A COMPARATIVE STUDY BETWEEN “DEFAULT METHOD” AND “STOCK CHANGE METHOD” OF GOOD PRACTICE GUIDANCE FOR LAND USE, LAND-USE CHANGE AND FORESTRY (IPCC, 2003) TO EVALUATE CARBON STOCK CHANGES IN FOREST

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The Intergovernmental Panel on Climate Change (IPCC) reports two methods for the evaluation of changes in the carbon stock of living biomass in the Good Practice Guidance for Land Use, Land Use Change and Forestry: 1) The default method requires the biomass carbon loss to be subtracted from the biomass carbon increment for the reporting year; 2) the stock change method requires two consecutive biomass carbon stock inventories for a given forest area at two points in time.
The aim of this study was the estimate of changes in carbon stock and the related uncertainty in a Douglas fir plantation constituted by plots with different planting densities, monitored at ages 15, 25, 30 and 40. Three methods were used to estimate above-ground biomass: 1) application of allometric equations; 2) constant BEF (biomass expansion factor); 3) age-dependent BEF. Results showed that estimates based on allometric equations had the lowest uncertainty, whereas biomass estimated with the constant BEF had higher uncertainty than biomass estimated with age dependent BEFs. With a constant BEF it is usually difficult to obtain a reliable value for the whole tree biomass because stem proportion increases with tree size at the expense of the other components. The age dependent BEF saim to reduce the bias representing the actual change in stock. The default method had the highest uncertainty (38.3% - 51.3%) and gave an estimate 47% higher than the stock change method, that had an uncertainty ranging from 2.5% (estimated by allometric equation) to 3.9% (estimated by constant BEF).

Keywords: carbon stock, uncertainty, douglas fir, allometric equation, BEF.
Parole chiave: carbon stock, incertezza, douglasia, equazioni allometriche, BEF.

http://dx.doi.org/10.4129/2cis-pam-com

1. Introduction

Forests exchange large quantities of carbon with the atmosphere through photosynthesis and respiration, and can switch between being a sink or a source (of atmospheric carbon) as consequence of human and natural causes (Brown *et al*., 1996), depending on the stage of succession, specific disturbance or management regime and activities (Masera *et al*., 2003). The rate at which a forest removes CO_2 from the atmosphere (sink), or release it (source) and the quantity of carbon retained as a reservoir (carbon stock) is fundamental to assess for better defining the role of forest in carbon cycle. This assessment should also consider the below-ground stock of carbon (either roots or soil), since on the global scale, forest soils hold about twice as much carbon as tree biomass (Dixon *et al*., 1994), but it is very difficult to evaluate. Studying carbon fluxes (e.g. with Eddy covariance technique) and carbon stocks in total and tree components (e.g surveying dendrometric parameters like diameter at breast height) and in soil (e.g. analysing soil cores) are the main steps to estimate forest carbon cycle. But while eddy covariance techniques represent a non destructive method, the estimate of stocks either in tree components (stem, foliage, roots) or in soil derives from a laborious and destructive work. It results that so far few allometric equations are available over the globe, mainly for above-ground compartments and largely species- and site-specific. Models or tables providing forecasts of timber growth and yield of forests can be used to estimate carbon stocks and accumulation rates, although only a range of management options are covered in published forest yield tables (Broadmeadow and Matthews, 2003). In cases where individual tree data are not available, biomass is normally estimated using biomass expansion factors (BEFs) that use estimated timber volume in combination with other stand-level variables to estimate plot-level biomass (e.g. Tobin and Nieuwenhuis, 2007). A biomass expansion factor can be constant (e.g. from National Inventory database), or it can be function of stand characteristic such as dimensions of the median tree of a stand, merchantable stem volume or stand age, which better reflect the variation according to tree age and stand conditions (Lethonen *et al*., 2004; Petersson *et al*., 2012). Investigation and quantification of tree biomass forms the basis of estimates of forest carbon pools and is therefore directly linked to some of the mechanisms for carbon offsetting and sequestration enshrined in the Kyoto protocol (Pajtik, 2008). Accurate estimates of forest biomass are necessary since as a Party to both the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, the European Community has to submit its annual GHG (greenhouse gases) inventory. During the first commitment period (2008-2012), 37 industrialized countries and the European Community planned to reduce GHG emissions by an average of 5% against 1990 levels. During the second commitment period, Parties aimed at reducing GHG emissions by at least 18% below 1990 levels in the eight-year period from 2013 to 2020. Italy reduced emissions by 7% in the first commitment and agreed to the -11% target against 2012. Under the Kyoto protocol (1997) the UNFCCC invited the Intergovernmental Panel on Climate Change (IPCC) to develop good practice guidance for land use, land-use change and forestry (LULUCF). Under these agreements (IPCC, 2003, 2006) it has become necessary to develop methods to estimate changes in carbon stocks and how these pools will change as a result of management (Mund *et al*., 2002). The information on biomass stock is essential to assess the amount of carbon that exists in the woody vegetation, and its change over time is considered as key characteristic of forest ecosystems (Cannell, 1982). Currently, the methods used for calculating the biomass and carbon stock of trees are imprecise and, in general, they lack estimation of the degree of uncertainty as suggested by the IPCC good practice guidance (Jalkanen *et al*., 2005). Uncertainty arises from the inability to perfectly measure key variables, the necessary use of models to make predictions and the natural variability of ecosystem processes across the landscape (Bolker, 2008). Information on the major uncertainties involved in the calculations of forest carbon stocks and stock changes is needed in the negotiations of the Climate Convention. According to the IPCC good practice guidance, the national reporting of changes of CO_2 equivalents in forest and other woody biomass stocks can be calculated by a default method as the difference between growth and drain (harvest, natural mortality and natural disturbances), or by the stock change method as the change in stocks between two consecutive inventories.

We carried out a plot-based estimate of carbon stock and carbon stock change, quantifying uncertainty in the carbon stock and carbon stock change estimates, analyzing the sources of error for each model adopted. We evaluated differences in the carbon stock and carbon stock change estimates and their uncertainties resulting from the use of three methods. Carbon stock was calculated (1) with the aid of currently applied constant biomass expansion factors (BEFs), (2) by applying age-dependent BEF sand, (3) using biomass equations applied directly to tree-wise data of the sample plots. We evaluated the changes in carbon stock with the two methods suggested by IPCC. Many studies have tended to focus on uncertainty in carbon stock estimates, rather than uncertainty in carbon change over time. Carbon change is arguably the most important of the two metrics as it is the basis for UNFCCC reporting (Pelletier *et al*., 2012).

2. Material and Methods

2.1. Study area

The sample plots considered for the carbon stock estimates are part of a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantation located on the northern coastal chain of Calabria, Tyrrhenian side of south Italy. The locality is called Serra Salinaro (39°, 25’ N, 16°, 2’ E, average altitude 900 m above sea level). It is property of Regional Service of State Forest who forested the area in 1967 mainly with Douglas-fir. The climate of the area is typical Mediterranean, with mild winter and arid summer. For what concerns climatic, geological and dendrometric characteristics we refer to Menguzzato and Tabacchi (1986) and Menguzzato (1989). The plantation was executed with differing planting densities (2500 trees ha^{-1}, 2000 trees ha^{-1}, 1667 trees ha^{-1}, 1250 trees ha^{-1}, 1000 trees ha^{-1}, 833 trees ha^{-1}) and monitored at 15, 25, 30 and 40 ages. We estimated carbon stocks of 2500, 2000 and 1667 trees ha^{-1} densities at ages 15 and 25.

2.2. Carbon stock estimates and uncertainty analysis

We applied three methods for biomass estimates:

1) Tree-wise stem volume was estimated using volume equation for Douglas-fir as reported by the National Italian Forest Inventory (INFC 2005), and stand level volume estimate was then multiplied by a constant biomass expansion factor (Mg m^{-3}) reported by IPCC (2006) for Douglas-fir.

2) Tree-wise stem volume was estimated using volume equation for the Douglas-fir plantation in Calabria (Menguzzato and Tabacchi, 1986), and stand level volume estimate was then multiplied by an age-dependent BEF elaborated for the Douglas-fir in Calabria (Marziliano *et al*., 2015).

3) Tree-wise above-ground biomass was estimated using allometric equations for the Douglas-fir in Calabria (Menguzzato and Tabacchi, 1986).

Height and diameter at breast height (DBH) were used as independent variables in the volume and biomass equations.

For all the models used (volume and allometric equations and expansion factors) the associated relative standard error (RSE) was calculated with the method of error propagation equations as suggested by IPCC (2003). Since the biomass and volume equations were directly applied to tree-wise data of the sample plots, the components of the errors accounted for are the sampling and models errors (assumed to be small). In the BEF-based method, the sampling error in the volume estimate and error of the BEFs are accounted for. While the error associated to the constant BEF cannot be assessed, since it has been drawn from literature without quantitative uncertainty estimates, the error of the age-dependent BEFs was combined with the sampling error for the stem volume of sample plots by density classes to obtain the RSE of the tree biomass stock in a given density class. Then, the RSE of the overall biomass estimate of trees was estimated using the following equation (Jalkanen *et al.*, 2005):

$$r_{tot} = \frac{\sqrt{\left(r_{stock,1} \times W_1\right)^2 + \left(r_{stock,2} \times W_2\right)^2 + .. \left(r_{stock,n} \times W_n\right)^2}}{|W_1 + W_2 + .. W_n|}$$

The carbon stock at age 15 and 25 for the sample plots of any density class was calculated using the approximation that the mass of woody parts contain ~50% carbon (Schlesinger, 1991).

2.3. Carbon stock change estimates and uncertainty analysis

Both the *default method* (also called "*growth and drain*") and the *stock change method* were used to estimate the variations in carbon stock over ten years with the three methods described above. When using the stock change method, to reduce the risk of bias, BEFs should reflect the actual change in stock by incorporating the accumulation of growth per tree fraction with the effects of harvest and natural thinning patterns in one constant (Petersson *et al.*, 2012). The method of age-dependent BEFs enables the ratio of whole tree biomass to stem volume to change with tree size. When using the default method a large bias for both growth and drain is expected when converting volume to biomass, but we reduced it deriving separate age-dependent BEFs for growth and harvest. Uncertainty associated to both methods was estimated using the following equation (Mäkipää *et al.*, 2005).

$$U_{StockChange} = \frac{\sqrt{(U_{Stock_{time2}} \bullet Stock_{time2})^2 + (U_{Stock_{time1}} \bullet Stock_{time1})^2}}{|Stock_{time2} + Stock_{time1}|}$$

3. Results and Discussion

We evaluated the reliability of the biomass estimates obtained with alternative methods (Table 1). The allometric equations by Menguzzato and Tabacchi (1986) are considered to give the most realistic reference values for the biomass of Douglas-fir in Calabria. We chose to use these equations built for a Douglas-fir plantation in the same environmental conditions but with different dendrometric characteristics, even if in 1995 Menguzzato and Tabacchi suggested density-dependent allometric equations for the plantation object of our study (the portion of plantation with differing planting densities). This choice is due to the fact that the allometric equations built in 1986 have been included in all international databases (see Zianis *et al.*, 2005 and http://www.globallometree.org/database/), therefore they are the most used and available reference for Douglas-fir above-ground biomass estimate in Mediterranean Italy.

Allometric equation estimated an above-ground biomass by 67 Mg ha^{-1} and 117 Mg ha^{-1} at age 15 and 25 respectively. Higher density plots had higher biomass stock at age 15, while at age 25 plots with 2000 trees ha^{-1} showed the highest biomass stock. At age 15 the method of age-dependent BEF gave the highest estimate for the total aboveground biomass of trees (81 Mg ha^{-1}, 21% higher than allometric equation estimates, Table 2). The lower value (58 Mg ha^{-1}) was estimated by the method of volume from INFC and constant BEF, whereas at age 25 this method gave the highest biomass estimate (150 Mg ha^{-1}, 28% higher than allometric equation estimates). The age-dependent BEFs overestimated biomass (compared to allometric equations) at both ages. The underestimation at age 15 and the overestimation at age 25 (compared to allometric equations) of constant BEF showed its unsuitableness to reflect the changes in tree allometry. The RSE (%) of carbon stock was higher in the lower density class and at age 15 (Fig. 1). Density and age strongly affect tree allometry, thus the accuracy of biomass estimates strictly depends on the sample trees used for the construction of regression relationships. When the conditions of stands under estimation move away from the conditions of sample plots for the calibration of models, estimates are given with uncertainty.

The estimates by allometric equations showed the lower RSE (5.4% at age 15, 3.6% at age 25), whereas the higher RSE was found for the estimates by volume equation from INFC and constant BEF (6% at age 15, 4.5% at age 25). The *stock change method* was applied to data from two consecutive inventories. The application with allometric equations gave an estimate of carbon stock variation by 2.5 Mg C ha^{-1}y^{-1}. The higher estimate was given by the volume from INFC and constant BEF (3.9 Mg C ha^{-1}y^{-1}). Lower densities showed higher carbon increments. The uncertainty (U%) associated to all the combined models resulted low, with the lowest U% for estimates by allometric equations (3.6%). In the *default method* estimates of both annual losses and growth are needed, thus all components of the drain (losses), such as natural mortality, fuel wood gathering and loggings, as well as growth on an annual basis have to be quantifiable. Since the plots under study are part of a continuous monitoring, we had mortality and current increment data available. The *default method* applied with the three methods gave a carbon change estimate ranging between 3.2 and 4 Mg C ha^{-1} y^{-1} (Fig. 2), about 47% higher than the *stock change method* and to all the methods the U% associated resulted very high (38.3% - 51.3%). This can be explained with cumulative model errors originated by the separate estimates of drain and losses from mortality and increment data.

4. Conclusion

Our results show that the aboveground carbon stock and carbon stock changes of trees estimated with the aid of the constant tree species-specific BEF had higher uncertainty than the estimates obtained by applying biomass equations directly to tree-wise data. With a constant BEF it is usually difficult to obtain a reliable value for the whole tree biomass because stem proportion increases with tree size at the expense of the other tree components.

The age dependent BEFs aim to reduce the bias representing the actual change in stock. The BEF derives from the ratio between above-ground biomass to the stem volume. This ratio vary considerably from year to year (e.g. Lehtonen *et al*., 2004; Marziliano *et al*., 2015), so that, in general, the age-dependent BEFs better reflect variation in tree allometry, as showed in this study, where uncertainty related to stock changes estimated with age-dependent BEF was very low. When accounting for carbon stock at the national level, the positive and negative differences could be balanced, and the overall difference in aboveground biomass between tree-wise estimates and age-dependent BEFs can be even lower. In almost all European countries, constant BEFs without quantitative uncertainty estimates have been applied in the reporting of carbon stock of trees. Consequently, the overall error occurring with use of these constant BEFs cannot be assessed. The age-dependent BEFs applied here were based on regionally representative sampling, and the both model and sampling errors have been accounted for. The IPCC recommends the use of BEFs and provides default values of BEFs for use in the Tier 1 method (less detailed estimates). Our results indicate that the applicability of the available BEFs needs to be carefully evaluated, especially for the possible presence of bias, before they can be used in the national inventories.

Table 1. Relative standard errors (RSE) of biomass estimates according to density classes and uncertainty (U%) averaged by density class. W_1: above-ground biomass estimated using constant BEF and Volume equation from INFC (2005); W_2: above-ground biomass estimated using age-dependent BEF and Volume equation from Menguzzato and Tabacchi (1986); W_3: above-ground biomass estimated using allometric equation from Menguzzato and Tabacchi (1986).

RSE of biomass estimates				
Age	*Density classes (trees ha^{-1})*	*W_1 (%)*	*W_2 (%)*	*W_3 (%)*
15	2500	2.8	2.6	2.3
	2000	5.7	5.0	4.8
	1667	9.3	9.3	9.1
25	2500	1.9	1.7	0.9
	2000	4.6	4.4	4.2
	1667	6.6	5.7	5.6
U (%) of biomass estimates (Average by density classes)				
15		7.3	6.8	6.7
25		5.8	5.0	4.7

Table 2. Above-ground biomass estimates and relative differences in biomass estimates with the three methods. W_1: above-ground biomass estimated using constant BEF and Volume equation from INFC (2005); W_2: above-ground biomass estimated using age-dependent BEF and Volume equation from Menguzzato and Tabacchi (1986); W_3: above-ground biomass estimated using allometric equation from Menguzzato and Tabacchi (1986).

Above-ground biomass estimates				
Age	*Density classes (trees ha^{-1})*	*W_1 (Mg ha^{-1})*	*W_2 (Mg ha^{-1})*	*W_3 (Mg ha^{-1})*
15	2500	60.9	84.2	70.2
	2000	59.4	85.0	70.0
	1667	53.9	73.8	61.0
25	2500	146.4	137.9	114.6
	2000	146.4	144.9	120.5
	1667	155.7	139.4	116.0

(Segue Tabella 2)

Relative differences between biomass estimates				
	Density classes (trees ha^{-1})	*W_3 vs W_1 (%)*	*W_3 vs W_2 (%)*	*W_2 vs W_1 (%)*
15	2500	12.2	-21.3	27.7
	2000	15.4	-21.3	30.2
	1667	11.6	-20.9	26.9
25	2500	-27.7	-20.3	-6.2
	2000	-21.5	-20.3	-1.0
	1667	-34.1	-20.1	-11.6

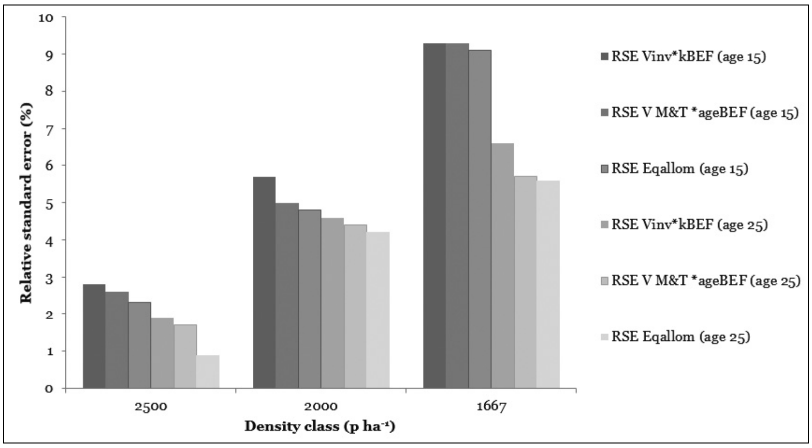

Figure 1. RSE (%) of carbon stock estimates with the three methods according to density classes at ages 15 and 25. Vinv*kBEF: carbon stock estimated from biomass calculated with the first method (volume equation from INFC multiplied by constant BEF); V M&T*ageBEF: carbon stock estimated from biomass calculated with the second method (volume equation from Menguzzato and Tabacchi (1986) multiplied by age-dependent BEF (Marziliano *et al*., 2014)); Eqallom: carbon stock estimated from biomass calculated with the third method (allometric equations from Menguzzato and Tabacchi (1986)).

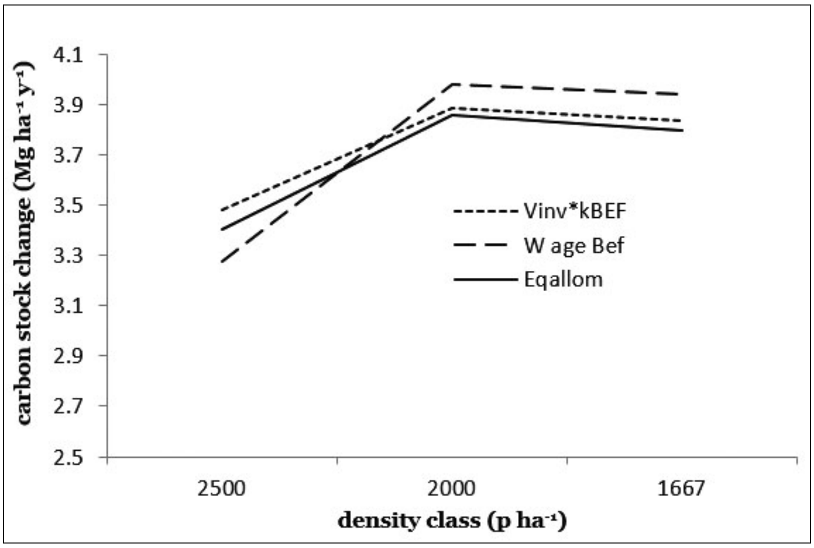

Figure 2. Carbon stock change estimated with the *default method*, considering all three methods used for biomass estimates. Vinv*kBEF: carbon stock estimated from biomass calculated with the first method (volume equation from INFC multiplied by constant BEF); W age BEF: carbon stock estimated from biomass calculated with the second method (volume equation from Menguzzato and Tabacchi (1986) multiplied by age-dependent BEF (Marziliano *et al,* 2014)); Eqallom: carbon stock estimated from biomass calculated with the third method (allometric equations from Menguzzato and Tabacchi (1986)).

RIASSUNTO

Uno studio comparativo tra il metodo "default" e quello dello "stock change" della Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003) per valutare le variazioni di stock di carbonio in foresta

Il Comitato Intergovernativo per i Cambiamenti Climatici(IPCC) ha riportato due metodi per la stima delle variazioni di stock di carbonio negli ecosistemi forestali (nella Good Practice Guidance for Land Use, Land Use Change and Forestry). Il primo metodo è il cosiddetto "default method" e si applica attraverso la sottrazione delle perdite di carbonio dagli incrementi di carbonio per l'anno di riferimento; il secondo è lo "stock change method" e si applica sommando algebricamente gli stock di carbonio di due inventari consecutivi.

In questo studio è stata stimata la variazione di carbonio e l'incertezza associata, in una piantagione di douglasia costituita da plot con diverse densità d'impianto e monitorata alle età 15, 25, 30 e 40. Sono stati utilizzati 3 metodi per la stima della biomassa epigea: 1) equazioni allometriche, 2) fattore di espan-sione della biomassa (BEF) costante e 3) BEF età-dipendenti. Le stime con equazioni allometriche hanno mostrato la minore incertezza, mentre quelle con BEF costante avevano un'incertezza maggiore rispetto alle stime con BEF età-dipendenti. Un BEF costante non riesce a rappresentare le variazioni di biomassa con l'età, poiché all'aumentare delle dimensioni dell'intera pianta il fusto aumenta a spese delle altre componenti. I BEF età dipendenti riducono tale errore riuscendo a rappresentare il cambiamento di stock nell'istante di valutazione.

Il metodo *default* è stato applicato con la più alta incertezza (38.3% - 51.3%) e ha dato stime maggiori del 47% rispetto al metodo *stock change,* che ha mostrato invece incertezze molto basse, da 2.5% (stime con equazione allometrica) a 3.9% (stime con BEF costante).

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