Forest Ecology and Management 361 (2016) 269–276

Contents lists available at ScienceDirect

Forest Ecology and Management

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

A national-scale, stand-level model to predict total above-ground tree biomass from growing stock volume

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ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 15 October 2015
Accepted 5 November 2015
Available online 21 November 2015

Keywords:
Forest biomass
Forest inventory
Upscaling
BEF
Biomass expansion factors
Harmonization

ABSTRACT

Interest in the accurate measurement of forest biomass has increased remarkably in the decades following the agreements made at the United Nations Framework Convention on Climate Change, particularly because of forest biomass' role in carbon storage. Information on forest biomass over large areas is generally obtained from National Forest Inventory (NFI) statistics; however, these data are usually estimates of stem volumes and only rarely estimate tree biomass through direct measurements. Conversion from stem volumes to biomass is commonly achieved through factors known as biomass expansion factors (BEFs). BEFs may also expand the estimation of tree components and, in such cases, are also referred to as conversion and expansion factors (BCEFs). Experience has proven that biomass factors vary with stand characteristics such as composition, age, volume and others. For this reason, models that predict such factors as a function of stand variables have been developed. In Italy, the total above-ground tree biomass (AGB) of forests was estimated by the second Italian NFI through direct measurements and, on the basis of the stock estimates of tree volume and biomass, BCEFs representative of Italian broad-spectrum forest conditions (e.g., composition, density, silviculture treatment and others) for reference year 2005 were published. This paper presents a stand-level model developed to predict AGB density (Mg ha^{-1}) from growing stock volume (GSV) density (m^3 ha^{-1}) by forest category. The model was calibrated using NFI plot level data. The fitted model was tested to estimate total AGB from aggregated data, which was represented as the mean GSV per hectare at the plot level, and two broader aggregation scales using the mean GSV per hectare of forest category in each administrative region and at the national level. The accuracy of the estimates generally decreased with the level of data aggregation, but the upscaling exercises only overestimated the national overall AGB value by a maximum of 2.00%, an acceptable difference given the broad datum used as the independent variable. The upscaling exercises proved that the model is also suitable for predicting AGB by forest category, particularly given that the estimated values always fell within the 95% confidence interval of the NFI reference estimates.

1. Introduction

Biomass is an expression of production, and as such it has been widely studied from a variety of perspectives (Satoo, 1982). Because it correlates well with climate and site factors (Pignatti, 1995), the distribution of biomass has been utilized in studies at the global and ecosystem level. Biomass is influenced by ecological processes, so that it may be an informative measure that can be applied to a wide range of scientific questions (Hero et al., 2013). Its value per unit area, or density, is useful for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions (Schroeder et al., 1997) and determines the amount of carbon emitted to the atmosphere when ecosystems are disturbed (Houghton et al., 2009). In recent decades, interest in the accurate measurement of forest biomass has increased remarkably, particularly because of the role that forest biomass plays in carbon storage and because of agreements made under the United Nations Framework Convention on Climate Change. Increasing carbon storage is seen as a mitigation mechanism for climate change, and countries can utilize forest growth to offset their emissions (Van Camp et al., 2004; Jalkanen et al., 2005). Over large areas, forest data are primarily provided by National Forest Inventories (NFIs) (Tomppo et al., 2010). NFI data are abundant and cover a wide range of conditions across a country (Qureshi et al., 2012). The importance of NFI estimates of forest

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http://dx.doi.org/10.1016/j.foreco.2015.11.008
0378-1127/

biomass and carbon stocks is nowadays widely recognized and accepted (e.g., Heath et al., 1993; Brown, 2002; Dieter and Elsasser, 2002; Goodale et al., 2002; Smith et al., 2004; Ciais et al., 2008; Mäkipää et al., 2008). However, NFIs generally provide estimates of stem volumes, and they rarely provide tree biomass estimates using direct measurements (Lehtonen et al., 2004). For this reason, the use of NFI data generally requires the use of a conversion factor to transform the stem volume cubic meters unit into a biomass tons unit and to account for other tree-components besides the stem in the whole-tree biomass value. This transformation process is generally known as expansion. Depending on the aim, the transformation factor is commonly called a biomass expansion factor (BEF) or a biomass conversion and expansion factor (BCEF); although, many terms have been used in the literature (Somogyi et al., 2007), and a standard is still missing. The use of such factors is suggested by the IPCC guidelines (IPCC, 2003), and their use may be the sole option in cases when only aggregated volume estimates, such as those related to inventory strata (geographical regions, districts, or vegetation classes), are available. Biomass factors are known to vary with stand characteristics such as composition, age or development stage, volume, structure and site conditions (Soares and Tomé, 2004; Lehtonen et al., 2004; Petersson et al., 2012; Magalhães and Seifert, 2015). As a result, the use of factors that were developed locally, or from a small number of trees collected from a few forest growing conditions, may lead to biased estimates if applied to estimate forest carbon stocks over large areas (Lehtonen et al., 2004; Jalkanen et al., 2005). Somogyi et al. (2007) identified this issue for most of the biomass factors available in the literature. An improvement in the use of BEFs has occurred with the development of models that predict BEFs as a function of tree/stand variables, particularly timber volume (Guo et al., 2010). When tree-scale data are available, the use of appropriate biomass models that rely on measured data (usually the diameter at breast height – DBH) from a single tree is generally preferred (Brown, 2002; Somogyi et al., 2007; Petersson et al., 2012). Models for tree-level biomass are now available for many species and geographic areas (e.g., Jenkins et al., 2003; Lambert et al., 2005; Zianis et al., 2005; Ung et al., 2008; Henry et al., 2011; Tabacchi et al., 2011; Chave et al., 2014). Total tree biomass is calculated first at the plot level by adding up the tree biomass of the individuals within the plot; then it is calculated for each stratum (district or forest type) and at the country level using the appropriate NFI estimators for population totals and densities. An intermediate approach consists of stand-level models that predict tree biomass per unit area from stand density variables, which is more frequently the stem volume per unit area. Stand level models are developed for specific forest types or geographical areas, and sometimes they refer to specific management techniques. The dependent variable of these models is generally the whole above-ground biomass of trees, but other variables are also possible, such as the biomass of standing dead trees or the biomass of a specific tree component. Similarly, the independent variable can be either the timber volume or the biomass of other tree components (e.g., Smith et al., 2003; Lehtonen et al., 2004; Boudewyn et al., 2007). Data used to construct this type of model generally come from tree measurements within sampling plots so that tree volume and biomass values per unit area are obtained from single-tree data and models. As for biomass factors, stand-level models may be particularly helpful in biomass calculations from volume per unit area statistics when plot data are no longer available. Their use may also be helpful in reconstructing time series of biomass values during scenario modelling, as shown in Smith et al. (2003), or in identifying stand statistics obtained thorough polygon-based inventories (Boudewyn et al., 2007). Based on the results of their comparative study, Petersson et al. (2012) strongly recommended the use of models that take into account the variation of BEFs over time, rather than the use of BEFs obtained from stock estimates.

In Italy, the above-ground biomass of forests was exhaustively estimated during the second Italian NFI (INFC2005) by directly measuring trees with a diameter at breast height (DBH) $\geqslant$4.5 cm. In addition, measurements and destructive laboratory sampling of undergrowth woody vegetation (shrubs and trees with regeneration higher than 50 cm) were performed (Gasparini and Di Cosmo, 2015). The biomass of tree species was found to be 913,067,042 Mg (104.2 Mg ha^{-1}), of which 95.8% stemmed from trees and 4.2% stemmed from regeneration (Gasparini et al., 2013). The volume and the total above-ground biomass of living trees (AGB) were

Table 1
BCEFs for Italian forest categories derived from the NFI estimates of growing stock volume and above-ground biomass of living trees. Minimum and maximum values observed in the regions are also reported, as well as the number of regions in which a forest category was found.

Forest category and characteristic species	BCEF (national)	BCEF Min (regional)	BCEF Max (regional)	N of regions
Larch and stone pine forests (*L. decidua*, *P. cembra*)	0.540	0.518	0.597	8
Norway spruce forests (*P. abies*)	0.521	0.504	0.592	13
Fir forests (*A. alba*)	0.539	0.511	0.679	14
Scots pine and mountain pine forests (*P. sylvestris*, *P. mugo*)	0.581	0.561	0.656	12
Black pines forests (*P. nigra*, *P. laricio*, *P. leucodermis*)	0.556	0.458	0.740	21
Mediterranean pines forests (*P. domestica*, *P. marittima*, *P. halepensis*)	0.594	0.566	0.621	16
Other coniferous forests	0.580	0.526	0.735	17
Beech forests (*F. sylvatica*)	0.767	0.639	0.804	20
Temperate oaks forests (*Q. petraea*, *Q. pubescens*, *Q. robur*)	0.838	0.761	0.893	21
Mediterranean oaks forests (*Q. cerris*, *Q. frainetto*, *Q. trojana*, *Q. macrolepis*)	0.817	0.616	0.852	16
Chestnut forests (*C. sativa*)	0.648	0.579	0.718	21
Hornbeam and hophornbeam forests (*Carpinus spp.*, *Ostrya carpinifolia*)	0.856	0.739	0.934	19
Hygrophilous forests	0.637	0.592	0.883	21
Other deciduous broadleaved forests	0.743	0.666	0.832	21
Holm oak forests (*Q. ilex*)	0.959	0.902	1.004	16
Coark oak forests (*Q. suber*)	0.977	0.937	0.981	6
Other evergreen broadleaved forests	0.782	0.733	1.022	9
Poplar plantations	0.529	0.491	0.796	14
Other broadleaved plantations	0.752	0.638	0.953	16
Coniferous plantations	0.552	0.516	0.683	9
Temporarily unstocked forests	0.678	0.540	1.094	15[a]
All categories (Italian forest)	0.689	0.525	0.895	21

[a] One region removed from the statistic (extreme value of maximum BCEF out of range and based on only two NFI plots, both with only one tree with DBH 5 cm and 10 cm, respectively).