de Carbone dans les grands ecosystemes forestiers en France. Quantification, spatialisation, vulnerabilite et impacts de differents scenarios climatiques et sylvicoles. Programme GICC 2001 "Gestion des impacts du changement climatique" Convention Gip ECOFOR n 3/2001, 138 p. (in French).

IPCC, 2006. CHAPTER 4 FOREST. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, 83 p.

ISPRA, 2013. Italian greenhouse gas inventory 1990–2011, National Inventory Report 2013. Italy, Rome, p. 516.

Jalkanen, A., Mäkipää, R., Ståhl, G., Lehtonen, A., Petersson, H., 2005. Estimation of the biomass stock of trees in Sweden: comparison of biomass equations and age-dependent biomass expansion factors. Ann. Forest Sci. 62, 845–851.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. Forest Sci. 49 (1), 12–35.

Johansson, T., 1999. Biomass equations for determining fractions of pendula and pubescent birches growing on abandoned farmland and some practical implications. Biomass Bioenergy 16 (3), 223–238.

Ketterings, Q.M., Coe, R., Van Noordwijk, V., Ambagau, Y., Palm, C.A., 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. For. Ecol. Manage. 146, 199–209.

Kittenberger, A., 2003. Generierung von Baumverteilungsmustern. diploma thesis. Universität für Bodenkultur, Wien, 79 p. (in German).

Klement, I., Réh, R., Detvaj, J., 2010. Základné charakteristiky lesných drevín – spracovanie drevnej suroviny v odvetví spracovania dreva. Národné lesnícke centrum, ISBN 978-80-8093-112-4 (in Czech).

Klopf, M., Thurnher, C., Hasenauer, H., 2011. Benutzerhandbuch MosesFramework. Universität für Bodenkultur, Wien, 124 p. (in German).

Kollmann, F., 1982. Technologie des Holzes und der Holzwerkstoffe. Springer-Verlag, Berlin, Heidelberg, New York (in German).

Kublin, E., 2002. Verfahrens- und Programmbeschreibung zum erweiterten BWI-Unterprogramm BDAT 2.0. Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, 30 p. (in German).

Lamlom, S.H., Savidge, R.A., 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. Biomass Bioenergy 25, 381–388.

Lamlom, S.H., Savidge, R.A., 2006. Carbon content variation in boles of mature sugar maple and giant sequoia. Tree Physiol. 26, 459–468.

Lang, M., Nilson, T., Kuusk, A., Kiviste, A., Hordo, M., 2007. The performance of foliage mass and crown radius models in forming the input of a forest reflectance model: a test on forest growth sample plots and Landsat 7 ETM+ images. Remote Sens. Environ. 110 (4), 445–457.

Lawrence, D.M., Oleson, K.W., Flanner, M.G., et al., 2011. Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model. J. Adv. Model Earth Syst. 3, M03001.

Le Goff, N., Ottorini, J.M., 2001. Root biomass and biomass increment in a beech (*Fagus sylvatica* L.) stand in North-East France. Ann. Forest Sci. 58, 1–13.

Ledermann, T., Neumann, M., 2006. Biomass equations from data of old long-term experimental plots. Aust. J. Forest Sci. 123 (1/2), 47–64.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., Liski, J., 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. For. Ecol. Manage. 188, 211–224.

Lexer, M.J., Hoenninger, K., 2001. A modified 3D-patch model for spatially explicit simulation of vegetation composition in heterogeneous landscapes. For. Ecol. Manage. 144, 43–65.

Lorey, T., 1878. Die mittlere Bestandeshöhe. Allgemeine Forst- und Jagdzeitung 54, 149–155.

MacLean, R.G., Ducey, M.J., Hoover, C.M., 2014. A comparison of carbon stock estimates and projections for the Northeastern United States. Forest Sci. 60 (2), 206–213.

MacPeak, M.D., Burkart, L.F., Weldon, D., 1990. Comparison of grade, yield, and mechanical properties of lumber produced from young fast-grown and old slow- grown planted slash pine. Forest Products J. 40 (1), 11–14.

MAF-ISAFA, 1988. Inventario Forestale Nazionale. Sintesi metodologica e risultati. Ministero dell'Agricoltura e delle foreste. Istituto Sperimentale per l'assestamento forestale e per l'Alpicoltura, Trento (in Italian).

Marklund, L.G., 1988. Biomassafunktioner för tall, gran och björk i Sverige. Rapporter Skog; 45: 1–73. Sveriges Landbruksuniversitet (in Swedish).

Marschall, J., 1992. Hilfstafeln für die Forsteinrichtung, fifth ed. Österreichischer Agrarverlag, Wien (in German).

Mátyás, C., Ackzell, L., Samuel, C.J.A., 2004. EUFORGEN Technical Guidelines for genetic conservation and use for Scots pine (*Pinus sylvestris*). International Plant Genetic Resources Institute, Rome, Italy, 6 p.

Mäkipää, R., Cienciala, E., Green, C., Gracia, C., Lehtonen, A., Muukkonen, P., Sabate, S., Somogyi, Z., Weiss, P., 2005. Multi-source inventory methods for quantifying carbon stocks and stock changes in European forests. Action COST CarboInvent. Final report for Deliverable 2.2. Document No.: WP2-D2.2-Metla. Date: October 28.

McGroddy, M., Daufresne, T., Hedin, L., 2004. Scaling of C:N:P stoichiometry in forests worldwide: implications of terrestrial Redfield-type ratios. Ecology 85 (9), 2390–2401.

McRoberts, R.E., Tomppo, E., Schadauer, K., Vidal, C., Chirici, G., Lanz, A., Cienciala, E., Winter, S., Smith, W.B., 2009. Harmonizing national forest inventories. J. Forest., 179–187

Miles, P.D., Smith, W.B., 2009. Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America. Research Note NRS-38.

Mitchell, S.R., Harmon, M.E., O'Connell, K.E.B., 2012. Carbon debt and carbon sequestration parity in forest bioenergy production. GCB Bioenergy 4, 818–827.

Mohren, G.M.J., Hasenauer, H., Köhl, M., Nabuurs, G.J., 2012. Forest inventories for carbon change assessments. Curr. Opinion Environ. Sustain. 4 (6), 686–695.

Montero, G., Ruiz-Peinado, R., Muñoz, M., 2005. Producción de biomasa y fijación de CO2 por los bosques españoles. Monografías INIA: Serie forestal 13. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, Ministerio de Investigación y Ciencia. Madrid. ISBN 84-7498-512-9 (in Spanish).

Muukkonen, P., 2007. Generalized allometric volume and biomass equations for some tree species in Europe. Eur. J. Forest Res. 126 (2), 157–166.

Müller-Starck, G., Baradat, P., Bergmann, F., 1992. Genetic variation within European tree species. New Forest. 6 (1–4), 23–47.

Nabuurs, G., Schelhaas, M., Pussinen, A., 2000. Validation of the European Forest Information Scenario Model (EFISCEN) and a Projection of Finnish Forests. Silva Fennica 34 (2), 167–179.
Nagel, J., 1999. Konzeptuelle Überlegungen zum schrittweisen Aufbau eines waldwachstum-kundlichen Simulationssystems für Nordwestdeutschland (A concept for the development of a forest growth model for Northwest Germany). Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Niedersächsischen Forstlichen Versuchsanstalt, J.D. Sauerländer's Verlag, Frankfurt am Main, 128 p.
Nabuurs, G., van den Wyngaert, I., Daamen, W., Helmink, A., de Groot, W., Knol, W., Kramer, H., Kuikman, P., 2005. National system of greenhouse gas reporting for forest and nature areas under UNFCCC in The Netherlands. Alterra-Report 1035 (1), 57 p.
National Institute for Public Health and the Environment, 2013. Greenhouse gas emission in The Netherlands 1990–2011, National Inventory Report 2013, 258 p.
Offenthaler, I., Hochbichler, E., 2006. Estimation of root biomass of Austrian forest tree species. Aust. J. Forest Sci. 123 (1/2), 65–86.
Pan, Y., Birdsey, R., Fang, J., Houghton, R., Kauppi, P., Kurz, W., Hayes, D., 2011. A large and persistent carbon sink in the World's forests. Science 333, 988–992.
Petráš, R., Košút, M., Oszlányi, J., 1985. Leaf biomass of trees in spruce, pine and beech. Lesnícky časopis 31 (2), 121–136 (in Slovak).
Petráš, R., Pajtík, J., 1991. Sústava česko-slovenských objemových tabuliek drevín. Lesnícky časopis 37 (1), 49–56 (in Slovak).
Petersson, H., Ståhl, G., 2006. Functions for below-ground biomass of *Pinus sylvestris, Picea abies, Betula pendula* and *Betula pubescens* in Sweden. Scand. J. For. Res. 21 (S7), 84–93.
Pietsch, S.A., Hasenauer, H., 2002. Using mechanistic modeling within forest ecosystem restoration. For. Ecol. Manage. 159, 111–131.
Pietsch, S.A., Hasenauer, H., Thornton, P.E., 2005. BGC-model parameters for tree species growing in central European forests. For. Ecol. Manage. 211 (3), 264–295.
Pollanschütz, J., 1974. Formzahlfunktionen der Hauptbaumarten Österreichs. Informationsdienst Forstliche Bundesversuchsanstalt Wien 153, 341–343 (in German).
Požgaj, A., Chovanec, D., Kurjatko, S., Babiak, M., 1993. Štruktúra a vlastnosti dreva. Príroda, Bratislava, 486 p. ISBN 80-07-00600-1 (in Slovak).
Pretzsch, H., Biber, P., Dursky, J., 2002. The single tree-based stand simulator SILVA: construction, application and evaluation. For. Ecol. Manage. 162, 3–21.
Repola, J., 2006. Models for vertical wood density of scots Pine, Norway spruce and birch stems, and their application to determine average wood density. Silva Fennica 40 (4), 673–685.
Repola, J., 2008. Biomass equations for birch in Finland. Silva Fennica 42 (4), 605–624.
Repola, J., 2009. Biomass equations for Scots Pine and Norway Spruce in Finland. Silva Fennica 43 (4), 625–647.
Ruiz-Peinado, R., Del Rio, M., Montero, G., 2011. New models for estimating the carbon sink capacity of Spanish softwood species. Forest Syst. 20 (1), 176–188.
Ruiz-Peinado, R., Montero, G., Del Rio, M., 2012. Biomass models to estimate carbon stocks for hardwood tree species. Forest Syst. 21 (1), 42–52.
Running, S., Nemani, R., Heinsch, F., Zhao, M., Reeves, M., Hashimoto, H., 2004. A continuous satellite-derived measure of global terrestrial primary production. Bioscience 54, 547–560.
Schelhaas, M.J., Varis, S., Schuck, A., Nabuurs, G.J., 1999. EFISCEN's European Forest Resource Database. European Forest Institute, Joensuu, Finland.
Schieler, K., 1988. Methodische Fragen in Zusammenhang mit der österreichischen Forstinventur. Diploma Thesis, Universität für Bodenkultur, Vienna, Austria. 99 p. (in German).
Schmidt-Vogt, H., 1977. Die Fichte. Band 1. Paul Parey, Hamburg (in German).
Schwarzmeier, M., 2000. Erhebung der oberirdischen Biomassevorräte von Fichtenbestanden (*Picea abies* (L.) Karst.) im Bereich der Waldklimastationen Ebersberg und Flossenbürg. Diploma Thesis, Fachhochschule Weihenstephan, Fachbereich Forstwirtschaft, Germany, 155 p. (in German).
Seidl, R., Lexer, M.J., Jäger, D., Hönninger, K., 2005. Evaluating the accuracy and generality of a hybrid patch model. Tree Physiol. 25 (7), 939–951.
Shinozaki, K., Yoda, K., Hozumi, K., Tira, T., 1964a. A quantitative analysis of plant form- the pipe model theory I. Basic analysis. Japanese J. Ecol. 14, 97–105.
Shinozaki, K., Yoda, K., Hozumi, K., Tira, T., 1964b. A quantitative analysis of plant form- the pipe model theory II. Further evidence of the theory and its application in forest ecology. Japanese J. Ecol. 14, 133–139.
Skrøppa, T., 2003. EUFORGEN Technical Guidelines for genetic conservation and use for Norway pruce (*Picea abies*). International Plant Genetic Resources Institute, Rome, Italy, 6 p.
Ståhl, G., Cienciala, E., Chirici, G., Lanz, A., Vidal, C., Winter, S., McRoberts, R.E., Rondeux, J., Schadauer, K., Tomppo, E., 2012. Bridging national and reference definitions for harmonizing forest statistics. Forest Sci. 58 (3), 214–223.
Statistics Finland, 2013. Greenhouse Gas emissions in Finland 1990–2011, National Inventory Report under the UNFCCC and the Kyoto Protocol.
Sterba, H., 1976. Ertragstafeln der ÖBF, Inst. f. forstl. Ertragslehre, Univ. f. Bodenkultur, Wien (in German).
Sterba, H., Monserud, R.A., 1997. Applicability of the forest stand growth simulator PROGNAUS for the Austrian part of the Bohemian Massif. Ecol. Model. 98, 23–34.
Tabacchi, G.,, Di Cosmo, L., Gasparini, P., Morelli, S., 2011. Stima del volume e della fitomassa delle principali specie forestali italiene, Equazioni di previsione, tavole del volume e tavole della fitomassa arborea epigea, 415 p. Trento: Consiglio per la Ricerca e la sperimentazione in Agricoltura, Unita di Ricerca per il Monitoraggio e la Pianificazione Forestale (in Italian).
Thomas, S.C., Martin, A.R., 2012. Carbon content of tree tissues: a synthesis. Forests 3, 332–352.
Thornton, P.E., 1998. Description of a Numerical Simulation Model for Predicting the Dynamics of Energy, Water, Carbon and Nitrogen in a Terrestrial Ecosystem. University of Montana, Missoula.
Thornton, P.E., Law, B.E., Gholz, H.L., Clark, K.L., Falge, E., Ellsworth, D.S., et al., 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. Agric. For. Meteorol. 113 (1–4), 185–222.
Thurnher, C., Gerritzen, T., Maroschek, M., Lexer, M.J., Hasenauer, H., 2013. Analysing different carbon estimation methods for Austrian forests. Aust. J. Forest Sci. 130 (3), 141–166.
Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E., 2010. National Forest Inventories: Pathways for common reporting. Springer, Berlin, 610 p.
Umweltbundesamt, 2013. Austria's National Inventory Report 2013, Submission under the United Nations Framework on Climate Change and the Kyoto Protocol. Umweltbundesamt GmbH (Federal Environment Agency Ltd) Vienna, Austria, Vienna.
Uri, V., Aosaar, J., Varik, M., Kund, M., 2010. The growth and production of some fast growing deciduous tree species stands on abandoned agricultural land. Forest. Stud. 52, 18–29.
Vallet, P., Dhôte, J.-F., Moguédec, G. Le, Ravart, M., Pignard, G., 2006. Development of total aboveground volume equations for seven important forest tree species in France. For. Ecol. Manage. 229, 98–110. http://dx.doi.org/10.1016/j.foreco.2006.03.013.
Vande Walle, I., Van Camp, N., Perrin, D., Lemeur, R., Verheyen, K., van Wesemael, B., Laitat, E., 2005. Growing stock-based assessment of the carbon stock in the Belgian forest biomass. Ann. For. Sci. 62, 853–864. http://dx.doi.org/10.1051/forest:2005076.
VEMAP Members, 1995. Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO2 doubling. Global Biogeochem. Cycles 9 (4), 407–437.
Veroustraete, F., Sabbe, H., Eerens, H., 2002. Estimation of carbon mass fluxes over Europe using the C-Fix model and Euroflux data. Remote Sens. Environ. 83, 376–399.
Vilén, T., Meyer, J., Thürig, E., Lindner, M., Green, T., 2005. Multi-source inventory methods for quantifying carbon stocks and stock changes in European forests – CarboInvent. EFI, 31.
Wagenführ, R., Scheiber, C., 1985. Holzatlas, second ed. VEB Fachbuchverlag, Leibzig (in German).
Waring, R., Schroeder, P., Oren, R., 1982. Application of the pipe model theory to predict canopy leaf area. Can. J. For. Res. 12, 556–560.
Westfall, J.A., 2012. A comparison of above-ground dry-biomass estimators for trees in the Northeastern United States. Northern J. Appl. Forest. 29 (1), 26–34.
Wirth, C., Schumacher, J., Schulze, E.D., 2004. Generic biomass functions for Norway spruce in Central Europe– a meta-analysis approach toward prediction and uncertainty estimation. Tree Physiol. 24 (2), 121–139.
Wutzler, T., Wirth, C., Schumacher, J., 2008. Generic biomass functions for Common beech (*Fagus sylvatica*) in Central Europe: predictions and components of uncertainty. Can. J. For. Res. 38 (6), 1661–1675.
Xiao, C.W., Curiel Yuste, J., Janssens, I.A., Roskams, P., Nachtergale, L., Carrara, A., Sanchez, B.Y., Ceulemans, R., 2003. Above- and belowground biomass and net primary production in a 73-year-old Scots pine forest. Tree Physiol. 23 (8), 505–516.
Zanne, A.E., Lopez-Gonzalez, G., Coomes, D.A., Ilic, J., Jansen, S., Lewis, S.L., Chave, J., et al., 2009. Data from: Towards a worldwide wood economics spectrum. Dryad Digital Repository.
Zasada, M., Bronisz, K., Bijak, S., Wojtan, R., Tomusiak, R., Dudek, A., Michalak, K., 2008. Empirical formulae for determination of the dry biomass of aboveground parts of the tree. Sylwan 3, 27–39 (in Polish).
Zhao, M., Running, S.W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329, 940–943.
Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M., 2005. Biomass and stem volume equations for tree species in Europe. Silva Fennica, Monographs, 63 p.

Supplementary material to *Neumann et al*. 2016, Comparison of carbon estimation methods for European forests, Forest Ecology and Management

- Tables on biomass and carbon results on stand level for tree species not presented in paper (Tables S.1, S.2 and S.3)

- Tables on properties of sample material tables for tree species not presented in paper (Tables S.4, S.5 and S.6)

Table S.1: Results for biomass in tree compartments, tree biomass (sum of all compartments) and tree carbon on stand level [t/ha] for *Pinus sylvestris,* results arranged according to the 4 Forest regions, first column give the results for the stand with quadratic mean diameter (DBH) of 10 cm, second column for DBH of 30 cm and third column for DBH of 50 cm. At the end of table selected statistics are given for each stand and each biomass and carbon estimate: Mean and Range (Maximum – Minimum) of the country estimates and variation expressed as Range divided by Mean.

Pinus sylvestris	**Stem biomass [t/ha]**			**Branch biomass [t/ha]**			**Foliage biomass [t/ha]**			**Root biomass [t/ha]**			**Tree biomass [t/ha]**			**Tree carbon [t/ha]**		
North Europe	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
Finland	30.3	128.8	158.3	15.1	36.1	34.3	7.0	8.2	5.4	14.4	53.5	69.1	59.8	218.3	261.7	29.9	109.1	130.9
Norway	30.6	137.2	194.6	13.2	28.0	25.0	7.4	7.2	5.5	16.0	55.7	64.6	59.8	220.9	284.2	29.9	110.4	142.1
Central-West Europe																		
Austria	35.6	154.2	249.4	15.9	28.8	35.5	3.6	5.4	5.8	12.7	25.4	32.4	64.2	208.5	317.2	32.1	104.2	158.6
Belgium	32.3	162.4	268.6	5.1	26.0	52.8	2.2	5.2	7.3	28.1	29.2	26.9	65.6	217.6	348.3	32.8	108.8	174.1
France	48.7	181.4	316.7	-	-	-	1.0	3.6	6.3	14.6	54.4	95.0	64.3	239.4	418.1	30.5	113.7	198.6
Germany	27.3	123.2	207.2	19.4	23.2	25.8	2.2	5.2	7.3	21.5	46.4	54.1	70.3	198.0	294.4	35.2	99.0	147.2
Netherlands	20.9	146.3	248.7	10.7	26.2	44.5	4.2	4.4	7.6	5.7	35.8	60.9	41.4	212.7	361.7	20.7	106.4	180.9
Central-East Europe																		
Czech Republic	22.6	145.2	256.0	22.8	25.6	34.7	6.2	6.0	5.8	20.2	85.1	157.1	71.8	261.9	453.7	35.9	130.9	226.8
Poland	37.7	168.5	268.8	12.3	27.9	47.6	8.3	11.8	14.1	17.5	73.0	117.0	75.8	281.1	447.5	37.9	140.5	223.8
Romania	22.0	115.7	186.7	11.3	20.7	33.4	4.4	3.5	5.7	6.0	28.3	45.7	43.8	168.3	271.5	21.9	84.1	135.7
South Europe																		
Italy	33.7	167.9	292.6	14.4	46.0	78.6	-	-	-	18.6	88.0	153.0	66.8	301.8	524.2	33.4	150.9	262.1
Spain	28.6	150.2	262.2	35.3	32.6	47.9	9.7	10.5	9.9	36.4	67.5	83.1	100.3	250.3	393.2	50.1	125.2	196.6
Mean [t/ha]	30.9	150.2	250.1	15.9	29.2	41.8	5.1	6.5	7.3	17.7	53.5	79.9	65.3	231.6	364.7	32.5	115.3	181.5
Range [t/ha]	27.8	65.6	158.5	30.2	25.2	53.6	8.8	8.3	8.7	30.7	62.6	130.2	58.9	133.5	262.5	29.4	66.8	131.3
Range/Mean [%]	90%	44%	63%	189%	87%	128%	172%	128%	118%	174%	117%	163%	90%	58%	72%	90%	58%	72%

Table S.2: Results for biomass in tree compartments, tree biomass (sum of all compartments) and tree carbon on stand level [t/ha] for *Quercur robur,* for details on the table and the content please see explanations provided for Table S.1

Quercus robur	**Stem biomass [t/ha]**			**Branch biomass [t/ha]**			**Foliage biomass [t/ha]**			**Root biomass [t/ha]**			**Tree biomass [t/ha]**			**Tree carbon [t/ha]**		
North Europe	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
Finland	35.6	158.8	194.4	10.3	25.0	29.3	5.3	3.1	1.7	19.9	39.5	48.0	71.1	226.3	273.4	35.6	113.2	136.7
Norway	38.4	161.9	195.5	14.8	33.5	36.6	0.7	2.9	3.5	24.0	63.2	95.0	77.9	261.5	330.6	38.9	130.7	165.3
Central-West Europe																		
Austria	54.1	204.6	297.2	47.9	54.1	54.3	3.1	3.8	4.2	15.2	45.8	77.1	120.4	308.2	432.8	60.2	154.1	216.4
Belgium	41.1	224.0	357.5	14.3	40.7	66.8	2.7	5.6	9.2	16.0	41.5	65.3	74.1	311.8	498.8	37.0	155.9	249.4
France	59.1	244.2	385.1	-	-	-	1.2	4.9	7.7	16.5	68.4	107.8	76.8	317.5	500.6	36.5	150.8	237.8
Germany	35.8	206.5	335.8	132.5	36.8	30.6	2.3	7.4	13.1	58.9	85.2	128.2	229.5	335.9	507.6	114.7	168.0	253.8
Netherlands	106.1	217.4	311.9	17.7	36.5	41.8	7.8	5.0	5.7	46.1	54.4	74.1	176.9	313.4	433.7	88.4	156.7	216.9
Central-East Europe																		
Czech Republic	25.5	184.8	309.8	15.5	27.6	38.0	2.3	2.8	3.8	17.8	48.8	78.9	61.1	264.1	430.5	30.5	132.0	215.3
Poland	60.3	199.5	295.3	11.0	64.5	148.9	2.6	5.5	8.2	17.7	64.7	108.6	91.7	334.1	561.0	45.8	167.1	280.5
Romania	46.0	191.2	300.3	7.9	29.3	46.6	2.1	10.5	16.9	10.5	69.3	111.9	66.5	300.3	475.7	33.2	150.2	237.8
South Europe																		
Italy	48.5	282.8	465.4	27.1	48.7	64.4	-	-	-	15.1	66.3	106.0	90.7	397.9	635.8	45.3	198.9	317.9
Spain	28.5	197.6	321.2	24.9	63.5	226.2	3.3	7.1	8.4	17.4	77.5	120.5	74.2	345.6	676.3	37.1	172.8	338.2

Mean [t/ha]	49.4	210.4	325.0	29.5	41.8	71.2	3.0	5.3	7.5	22.9	60.4	93.4	100.9	309.7	479.7	50.3	154.2	238.8
Range [t/ha]	80.6	124.0	271.0	124.6	39.5	196.9	7.1	7.7	15.2	48.4	45.7	80.2	168.4	171.6	403.0	84.2	85.8	201.5
Range/Mean [%]	163%	59%	83%	423%	94%	276%	236%	145%	202%	211%	76%	86%	167%	55%	84%	167%	56%	84%

Table S.3: Results for biomass in tree compartments, tree biomass (sum of all compartments) and tree carbon on stand level [t/ha] for *Betula pendula,* for details on the table and the content please see explanations provided for Table S.1

Betula pendula	**Stem biomass [t/ha]**			**Branch biomass [t/ha]**			**Foliage biomass [t/ha]**			**Root biomass [t/ha]**			**Tree biomass [t/ha]**			**Tree carbon [t/ha]**		
North Europe	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm
Finland	33.4	148.4	152.7	9.8	23.3	22.8	5.0	2.9	1.3	18.8	36.9	37.9	67.0	211.4	214.7	33.5	105.7	107.4
Norway	36.0	151.3	153.5	14.0	31.3	28.6	0.6	2.7	2.7	22.7	59.0	76.0	73.3	244.3	260.8	36.6	122.1	130.4
Central-West Europe																		
Austria	41.4	139.9	138.8	26.0	67.5	90.5	2.3	2.8	2.7	9.0	21.4	28.1	78.7	231.6	260.1	39.3	115.8	130.0
Belgium	33.5	164.1	203.7	13.5	38.1	54.1	2.5	5.2	7.5	15.1	38.7	52.8	64.6	246.1	318.0	32.3	123.1	159.0
France	55.5	228.2	310.0	-	-	-	1.1	4.6	6.2	15.5	63.9	86.8	72.1	296.6	403.0	34.3	140.9	191.4
Germany	30.5	166.6	246.3	24.4	26.3	34.6	0.6	2.9	4.0	23.6	46.3	67.4	79.1	242.1	352.4	39.5	121.0	176.2
Netherlands	51.3	154.6	231.9	8.5	25.7	29.4	3.8	3.5	4.6	22.3	38.8	56.8	85.5	222.7	322.6	42.7	111.3	161.3
Central-East Europe																		
Czech Republic	14.5	133.1	174.0	22.8	26.2	35.8	2.2	2.6	3.1	16.6	50.5	74.5	56.1	212.4	287.4	28.1	106.2	143.7
Poland	33.4	148.2	152.5	9.8	24.6	32.5	1.8	3.8	2.7	10.8	42.4	45.0	55.7	218.9	232.7	27.9	109.5	116.4
Romania	29.7	132.3	167.4	4.8	22.1	22.6	1.5	3.0	3.1	9.3	33.1	39.8	45.4	190.4	232.8	22.7	95.2	116.4
South Europe																		
Italy	44.6	91.8	111.3	16.0	46.8	60.6	-	-	-	14.5	33.3	41.2	75.1	171.9	213.1	37.6	85.9	106.5
Spain	64.2	136.6	169.5	33.4	41.6	64.4	3.5	4.0	3.7	40.2	29.9	22.3	124.0	182.8	226.6	62.0	91.4	113.3

Mean [t/ha]	39.5	149.7	187.2	16.6	34.0	43.3	2.3	3.5	3.8	18.2	41.2	52.4	73.1	222.6	277.0	36.4	110.7	137.7
Range [t/ha]	49.7	136.4	198.7	28.7	45.4	67.9	4.4	2.6	6.2	31.2	42.5	64.5	78.6	124.8	189.9	39.3	55.0	84.9
Range/Mean [%]	126%	91%	106%	172%	134%	157%	194%	75%	164%	172%	103%	123%	108%	56%	69%	108%	50%	62%

Table S.4: Properties of the sample material used for volume and biomass functions for *Pinus sylvestris* by country and region: if multiple references are used for the compartments in one country, each reference is covered by one row. Given for each reference is DBH (diameter at breast height) and tree height of the sample material, the Origin of the samples (the country where the sample material was collected), the Number of samples, the Age of the sample trees in years as well as the Reference. Boxes with a hyphen (-) indicate that this information is not given by the reference. For the volume functions used in Czech Republic only the maximum diameter and height of the samples is given (Petras and Pajtik 1991)

Pinus sylvestris	**Country**	**Compartments**	**DBH [cm]**	**Height [m]**	**Origin**	**No. Samples**	**Age [a]**	**References**
North Europe	Finland	all	1.5 - 35.8	2.0 - 28.6	Finland	908	11 - 146	Repola 2009
	Norway	aboveground	0.0 - 48.0	1.3 - 28.0	Sweden	493	-	Marklund 1988
		roots	0.0 - 48.0	1.3 - 28.0	Sweden	330	20 - 117	Petersson and Stahl 2006
Central-West Europe	Austria	stem volume	-	-	Austria	1429	-	Pollanschütz 1974
		branch, foliage	5.3 - 34.8	3.9 - 25.3	Austria	23	25 - 60	Hochbichler et al 2006
		roots	4.0 - 45.0	3.5 - 32.0	Europe	38	12 - 149	Offenthaler and Hochbichler 2006
	Belgium	stem volume	-	-	Belgium	-	-	Dagnelie et al. 1985
		branch, foliage, roots	22.0 - 39.5	18.6 - 24.5	Belgium	9	73	Xiao et al. 2003
	France	aboveground	4.8 - 52.5	-	France	389	-	Vallet et al. 2006
	Germany	wood volume	-	-	Germany	-	-	Kublin 2002
		foliage	22.0 - 39.5	18.6 - 24.5	Belgium	9	73	Xiao et al. 2003
	Netherlands	aboveground	1.0 - 34.0	-	European Russia	315	20 - 89	Hamburg et al. 1997
Central-East Europe	Czech Republic	wood volume	-56.0	-34.0	Czechoslovakia	1659	-	Petras and Pajtik 1991
		foliage, twigs	4.0 - 60.0	4.0 - 36.0	Czechoslovakia	253	-	Petras et al. 1985
		roots	4.0 - 24.0	-	Finland	20	8 - 55	Drexhage and Collin 2001
	Poland	all	6.7 - 31.5	3.9 - 25.7	Poland	90	24 - 105	Zasada et al. 2008
	Romania	aboveground	-	-	Romania	618	-	Giurgiu et al. 1985
South Europe	Italy	all	8.0 - 40.6	5.0 - 30.0	N Italy	43	-	Tabacchi et al. 2011
	Spain	all (excl. foliage)	6.2 - 76.0	4.6 - 27.7	Spain	305 (roots 14)	-	Ruiz Peinado et al. 2011
		foliage	5.3 - 49.2	7.1 - 23.8	NW Spain	125	34 - 44	Diéguez-Aranda et al. 2009

Table S.5: Properties of the sample material used for volume and biomass functions for *Quercus robur* by country and region: for details on the table and the content please see explanations provided for Table S.4

Quercus robur	**Country**	**Compartments**	**DBH [cm]**	**Height [m]**	**Origin**	**No. Samples**	**Age [a]**	**References**
North Europe	Finland	all	2.5 - 38.7	3.9 - 29.0	Finland	127	7 - 132	Repola 2008
	Norway	aboveground	0.0 - 36.0	1.3 - 24.0	Sweden	242	-	Marklund 1988
		roots	0.5 - 26.7	1.7 - 20.8	Sweden	14	7 - 59	Petersson and Stahl 2006
Central-West Europe	Austria	stem volume	-	-	Austria	216	-	Pollanschütz 1974
		branches	3.6 - 26.3	6.6 - 22.4	Austria	96	35 - 84	Ledermann and Neumann 2006
		foliage	3.2 - 67.0	5.0 - 32.0	Switzerland	53	13 - 155	Burger 1947
		roots	5.0 - 16.0	8.0 - 12.0	France	55	20 - 28	Drexhage et al. 1999
	Belgium	stem volume	-	-	Belgium	290	-	Dagnelie et al. 1985
		branches	5.7 - 62.1	9.2 - 33.9	Czech Republic	20	40 - 114	Cienciala et al. 2005
		foliage	2.0 - 33.0	3.5 - 22.5	Netherlands	38	8 - 59	Bartelink 1997
		roots	3.0 - 38.0	7.0 - 29.0	Central Europe	48	21 - 160	Wutzler et al. 2008
	France	aboveground	4.8 - 90.7	-	France	1222	-	Vallet et al. 2006
	Germany	wood volume	-	-	Germany	-	-	Kublin 2002
		foliage	24.1 (mean)	17.2 (mean)	Belgium	9	67 - 74	Curiel Yuste et al. 2005
	Netherlands	aboveground	1.0 - 61.0	2.5 - 19.0	Austria	33	-	Hochbichler 2002
Central-East Europe	Czech Republic	wood volume	-70.0	-38.0	Czechoslovakia	1893	-	Petras and Pajtik 1991
		foliage, twigs	8.0 - 84.0	8.0 - 36.0	Czechoslovakia	285	-	Petras et al. 1985
		roots	5.0 - 16.0	8.0 - 12.0	France	55	20 - 28	Drexhage et al. 1999
	Poland	all	2.0 - 64.0	3.5 - 29.0	Europe	68	-	Muukkonen 2007
	Romania	aboveground	-	-	Romania	8707	-	Giurgiu et al. 1985
South Europe	Italy	all	5.5 - 55.9	3.5 - 24.3	Italy	117	-	Tabacchi et al. 2011
	Spain	all	14.6 - 67.5	11.3 - 27.6	NW Spain	31	-	Balboa-Murias et al. 2006

Table S.6: Properties of the sample material used for volume and biomass functions for *Betula pendula* by country and region: for details on the table and the content please see explanations provided for Table S.4

Betula pendula	**Country**	**Compartments**	**DBH [cm]**	**Height [m]**	**Origin**	**No. Samples**	**Age [a]**	**References**
North Europe	Finland	all	2.5 - 38.7	3.9 - 29.0	Finland	127	7 - 132	Repola 2008
	Norway	aboveground	0.0 - 36.0	1.3 - 24.0	Sweden	242	-	Marklund 1988
		roots	0.5 - 26.7	1.7 - 20.8	Sweden	14	7 - 59	Petersson and Stahl 2006
Central-West Europe	Austria	stem volume	-	-	Austria	-	-	Schieler 1988
		branches	2.0 - 67.1	3.6 - 39.0	Austria	4213	35 - 125	Ledermann and Neumann 2006
		foliage	0.8 - 57.0	2.6 - 39.6	Switzerland	91	14 - 128	Burger 1949
		roots	4.0 - 53.0	7.0 - 28.0	Germany	27	44 - 127	Bolte et al. 2004
	Belgium	stem volume	-	-	Belgium	329	-	Dagnelie et al. 1985
		branches	5.7 - 62.1	9.2 - 33.9	Czech Republic	20	40 - 114	Cienciala et al. 2005
		foliage	2.0 - 33.0	3.5 - 22.5	Netherlands	38	8 - 59	Bartelink 1997
		roots	3.0 - 38.0	7.0 - 29.0	Central Europe	48	21 - 160	Wutzler et al. 2008
	France	aboveground	4.8 - 90.7	-	France	1222	-	Vallet et al. 2006
	Germany	wood volume	-	-	Germany	-	-	Kublin 2002
		foliage	-	-	Finland	-	-	Hytönen et al. 1995
	Netherlands	aboveground	0.8 - 13.7	2.3 - 19.9	Sweden	197	6 - 32	Johansson et al. 1999
Central-East Europe	Czech Republic	wood volume	-54.0	-34.0	Czechoslovakia	1355	-	Petras and Pajtik 1991
		foliage, twigs	8.0 - 84.0	8.0 - 36.0	Czechoslovakia	285	-	Petras et al. 1985
		roots	3.0 - 20.0	9.9 (mean)	NE France	16	24 - 35	Le Goff and Ottorini 2001
	Poland	all	2.5 - 38.7	3.9 - 29.0	Finland	127	7 - 132	Repola 2008
	Romania	aboveground	-	-	Romania	2341	-	Giurgiu et al. 1985
South Europe	Italy	all	5.3 - 31.6	4.8 - 28.3	Italy	22	-	Tabacchi et al. 2011
	Spain	all	9.9 - 21.0	12.6 - 26.2	NW Spain	16	-	Diéguez-Aranda et al. 2009

7.3 Paper 3

Neumann, M., Moreno, A., Thurnher, C., Mues, V., Härkönen, S., Mura, M., Bouriaud, O., Lang, M., Cardellini, G., Thivolle-Cazat, A., Bronisz, K., Merganic, J., Alberdi, I., Astrup, R., Mohren, F., Zhao, M., & Hasenauer, H. (2016). Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests. Remote Sensing, 8(554), 1–18. http://doi.org/10.3390/rs8070554

remote sensing

MDPI

Article

Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests

Mathias Neumann [1,*], Adam Moreno [1], Christopher Thurnher [1], Volker Mues [2], Sanna Härkönen [3,4], Matteo Mura [5,6], Olivier Bouriaud [7], Mait Lang [8], Giuseppe Cardellini [9], Alain Thivolle-Cazat [10], Karol Bronisz [11], Jan Merganic [12], Iciar Alberdi [13], Rasmus Astrup [14], Frits Mohren [15], Maosheng Zhao [16] and Hubert Hasenauer [1]

1 Institute of Silviculture, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Vienna 1190, Austria; adam.moreno@boku.ac.at (A.M.); Cthurnhe@groupwise.boku.ac.at (C.T.); hubert.hasenauer@boku.ac.at (H.H.)
2 Centre for Wood Science, World Forestry, University of Hamburg, Hamburg 21031, Germany; volker.mues@uni-hamburg.de
3 Department of Forest Sciences, University of Helsinki, Helsinki 00014, Finland; sanna.harkonen@helsinki.fi
4 Finnish Forest Research Institute, Joensuu 80101, Finland
5 Department of Bioscience and Territory, University of Molise, 86090 Pesche (IS), Italy; matteo.mura@unifi.it
6 geoLAB—Laboratory of Forest Geomatics, Department of Agricultural, Food and Forestry Systems, Università degli Studi di Firenze, Firenze 50145, Italy
7 Facuty of Forestry, Universitatea Stefan del Mare, Suceava 720229, Romania; obouriaud@gmail.com
8 Tartu Observatory, Tõravere 61602, Estonia; Mait.Lang@emu.ee
9 Division Forest, Nature and Landscape, Department of Earth and Environmental Sciences, KU Leuven—University of Leuven, Leuven 3001, Belgium; giuseppe.cardellini@kuleuven.be
10 Technological Institute, Furniture, Environment, Economy, Primary Processing and Supply, Champs sur Marne 77420, France; Alain.THIVOLLECAZAT@fcba.fr
11 Laboratory of Dendrometry and Forest Productivity, Faculty of Forestry, Warsaw University of Life Sciences, Warsaw 02-776, Poland; karol.bronisz@wl.sggw.pl
12 Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Prague 16521, Czech Republic; j.merganic@forim.sk
13 Departamento de Selvicultura y Gestión de los Sistemas Forestales, INIA-CIFOR, Madrid 28040, Spain; alberdi.iciar@inia.es
14 Norwegian Institute for Bioeconomy Research, Ås 1431, Norway; rasmus.astrup@nibio.no
15 Forest Ecology and Forest Management Group, Wageningen University, Wageningen 6700, The Netherlands; frits.mohren@wur.nl
16 Department of Geographical Sciences, University of Maryland, Collage Park, MD 20742, USA; zhaoms@umd.edu
* Correspondence: mathias.neumann@boku.ac.at; Tel.: +43-1-47654-4059

Academic Editors: Lars T. Waser and Prasad S. Thenkabail
Received: 5 April 2016; Accepted: 25 June 2016; Published: 29 June 2016

Abstract: Net primary production (NPP) is an important ecological metric for studying forest ecosystems and their carbon sequestration, for assessing the potential supply of food or timber and quantifying the impacts of climate change on ecosystems. The global MODIS NPP dataset using the MOD17 algorithm provides valuable information for monitoring NPP at 1-km resolution. Since coarse-resolution global climate data are used, the global dataset may contain uncertainties for Europe. We used a 1-km daily gridded European climate data set with the MOD17 algorithm to create the regional NPP dataset MODIS EURO. For evaluation of this new dataset, we compare MODIS EURO with terrestrial driven NPP from analyzing and harmonizing forest inventory data (NFI) from 196,434 plots in 12 European countries as well as the global MODIS NPP dataset for the years 2000 to 2012. Comparing these three NPP datasets, we found that the global MODIS NPP dataset differs from NFI NPP by 26%, while MODIS EURO only differs by 7%. MODIS EURO also agrees with NFI NPP across scales (from continental, regional to country) and gradients (elevation, location, tree age, dominant species, etc.). The agreement is particularly good for elevation, dominant species or tree height. This suggests that using improved climate data allows the MOD17 algorithm to provide realistic NPP estimates for Europe. Local discrepancies between MODIS EURO and NFI NPP can be related to differences in stand density due to forest management and the national carbon estimation methods. With this study, we provide a consistent, temporally continuous and spatially explicit productivity dataset for the years 2000 to 2012 on a 1-km resolution, which can be used to assess climate change impacts on ecosystems or the potential biomass supply of the European forests for an increasing bio-based economy. MODIS EURO data are made freely available at ftp://palantir.boku.ac.at/Public/MODIS_EURO.

Keywords: NPP; bioeconomy; forest inventory; NFI; climate; carbon; biomass; downscaling; increment; MOD17

---

1. Introduction

Net primary production (NPP), the difference between Gross Primary Production (GPP) and plant autotrophic respiration, is the net carbon or biomass fixed by vegetation through photosynthesis. NPP represents the allocation rate of photosynthetic products into plant biomass and can be used to measure the quantity of goods provided to society by ecosystems [1–3]. NPP of forest ecosystems is essential to estimate the potential supply of biomass for bioenergy, fiber and timber supply. NPP is also a key variable to assess environmental change impacts on ecosystems [4] since any variation in the growing conditions influences the carbon cycle due to changes in carbon uptake and/or respiration. As interest grows in utilizing forests for a "bio-based economy" [5,6], more accurate and realistic forest productivity estimates become increasingly important. In addition, competing forest ecosystem services, such as biodiversity or and nature conservation, need to be considered to ensure sustainable use of our forests and to avoid unsustainable over-exploitation of renewable resources.

Within the EU-28 160.9 million ha or 37.9% of the total land area are covered with forests [7]. These forests provide resources for the timber industry, the energy sector (24.3% of the energy in the EU-28 is generated from renewable sources of which 64.2% consists of forest biomass and waste [8]), but also for non-timber ecosystem services such as clean air, water, biodiversity or protection against natural hazards. Accurate and consistent forest information is a precondition for assessing the production and harvesting potential of forest resources in Europe.

There are conceptually different data sources and methods to assess forest productivity like:

(i) The MODIS algorithm MOD17 uses remotely sensed satellite-data and climate data to predict spatially and temporally continuous NPP and GPP (Gross Primary Production or carbon assimilation) based on an ecophysiological modelling approach [2]. In addition to satellite reflectance data and climate data, it requires the biophysical properties of land cover types, which are stored in the Biome Property Look-Up Tables (BPLUT) [9].

(ii) National forest inventory data can be used to assess the timber volume stocks as well as volume increment and removal, if repeated observations are available [10]. This terrestrial bottom-up approach collects forest information by measuring sample plots arranged on a systematic grid design across larger areas. In combination with biomass expansion factors or biomass functions, volume or tree information can be converted into biomass or carbon estimates to account for differences in wood densities, the carbon fraction and different allocation into compartments [11,12].

(iii) Flux towers record the gas-exchange in plant-atmosphere interactions [13], which can be used to derive GPP from Net Ecosystem exchange (NEE). NEE is estimated using eddy covariance data, climate measurements and other ancillary data [14].

Net Primary Production (NPP) from (i) top-down satellite-driven MOD17 algorithm and (ii) bottom-up NPP estimates using terrestrial forest inventory data were compared in a pilot study for Austria on national scale [15]. Top-down and bottom-up refer to the level of scaling of the primary recorded information (for MOD17 1-km remote sensing products and for Terrestrial NPP single tree observations). Our definition for top-down differs from traditional carbon cycle modelling [16]. This study wants to extend and test this concept for Europe on a continental scale.

For this purpose, we obtain two wall-to-wall spatially-explicit and consistent MODIS NPP datasets by acquiring the global dataset using global climate driver and by creating a regional dataset MODIS EURO using 1-km European climate data. We evaluate these two datasets by comparing with the NPP derived from forest inventory data from 12 European countries. We assess the reliability and potential discrepancies of the MODIS satellite-driven top-down versus the terrestrial bottom-up NPP estimates from continental to national scale and across different gradients like location, elevation or stand density. This will provide a better understanding of the reliability of remote sensing based NPP estimates, which could be used also for regions, where no terrestrial measurements are available.

2. Materials and Methods

We used two conceptually different methods to estimate NPP, (i) the MODIS NPP algorithm MOD17 and (ii) terrestrial forest inventory data and tree carbon estimation methods. Both have their respective strengths and weaknesses. MODIS NPP has the advantage of providing spatially continuous estimates with a consistent methodology, which is important for any large-scale studies. It incorporates biogeochemical principles in mechanistic modelling environment and the vegetation feedback to climate conditions through changes in Leaf Area Index and absorbed radiation [17]. It does not distinguish between different vegetation apart from general Land Cover types, has a coarse spatial resolution and might not be able to represent specific local conditions due to its calibration to global conditions. In contrast, terrestrial forest inventory NPP assesses the actual carbon allocation by trees and captures local small-scale effects (e.g., site conditions, tree age or forest management) as well as regional differences in estimating tree carbon [12,18]. It covers only the increment of trees assessed by the inventory system and might not capture local specifics of litter fall and fine root turnover very well, since broad model assumptions have to be used.

2.1. MODIS NPP

Since the year 2000, the MOD17 product provides spatially and temporally continuous NPP estimates across the globe [17]. The algorithm behind uses the reflectance data from the sensor MODIS (MODerate resolution Imaging Spectroradiometer) of the TERRA and AQUA satellites operated by National Aeronautics and Space Administration of the United States (NASA). MOD17 provides GPP and NPP estimates at a 1-km resolution [2,17] and incorporates basic biogeochemical principles adopted from Biome-BGC [19]. It integrates a light use efficiency logic using remotely sensed vegetation information to estimate GPP (Equation (1)) with a maintenance and growth respiration module to derive NPP (Equation (2)).

$$\mathrm{GPP} = \mathrm{LUE_{max}} \times \mathrm{f_{Tmin}} \times \mathrm{f_{vpd}} \times 0.45 \times \mathrm{SW_{rad}} \times \mathrm{FPAR} \tag{1}$$

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{R_M} - \mathrm{R_G} \tag{2}$$

LUEmax is the maximum light use efficiency, which get adjusted by f_{Tmin} and f_{vpd} to address water stress due to low temperature (Tmin) and vapor pressure deficit (VPD). SWrad is short wave solar radiation load, of which 45% is photosynthetically active. FPAR is the fraction of absorbed photosynthetic active radiation. R_M is the maintenance respiration and is estimated using LAI (Leaf Area Index), climate data and biome-specific parameters. R_G is the growth respiration and is estimated to be approx. 25% of NPP. The complete algorithm is documented in [18] and more details are found in the cited literature therein.

The MOD17 algorithm requires climate data, FPAR and LAI (leaf area index) data as well as land cover data, which is derived from MODIS reflectance data [20]. We obtained the global MODIS NPP product (MOD17A3 Version 055) provided by the Numerical Terradynamic Simulation Group (NTSG) at University of Montana available at ftp://ftp.ntsg.umt.edu/pub/MODIS/NTSG_Products/. This data set (hereafter called MODIS GLOB) covers the period of 2000 to 2012, which is the time period covered by our terrestrial data (see next chapter), and provides the annual NPP in $gC \cdot m^{-2} \cdot year^{-1}$.

The source of FPAR and LAI input is MODIS15 LAI/FPAR Collection 5, which was temporally gap filled to close data gaps due to unfavorable atmospheric conditions such as cloudiness or heavy aerosol presence [9]. For Land cover, we used the land cover product MOD12Q1 Version 4 Type 2 [21] representing the conditions in year 2001.

Climate data are important input into the MODIS NPP algorithm and climate data have a strong impact on the MODIS NPP results [15,22]. MODIS GLOB uses the global climate data set NCEP2 [23] described in the following Section 2.2. In Europe, we have high quality daily climate data, the E-OBS data set [24], which was recently downscaled to a 1-km resolution [25].

We next ran the MOD17 algorithm with the downscaled European climate data [25] and obtained an additional MODIS NPP estimate for the period 2000–2012 (hereafter called MODIS EURO), which differ from MODIS GLOB provided by NTSG only in the used daily climate input data. We used the same FPAR, LAI and Land cover input, as used for the global NPP product, MODIS GLOB. MODIS EURO covers our study region, the EU-28 including Norway, Switzerland and the Balkan states (see Figure 1) and is made available under ftp://palantir.boku.ac.at/Public/MODIS_EURO.

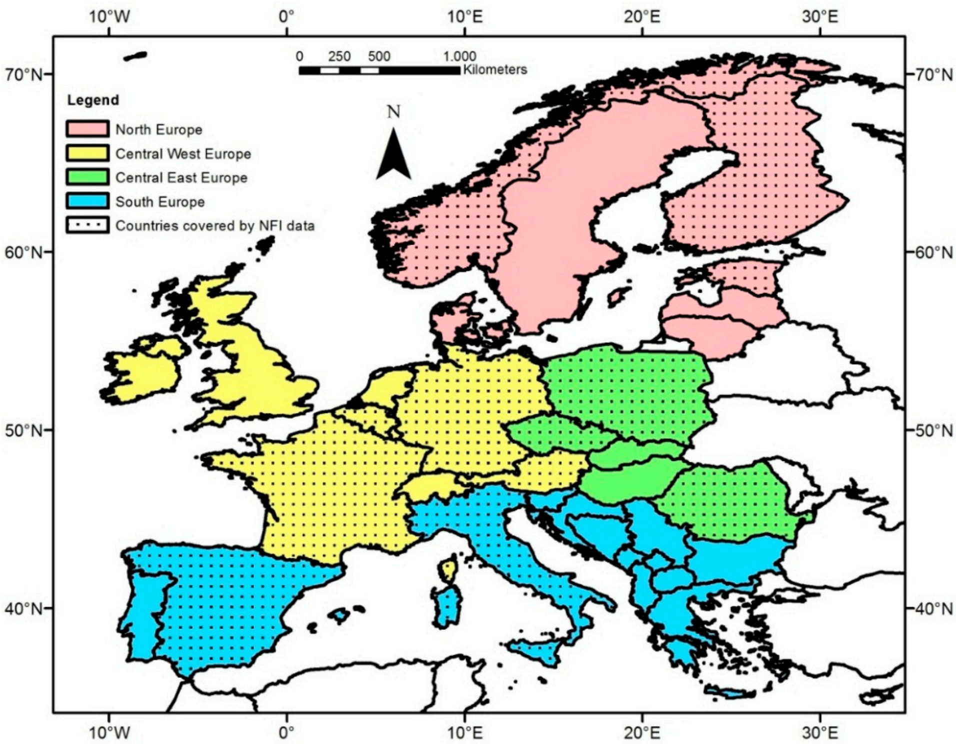

Figure 1. Our study region separated into four regions, countries with forest inventory data for estimating terrestrial National Forest Inventory (NFI) Net Primary Production (NPP) are marked with dots.

2.2. Climate Data

As outlined, the two MODIS NPP estimates, MODIS GLOB and MODIS EURO, differ only in the daily climate data input: MODIS GLOB employs the global NCEP2 climate data set [23] and MODIS

EURO uses European downscaled climate data [25]. We provide here a brief overview of the two climate data sets.

The NCEP2 data set (NCEP-DOE Reanalysis 2) is a reanalyzed global daily climate data set with a spatial resolution of 1.875° × 1.875°. This corresponds to approx. 220 km at the equator at latitude 0° (approx. 136 × 220 km at latitude 50°). To compensate the coarse spatial resolution, for MODIS GLOB the climate data for the 1 km MODIS pixels was deduced with an bilateral interpolation method based on the neighboring NCEP2 pixels [9].

The downscaled climate data used for MODIS EURO provide daily climate data on a 0.0083° × 0.0083° resolution (approx. 1 × 1 km at the equator and approx. 0.6 × 1 km at 50° latitude) [25]. This data set was developed out of the E-OBS gridded climate data set (0.25° resolution, using data from 7852 climate stations) [24] in conjunction with the WorldClim data set [26].

2.3. Terrestrial NFI NPP

Terrestrial forest data such as national forest inventory (NFI) data assess accumulated carbon on a systematic grid using a permanent plot design. From repeated observations of diameter at breast height (DBH) and/or tree height (H) in combination with biomass functions or biomass expansion factors the carbon accumulation of trees is estimated. Since this method is based on single tree measurements and local biomass studies, NPP derived from forest inventory data incorporates local effects such as weather patterns, climate anomalies, stand age, differences in biomass allocation, site and soil effects and different forest densities due to forest management [15,27].

We obtained 196,434 forest inventory plots covering 12 European countries. In Europe, each country has its own National Forest Inventory (NFI) system, which all have different measurement periods, sampling designs and methodologies [10] (Table S1 in the Supplementary Material). Thus, we first had to develop a harmonized and consistent terrestrial dataset for estimating Terrestrial NPP. We calculated NPP using the forest inventory data according to Equation (3).

$$\mathrm{NPP} = \mathrm{CARB_{INC}} + \mathrm{FR_{TO}} + \mathrm{C_{LF}} \tag{3}$$

$\mathrm{CARB_{INC}}$ is the carbon increment of trees ($\mathrm{gC \cdot m^{-2} \cdot year^{-1}}$). $\mathrm{FR_{TO}}$ is the carbon used for fine root turnover [28,29]. Fine root turnover $\mathrm{FR_{TO}}$ is assumed to be equal to the carbon flow into litter $\mathrm{C_{LF}}$ [27,30]. Both processes are controlled by the same factors and the assumption of similarity between the above- and belowground turnover of short-living plant organs is supported by recently collected European data on fine root turnover [29] and litter fall [31]. $\mathrm{C_{LF}}$ is the flow of carbon into litter ($\mathrm{gC \cdot m^{-2} \cdot year^{-1}}$) estimated using a climate-sensitive and species-dependent model [31] and is calculated as:

$$\text{Broadleaf-dominated}: \mathrm{C_{LF}} = \mathrm{CF} \exp(2.643 + 0.726\,\mathrm{Ln}(\mathrm{T} + 10) + 0.181\,\mathrm{Ln}(\mathrm{P})) \tag{4}$$

$$\text{Coniferous-dominated}: \mathrm{C_{LF}} = \mathrm{CF} \exp(2.708 + 0.505\,\mathrm{Ln}(\mathrm{T} + 10) + 0.240\,\mathrm{Ln}(\mathrm{P})) \tag{5}$$

CF is the carbon fraction of dry biomass which is set equal to 0.5 [11]. T is the mean annual temperature from the year 2000 to 2012 (°C). P is the mean annual precipitation 2000 to 2012 [mm]. For temperature and precipitation we use the European climate data [25] to capture important small-scale regional effects such as elevation or topography in a more realistic way. Equation (4) is applied for all plots where broadleaf species contribute most to total basal area and Equation (5) is used for coniferous-dominated plots (see Table S2 of the Supplementary Material).

We used data from nine National Forest Inventories (Austria, Czech Republic, Germany, France, Finland, Norway, Poland, Romania, Spain), and three Regional Forest Inventories (Belgium, Estonia, Italy). We grouped our 12 countries in four geographic regions, North Europe, Central-West Europe, Central-East Europe and South Europe [7], to address the large environmental, elevational and climatic gradients in Europe. Countries within a region should have similar climatic and edaphic conditions as well as similar tree allometries and allocation patterns [32]. The original locations of the inventory plots were falsified to the nearest pixel of the MODIS grid to guarantee the locations of the plots remain unknown. Temporal consistency with the MODIS data (available since year 2000) was ensured by using only inventory data, which provide $CARB_{INC}$ (Equation (3)) for the time period 2000 to 2012. Figure 1 shows our study region with the four geographic regions completely covered by MODIS EURO, and the 12 countries, where we have NFI NPP.

Although all our terrestrial forest inventory data assess properties of trees, there are different sampling methods and increment calculation by country in place, which may strongly affect the resulting estimates [33,34]. Four different methods to estimate tree carbon increment $CARB_{INC}$ are used in our data: (1) repeated observations of fixed area plots (used in Norway, Poland, Belgium); (2) repeated angle count sampling (for Austria, Germany, Finland); (3) increment cores (France, Romania, Italy); as well as increment predictions from (4) tree growth models (Czech Republic, Estonia, Italy). Tree growth model predictions were used if no increment observations, either from repeated observations or from increment cores, were available.

In the Supplementary Material, we provide all details for our 12 inventory data sets, the local sampling system, the available data and the used increment method (Table S1 in the Supplementary Material).

The tree carbon results for determining carbon increment $CARB_{INC}$ (Equation (3)) were estimated using the carbon calculation method applied by the local forest inventory organization and compiled in [32]. Local biomass functions and biomass expansion factors were used to derive tree biomass and carbon fractions to convert biomass into carbon. In the Supplementary Material, we provide a detailed description on processing the NFI data, the tree carbon estimates and stand variables to describe the represented forests (e.g., mean age, basal area or stand density index).

Using this methodology, we processed the forest inventory data from the 12 countries (Table S1) and derived harmonized carbon stocks for all inventory plots. The forest inventory data set consists of 196.434 plots, harmonized across 12 European countries. We applied the carbon increment method for each country and calculated NPP by inventory plot (hereafter called NFI NPP) using Equations (3)–(5).

2.4. Analysis of NPP Results

We thus have three NPP sources: two using the MOD17 algorithm with different daily climate data: (i) MODIS GLOB produced by the Numerical Terradynamic Simulation Group (NTSG) at University of Montana and (ii) MODIS EURO by running the original MOD17 algorithm and the latest BPLUTs parametrized by [9] with downscaled daily climate data from Europe [25] as well as (iii) Terrestrial NFI NPP using forest inventory data from the 12 countries (Table S1) and local carbon estimation methods [32].

We compared the three NPP datasets across Europe, by our 4 regions (Figure 1) and the 12 countries to analyze our results across different spatial scaling. We extracted for each forest inventory plot at the corresponding MODIS cell the average NPP from MODIS GLOB and MODIS EURO for 2000 to 2012. We next computed for all plots the difference between the two MODIS NPP estimates and the Terrestrial NFI NPP (ΔNPP_{GLOB} = MODIS GLOB minus NFI NPP and ΔNPP_{EURO} = MODIS EURO minus NFI NPP).

We used each NFI plot separately and did not compute average values for MODIS pixels. This avoided smoothing effects due to different spacing between inventory grid points and the plot clusters used in some countries (Table S1).

To analyze the effect of gradients on the NPP results, we collected potentially meaningful meta-information such as plot location (Longitude and Latitude in WGS1984), Elevation (EU-DEM 30 m resolution), MODIS Land Cover type or forest characteristics (dominant tree species, mean age, stand density, tree height, etc.) and analyzed patterns of ΔNPP_{GLOB} and ΔNPP_{EURO} across these gradients.

Terrestrial and remote sensing NPP estimates exhibited discrepancies in previous research [15,18] and as explanation the authors suggested changes in stand density, which are commonly caused by forest management and disturbances [15,18]. Since major parts of the forests in Europe are managed [7] and affected by natural disturbances such as wind damage or forest fire [35], they should have experienced changes in stand density as compared to unmanaged forests. Stand density directly affects terrestrial NPP estimates by its impact on the development of DBH and H of the remaining trees after forest management operations until canopy closure is reached. On the other hand MODIS NPP is based on the "big leaf" concept and assumes a full coverage of forest area. We thus use Stand density index (SDI) [36] in the analysis of our NPP estimates.

3. Results

NPP estimated using the MOD17 algorithm has the advantage of providing spatial- and temporal-continuous NPP estimates across Europe on a 1-km resolution and Figure 2 illustrates this by showing MODIS EURO for the years 2000 to 2012. Note that MODIS EURO also covers not-forest land cover types such as crops, shrub- or grassland.

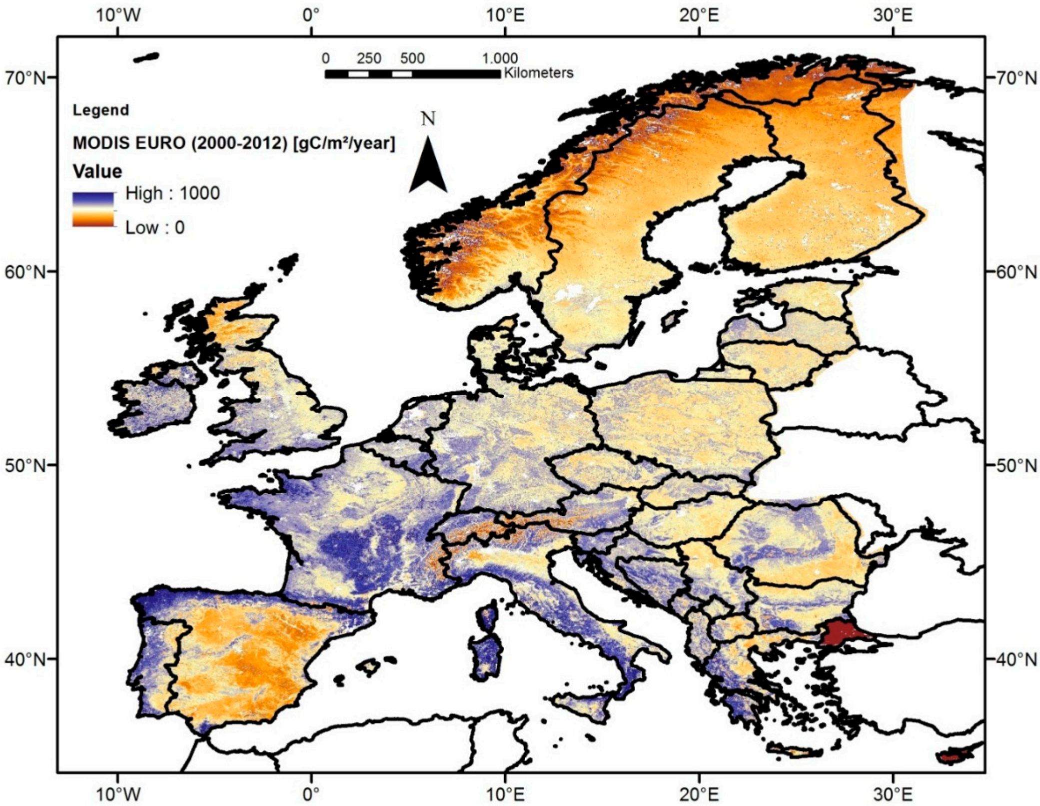

Figure 2. MODIS EURO NPP on 1-km resolution representing average NPP for the period 2000–2012 using European daily climate data (available under ftp://palantir.boku.ac.at/Public/MODIS_EURO).

Terrestrial NFI NPP is driven by forest information collected by field crews. Thus it provides NPP and the carbon accumulation by forest stands during a certain time period. Table 1 gives a summary of the forest inventory results by country, by region and the whole dataset, with the terrestrial NFI NPP at the right side.

Table 1. Summary of the forest inventory results: Number of plots with data, Time period covered by NFI NPP, Mean elevation (range Minimum–Maximum) in meter above sea level (EU-DEM 30 m resolution). For the following plot statistics we provide mean and standard deviation: Mean quadratic DBH (cm), Mean Tree height (m), Basal area at 1.3 m height ($m^2 \cdot ha^{-1}$), Stem number (ha^{-1}), Tree carbon per hectare ($gC \cdot m^{-2}$), Median age class, SDI Stand Density Index [36] (for details on this variables see Supplementary Material), NPP is the NFI Net primary production ($gC \cdot m^{-2} \cdot year^{-1}$) according to Equation (3), For Czech Republic we only have country means. Empty cells (-) indicate that this variable is not available from the NFI data set. At the end of each section, statistics of the region are given and at the bottom of the table summary statistics for whole Europe.

Region	Country	Number of Plots	Time Period	Mean Elevation (min–max) (m)	Mean DBH (cm)	Mean Tree Height (m)	Basal Area ($m^2 \cdot ha^{-1}$)	Stem Number (ha^{-1})	Tree Carbon ($gC \cdot m^{-2}$)	Median Age (Years)	SDI	NPP ($gC \cdot m^{-2} \cdot year^{-1}$)
North Europe	Estonia	19930	2000–2010	66 (2–275)	17 ± 8	17 ± 7	19 ± 8	1540 ± 2554	5240 ± 2929	40–60	449 ± 192	509 ± 163
	Finland	6442	2000–2008	141 (1–400)	18 ± 7	14 ± 5	18 ± 8	3522 ± 13251	4859 ± 3020	40–60	400 ± 236	446 ± 173
	Norway	9562	2000–2009	391 (0–1253)	15 ± 6	9 ± 3	15 ± 12	930 ± 682	4003 ± 3691	60–80	368 ± 265	442 ± 143
	all	35379	2000–2010	161 (0–1253)	16 ± 7	14 ± 7	18 ± 9	1736 ± 5983	4856 ± 3199	40–60	419 ± 224	482 ± 162
Central-West Europe	Austria	9562	2000–2009	912 (113–2299)	32 ± 14	21 ± 7	32 ± 19	987 ± 1070	10364 ± 6973	60–80	688 ± 396	681 ± 251
	Belgium	512	2009–2013	39 (2–278)	29 ± 12	18 ± 6	30 ± 13	660 ± 446	11507 ± 6475	40–60	648 ± 279	671 ± 195
	France	33152	2001–2011	444 (0–2707)	23 ± 11	15 ± 7	23 ± 15	778 ± 602	8083 ± 6457	60–80	512 ± 298	649 ± 254
	Germany	5894	2000–2008	344 (−5–1879)	28 ± 12	22 ± 7	31 ± 14	833 ± 814	11811 ± 6371	60–80	628 ± 302	754 ± 185
	all	49120	2000–2013	514 (−5–2707)	25 ± 12	17 ± 8	25 ± 17	824 ± 749	9034 ± 6698	60–80	564 ± 328	667 ± 253
Central-East Europe	Czech Rep.	13929	2001–2004	541 (138–1503)	25	20	33	812	17340 ± 10858	60–80	809 ± 441	643 ± 266
	Poland	17281	2005–2013	193 (−4–1459)	23 ± 9	18 ± 5	29 ± 14	883 ± 614	10656 ± 6623	40–60	612 ± 263	720 ± 288
	Romania	5509	2003–2011	542 (−1–1968)	24 ± 11	-	28 ± 15	878 ± 723	10355 ± 7256	40–60	582 ± 289	571 ± 164
	all	36719	2001–2013	443 (−4–1968)	23 ± 10	18 ± 5	28 ± 15	881 ± 673	12376 ± 8793	40–60	652 ± 345	649 ± 248
South Europe	Italy	15183	2002–2009	860 (7–2891)	20 ± 8	12 ± 4	22 ± 13	839 ± 636	6315 ± 4897	20–40	497 ± 293	635 ± 179
	Spain	60033	2000–2008	842 (1–2549)	23 ± 13	10 ± 4	13 ± 11	491 ± 516	4003 ± 3918	40–60	288 ± 246	606 ± 293
	all	75216	2000–2009	831 (1–2891)	22 ± 12	10 ± 4	15 ± 12	561 ± 560	4469 ± 4237	40–60	330 ± 269	578 ± 275
All countries	-	196434	–	548 (−5–2891)	22 ± 11	13 ± 7	20 ± 15	900 ± 2646	7298 ± 6916	40–60	469 ± 325	597 ± 252

Our NFI dataset covers the full elevational and latitudinal range of forest conditions in Europe including different site conditions, tree species, development stages or management practices. For most countries we have more than 5000 inventory plots (exception: Belgium with 512 plots) and in most cases a plot spacing of at least 4 by 4 km (Table S1). This dataset also provides information on forest properties such as tree age, carbon stocks or stand density and Table 2 indicates that these characteristics vary across Europe.

Table 2. NPP and ΔNPP (always using median) for the whole dataset ("All Countries"), for each country separately and for each region (MODIS NPP using global climate data—MODIS GLOB; MODIS NPP using local European climate data—MODIS EURO and NPP using forest inventory data—NFI NPP); ΔNPP and Rel. ΔNPP both for MODIS GLOB and MODIS EURO. Positive differences indicate that MODIS NPP overestimates NFI NPP and vice versa.

NPP and ΔNPP (gC· m^{-2}· $year^{-1}$)		**MODIS**	**MODIS**		**ΔNPP**		**Rel. ΔNPP [%]**	
		GLOB	**EURO**	**NFI NPP**	**GLOB**	**EURO**	**GLOB**	**EURO**
	All Countries	**680**	**577**	**539**	**141**	**38**	**26%**	**7%**
North Europe	Finland	471	399	414	57	−15	14%	−4%
	Norway	484	406	409	75	−3	18%	−1%
	Estonia	534	504	492	42	12	9%	3%
	all	519	479	461	58	18	13%	4%
Central-West Europe	Austria	739	612	634	105	−22	17%	−4%
	Belgium	732	599	644	88	−45	14%	−7%
	France	787	666	604	183	62	30%	10%
	Germany	692	602	716	−24	−114	−3%	−16%
	all	759	645	615	144	30	23%	5%
Central-East Europe	Czech Republic	696	618	553	143	65	26%	12%
	Poland	641	571	659	−19	−88	−3%	−13%
	Romania	713	562	565	148	−3	26%	−1%
	all	677	592	595	82	−3	14%	−1%
South Europe	Italy	862	657	635	227	22	36%	4%
	Spain	632	555	503	129	52	26%	10%
	all	691	584	519	172	65	33%	13%

3.1. NPP Estimates across Different Scales

Comparing all our three NPP estimates on a European scale allowed us to explore the general behaviour and evaluate the agreement of the two remote sensing driven NPP products, MODIS GLOB and MODIS EURO, with the terrestrial driven NFI NPP estimates (Figure 3).

Re-running the MOD17 algorithm with local climate data reduced the remotely sensed MODIS NPP in terms of median, mean and variation as compared to the global climate driver (Figure 3). NFI NPP is close to MODIS EURO regarding median and mean, but show larger variation. In addition, Figure 3 confirms that our data is clearly right-skewed (NFI NPP in particular).

Zooming in and examining the different NPP estimates by ecoregion and country allowed us to analyze our results on a higher spatial resolution and to assess local effects such as different regional growing conditions, the impact of local biomass allometries or tree species composition [32] as well as the potential effect of different forest management practices in Europe [7].

We provide in Table 2 the median NPP for the three NPP sources (MODIS GLOB, MODIS EURO and NFI NPP) and the differences between MODIS and NFI NPP (ΔNPP_{GLOB} and ΔNPP_{EURO}), both in absolute values in gC· m^{-2}· $year^{-1}$ and normalized in relation to NFI NPP (Rel. ΔNPPi in %). Results are given in Table 2 for Europe, by country and for the four eco-regions [7].

At the European level, the MODIS GLOB gives an NPP of 680 gC· m^{-2}· $year^{-1}$, the MODIS EURO resulted in 577 gC· m^{-2}· $year^{-1}$, and the NPP from the NFI data exhibit a value of 539 gC· m^{-2}· $year^{-1}$. The differences in NPP (ΔNPP_{GLOB}) using the global dataset MODIS GLOB are larger than ΔNPP_{EURO} using the regional dataset MODIS EURO (+26% vs. +7%). The same pattern is evident across all four regions and most countries. Only for Poland and Germany ΔNPP_{GLOB} is smaller than ΔNPP_{EURO}. ΔNPP_{GLOB} is positive for most countries (negative in only 2 countries), while the discrepancy of MODIS EURO is more randomly distributed in Europe and the 4 regions (ΔNPP_{EURO} positive in 5 countries and negative for 7 countries). In addition, Table 2 shows that Rel. ΔNPP_{EURO} is smaller than 10% for all countries except five (France, Germany, Czech Republic, Poland and Spain).

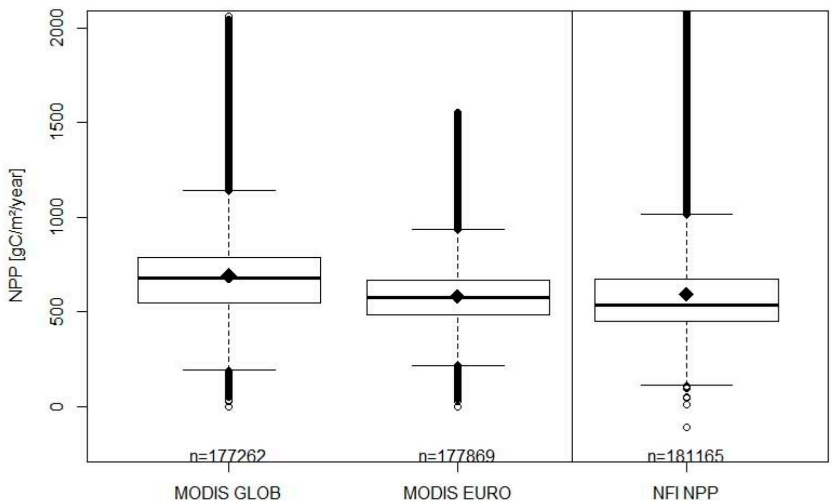

Figure 3. Comparison of MODIS GLOB and MODIS EURO with NFI NPP: The box represent the Median and the 25th and 75th percentile, the diamond give the arithmetic mean, the whiskers extend to 1.5 of the interquartile range, values outside this range are indicated by circles, on the bottom the number of values represented by the boxplots are given. The number of observations is different since climate data is missing for certain pixels to compute MODIS NPP. To enhance the interpretability of the image, NFI NPP results larger 2100 gC· m^{-2}· $year^{-1}$ (445 observations) are not shown, but are included in the boxplot.

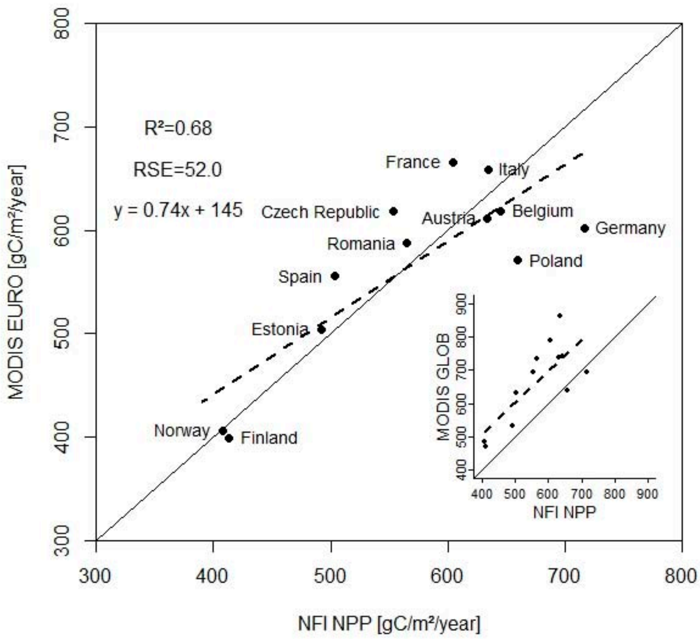

Figure 4. Comparison of MODIS EURO using European climate data and NFI NPP (MODIS GLOB vs. NFI NPP in the subplot in the bottom-right corner), we present median by country, solid line is 1:1 line, dashed line represents the linear trend of the 12 countries, Coefficient of determination R^2, Residual standard error (RSE) and the trend function are given.

This suggests that the discrepancy between MODIS EURO and NFI NPP is smaller than for MODIS GLOB and NFI NPP and we wanted to confirm this along the NPP gradient by showing the country medians in Figure 4.

Figure 4 provides the results by country of the NPP estimates resulting from the NFI data versus MODIS EURO with an R^2 0.68, a residual standard error (RSE) of 52.0 $gC \cdot m^{-2} \cdot year^{-1}$ or 9.7% of median of the NFI NPP. Aside from Germany and Poland MODIS EURO and NFI NPP are similar across the NPP gradient for the analyzed countries. The results for MODIS GLOB in the right corner exhibit consistent overestimation of NFI NPP, smaller agreement ($R^2 = 0.59$) and larger error (RSE 80.6 $gC \cdot m^{-2} \cdot year^{-1}$ equal 15.0% of median NFI NPP).

We used in Figure 4 the aggregated NPP of all inventory plots of one country, since the spatial coverage and thus the error structure of the two NPP sources are very different (one MODIS pixel covering 1 km^2 or 100 ha and the size of an NFI plot ranging from approx. 0.01 to 0.2 ha; Table S1). A direct plot-to-pixel comparison is provided in Figure S1 in the Supplementary Material.

3.2. NPP across Elevational, Latitudinal and Longitudinal Gradients

From Figures 3 and 4 as well as Table 2, we can see that the top-down MODIS EURO NPP estimates are consistent with the bottom-up terrestrial driven forest inventory NPP estimates at the European, regional and country level. Next, we investigated whether any patterns across gradients between MODIS EURO and NFI NPP may exist. For this purpose, we showed here ΔNPP_{EURO} for selected gradients, Elevation, Latitude and Longitude. We chose these gradients, since they have a strong effect on environmental and climatic conditions such as growing season length or weather patterns, but also on tree allometries and species composition, and are irrespective of country borders.

We aggregated our results into classes to increase the readability and show Figure 5 the results for whole Europe (results on the different regions are available in Figures S2–S5 in the Supplementary Material). Images for additional gradients like tree age, tree height, MODIS land cover and dominant tree species are provided in Figures S6–S9 in the Supplementary Material.

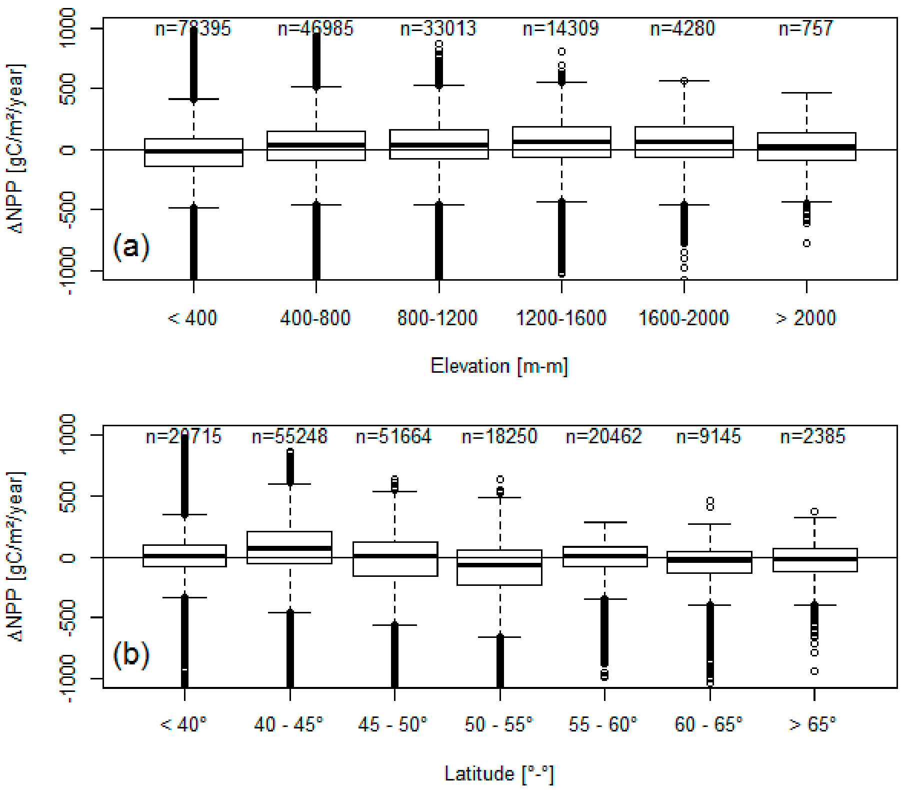

Figure 5. *Cont.*

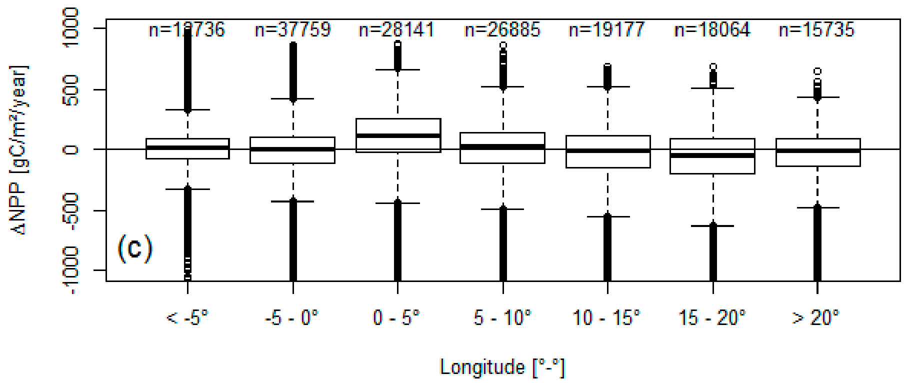

Figure 5. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP by Elevation classes (**a**), by Latitude (**b**) and by Longitude (**c**), properties of illustration analogous to Figure 3, on the top the number of values represented by the boxplots are given.

Grouping by elevation in Figure 5a does not indicate striking differences and shows, that the agreement between MODIS EURO and NFI NPP is consistent across the elevational gradients. At certain latitude and longitude classes however local discrepancies exist, which may correspond to the findings in Table 2 and Figure 4.

3.3. Stand Density Effects

We analyzed ΔNPP_{EURO} (differences in NPP between MODIS EURO versus NFI NPP) by SDI (Stand Density Index [36] calculated with Equation (S10) in the Supplementary Material) for all of Europe (Figure 6).

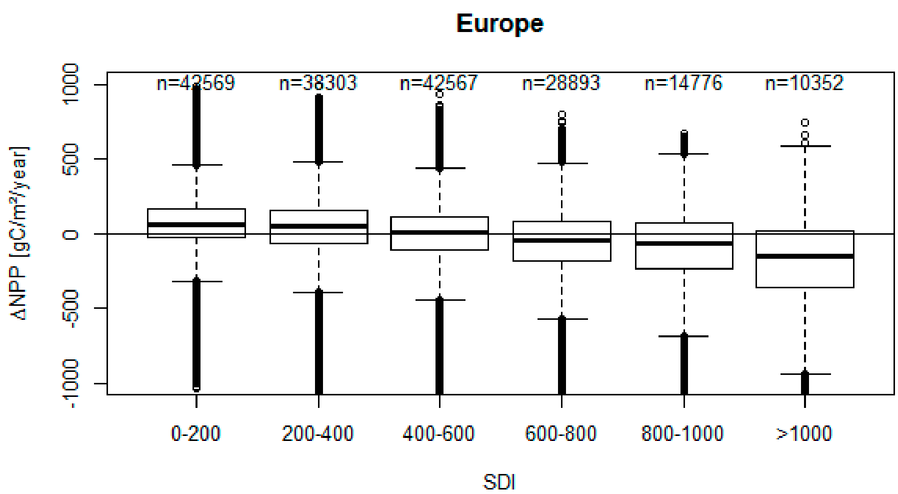

Figure 6. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP by Stand Density Index classes (SDI), for details see Figure 5.

ΔNPP shows in Figure 6 a significant trend by stand density index SDI (using linear regression; R 0.31; $\Delta NPP = 103.1 - 0.247 \times SDI$; $p < 0.001$), which confirms that differences in stand density have an effect in our data from the 12 European countries. MODIS EURO NPP estimates are higher than NFI NPP at low SDI classes, while at intermediate SDI classes no discrepancies are evident (Figure 6). At high SDI classes MODIS EURO are lower than NFI NPP.

We analyzed the effect of SDI for each country, since SDI could be an explanation for the discrepancies visible in Table 2, Figures 4 and 5. Local effects of forest management intensity, disturbances or differences in the local inventory data design and methodology (Table S1) could lead to differences in SDI. We performed similar graphical analysis as shown in Figure 6 for each country and present here as examples two "extreme" countries: (i) France—positive ΔNPP +10%, with MODIS EURO overestimating NFI NPP; and (ii) Germany—negative ΔNPP −16%, where MODIS EURO underestimates NFI NPP.

For France, MODIS EURO and NFI NPP results agree at high stand density and show discrepancies at low stand density (Figure 7a). Apparently, MODIS EURO does well in capturing the NPP of stands with high densities, but does not agree with NFI NPP from very open stands. The same patterns are also visible for other countries, where MODIS EURO overestimates NFI NPP such as Spain or Czech Republic (not shown).

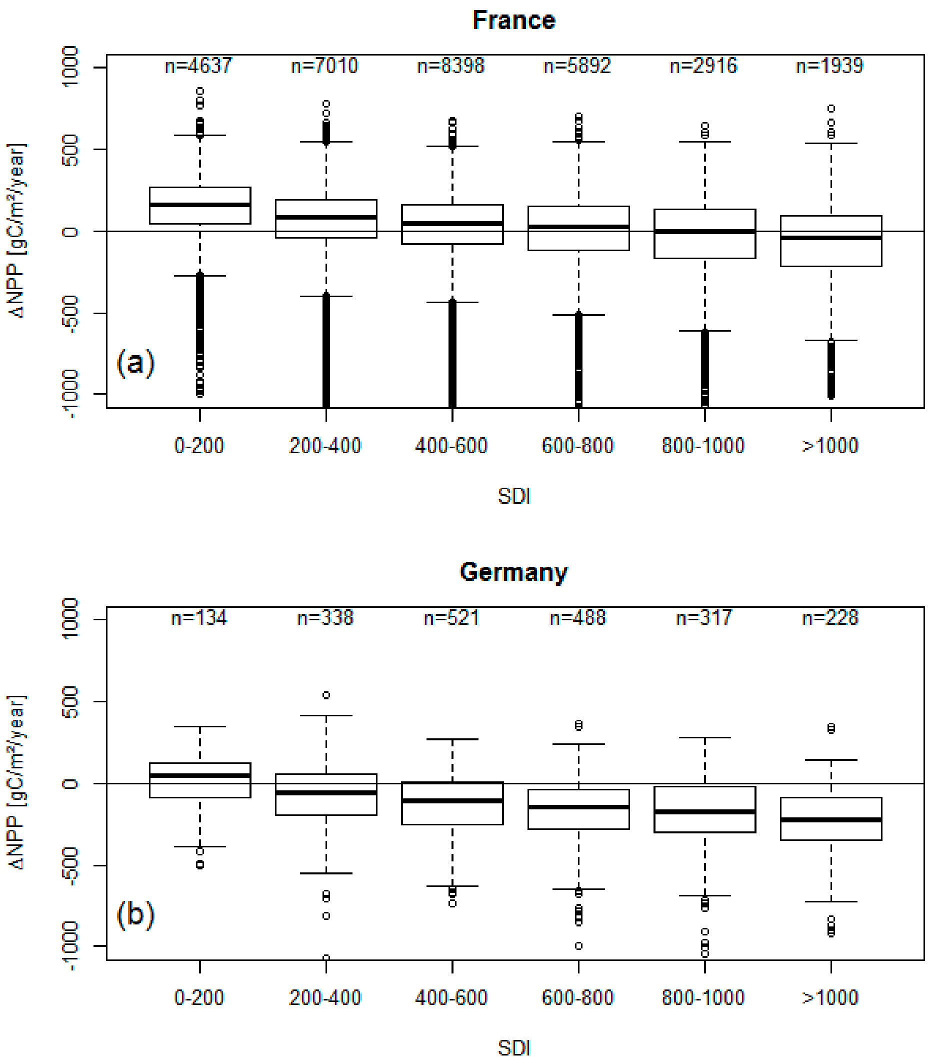

Figure 7. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP by Stand Density Index classes (SDI) for selected countries: France (**a**)—MODIS EURO overestimates NFI NPP (on average positive ΔNPP) and Germany (**b**)—MODIS EURO underestimates NFI NPP (on average negative ΔNPP), for details see Figure 5.

For Germany on the other hand, MODIS EURO and NFI NPP are similar at low stand density classes, but show increasing deviations with increasing stand densities (Figure 7b). We see the same result for other countries as well, where MODIS EURO underestimates NFI NPP such as Poland (not shown). This may be seen as an indication that besides stand density an additional driver might cause discrepancies between MODIS EURO versus terrestrial NFI NPP.

4. Discussion

Top-down satellite driven MODIS NPP (Net Primary Production) estimates using local European daily climate data (MODIS EURO) exhibit smaller differences from the bottom-up terrestrial forest inventory NFI NPP estimates (Table 1) than the original MODIS GLOB estimates using global climate data (Figure 3; Table 2). This confirms that the output from the climate sensitive MOD17 algorithm can be substantially improved by using enhanced daily climate data [22] and supports the findings of the pilot study in Austria [15] by extending the focus to a continental scope. The local European daily climate data [25] used for MODIS EURO reduced across scales from continental (Figure 3) to national scale (Figure 4) substantially the differences between NPP using the MOD17 algorithm and terrestrial forest inventory data (Table 2). Both NPP estimates are also consistent across various gradients (elevation, latitude and longitude in Figure 5 and tree age, tree height, MODIS Land cover type and dominant species in Figures S6–S9).

In this study we evaluated MODIS EURO in comparison to the global MODIS NPP dataset [17] using our terrestrial NFI NPP. The specific methodologies and differences of our forest inventory data sets (Table S1) and missing information on fine roots and litter fall do not permit a proper validation of NPP. Since the forest inventory data was collected with a different purpose [10], it contains a different error structure due to the small sample plot size and large grid spacing (one or very few plots within a MODIS pixel) as compared to the continuous 1-km MODIS grid.

The large variations and local discrepancies apparent in this study (Figure 3; Table 2) are also reflected in a study on evaluating NPP and GPP (Gross Primary Production) from the MOD17 algorithm for North and South America [37]. While the authors reported no general bias in the MODIS NPP product, they found over- as well underestimation especially for certain locations and forest biomes of more than 30%. This study shows that in Europe discrepancies between MODIS EURO and terrestrial NFI NPP exceeds 10% in three out of twelve countries (Table 2).

This study improves the knowledge on explaining discrepancies between remote sensing and terrestrial NPP estimates by highlighting the effect of stand density index (SDI). Forests with stand density of 200 or lower are expected to have gaps, canopy cover below 100% and low competition between trees. Under such conditions the NFI NPP is substantial lower than MODIS NPP (Figures 6 and 7). This can be explained that at low stand density a substantial share of NPP is undetected by the forest inventory system (gaps filled with young trees or shrubs below diameter threshold), while MODIS NPP is able to capture these gaps via leaf area index provided by the satellite [15]. Figure S10 in Supplementary Material confirms that the stand density related trend of ΔNPP in Figures 6 and 7 is mainly caused by NFI NPP, which shows a stronger increase with SDI than MODIS NPP.

Since we tested this effect with MODIS GLOB as well, we can conclude that any MODIS productivity estimates irrespective from the used climate input cannot detect such important effects adequately. The relatively large pixel size of 1-km apparently does not allow MODIS NPP to capture small scale patterns such as clear-cuts, thinning operations or disturbance events, while a forest inventory can detect them better. This confirms the findings of the pilot study in Austria [15] and indicates that differences in stand density needs consideration also on the much larger European scale.

MODIS EURO agrees very well with NFI NPP at average stand densities (Figure 6). This could be explained with the calibration of the BPLUT tables used in the MOD17 algorithm [9] using large-scale global terrestrial NPP data [27]. The calibration data most likely represents average forest conditions and may not capture very open or very dense forests adequately. The NFI NPP on the one hand represents the conditions of the (small) area covered by an inventory plot, while MODIS NPP provides a smoothed average NPP of a 1-km pixel. A consistent stand density map at 1-km resolution would be needed to test this hypothesis.

But NFI NPP estimates capture not only differences in stand density and forest management, they are also strongly influenced by local tree allometries and local carbon estimation methods [38]. For Germany, stand density cannot explain the observed discrepancies satisfactory in Figure 7b.

In fact the results are quite different compared to whole Europe (Figure 6), France (Figure 7a) or our pilot study [15]. Germany is planning to modify the currently used tree biomass estimation methodology [39] which is used in this study, for future carbon assessments. Following reanalysis of existing data [40] and collection and analysis of new sample data [41], improved biomass functions were developed for Germany [42]. This new updated methodology results in approx. 5% lower aboveground biomass estimates. Thus future German NFI NPP estimates will be lower as well, which will most likely reduce the gap between MODIS and NFI NPP observed for this country in this study. This suggests that, interpretation of discrepancies between NPP estimates needs consideration of the tree carbon estimation methods, since they directly affect increment estimates.

However, there might be other potential drivers leading to inconsistencies both in MODIS EURO and NFI NPP, that could be analyzed in future studies.

Concerning NFI NPP, few countries do not consider adequately the contribution of small trees to the NPP of a forest, either by not considering the ingrowth of small trees [33] or a particular large diameter threshold in some countries (Table S1). This could explain, why in Spain and France MODIS EURO is higher than NFI NPP, as we were not able to include ingrowth here and thus the French and the Spanish NFI NPP estimates might not represent the NPP of their forests sufficiently.

The accuracy of the litter fall and fine root estimates for NFI NPP (Equations (3)–(5) need further research as well. The litter fall models used in this study were derived in a meta-analysis using Eurasian litter fall data [31]. They have substantial variation in the used input data and might contain potential inaccuracy, when applied in certain regions. In addition, the estimates for litter fall and fine roots are driven by the same climate data than MODIS EURO. Although the specific climate input differs (periodic average climate used in Equations (4) and (5) for NFI NPP versus daily maximum, minimum temperature and precipitation used in MOD17), it cannot be ruled out yet that the climate source explains the better match of MODIS EURO and NFI NPP. Thus, the performance of the currently used approach and alternative options for instance by using Foliage mass and Leaf longevity [43] needs to be tested using European litter fall data.

Potential errors in the MODIS EURO product could involve wrong classification of forest biomes by MODIS Land cover [44], limitations of the global parameters of the MOD17 algorithm capturing European forest conditions (see discrepancies in NPP for evergreen broadleaf forests in Figure S3), mismatches in LAI and FPAR by region or forest fragmentation [45].

5. Conclusions

In this study we created a regional Net Primary Production (NPP) dataset by running the MOD17 algorithm with local European climate data on 1-km resolution for the years 2000 to 2012 (MODIS EURO). We additionally obtained the global MODIS NPP product (MODIS GLOB) and evaluated the two MODIS NPP datasets with bottom-up forest inventory driven NPP (NFI NPP). We thus compared two conceptually different methods for assessing forest productivity across Europe, and test whether local climate data enhances the ability of the MOD17 algorithm to capture European forest conditions.

Running the MOD17 algorithm with local daily climate data substantially improves the quality of MODIS satellite-driven NPP across Europe as compared to the global NPP product (MODIS GLOB). Top-down satellite-driven MODIS EURO and bottom-up NFI NPP agree by regions and by countries, across gradients by longitude, latitude and elevation, if potential discrepancies by stand density due to forest management or the used carbon estimation methods are addressed.

This newly created MODIS EURO dataset is a consistent, continuous, spatial and temporal explicit forest productivity measure of the European forest area providing realistic estimates, which compare well with forest inventory information. This is important since reliable wall-to-wall forest productivity estimates are increasingly important for the growing bio-economy or for increasing our knowledge on other forest ecosystem services such as carbon sequestration.

As long as the MODIS program (based on Satellite "Terra" launched in 1999 and "Aqua" in 2002) is operational and local climate data is available, we can obtain reliable large-scale forest productivity measures for European forests. Since the lifetime of the satellites carrying the MODIS sensor is unknown, we strongly suggest the implementation and testing of this concept in the upcoming European satellite technologies such as the Copernicus Programme to ensure consistent and realistic productivity estimates also in the future.

MODIS EURO data are made freely available for 2000 until 2012 under ftp://palantir.boku.ac.at/Public/MODIS_EURO.

Supplementary Materials: The following are available online at www.mdpi.com/2072-4292/8/7/554/s1, Table S1: Summary of the properties of the different forest inventory datasets, Table S2: Tree species groups used in this study, description and selected tree species, Figure S1: Direct pixel-to-plot comparison of MODIS EURO and NFI NPP, Figure S2: For North Europe ΔNPP grouped by Elevation, Latitude and Longitude, Figure S3: For Central-West Europe ΔNPP grouped by Elevation, Latitude and Longitude, Figure S4: For Central-East Europe ΔNPP grouped by Elevation, Latitude and Longitude, Figure S5: For South Europe ΔNPP grouped by Elevation, Latitude and Longitude, Figure S6: Difference ΔNPP grouped by age classes, Figure S7: Difference ΔNPP grouped by tree height classes, Figure S8: Difference ΔNPP grouped by MODIS Land cover types, Figure S9: Difference ΔNPP grouped by dominant species, Figure S10: MODIS EURO and NFI NPP by Stand density Index (SDI) classes.

Acknowledgments: This work was conducted as part of the collaborative project "FORest management strategies to enhance the MITigation potential of European forests" (FORMIT). The research leading to these results has received funding from the European Union Seventh Framework Programme under grant agreement n° 311970. Special thanks to all the field crews collecting the sample data for the inventory plots. We are also grateful to the responsible people from the various forest inventory organizations for providing us with the data of their forest inventory systems and thereby making this work possible in the first place. We also want to acknowledge the open data policy of NASA and the work of the MODIS land product science team providing us with the FPAR and LAI products. We further want to thank Loretta Moreno for proof reading the manuscript. We want to thank in particular the editor and the anonymous reviewer on their helpful comments on an earlier draft of the manuscript.

Author Contributions: M.N. conceived and designed the study, coordinated compiling the NFI NPP dataset, calculated the forest inventory results for Austria and wrote the first draft of the manuscript, A.M. and C.T. developed the code for computing MODIS EURO and maintain the ftp-server, V.M. calculated the forest inventory results for Germany, S.H. for Finland, M.M. for Italy, O.B. for Romania, M.L. for Estonia, G.C. for Belgium, A.T. for France, K.B. for Poland, J.M. for Czech Republic, I.A. for Spain, R.A. for Norway, M.Z. provided the original MOD17 code and helped in preparation of the input data, F.M. and H.H. coordinated and supervised the analysis and the manuscript writing, all authors contributed equally in writing and revising the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gower, S.T.; Kucharik, C.J.; Norman, J.M. Direct and Indirect Estimation of Leaf Area Index, f APAR, and Net Primary Production of Terrestrial Ecosystems. *Remote Sens. Environ.* **1999**, *70*, 29–51. [CrossRef]
2. Running, S.W.; Nemani, R.R.; Heinsch, F.A.; Zhao, M.; Reeves, M.; Hashimoto, H. A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. *Bioscience* **2004**, *54*, 547–560. [CrossRef]
3. Imhoff, M.L.; Bounoua, L.; DeFries, R.; Lawrence, W.T.; Stutzer, D.; Tucker, C.J.; Ricketts, T. The consequences of urban land transformation on net primary productivity in the United States. *Remote Sens. Environ.* **2004**, *89*, 434–443. [CrossRef]
4. Friedlingstein, P. A steep road to climate stabilization. *Nature* **2008**, *451*, 297–298. [CrossRef] [PubMed]
5. Enriquez, J. GENOMICS: Genomics and the World's Economy. *Science* **1998**, *281*, 925–926. [CrossRef] [PubMed]
6. McCormick, K.; Kautto, N. The Bioeconomy in Europe: An Overview. *Sustainability* **2013**, *5*, 2589–2608. [CrossRef]
7. FOREST EUROPE State of Europe's Forests 2015. Available online: http://www.foresteurope.org/docs/fullsoef2015.pdf (accessed on 27 June 2016).
8. EUROSTAT Europe in Figures—Eurostat Yearbook. Available online: http://ec.europa.eu/eurostat/ (accessed on 26 February 2016).
9. Zhao, M.; Heinsch, F.A.; Nemani, R.R.; Running, S.W. Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sens. Environ.* **2005**, *95*, 164–176. [CrossRef]
10. Tomppo, E.; Gschwantner, T.; Lawrence, M.; McRoberts, R. *National Forest Inventories: Pathways for Common Reporting*; Springer: Berlin, Germany, 2010; p. 610.

11. IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry, CHAPTER 4 FOREST. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Kanagawa, Japan, 2006; p. 83.
12. Zianis, D.; Muukkonen, P.; Mäkipää, R.; Mencuccini, M. Biomass and stem volume equations for tree species in Europe. *Silva Fenn. Monogr.* **2005**, *4*, 63.
13. Baldocchi, D. "Breathing" of the terrestrial biosphere: Lessons learned from a global network of carbon dioxide flux measurement systems. *Aust. J. Bot.* **2008**, *56*, 1–26. [CrossRef]
14. Jung, M.; Reichstein, M.; Margolis, H.A.; Cescatti, A.; Richardson, A.D.; Arain, M.A.; Arneth, A.; Bernhofer, C.; Bonal, D.; Chen, J.; et al. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *J. Geophys. Res.* **2011**, *116*, G00J07. [CrossRef]
15. Neumann, M.; Zhao, M.; Kindermann, G.; Hasenauer, H. Comparing MODIS Net Primary Production Estimates with Terrestrial National Forest Inventory Data in Austria. *Remote Sens.* **2015**, *7*, 3878–3906. [CrossRef]
16. Jiang, F.; Chen, J.M.; Zhou, L.; Ju, W.; Zhang, H.; Machida, T.; Ciais, P.; Peters, W.; Wang, H.; Chen, B.; et al. A comprehensive estimate of recent carbon sinks in China using both top-down and bottom-up approaches. *Sci. Rep.* **2016**, *6*. [CrossRef] [PubMed]
17. Zhao, M.; Running, S.W. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* **2010**, *329*, 940–943. [CrossRef] [PubMed]
18. Hasenauer, H.; Petritsch, R.; Zhao, M.; Boisvenue, C.; Running, S.W. Reconciling satellite with ground data to estimate forest productivity at national scales. *For. Ecol. Manag.* **2012**, *276*, 196–208. [CrossRef]
19. Thornton, P.E. *Description of a Numerical Simulation Model for Predicting the Dynamics of Energy, Water, Carbon and Nitrogen in a Terrestrial Ecosystem*; University of Montana: Missoula, MT, USA, 1998; p. 280.
20. Yang, W.; Huang, D.; Tan, B.; Stroeve, J.C.; Shabanov, N.V.; Knyazikhin, Y.; Nemani, R.R.; Myneni, R.B. Analysis of Leaf Area Index and Fraction of PAR absorbed by Vegetation Products from the Terra MODIS sensor: 2000–2005. *IEEE Trans. Geosci. Remote Sens.* **2006**, *44*, 1829–1842. [CrossRef]
21. Friedl, M.; Sulla-Menashe, D.; Tan, B.; Schneider, A.; Ramankutty, N.; Sibley, A.; Huang, X. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sens. Environ.* **2010**, *114*, 168–182. [CrossRef]
22. Zhao, M.; Running, S.W.; Nemani, R.R. Sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. *J. Geophys. Res.* **2006**, *111*, G01002. [CrossRef]
23. Kanamitsu, M.; Ebisuzaki, W.; Woollen, J.; Yang, S.-K.; Hnilo, J.J.; Fiorino, M.; Potter, G.L. NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1631–1643. [CrossRef]
24. Haylock, M.R.; Hofstra, N.; Klein Tank, A.M.G.; Klok, E.J.; Jones, P.D.; New, M. A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. *J. Geophys. Res.* **2008**, *113*, D20119. [CrossRef]
25. Moreno, A.; Hasenauer, H. Spatial downscaling of European climate data. *Int. J. Climatol.* **2015**. [CrossRef]
26. Hijmans, R.J.; Cameron, S.E.; Parra, J.L.; Jones, P.G.; Jarvis, A. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **2005**, *25*, 1965–1978. [CrossRef]
27. Olson, R.J.; Johnson, K.R.; Zheng, D.L.; Scurlock, J.M.O. *Global and Regional Ecosystem Modeling: Databases of Model Drivers and Validation Measurements*; Oakridge Laboratory: Oak Ridge, TN, USA, 2001; p. 95.
28. Jackson, R.; Mooney, H.; Schulze, E. A global budget for fine root biomass, surface area, and nutrient contents. *Proc. Natl. Acad. Sci. USA* **1997**, *94*, 7362–7366. [CrossRef] [PubMed]
29. Finér, L.; Ohashi, M.; Noguchi, K.; Hirano, Y. Fine root production and turnover in forest ecosystems in relation to stand and environmental characteristics. *For. Ecol. Manag.* **2011**, *262*, 2008–2023. [CrossRef]
30. Raich, J.; Nadelhoffer, K. Belowground carbon allocation in forest ecosystems: Global trends. *Ecology* **1989**, *70*, 1346–1354. [CrossRef]
31. Liu, C.; Westman, C.J.; Berg, B.; Kutsch, W.; Wang, G.Z.; Man, R.; Ilvesniemi, H. Variation in litterfall-climate relationships between coniferous and broadleaf forests in Eurasia. *Glob. Ecol. Biogeogr.* **2004**, *13*, 105–114. [CrossRef]

32. Neumann, M.; Moreno, A.; Mues, V.; Härkönen, S.; Mura, M.; Bouriaud, O.; Lang, M.; Achten, W.M.J.; Thivolle-Cazat, A.; Bronisz, K.; et al. Comparison of carbon estimation methods for European forests. *For. Ecol. Manag.* **2016**, *361*, 397–420. [CrossRef]
33. Hasenauer, H.; Eastaugh, C.S. Assessing Forest Production Using Terrestrial Monitoring Data. *Int. J. For. Res.* **2012**. [CrossRef]
34. Huber, M.O.; Eastaugh, C.S.; Gschwantner, T.; Hasenauer, H.; Kindermann, G.; Ledermann, T.; Lexer, M.J.; Rammer, W.; Schörghuber, S.; Sterba, H. Comparing simulations of three conceptually different forest models with National Forest Inventory data. *Environ. Model. Softw.* **2013**, *40*, 88–97. [CrossRef]
35. Seidl, R.; Schelhaas, M.-J.; Rammer, W.; Verkerk, P.J. Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Chang.* **2014**, *4*, 806–810. [CrossRef] [PubMed]
36. Reineke, L. Perfecting a stand-density index for even-aged forests. *J. Agric. Res.* **1933**, *46*, 627–638.
37. Turner, D.P.; Ritts, W.D.; Cohen, W.B.; Gower, S.T.; Running, S.W.; Zhao, M.; Costa, M.H.; Kirschbaum, A.A.; Ham, J.M.; Saleska, S.R.; et al. Evaluation of MODIS NPP and GPP products across multiple biomes. *Remote Sens. Environ.* **2006**, *102*, 282–292. [CrossRef]
38. MacLean, R.G.; Ducey, M.J.; Hoover, C.M. A Comparison of Carbon Stock Estimates and Projections for the Northeastern United States. *For. Sci.* **2014**, *60*, 206–213. [CrossRef]
39. *Austrias National Inventory Report 2012: Umweltbundesamt Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 National Inventory Report for the German Greenhouse Gas Inventory 1990–2010*; Umweltbundesam: Dessau, Germany, 2012; p. 827.
40. Kändler, G.; Bösch, B. Methodenentwicklung für die 3. Bundeswaldinventur: Modul 3 Überprüfung und Neukonzeption einer Biomassefunktion—Abschlussbericht. *Tech. Rep. FVA-BW* **2013**, 1–72. (In German)
41. Neubauer, M.; Demant, B.; Bolte, A. Tree-based estimator for below-ground biomass of *Pinus sylvestris* L. *Forstarchiv* **2015**, *86*, 42–47.
42. Umweltbundesamt Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto- Protokoll 2014 Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990–2012. *Clim. Chang.* **2014**, *24*, 965. (In German)
43. He, L.; Chen, J.M.; Pan, Y.; Birdsey, R.; Kattge, J. Relationships between net primary productivity and forest stand age in U.S. forests. *Glob. Biogeochem. Cycles* **2012**, *26*, 1–19.
44. Moreno, A.; Neumann, M.; Hasenauer, H. Optimal Resolution for Linking Remotely Sensed and Forest Inventory Data in Europe. *Remote Sens. Environ.* **2016**, *183*, 109–119. [CrossRef]
45. Härkönen, S.; Lehtonen, A.; Manninen, T.; Tuominen, S.; Peltoniemi, M. Estimating forest leaf area index using satellite images: Comparison of *k*-NN based Landsat-NFI LAI with MODIS- RSR based LAI product for Finland. *Boreal Environ. Res.* **2015**, *6095*, 181–195.

Supplementary Materials: Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests

Mathias Neumann, Adam Moreno, Christopher Thurnher, Volker Mues, Sanna Härkönen, Matteo Mura, Olivier Bouriaud, Mait Lang, Giuseppe Cardellini, Alain Thivolle-Cazat, Karol Bronisz, Jan Merganic, Iciar Alberdi, Rasmus Astrup, Frits Mohren, Maosheng Zhao and Hubert Hasenauer

This supplement provides additional information on the 12 forest inventory datasets (Table S1), it documents the methodology for estimating carbon increment (Equations (S1)–(S4)) and carbon stocks using forest inventory data (Equation (S5)) as well how auxiliary information were derived using forest inventory data (Tables S2 and S3 and Equations (S6)–(S10)). We also provide as Supplementary Results additional images to complement the publication (Figures S1–S10).

1. Supplementary Methods and Analysis

Forest inventory data from 12 European countries is used (Table S1), which have varying sampling technique as well as inventory design [1]. 8 countries use Fixed Area plots (Belgium, Czech Republic, France, Italy, Norway, Poland, Romania, Spain), 3 countries Angle Count Sampling plots or Bitterlich sampling (Austria, Germany and Finland) and 1 country a stand-wise survey system or taxation (Estonia).

The plot area for the Fixed area plot ranges between 12.6 and 1963.5 m^2 and the basal area factor for the angle count sampling between 1.5 and 4. 6 countries have their plots arranged in clusters with 2–18 plots per cluster, while 5 countries have single plots. The grid distance between the clusters/single plots range from 0.5 to 11 km. Due to the different spacing, the area covered by the inventory system and the relative forest cover the number of plots on forest vary from 2495 (Belgium) to 69853 (Spain).

Most inventory systems employ a minimum diameter threshold (usually 5 or 7 cm). The inventory data thus covers only trees bigger than the threshold. Only Estonia and Finland assess all trees that reach breast height of 1.3 m (DBH threshold of 0 cm).

Our data cover the following 4 methods to estimate tree carbon increment $CARB_{INC}$: (1) repeated observations of fixed area plots (FPM) and (2) repeated angle count sampling (ACM); (3) increment cores (COR); and increment predictions from (4) tree growth models (MOD). Tree growth model predictions were used if no increment observations, neither from repeated observations nor from increment cores, were available.

6 countries provided repeated observations from two consecutive inventory measurements using a permanent plot design (Table S1) and we were able to estimate two subsequent tree carbon stocks for each inventory plot. After accounting for mortality and harvesting, the difference between the carbon stock estimates divided by the inventory measurement interval is the tree carbon increment [2].

3 countries with repeated observation (Belgium, Norway, and Poland) have fixed area plots so we used the Fixed area Plot Method (FPM). The remaining countries (Austria, Finland, and Germany) use angle count sampling [3] and we used the Angle Count Method (ACM) [4].

For countries without repeated observations, we applied the CORe method for France, Romania and the region Sicily in Italy, since diameter increment rates from increment cores were available [5], or employed empirical forest growth models (MOD) to estimate increment rates [6] for countries without increment cores (Estonia, Czech Republic, Spain and the regions Trento and Piemonte in Italy).

Table S1. Summary of the properties of the different forest inventory datasets, Sampling system ACS (Angle Count Sampling), FAP (Fixed Area Plots), k (Basal area factor) only for countries with ACS and Plot area only for FAP, Plot layout (single plots or cluster of plots), Grid distance between clusters/plots, Min. DBH is diameter threshold for sample trees (inventory covers only trees bigger than threshold), availability of repeated observations, time period covered (period 2 only for countries with repeated observations).

Country	Number of Plots	Sampling System	k ($m^2 \cdot ha^{-1}$)	Plot Area (m^2)	Plot Layout	Grid Distance (km)	Min.DBH (cm)	Repeated Observations?	Increment Method	Period 1	Period 2	Reference
Austria	9562	ACS (FAP)	4	21.2	clusters of 4 plots	3.889 × 3.889	5	yes	ACM	2000–2002	2007–2009	[7]
Belgium	2495	FAP	-	3 circles: 63.6, 254.5 and 1017.9	single plots	1 × 0.5	7	yes	FPM	1996–1999	2009–2013	[8]
Czech Republic	13929	FAP	-	2 circles: 28.3 and 500	clusters of 2 plots	2 × 2	7	no	MOD	2001–2004	–	[9]
Estonia	19930	Taxation	-	-	-	-	0	no	MOD	2000–2010	–	[10]
Finland	6442	ACS	2 (south) 1.5 (north)	-	clusters of 14 to 18 plots	6–8 (south) 6–11 (north)	0	yes	ACM	1996–2003	2004–2008	Tomppo and Tuomainen in [1]
France	33152	FAP	-	3 circles: 113, 255 and 706	single plots	2 × 2	7.48	no	COR	2006–2011	–	Nikolas et al. in [1]
Germany	6153	ACS	4	-	clusters of 4 plots	4 × 4 (2000–2002) 8 × 8 (2008)	7	yes	ACM	2000–2002	2008	[11]
Italy (Sicily)	1270	FAP	-	2 circles: 12.6 and 132.7	single plots	0.5 × 0.5	4.5	no	COR	2009	–	[12]
Italy (Trento)	150	FAP	-	1 circle: 600	single plots	1 × 1	2.5	no	MOD	2003	–	[13]
Italy (Piemonte)	13750	FAP	-	1 circle: 50.3–176.7	single plots	0.5 × 0.5	7.5	no	MOD	2002	–	[14]
Norway	9200	FAP	-	250	single plots	3 × 3	5	yes	FPM	2000–2004	2005–2009	Tomter et al. in [1]
Poland	17281	FAP	-	200, 400 or 500	cluster of 5 plots	4 × 4	7	yes	FPM	2005–2008	2010–2013	[15,16]
Romania	5509	FAP	-	2 circles: 200 and 500	cluster of 4 plots	4 × 4 (mountains) 2 × 2 (lowlands)	5.6	no	COR	2008–2012	–	Marin et al. in [1]
Spain	60033	FAP	-	4 circles: 78.5, 314.2, 706.9 and 1963.5	single plots	1 × 1	7.5	no	MOD	2000–2008	–	Alberdi et al. in [1]

2. Fixed Area Plot Method (FPM)

Three countries (Belgium, Norway, Poland) have fixed area plots and repeated observations and the fixed area plot method is used [4].

Carbon increment using the fixed area plot method is derived according to Equation (S1).

$$CARB_{INC} = (C_2 - C_1 + C_{mort} + C_{harv})/time \quad (S1)$$

$CARB_{INC}$ is carbon increment of trees (gC·m^{-2}·year^{-1}), C_1 and C_2 are the sum of carbon estimates at time 1 and 2 (Table S1), C_{mort} is the sum of carbon of trees that died between the two inventory measurements and C_{harv} the carbon of trees that were harvested and removed between the measurements. time is the duration of the period between the two inventory measurements [years]. The carbon estimates C_i (gC·m^{-2}) are estimated using the tree carbon estimation methods.

3. Angle Count Sampling Method (ACM)

Three countries (Austria, Finland and Germany) have angle count sample plots and repeated observations. Deriving increment using inventory data collected with the angle count sampling technique can be done with three methods: the difference method, the starting value method or the end value method. All methods deliver unbiased results, with starting value method and end value method having the lowest error [4]. We selected the same increment calculation method then the local forest inventory organizations. The general equation is given in Equation (S2).

$$CARB_{INC} = inc_{survivors} + inc_{ingrowth} \quad (S2)$$

$inc_{survivors}$ is carbon of survivor trees (present at both inventory measurements) and $inc_{ingrowth}$ is increment of ingrowth trees (present only at the second measurement) all in (gC·m^{-2}·year^{-1}). For Austria the starting value method is used [17]. Finland we use the starting value method as well. Since the NFI in Finland do not have a diameter threshold for selecting sample trees (Table S1), estimating $inc_{ingrowth}$ is not necessary. In Germany the end value method is used [4]. The required information of previous dimension of sample trees is obtained using DBH- and age-dependent growth functions [18].

4. Core Method (COR)

For France, Romania and the Italian region of Sicily the core method is used [6,19]. For this method in principle, diameter increment from increment cores [5] are used to determine the tree dimensions in the past. From diameter increment the volume increment of single trees is derived. Multiplying with an expansion factor and adding the single tree results per plot provide carbon increment (Equations (S3) and (S4)).

$$CARB_{INC} = \sum VOL_{INC} * EF \quad (S3)$$

$$EF = CARB_{TREE}/VOL \quad (S4)$$

With VOL_{INC} volume increment (m^3·ha^{-1}·year^{-1}), EF Expansion factor for deriving carbon (gC·m^{-3}), $CARB_{TREE}$ total tree carbon [gC] and VOL tree volume (m^3) (see following section).

Due to differences in the available data the method differs by country. For Sicily VOL_{INC} is already provided by the Regional forest inventory of Sicily and we only have to multiply with expansion factor EF to derive carbon increment (Equation (S3)).

For France and Romania historic diameter was reconstructed using increment cores. By applying the carbon calculation methods (see following section) using the current and historic dimensions of trees we are able to calculate two estimates of carbon stock. Carbon increment is derived as the difference of the two carbon stock estimates (analogous to Equation (S1)).

5. Increment Models (MOD)

For Czech Republic, Estonia, Spain and the Italian provinces Trento and Piemonte we employ empirical increment models.

In Spain volume increment on tree level is already provided in the database of the Spanish NFI (http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ifn3.aspx). It is estimated using species-, DBH- and height-dependent regression models. Carbon increment is derived using expansion factors, similar as in Equations (S3) and (S4).

In Czech Republic the development of diameter and height is calculated using Korf functions [20] fitted using NFI data. Stem number development is estimated using Reineke's rule [21]. These stand variables are estimated for year 2010 and allow estimating carbon stocks for this year. The Carbon increment is calculated as the difference of the two carbon stock estimates.

In Estonia volume increment on stand level is derived with empirical models dependent on stand age, tree species, bonity (site index) and density [10]. Carbon increment is estimated according to Equation (S3) using expansion factor derived from carbon calculation methods (see following section).

In Italy (Trento and Piemonte) we estimate increment on stand level with an empirical model that is dependent on species, growing stock and mean height [22]. Again by applying Equation (S3) and expansion factors *EF* derived from carbon calculation methods we obtain carbon increment.

6. Tree Carbon Estimation

Carbon estimates are needed for the carbon increment estimates and are derived using the country-specific calculation method employed by the local forest inventory organization and documented in a comprehensive volume [23]. In Czech Republic, we use a similar but slightly different method, since the method used by the local forest inventory organization is not reproducible and not available in published form.

Tree carbon is the sum of the biomass in the compartments stem, branches, foliage and coarse roots multiplied with the carbon fraction factor (Equation (S5)).

$$CARB_{TREE} = (BM_{STEM} + BM_{BRANCH} + BM_{FOLIAGE} + BM_{ROOT}) * CF \tag{S5}$$

$CARB_{TREE}$ is total carbon of a tree [kg], BM_{STEM} biomass of stem, all biomass compartments in (kg), BM_{BRANCH} biomass of branches, $BM_{FOLIAGE}$ biomass of foliage, BM_{ROOT} biomass of roots, CF the carbon fraction to convert biomass into carbon (kg/kg). The biomass calculation methods and carbon fraction CF for 5 important European tree species (*Fagus sylvatica*, *Quercus robur*/*Q. petraea*, *Betula* sp., *Picea abies* and *Pinus sylvestris*) are described in detail in [23]. For all other species a separate carbon calculation method is used or the method from another similar species is applied according to the methodology of the local forest inventory organizations.

Volume required in Equation (S4) is estimated using local volume functions.

7. Stand Variables

Using the forest inventory data several stand variables at plot level are derived to describe the stand characteristics for Table 1 and for Figures S6–S10: Basal area, Stem number, Mean diameter, Mean height, Stand density index, Dominant species and Mean Age.

Basal area is the sum of basal area of all trees on a sample plot

$$BA = \sum(DBH^2/40{,}000\ \pi\ nrep) \tag{S6}$$

With BA basal area per hectare ($m^2{\cdot}ha^{-1}$), DBH diameter at breast height [cm], nrep the represented stem number by a given tree [/], for Fixed Area plots calculated according Equation (S6), for Angle count sample plots according Equation (S7).

$$nrep = 10{,}000/Aplot \tag{S7}$$

$$nrep = 4\ k/(DBH^2\ \pi) \tag{S8}$$

With DBH [m], k basal area factor of an angle count sample ($m^2 \cdot ha^{-1}$), Aplot the size of a sample plot (m^2) (see Table S1) and nrep is the represented stem number of a single tree (ha^{-1}).

Stem number NHA is the sum of nrep for all trees on a plot per hectare.

Mean quadratic diameter DG is derived using basal area and stem number and represents the mean diameter weighted by the basal area of each single tree.

$$DG = (4\ BA/NHA/\pi)^{0.5} \quad (S9)$$

Stand density index [21] is a measure of stand density and competition.

$$SDI = NHA\ (DG/25)^{1.605} \quad (S10)$$

Dominant species is the tree species that contributes most to the plots basal area. For the sake of clarity and comparability we aggregate the original tree species provided by the NFI into 7 tree species groups (TSG) according to their leaf shedding and growth behaviour. TSG 1 to 3 cover coniferous species and TSG 4 to 7 broadleaf species (Table S2).

Table S2. Tree species groups (TSG) used in this study, description and selected tree species.

TSG	Description	Selected Species Included Therein
1	Light demanding conifers	*Pinus sylvestris, P. nigra, P. cembra, P. radiata*, *Larix* sp.
2	Shade tolerant conifers	*Picea* sp., *Pseudotsuga* sp., *Abies* sp.
3	Mediterranean conifers	*Cupressus* sp., *Pinus pinea, Pinus* sp. not included in TSG 1
4	Fast growing deciduous	*Betula* sp., *Populus* sp., *Alnus* sp., *Salix* sp., *Robinia* sp., *Eucalyptus* sp.
5	Light demanding, slow growing deciduous	*Quercus robur, Q. petreae, Fraxinus* sp., *Castanea* sp.
6	Shade tolerant, slow growing deciduous	*Fagus* sp., *Tilia* sp., *Ulmus* sp., *Acer* sp., *Carpinus* sp.
7	Evergreen broadleaf	*Olea europea* or *Quercus* sp. not included in TSG 6

Some forest inventories provide tree age estimates on stand level, while others give age estimates for single trees. Either age classes (e.g., 21–40 years) or discrete values (e.g., 34 years) are given. To harmonize the age estimates, we use 8 consistent age classes (0–20 years, 21–40, 41–60, ... 121–140, >140). If a forest inventory dataset provided age estimates for single trees, we calculated the mean age and then classified the plots according to the 8 age classes.

8. Supplementary Results and Analysis

We provide here additional images not presented in the paper.

Figure S1 provide a direct pixel-to-plot comparison of MODIS EURO and NFI NPP for each inventory plot along with statistics analogue to Figure 4 showing the country median NPP.

Figures S2–S5 show for the four regions (North Europe. Central-West Europe, Central-East Europe and South Europe) the effect of Elevation, Latitude and Longitude on the NPP discrepancy ΔNPP between MODIS EURO and NFI NPP.

Figures S6–S9 show NPP discrepancy ΔNPP for both MODIS NPP sources, MODIS GLOB using global climate data [24] and MODIS EURO using local European climate data [25] for tree age, tree height, MODIS Land cover type and Dominant species.

Figure S10 show the effect of Stand density Index (SDI) [21] on MODIS EURO and on NFI NPP separately. This image suggests that the pattern in Figure 6 is mainly due to NFI NPP, which is more affected by SDI than MODIS EURO.

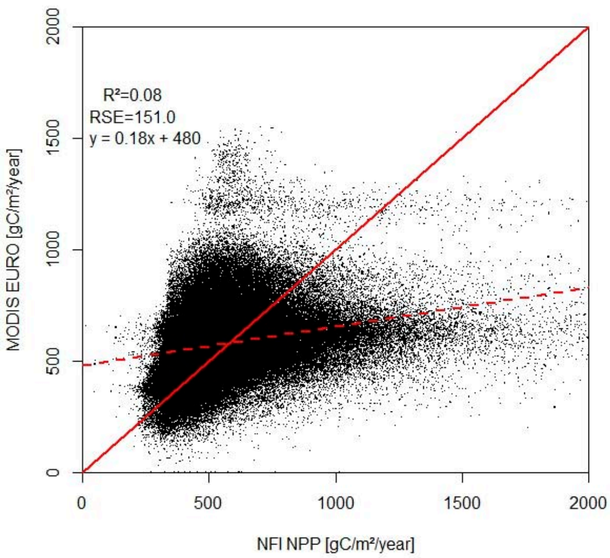

Figure S1. Direct pixel-to-plot comparison of MODIS EURO using European climate data and NFI NPP, solid line is 1:1 line, dashed line represents the linear trend of the 12 countries, Coefficient of determination R^2, Residual standard error (RSE) and the trend function are given.

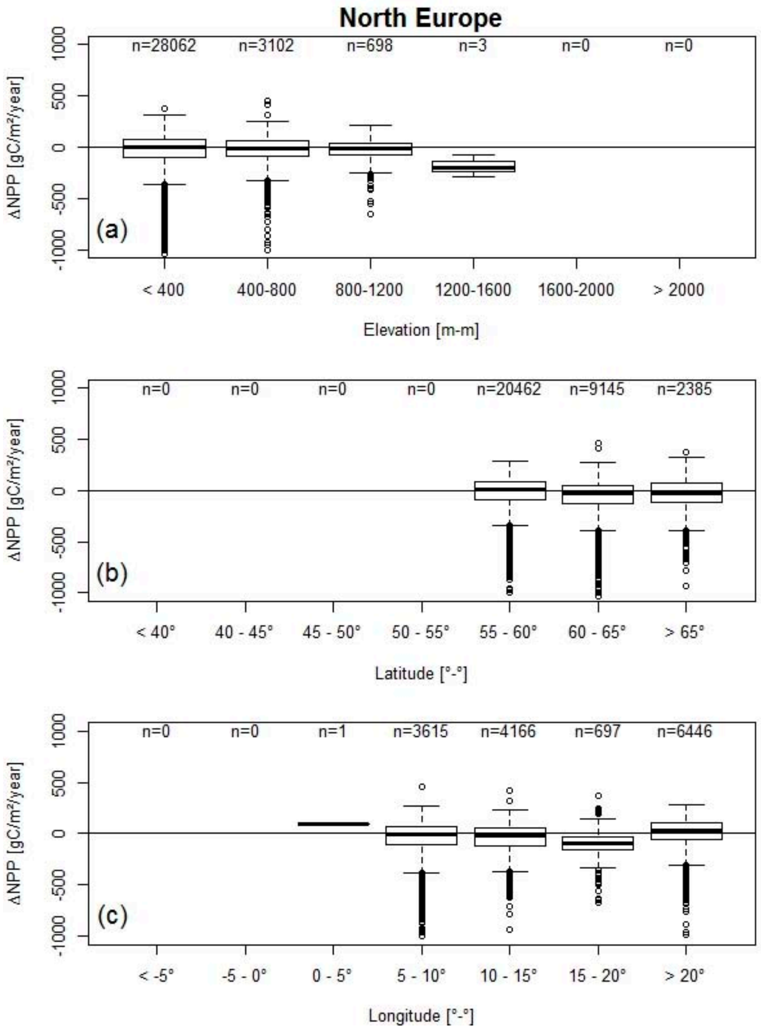

Figure S2. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for North Europe by Elevation classes (**a**), by Latitude (**b**) and by Longitude (**c**), the box represent the Median and the 25th and 75th percentile, the whiskers extent to 1.5 of the interquartile range, values outside this range are indicated by dots, on the top the number of values represented by the boxplots are given.

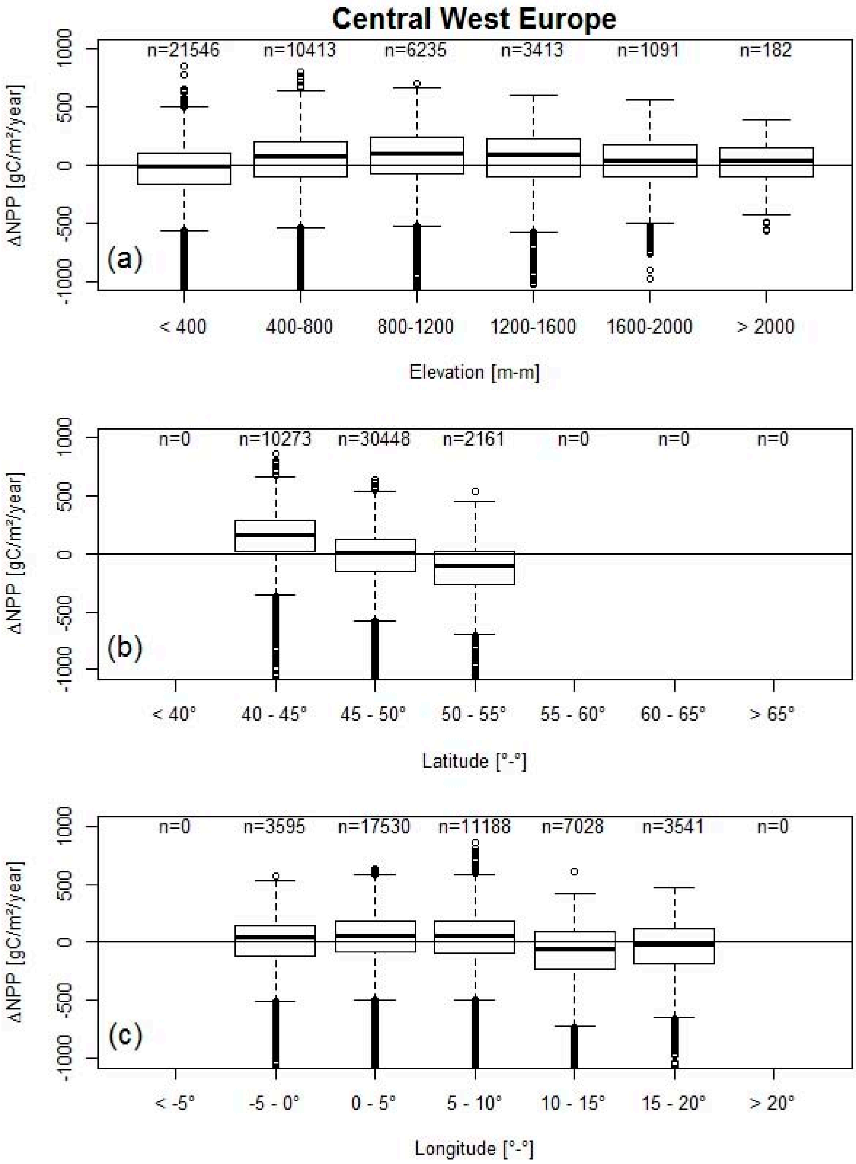

Figure S3. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for Central-West Europe by Elevation classes (**a**); by Latitude (**b**) and by Longitude (**c**), Properties of illustration analogous to Figure S2.

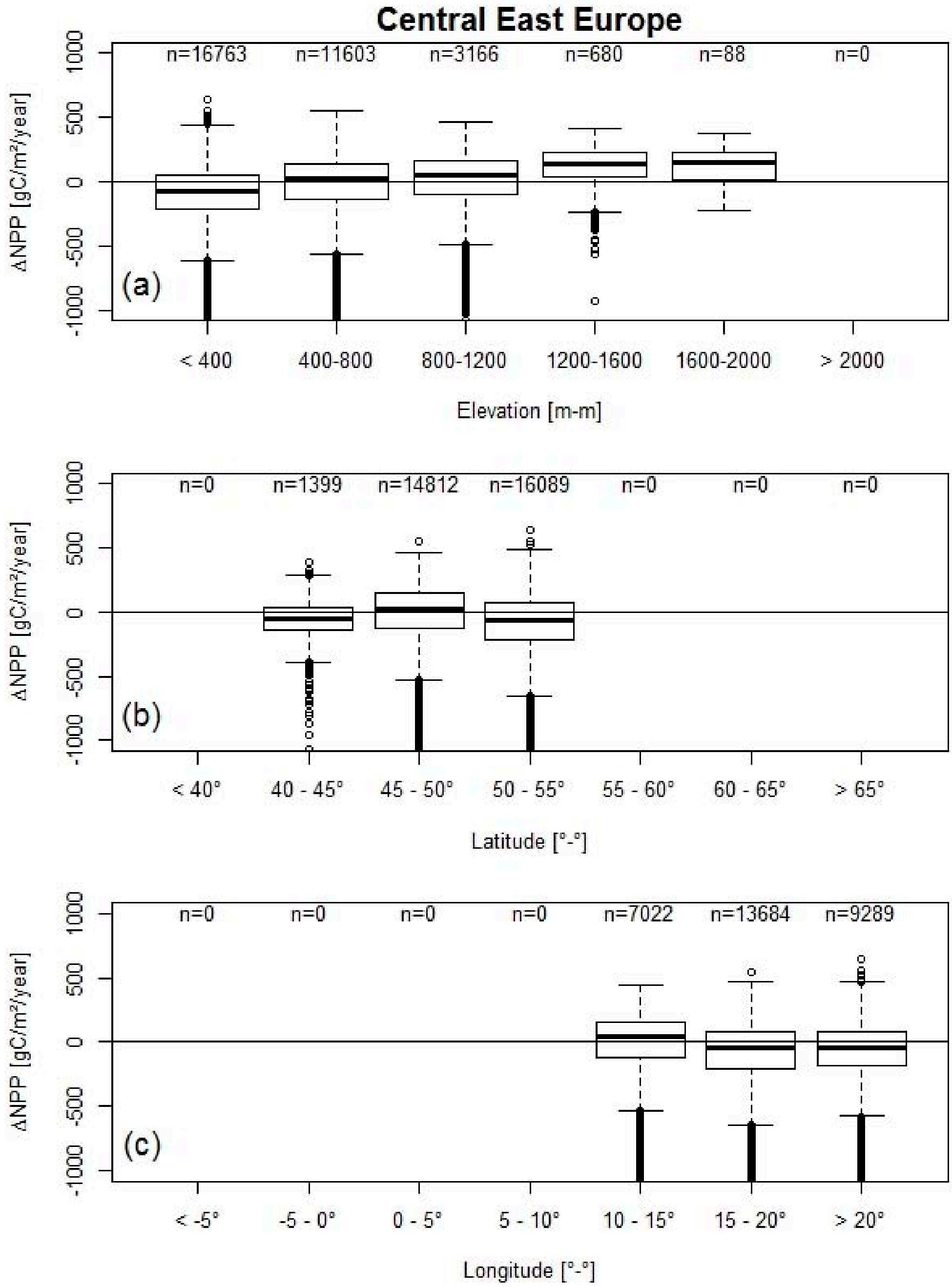

Figure S4. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for Central-East Europe by Elevation classes (**a**); by Latitude (**b**) and by Longitude (**c**), Properties of illustration analogous to Figure S2.

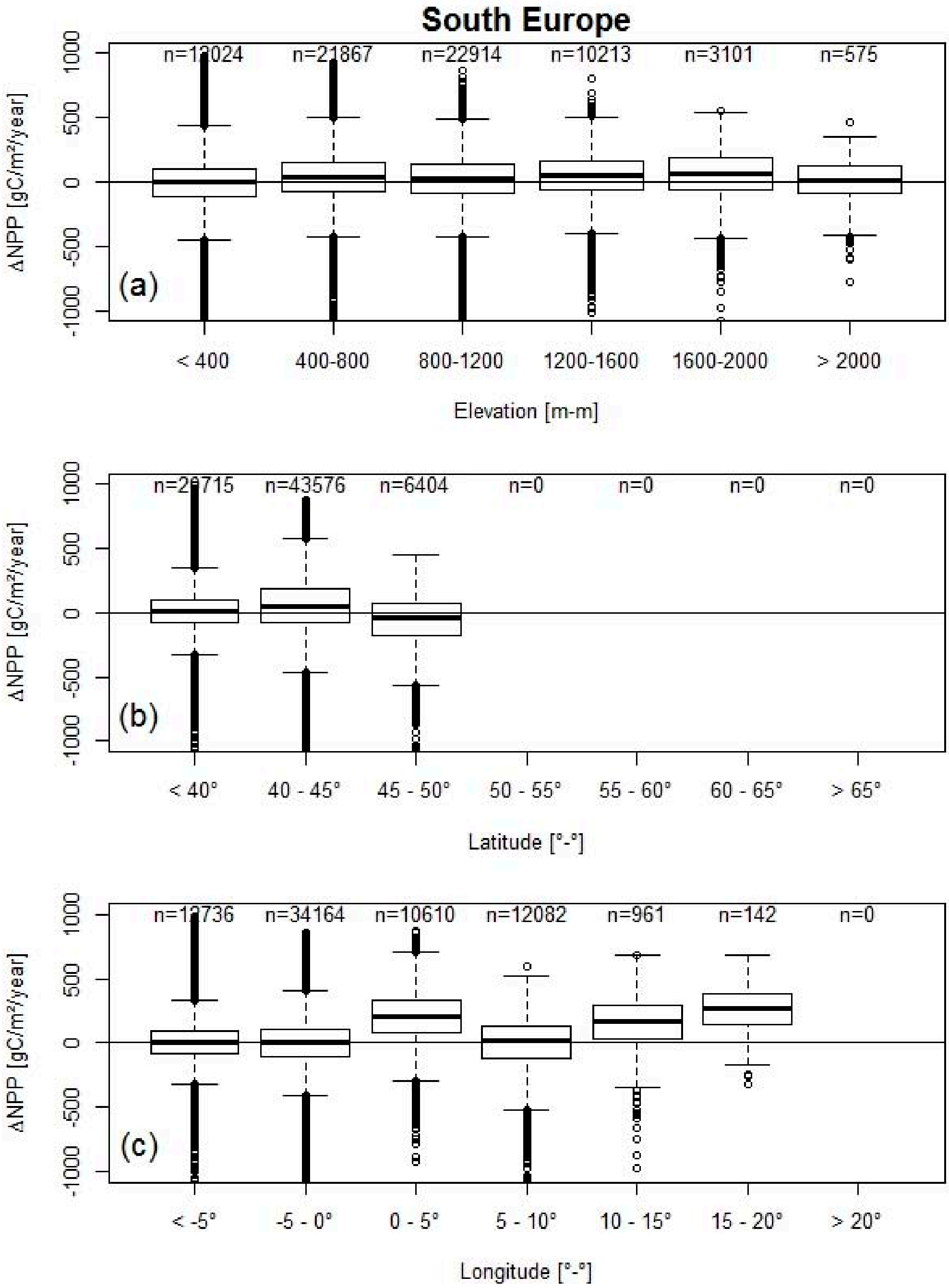

Figure S5. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for South Europe by Elevation classes (**a**); by Latitude (**b**) and by Longitude (**c**), Properties of illustration analogous to Figure S2.

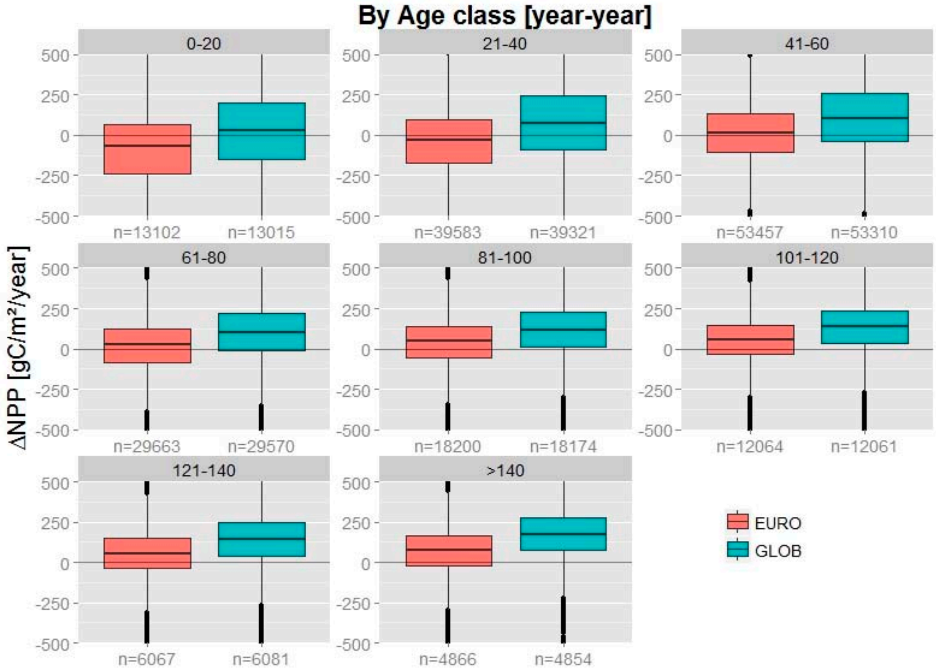

Figure S6. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) grouped by Age classes. Properties of illustration analogous to Figure S2. Under the plots the number of represented samples are given.

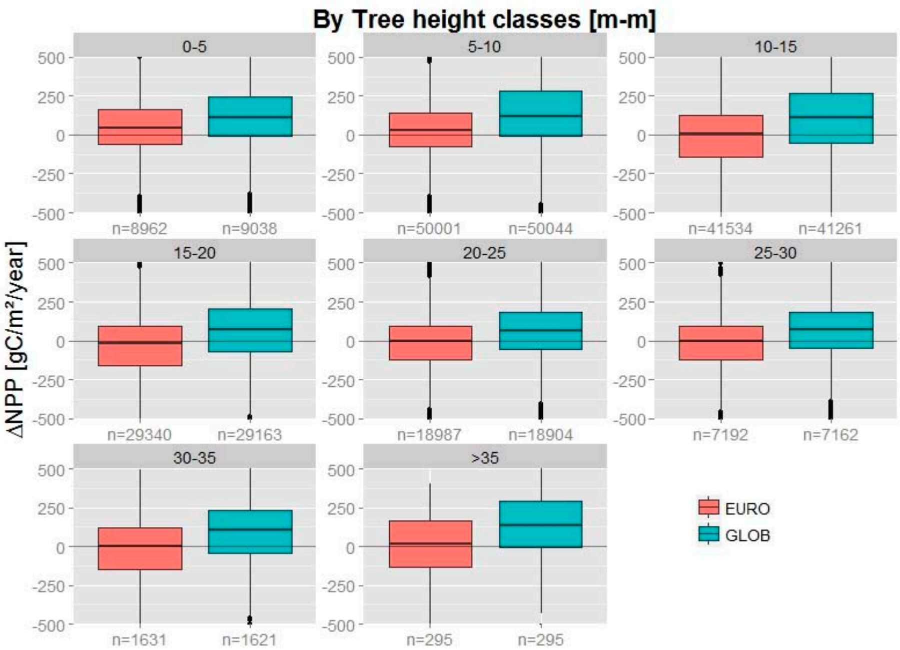

Figure S7. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) grouped by Tree height classes. Properties of illustration analogous to Figure S1.

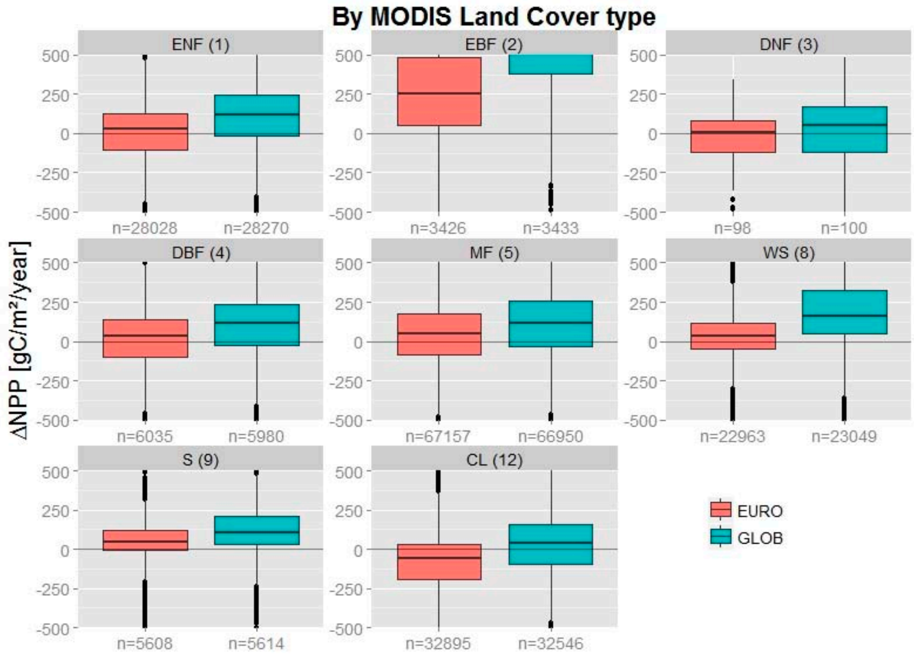

Figure S8. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) by MODIS Land cover types: we show 5 forest land cover classes (ENF evergreen needleleaf forest, EBF evergreen broadleaf forest, DNF deciduous needleleaf forest, DBF deciduous broadleaf forest, MF mixed forest) 2 classes that contain more than 10% Forest (WS woody savannahs, S Savannahs) and CL Cropland, since it is q very frequent land cover type due to Europe's forest fragmentation (in brackets the original MODIS Landcovertype code used for the in biome-property-lookup tables (BPLUTs) [26]). Properties of illustration analogous to Figure S1.

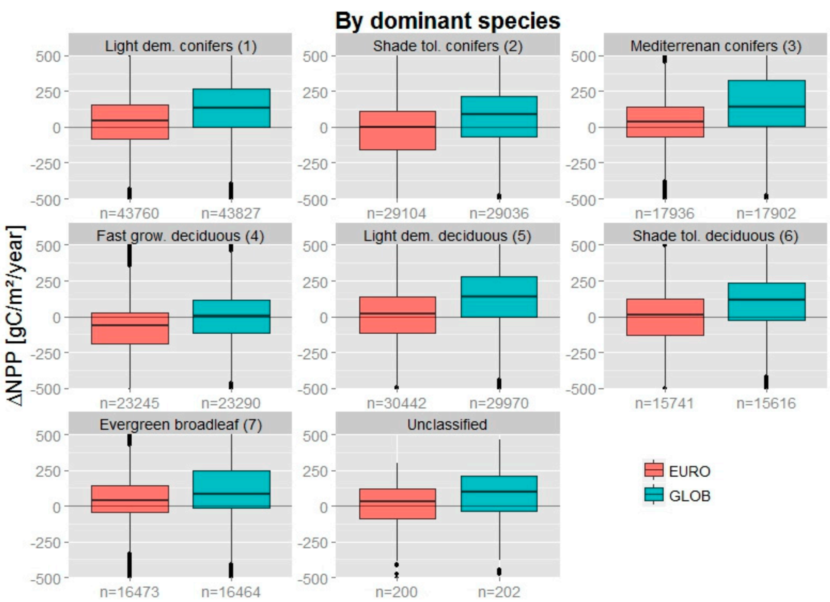

Figure S9. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) by dominant tree species, the first row show the coniferous tree species groups 1–3 (light demanding conifers, shade tolerant conifers and Mediterranean conifers) followed by the broadleaf TSGs 4–7 (Fast growing deciduous, Shade tolerant slow growing deciduous, Light demanding slow growing deciduous and evergreen broadleaf trees). Properties of illustration analogous to Figure S1.

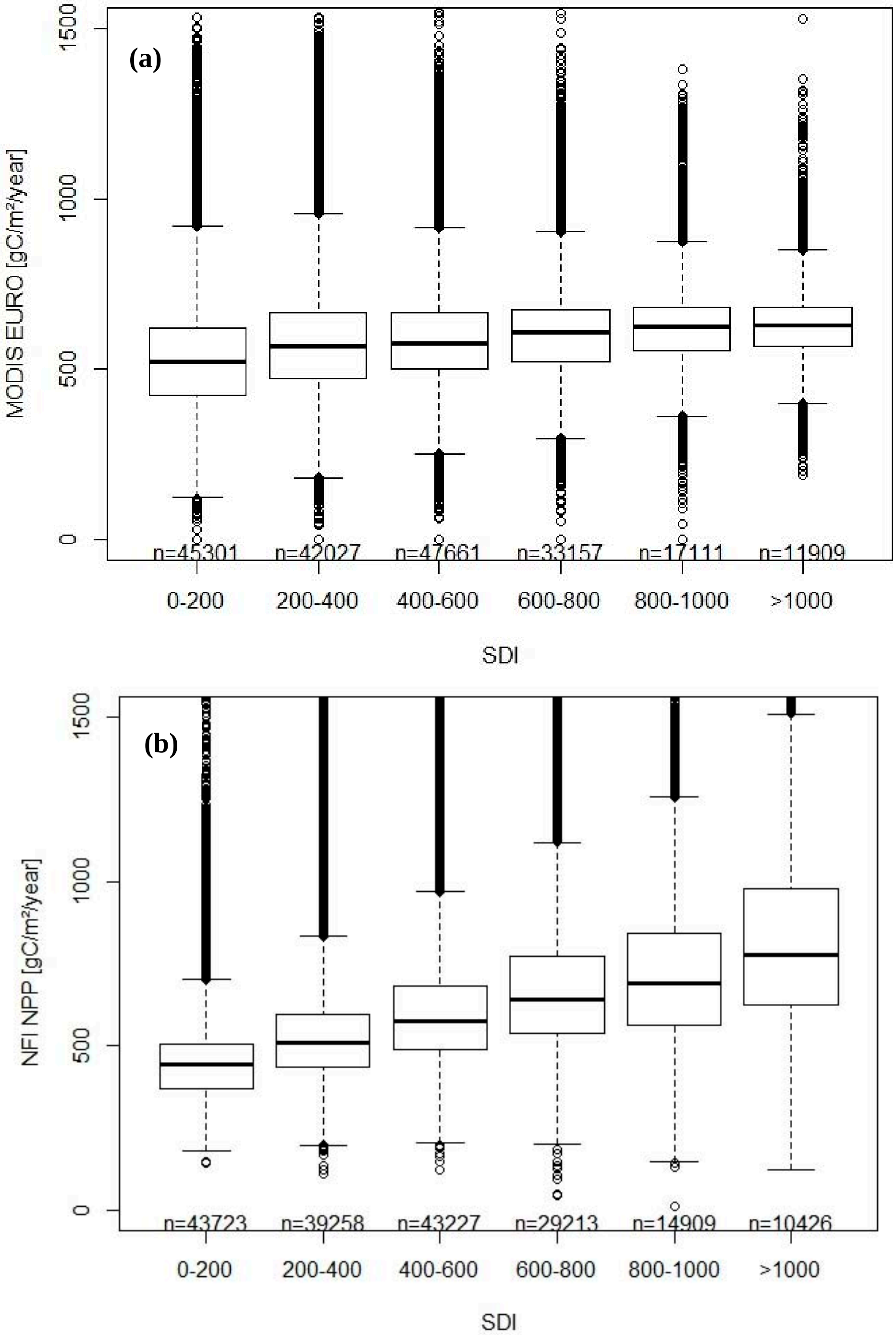

Figure S10. NPP estimates by Stand density Index: MODIS EURO (**a**) and NFI NPP (**b**) (SDI) classes [21]. Properties analogous to Figure S2.

References

1. Tomppo, E.; Gschwantner, T.; Lawrence, M.; McRoberts, R. *National Forest Inventories: Pathways for Common Reporting*; Springer: Berlin, Germany, 2010; p. 610.
2. Olson, R.J.; Johnson, K.R.; Zheng, D.L.; Scurlock, J.M.O. *Global and Regional Ecosystem Modeling: Databases of Model Drivers and Validation Measurements*; ORNL/TM-2001/196, 2001; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2001; p. 95.
3. Bitterlich, W. Die Winkelzaehlprobe. *Forstwiss. Centralblatt* **1948**, *59*, 4–5.
4. Hasenauer, H.; Eastaugh, C.S. Assessing Forest Production Using Terrestrial Monitoring Data. *Int. J. For. Res.* **2012**, *2012*, 1–8.

5. Grissino-Mayer, H.D. A Manual and Tutorial for the proper use of an increment borer. *Tree-Ring Res.* **2003**, *59*, 63–79.
6. Huber, M.O.; Eastaugh, C.S.; Gschwantner, T.; Hasenauer, H.; Kindermann, G.; Ledermann, T.; Lexer, M.J.; Rammer, W.; Schörghuber, S.; Sterba, H. Comparing simulations of three conceptually different forest models with National Forest Inventory data. *Environ. Model. Softw.* **2013**, *40*, 88–97.
7. Gabler, K.; Schadauer, K. Methods of the Austrian Forest Inventory 2000/02 Origins, Approaches, Design, Sampling, Data Models, Evaluation and Calculation of Standard Error. BFW-Berichte; Bundesforschungs—und Ausbildungszentrums für Wald, Naturgefahren und Landschaft, Wien, Österreich, Available online: http://bfw.ac.at/030/pdf/Bericht142.pdf (accessed on 27 June 2016).
8. Wouters, J.; Quataert, P.; Onkelinx, T.; Bauwens, D. *Ontwerp en handleiding voor de Tweede Regionale Bosinventarisatie van het Vlaamse Gewest*; Rapporten van het Instituut voor Natuur-en Bosonderzoek*:* Geraardsbergen, Belgium, 2008; p. 176. (In Flemish)
9. Forest Management Institute National Forest Inventory in the Czech Republic 2001–2004 Introduction, Methods, Results. 2007, p. 224. Available online: https://www.researchgate.net/publication/40369751_Narodni_inventarizace_lesu_v_Ceske_republice_2001-2004_uvod_metody_vysledky_National_forest_inventory_in_the_Czech_Republic_2001-2004_introduction_methods_results(accessed on 26 February 2016).
10. Metsa Korraldamise Juhend (Forest Inventory Guidelines), RTL 2009, 9, 104. https://www.riigiteataja.ee/akt/13124148 (accessed on 28 June 2016). (In Estonian)
11. Schmitz, F.; Polley, H.; Hennig, P.; Dunger, K.; Schwitzgebel, F. Die zweite Bundeswaldinventur—BWI^2 Inventur—und Auswertungsmethoden. Arbeitsbericht aus dem Inst. für Waldökologie und Waldinventuren 2008. Available online: http://literatur.thuenen.de/digbib_extern/dk041201.pdf (accessed on 26 February 2016).
12. Hofmann, A.; Cibella, R.; Bertani, R.; M, M.; Fantoni, I.; Luppi, S. Strumenti Conoscitivi per la Gestione Delle Risorse Forestali Della Sicilia. Sistema Informativo Forestale. Available online: https://sif.regione.sicilia.it/ilportale/documents/10179/66166/Sistema+informativo+forestale+regionale.pdf/9f3ab435-2d90-4029-9e05-031fe1049571 (accessed on 28 June 2016). (In Italian)
13. Tonolli, S.; Salvagni, F. InFoCarb Inventario Forestale del Carbonio Della Provincial di Trento. Cent. di Ecol. Alpina, Trento 2007. Available online: http://www.fmach.it/Servizi-Generali/Editoria/InFoCarb-Inventario-Forestale-del-Carbonio-della-Provincia-di-Trento (accessed on 26 February 2016).
14. IPLA Inventario e Carta Forestale Della Regione Piemonte—Manual of Codes and Methodologies. 2003. Available online: http://www.sistemapiemonte.it/ris/montagna/sifor/area_documenti.shtml (accessed on 28 June 2016). (In Italian)
15. Michalak, R.; Broda, J.; Glaz, J.; Jablonski, M.; Lech, P.; Smykala, J.; Wawrzoniak, J.; Zajaczkowski, S. Instrukcja Wykonywania Wielkoobszarowej Inwentaryzacji Stanu Lasu (Manual instruction of National Forest Inventory—In polish). Available online: https://www.mos.gov.pl/fileadmin/user_upload/mos/srodowisko/lesnictwo/Instrukcja_wykonywania_wielkoobszarowej_inwentaryzacji_stanu_lasu.pdf (accessed on 28 June 2016). (In Polish)
16. Jablonski, M.; Budniak, P.; Lech, P.; Mionskowski, M.; Przypasniak, J.; Brode, J.; Neroj, B.; Zajaczkowski, S. Instrukcja Wykonywania Wielkoobszarowej Inwentaryzacji Stanu Lasu. Instytut Badawczy Leśnictwa, 2014. Available online: http://www.buligl.pl/documents/10192/278026/Instrukcja+WISL+2015-2019.pdf/a2b24061-be31-4c4e-bbd0-ea24caa405d8 (accessed on 28 June 2016). (In Polish)
17. Neumann, M.; Zhao, M.; Kindermann, G.; Hasenauer, H. Comparing MODIS Net Primary Production Estimates with Terrestrial National Forest Inventory Data in Austria. *Remote Sens.* **2015**, *7*, 3878–3906.
18. Sloboda, B. *Zur Darstellung von Wachstumsprozessen mit Hilfe von Differentialgleichungen Erster Ordnung*; Mitteilungen der Baden-Württembergischen Forstl. Versuchs- und Forschungsanstalt*:* Freiburg im Breisgau, Germany 1971; p. 109. (In German)
19. Kindermann, G. Erste österreichweite Jahrringanalyse: Daten, Methoden und Ergebnisse (First tree ring analysis throughout Austria: Data, methods and results). *BFW-Dokumentation* **2010**, *11*, 6–77. (In German)
20. Korf, V. Príspevek k matematické definici vzrustového zákona hmot lesních porostu. *Lesn. Práce* **1939**, *18*, 339–379. (In Czech)
21. Reineke, L. Perfecting a stand-density index for even-aged forests. *J. Agric. Res.* **1933**, *46*, 627–638.

22. Gasparini, P.; Tabacchi, G. L'inventaro Nazionale Delle Foreste e dei Serbatoi Forestali di Carbonio. INFC 2005. Second. Inventar. For. Naz. Ital. Metod. e Risult. EDAGRICOLE. 2011, 1–178. Available online: http://www.sian.it/inventarioforestale/ (accessed on 26 February 2016).
23. Neumann, M.; Moreno, A.; Mues, V.; Härkönen, S.; Mura, M.; Bouriaud, O.; Lang, M.; Achten, W.M.J.; Thivolle-Cazat, A.; Bronisz, K.; et al. Comparison of carbon estimation methods for European forests. *For. Ecol. Manag.* **2016**, *361*, 397–420.
24. Kanamitsu, M.; Ebisuzaki, W.; Woollen, J.; Yang, S.-K.; Hnilo, J.J.; Fiorino, M.; Potter, G.L. NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1631–1643.
25. Moreno, A.; Hasenauer, H. Spatial downscaling of European climate data. *Int. J. Climatol.* **2015**, 109–119.
26. Zhao, M.; Heinsch, F.A.; Nemani, R.R.; Running, S.W. Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sens. Environ.* **2005**, *95*, 164–176.