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Research paper

Artificial neural network application in comparison with modeling allometric equations for predicting above-ground biomass in the Hyrcanian mixed-beech forests of Iran

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ABSTRACT

There is a lack of accurate protocol for predicting aboveground biomass (AGB) and carbon pools in Iran's Hyrcanian forests. This study aimed to figure out the most accurate model for the site-specific prediction of AGB. Site-specific allometric equations on the basis of power-law function and artificial neural network (ANN) type of multi-layer perception based on back-propagation training algorithm were developed to model engineering application for predicting the AGB. The AGB was measured by destructively sampling and weighing 174 fallen trees in the field and breast height diameter (D), total height (H) and basic wood density (ρ) were recorded as explanatory variables for developing allometric equations and ANN models. The findings showed that the simple allometry model including the geometrical variable ($D^2H\rho$) was a highly accurate predictor with the highest certainty among the allometric equations (Adj. $R^2 = 0.91$; CF = 1.04; AIC = −430). Furthermore, the product of$D^2H\rho$ and the primary variables were the effective input nodes for training algorithm in the ANN. Statistical issues such as collinearity among the parameters, reliability of parameters and application of dubious empirical equations (…) were the main problems for developing allometric equations; however, there was no limiting factor for designing the models in ANN. According to training and testing data set, the best architecture designed in the ANN model was composed of two hidden layers and 20 neurons in each layer including function of tangent sigmoid. The results showed that the best designed model in ANN predicted the AGB with the higher accuracy (RMSE% = 7.3) than allometric equations. Thus, ANN is offered rather than traditional protocols for predicting the AGB in natural forest ecosystems.

1. Introduction

More accurate estimation of trees aboveground biomass (AGB) in forests is needed to determine commercial use of forest production, stand density, fuel (and bio-energy) contribution and role of forest biomass in global carbon cycle [1]. According to increase of CO_2 emission and current interest in forest carbon stocks to design a comprehensive plan to deal with global warming, modeling allometry based on statistical tools has been increasingly emphasized to estimate AGB of trees in forest ecosystems [2,3]. First outlined by Otto [4], the term 'allometry' is the study of the relationship of body size to shape, physiology and behavior in biology associated with differential growth rates of the parts of a living organism's body. Tree allometry is represented by allometric equations in the form of regression models reflecting the empirical relationship between biomass and easily measured dendrometrical variables of trees [3,5,6]. The most commonly used function to estimate tree AGB is power model of $Y = ax^b$ considered simple allometric equation which in turns 'a' and 'b' are integrating and scaling parameters, and 'x' is the tree dendrometrical variable, often diameter [3,7–9]. There are major concerns with selecting the best regression model to estimate tree AGB in natural forests. Stevens [10] declared that because many growth data empirically turned out to align along a straight line when plotted in log-transformed scales, power models have played a substantial role in allometry [3]. In contrast, others feel allometry should go beyond power-law models because the growth data does not exactly align along a straight line in log–log plots [3,11]. Furthermore, Sileshi [8] argued that some allometric equations are dubious equations due to not taking consideration some validation indicators like collinearity among the predictors and reliability of parameters estimate.

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To reexamine the issue of whether or not power-law models are the best predictors for biomass estimation, artificial neural network (ANN) based-system was used to be compared to traditional allometric method (regression analysis).

There has been a substantial increase in the interest of artificial neural networks (ANNs) during the last 15 years [12]. Considering complexity of relationships between the response and explanatory variables and of different views and major concerns associated with allometric equations application for prediction of trees AGB, ANN may be the best alternative to decrease obscurity of biomass estimation. ANNs are one of the most commonly modeling techniques having highly interconnected structure like human's brain systems that emulate the operations and connectivity of biological neurons [13,14]. There are complex relationships of tree dendrometrical dimensions to biomass in the natural forest ecosystems. Since the exact nature of such relationships in the natural ecosystems is unknowable, it is expected that the ANN models can be more accurate than regression models. Moghaddasi et al. [15] reported efficiency of ANN to handle non-linear relationships in data even when there are conflicting relationships of response variable to explanatory variables. One of the disadvantages of the ANN application is its inability for predicting response variable with high certainty when there are few data or absence of sufficient data volume. In the other words, unlike allometric regression models which can be formulated based on few data [9,16–18], ANNs modeling requires large data sets to access the reliable certainty for biomass estimation.

The current study was conducted in one of the Hyrcanian mixed-beech forests in the north of Iran. Mixed-beech forests are one of the most important natural ecosystems with the highest commercial value and contribute to the majority of the volume stock and bio-energy in the Hyrcanian forests [19]. Therefore, it is expected that the mentioned forests account for considerable contribution to AGB and carbon sequestration across the Hyrcanian forests. Species- or site-specific allometric equations have not been developed for estimating the AGB in large scales of the natural Hyrcanian forests to find out which internationally standard protocol or model has much higher certainty for prediction of AGB. This study aimed to introduce technique of ANN application compared to site-specific allometric equations to verify and examine accuracy and certainty of AGB prediction in natural forests.

2. Material and methods

2.1. Study area

This study was conducted in Glandroud forests district (36°27′30″–36°32′15″ N and 51°53′ 25″–51°57′ 25″ E), located in north of Iran within Hyrcanian forests, which has the total area of 1521 ha with altitudes range between 940 and 1520 m a.s.l. The studied forests belong to the beech community widely distributed in most parts of the district. The bedrock is of lime stone and the soil texture ranges from silty clay loam to clay. Meteorological parameters directly measured between 1985 and 2014 at Nowshahr Meteorological Station, located in 36° 39′ N and 51° 30′ E, and 7.5 m above the level of the Caspian Sea [20], indicated that mean annual precipitation and temperature of this studied area were 1293.5 mm and 16.1 °C, respectively.

2.2. Data

In the forest industry and reform sector, Oriental beech (*Fagus orientalis* Lipsky), Hornbeam (*Carpinus betulus* Lipsky), Alder (*Alnus subcordata* C.A. May), Caucasian Persimmon (*Diospyros lotus* Lipsky), Ironwood (*Parrotia persica* DC. C.A. May), Maple (*Acer velutinum* Boiss.), Oak (*Quercus castaneifolia* C.A. May), Caspian Zelkova (*Zelkova carpinifolia* Pall. Dippel), and Ash (*Fraxinus excelsior* Lipskey) were destructively sampled. All the trees were selected following lines of exploitation carried out by the Forestry Department of Nowshahr. A total of 174 trees covering the above species were directly felled to measure AGB. Based on field measurements, three different breast height diameter (D) classes of trees were recognized: 30–60, 60–80, >80 cm (these are commonly used diameter classification system in Iran's Hyrcanian forests). For each standing sample tree the *D* and total height (*H*) were first recorded. The felled trees were separated into bole and crown and were weighed in the field using a steelyard to the nearest 0.1 kg. In addition, large branches with basal diameter greater than 10 cm were separately weighed [21]. Due to the harvesting in the winter, the leaves and stump of each sampled tree were not considered during the measurement. A 2-cm thick disk was cut from the base of each 2-m section of trees stem and of large branches [9,21,22]. Then, two sub-samples of $2 \times 2 \times 2$ cm^3 were extracted from the opposite sides of each disk and oven-dried at 105 °C until weight stabilized [16]. Moreover, for the small branches of each felled tree which were also weighed in the field, three branches were randomly selected to determine the dry mass [21]. Basic wood density (ρ) was measured by ratio of dry mass to fresh volume of the wood sample. Biomass of each component of each sampled tree was calculated by multiplying the wet mass by the dry mass/wet mass ratio of each woody sample extracted from the disk [23].

2.3. Modeling allometric equations

For allometric studies, two protocols consisting of multiple linear regression (MLR) and curve estimation regression (CER) analysis were used to represent the relationships between response value (AGB) and tree dendrometrical variables such as *D*, *H* and ρ. Linear regression provides estimates and other inferential results for the parameters as following [24]:

$$Y_n = \beta_1 x_{n1} + \beta_2 x_{n2} + \ldots + \beta_p x_{np} + Z_n \rightarrow (x_{n1}, \ldots x_{np})\beta + Z_n \quad (1)$$

In this model, the random variable Y_n, representing the response for case *n*, has a deterministic part and a stochastic part. A nonlinear regression model is presented as following [24]:

$$Y_n = f(x_n, \theta) + Z_n \quad (2)$$

where *f* is the expectation function and x_n is a vector of associated independent variables for the *n*th case. This model is of exactly the same form as model (1) except that the expected responses are nonlinear functions of the parameters.

Many studies reported and concluded that simple power function including *D* is the best model to estimate trees biomass in forest ecosystems [8,9,17,25]. The power-law parameters were extracted from either the non-linear regression ($Y = a(D)^2$) or linear regression based on log-transformed power model $Y = ln(a) + bln(D)$ [8]. Log–log scale introduces systematic bias which is corrected by correction factor (CF) depending on standard error of estimate (*SEE*) as following [6,9]:

$$SEE = \sqrt{\frac{\left(\ln Y_i - \ln \widehat{Y}_i\right)^2}{n - p}} \quad (3)$$