BAYESIAN AND CLASSICAL MODELS TO ESTIMATE ABOVEGROUND STAND BIOMASS IN AN OAK SILVOPASTORAL SYSTEM

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ABSTRACT

Forest biomass is one of the key variables in understating structural and functional dynamics of ecosystem processes. In this paper, four different empirical models derived by Bayesian and classical theory had been applied to the diameter distribution of valonia oak (*Quercus ithaburensis* subsp. *macrolepis*) trees, dominating a silvopastoral ecosystem located at western part of central Greece, to estimate aboveground woody biomass (*M*). The novelty of the present article is based on the fact that error variance in *M*, for each plot and for each model, is also reported along with the average value. Prediction intervals on *M* are rarely being reported in forest biomass studies. Results indicated that *M* ranged from 15.60 to 164.23 ton/ha across 40 plots. At forest scale, the average *M* value derived by four models amounted to 445,848 ton and divided by two defines the aboveground carbon stock value in oak trees. Even though the applied models obtained quite similar mean plot biomass values, prediction intervals differed substantially. Log-linear and non-informative Bayesian approaches provided very large variation in predicted values (*e.g.*, reaching up to 102% difference in plot 31), while non-linear regression equation provided unrealistic (near to zero biomass in plot 35) values. It is therefore concluded that the informative Bayesian model seems to provide biologically sound results and may be preferred over the rest of the methods, but further research is needed to take place in the studied ecosystem to reach unambiguous conclusions. The output of this study may be used, in conjunction to older plot inventories, to deeper understand the carbon dynamics in the specific forest. The adaptation of such an approach may provide qualitative and certified outputs for the fulfilment of Greek reporting obligations in international treaties on climate change. Finally, the obtained *M* values at plot level may be incorporated into the process of forest management plan in order to set appropriate objectives for the sustainable development of valonia oak stands.

Keywords: Aboveground stand biomass, Bayesian regression, Allometry, Kyoto Protocol, Silvopastoral system, *Q. ithaburensis* subsp. *macrolepis*

1. Introduction

A rejuvenated interest for forest biomass estimation has been documented the last 25 years (Hall, 1997; Jenkins *et al.,* 2003; Zianis, 2008; Nickless *et al.,* 2011). In ecological research, forest biomass plays a key role in calibrating and/or validating process based models for primary productivity estimation, for understanding ecophysiological processes and for the sustainable management of forest resources. In the political agenda, the United Nations Framework Convention on Climate Change recognize the importance of forest resources in sequestrating atmospheric CO_2, while Kyoto Protocol (KP) mechanisms put emphasis on the estimation of dry biomass of different forest biomes, since *ca.* 50% of the organic matter consists of carbon. Cannell (1982) reviewed empirical studies conducted in the forested ecosystems across the globe and provided a comprehensive list of biomass values on a per ha basis. In Greece, a limited number of studies on forest biomass estimation has been conducted so far (Tsiouvaras, 1978; Zianis and Mencuccini, 2003; Mitsopoulos and Dimitrakopoulos, 2007; Zerva *et al*.,2008), which do not meet the needs arising from the requirements of Kyoto Protocol procedures

Three methods have been applied to estimate forest biomass: i) the mean plot method, according to which all trees located within the plot are destructively sampled and their biomass is recorded, ii) the mean tree method, according to which the 'mean' tree in a plot is destructively sampled and its biomass is multiplied by the number of trees located within the plot and iii) the application of empirical allometric model - which relate tree biomass (*M*) to its linear dimensions - on the diameter (*D*) distribution of a given plot. In all cases, several plots are being sampled and the average value of all the plots, on a per ha basis, is multiplied by the total forested area to estimate total biomass. The vast majority of forest biomass studies applied the third method which is developed under the classical statistical theory (Sileshi, 2014). However, to derive biologically sound *M* estimates and associated prediction intervals, the parameters in the allometric models should be represented by probability distributions rather than as fixed values, as implied in classical statistics. Thus, quite recently, Bayesian methods have been developed to obtain tree biomass allometric equations (Zapata-Cuartas *et al.*, 2012; Zhang *et al.*, 2013), which is believed to hold valid irrespectively of tree growing conditions.

Prediction errors arising from the application of empirical allometric equations in forested ecosystems and woodlands are not usually reported in biomass studies and metrics associated with the reliability of average *M* intervals are not fully documented (see Nickless *et al.*, 2011 as an exception). Forest biomass errors usually originate from the incomplete sampling of forest stem density and the statistical technique being used. The plethora of forest biomass studies were realised for trees growing in closed stands and only a limited number is related to open grown trees. Specifically in Greece a harmonised approach to estimate stand *M* across the diverse forested ecosystems, in order to comply with the KP requirements, has not been developed yet.
In this article a methodology is presented to estimate forest aboveground woody biomass and its associated prediction intervals in a silvopastoral system, mainly dominated by open grown valonia oak (*Q. ithaburensis* subs. *macrolepis* L.) trees. Four different empirical allometric equations originated from the studied area, had been applied in the recorded diameter distribution of the aforementioned species and *M* predictions were therefore derived. The obtained results can be used in the forest management planning activities as well as in the reporting procedure of KP mechanism.

2. Material and methods

2.1. Study area

The studied forest is located in the western part of central Greece and about 23 km west of Agrinio town. The heterogeneity of the landscape, consisting of agricultural, grazing and forest land, characterises the studied and in general the valonia oak silvopastoral systems in Greece (Pantera *et al.* 2008). The previous forest management plan aimed at the production of acorns and fuelwood. Protection measures were not firmly applied and in turn the natural ecosystem has been under degradation for about 40 years. The present managerial objectives focus on the enhancement of several ecological functions and the restoration of the deteriorated ecosystem by protecting natural regeneration and improving standing volume potential for the oak stands. The forested stands cover an area of more than 4400 ha, while partially forested area amounts to 3300 ha. The stands are even-aged and range from 150 to 290 years (on average 200 to 240 years across the valonia forest). There are individual trees of over 400 years old in the forest with regular growth rate (Papadopoulos and Pantera, 2013).

2.2. Diameter distribution of valonia oak trees

In total, 40 plots located across the stands of the studied forested area had been established under a randomised stratified regime. The area of the plots varied between 0.175 and 0.5 ha according to local conditions and tree density. The plots follow a rectangular shape with the smaller dimension perpendicular to the isolines. The breast height diameter (*D*), measured at 1.3 m aboveground, was recorded in each plot for trees with *D* > 10 cm, and subsequently grouped in 2 cm classes.

2.3. Aboveground woody biomass predictions

To derive aboveground woody biomass (*M*) prediction for trees located in each plot, the diameter distribution was applied in four different empirical allometric models, previously developed for the studied area. Log-linear regression (LR) and non-linear regression (NLR) techniques were developed within a classical statistical approach, while a non-informative (NB) and an informative (IB) model were built based on Bayesian theory. The error in LR model follows a normal distribution in log-scale and a log-normal probability is obtained, after appropriate transformation, in normal scale (after Nickless *et al.*, 2011). In NLR approach, appropriate weights had been applied and the error is allowed to follow a normal probability distribution. The priors for the allometric parameters and the error variance in the NB model were given appropriate conjucate probability distributions as recommended by McCurthy (2009). Priors for the allometric parameters in IB approach were derived by Zapata-Cuartas *et al.* (2012), while error variance was modelled by the application of Ducey *et al*. (2009) formula. In NB and IB approaches, the predicted *M* value, for a specific *D*, follows a log-normal distribution and the prediction intervals for *M* were straightforwardly obtained through the WinBugs software based on Markov chain Monte Carlo methods (Spiegelhalter *et al*. 2007).

Predictions of *M* obtained for different *D* classes are aggregated and the sum is divided by the occupied area in order to derive a ton/ha value for each plot. It is expected that the distribution of the sum of lognormal variables may be approximated by a lognormal probability density function with mean value equal to the summation of the individual mean values (in this case *M* prediction from each class) and variance equal to the sum of variance from each class. Thus, according to Zou *et al*. (2009), the estimation of predicted intervals at plot level, for LR, NB and IB was based on the following formulae (application of equations 3 and 4 in the aforementioned reference for n =1)

$$\text{Lower limit of } M_P = M_P \exp[-(z^2_{1\text{-}a/2}\, v + (v/2)^2)^{1/2}] \quad (1)$$

$$\text{Upper limit of } M_P = M_P \exp[(z^2_{1\text{-}a/2}\, v + (v/2)^2)^{1/2}] \quad (2)$$

where M_P denotes the sum of *M* from individual classes, *v* the sum of *M* variances (at log-scale) associated to each class and $z_{1\text{-}a/2}$ denotes the respected quantile of the standard normal distribution. For NLR, prediction interval of M_P follows a normal distribution with mean equal to the sum of *M* obtained from individual *D* classes and the variance is equal to the sum of variances of *M* obtained in different *D* classes.

3. Results

The recorded plots present variable structural characteristics in terms of stem density, basal area and *D* range on per hectare basis. Three groups may be distinguished (excluding plot 35). In the first one, plot density varies from 32 to 360 trees/ha, total basal area from 7.39 to 13.90 m^2/ha and *D* range from 10-30 to 32-70 cm (plots 3, 5, 21, 25-29, 31-34, 38-40). In the second group (plots 1, 4, 7, 12, 14-18, 22-24, 30, 37), plot density varied from 53 to 204, total basal area from 15.38 to 19.73 m^2/ha and *D* range from 20-80 to 48-80 cm. In the third class, plot density ranges from 87 to 133 trees/ha, total basal area from 20.17 to 23.46 m^2/ha and *D* range from 18-80 to 28-84 cm (plots 2, 13, 19, 20). For plot 35, plot density is 440 trees/ha, total basal area equals to 4.80 m^2/ha and *D* ranges from 10 to 20 cm. In each plot, aboveground dry woody biomass (M_P) per hectare, was not statistically different for the four empirical models (namely NLR, LR, IB and NB) as illustrated in Fig. 1.

The largest M_P value was amounted to 164.23 ton/ha in plot 10 and the smallest one, excluding plot 35, was 50.25 ton/ha in plot 5. These values fell within the range of a large compendium of aboveground forest biomass across the globe, compiled by Cannell (1982). In plot 35, M_P ranged from 15.60 (IB) to 17.92 (NLR) ton/ha and attained the minimum value across the plots. The largest M_P value in 38 plots (except plots 32 and 35) was recorded by LR model, following by NB, NLR and IB approaches. In plots 32 and 35 the largest M_P value obtained by NLR, following by LR, NB and IB. To derive aboveground woody biomass at forest scale, the total forested area in each stand was multiplied by the mean value of the corresponding plot located in the specific stand. The obtained values were summed up and results indicated that the minimum aboveground woody biomass (from IB) equalled 431,803 ton and maximum value (from LR) was 464,631 ton. The average value across the four models amounted to 445,848 ton.

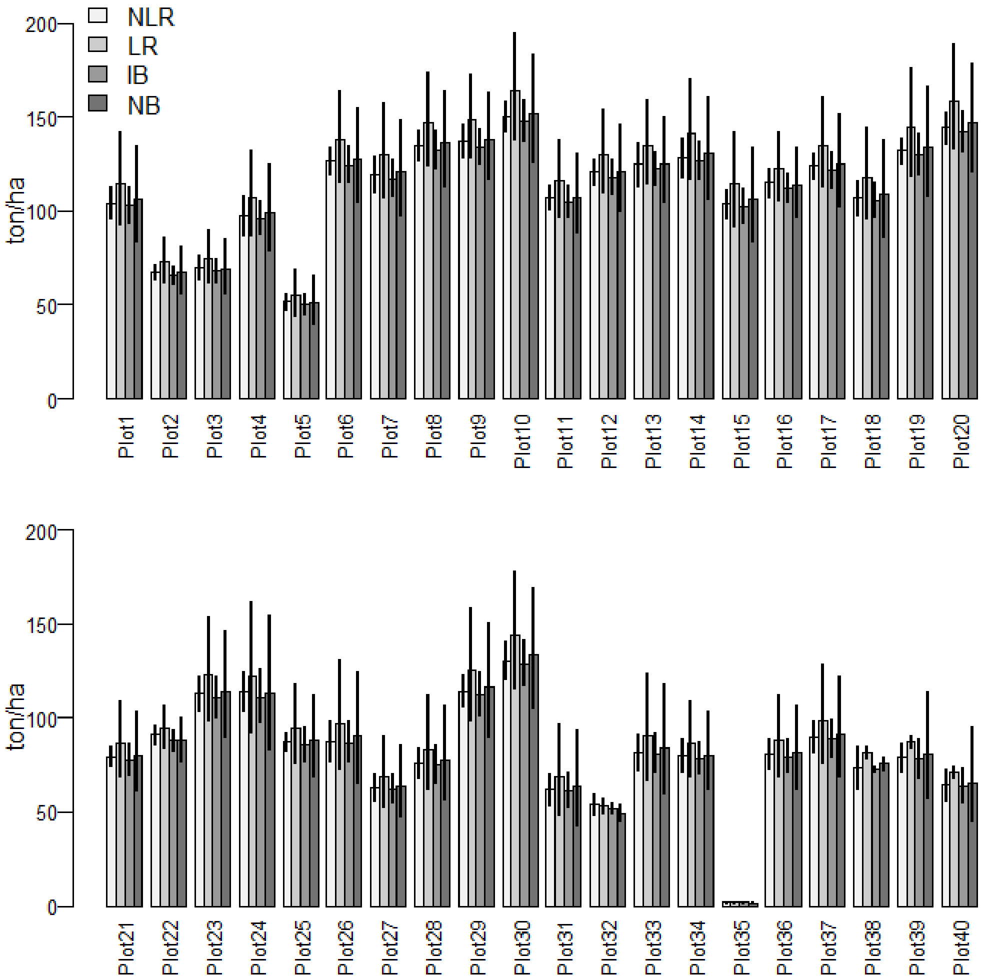

Figure 1: Aboveground plot woody biomass on a per hectare basis under four different allometric models. Bold lines denote prediction intervals at 95% level.

4. Conclusions

A straightforward approach to estimate aboveground woody biomass in a valonia oak dominated silvipastoral system is described in this paper. Four different empirical allometric models were applied in the diameter distribution of 40 plots and mean biomass values along with prediction intervals were derived. Even thought the applied models derived quite similar mean plot biomass values, prediction intervals differed substantially. Log-linear and non-informative Bayesian approaches provided very large variation in predicted values (*e.g.*, reaching up to 102% difference in plot 31), while NLR equation may provide unrealistic (near to zero biomass in plot 35) values. The informative Bayesian model seems to provide biologically sound results and may be preferred over the rest of the methods, but further research is needed to take place in the studied ecosystem to reach unambiguous conclusions. Finally, it should be pointed out that the integration of allometric models into the forest management inventory is a straightforward low-cost procedure. The output of this study may be used, in conjunction to older plot inventories, to deeper understand the carbon dynamics in the specific forest. The adaptation of such an approach may provide qualitative and certified outputs for the fulfilment of country’s reporting obligations in international treaties on climate change.

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