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Sincerely,

Mike Renslow
Technical Editor – PE&RS
2880 Bailey Hill Road
Eugene, OR 97405
Tele: (541) 335-1251
E-mail: renslow76@comcast.net
Abstract
The objective of this study is to develop a method based on multivariate relevance vector regression (MVRVR) as a kernel-based Bayesian model for the estimation of above-ground biomass (AGB) in the Hyrcanian forests of Iran. Field AGB data from the Hyrcanian forests and multi-temporal PALSAR backscatter values are used for training and testing the methods. The results of the MVRVR method are then compared with other methods: multivariate linear regression (MLR), multilayer perceptron neural network (MLPNN), and support vector regression (SVR). The MLR model showed lower values of R2 than the three other approaches. Although the SVR model was found to be more accurate than MLPNN, it had the lowest saturation point of 224.75 Mg/ha. The use of MVRVR model significantly improves the estimation of AGB (R2 = 0.90; RMSE = 32.05 Mg/ha), and the model showed a superior performance in estimating AGB with the highest saturation point (297.81 Mg/ha).

Introduction
Biomass is the total mass of living matter within a given unit of an environmental area. It is thus a measure of the carbon stock of an ecosystem, and the importance of estimating the amount of biomass has been reported in a number of studies (Heimann and Reichstein, 2008; Le Quere et al., 2009; Peregon and Yamagata, 2013; Simard et al., 2006; Tanasea et al., 2014). In this respect, biomass mapping is an important practical tool for use in forest management, and in particular for use in forest monitoring and making assessments of deforestation processes. The most accurate way of AGB retrieval are forest inventories which use field-based measurements (e.g., tree height, diameter at breast height) to calculate the biomass on the basis of allometric equations (Chave et al., 2005; Lu, 2006). Satellite observations can also be used, and although they have the advantage of enabling monitoring of large and remote areas, their measurements are less accurate (Lu, 2006).

Polarimetric Synthetic Aperture Radar (PolsAR) provides information on changes in the polarization state of electromagnetic waves reflected from the earth surface that can be exploited to extract information for identification and classification of different natural features, as each polarization is sensitive to different surface characteristics and properties. In forestry, one of the most important applications of PolsAR data processing is its use in biomass estimation (Carreiras et al., 2012; Englhart et al., 2012; Huang et al., 2009; Lucas et al., 2010; Minh et al., 2014; Ormsby et al., 1985; Sandberg et al., 2011; Soja et al., 2013; Ticehurst et al., 2004). Previous studies have indicated that radar backscatter of PolsAR data at lower frequencies has a positive correlation with the AGB of forests, especially in the cross-polarized Horizontal-Vertical (HV) backscatter (Englhart et al., 2012; Dobson et al., 1992; Imhoff and Gesch, 1990; Imhoff, 1995; Fransson and Israelsson, 1999; Santos et al., 2002; Saatchi et al., 2007; Sader, 1987; Sartori et al., 2011; Lucas et al., 2006). These studies have shown that when used in conjunction with a suitable type of polarization and a robust estimation model, multi-temporal SAR data recorded during the dry season can provide an improvement in the accuracy of AGB estimations (Hame et al., 2013; Townsend, 2001). Thus, in order to find a mapping function between AGB of forests and SAR backscatters, linear regression methods (Kasischke and Bourgeau-Chavez, 1997; Mitchard et al., 2009; Watanabe et al., 2006), artificial neural networks (ANN) (Amini and Sumantyo, 2009; Del Frate and Solimini, 2004), and support vector regression (SVR) (Camps-Valls et al., 2006; Enghaert et al., 2012; Monnet et al., 2011) have all been proposed.

Although multivariate linear regression (MLR) is a comparatively comprehensible model, some studies (Mitchard et al., 2009; Watanabe et al., 2006) have indicated that the results of MLR model may have been underestimated because of its linear nature and improper target results. In addition, the multi-layer perceptron neural networks (MLPNN) model proposed for AGB estimation by Amini and Sumantyo (2009) tended to overfit data when few observations were used in the training data set. Wang et al. (2008) reported that deep neural nets with a large number of observations are very powerful machine learning systems; overfitting can be a serious problem in such networks when only a few observations are included. In addition, large networks are slow to use, making it difficult to deal with overfitting by combining the predictions of many different large neural nets at test time. Englhart et al. (2012) reported that the SVR model is the best machine learning method for biomass estimation, but the results have not yet been acceptable at high biomass levels (Amazon rainforest, Pacific temperate rainforest, Congo rainforest, and Sinharaja forest are well-known forests which have high biomass level) where radar backscatters eventually reach saturation level.

The introduction of a new technique in relation to a model that used fewer observations would be very useful in making forest AGB estimations, as it would deliver the advantage of being less time-consuming and would simplify the need for ground data collection. Therefore, in consideration of the limitations of the regression models mentioned above, we propose a Bayesian kernel-based regression model known as multivariate relevance vector regression (MVRVR) (Thyananthan et al., 2006), which is a multivariate version of the relevance vector machine proposed by Tipping (2001). This approach utilizes a number of relevance vectors (scarcity concept) to synthesize the output values used for image analysis, and in addition, uses a limited amount of ground data (Pal and Foody, 2012; Sharifi and Amini, 2015).

Alireza Sharifi and Jalal Amini are with the Department of Remote Sensing, Faculty of Survey Engineering and Spatial Information, University of Tehran (jamini@ut.ac.ir).

Ryutaro Tateishi is with the Center of Environmental Remote Sensing, Chiba University, Chiba, Japan.

Estimation of Forest Biomass Using Multivariate Relevance Vector Regression
Alireza Sharifi, Jalal Amini, and Ryutaro Tateishi

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The objective of this paper therefore, is to develop a method based on multivariate relevance vector regression (MVRVR) as a kernel-based Bayesian model for above-ground biomass (AGB) estimation, and then to compare the results with those of three methods, MLR, MLPNN, and SVR. In this study, we use ALOS PALSAR Fine Beam Dual (FBD) imagery with HH and HV polarizations acquired in 2007, 2008, and 2010. The study area is that of the western Hyrcanian forests of Iran (south west of the Caspian Sea). Field AGB data relating to 110 plots are provided from 2007. The paper is organized as follows. The next Section provides details of the materials and methods used in the research, including a brief description of the study area, field measurements, ALOS PALSAR data, modeling, and validation of the models; followed by the results and corresponding discussion, respectively. The final Section presents the conclusions.

Materials and Methods

Study Area

The study area is located within the Hyrcanian forests of Iran (Plate 1), which are situated southwest of the Caspian Sea between 37.3° to 37.65° N and 48.7° to 49.1° E (upper panel in Plate 1), in the temperate zone. The forests grow at elevations ranging from 600 m to 950 m above mean sea level, and the region is one of the rainiest areas in Iran. As such, it is a suitable habitat for broadleaved trees, and is home to four main tree species: Fagus orientalis, Alnus serrulata, Carpinus betulus, and Ulmus glabra.

Field Measurements

In the summer of 2007, field work was undertaken in the study area. This consisted of measuring tree height and diameter at breast height (DBH) in 110 plots. The DBH was measured using a simple tape scale, known as a diameter tape, at a height of 1.3 m above the ground. Tree heights were calculated using a hypsometer based on the geometric method (West, 2009). The geographic coordinates of each plot were obtained using a Global Positioning System (GPS), which enabled location of the plots (errors up to 3 to 5 m) (lower panel in Plate 1 (lower panel)).

The plots each measured 50 m x 50 m, and contained four dominant species: Fagus orientalis, Alnus serrulata, Carpinus betulus, and Ulmus glabra. The number of species in each plot was measured to achieve a desired precision level. Table 1 summarizes the field measurements and resulting calculations.

<table>
<thead>
<tr>
<th>Dominant Species</th>
<th># of plots</th>
<th>Mean height (m)</th>
<th>Mean DBH (cm)</th>
<th>Mean AGB (Mg.ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fagus orientalis</td>
<td>39</td>
<td>27</td>
<td>58</td>
<td>39.2</td>
</tr>
<tr>
<td>Alnus serrulata</td>
<td>28</td>
<td>22</td>
<td>46</td>
<td>16.9</td>
</tr>
<tr>
<td>Carpinus betulus</td>
<td>23</td>
<td>21</td>
<td>45</td>
<td>27.1</td>
</tr>
<tr>
<td>Ulmus glabra</td>
<td>20</td>
<td>19</td>
<td>35</td>
<td>17.2</td>
</tr>
</tbody>
</table>

The number of speckles was first reduced using the proposed algorithm by Sharifi et al. (2015), and the equivalent number of looks (ENLs) (Equation 2) was then estimated over a set of homogeneous areas belonging to the species classes (Woodhouse, 2005):

\[
\text{ENL} = \pi \frac{\mu^2}{\sigma^2}
\]

where \(\mu\) and \(\sigma^2\) are the mean and variance of the backscatter intensity values. The estimated ENL mean values were 3.12 and 3.35, for the HH and HV polarizations, respectively.

The ALOS images were first geocoded using tie points and orbit parameters. The study area is very mountainous, and therefore without topographic normalization, the backscatter values would be related to both slope and backscatter (Guo et al., 2010). The topography normalization was undertaken using an extracted DEM from a 1:25 000 scale topographic map. The RMSE values of geolocation for three images were 0.24, 1.59, and 0.87 pixels, respectively. Plate 1 (lower panel) shows the processed PALSAR image acquired in 25 July 2010. Also, topographic normalization of backscatters values can be calculated using Equation 3, as reported by Carreiras et al. (2006):

\[
\sigma_j^H = \sigma_j^H \frac{A_{\text{flat}} \cos \theta_{\text{ref}}}{A_{\text{slope}} \cos \theta_{\text{loc}}} \frac{\log_{10}(\text{DN}) + CF}{10}
\]

where \(\sigma_j^H\) and \(\sigma_j^H\) represent the topographically normalized and uncorrected backscatter intensity, respectively; \(\theta_{\text{ref}}\) is the incidence angle at a reference location (e.g., mid-swath); \(\theta_{\text{loc}}\) is the local incidence angle, \(A_{\text{flat}}\) and \(A_{\text{slope}}\) are the SAR pixels size for flat terrain and the true local SAR pixel size, respectively.

Digital numbers (DNs) were converted to sigma naught values to obtain backscatters using the following Equation 4 (Shimada et al., 2009):

\[
\sigma_j^H = 10 \left( \log_{10}(\text{DN}) + CF \right)
\]

where \(CF\) is the calibration factor, set at -80.2 for HV polarization and at -83.2 for HH polarization.

The ALOS PALSAR backscatter coefficients were then temporally averaged, because the average values of multi-temporal backscatter of the dry season are very stable, and there is little variation with the climatic conditions (Englard et al., 2011; Townsend, 2001). Figure 1 shows the average of the HH- and HV-polarized backscatters versus AGB. It can be seen from this figure that the backscatters increase with the AGB up to a point of approximately 150 Mg.ha⁻¹, and thereafter do not increase in line with higher values of AGB.

AGB Estimation Modeling

In order to investigate the relationship between PALSAR intensity backscatter and the AGB, four different models were
used: MLR, MLPNN, SVR, and MVRVR. The results obtained were then compared to examine their ability to retrieve the AGB from multitemporal ALOS PALSAR imagery. In this respect, 80 percent of all the field data sets were chosen for training, and the remaining were used to validate the models through a five-fold cross-validation approach, in which the original sample was randomly partitioned into five equal size subsamples. Then, a single subsample was selected as validation data for testing the model, and the remaining subsamples were used as training data. The cross-validation process was then repeated once for each of the five subsamples to obtain the validation data (Geisser, 1993).

In the MLR model, the backscatter values were entered into a regression function to calculate the RMSE and $R^2$ values. MLPNN is a type of machine learning model that acts as a function approximation technique for estimating the nonlinear behavior of the relationship between two separate data spaces. To begin with, let us propose that $x$ is a vector of the source space (multitemporal ALOS PALSAR backscatter values) and that AGB is a scalar quantity in the target space (forest biomass values). In this respect, the relationship between source and target spaces can reasonably be written as:

Plate 1. (Upper panel) Position of study area (red), and (Lower panel) ALOS PALSAR FBD scene (yellow); (lower panel) a topographically normalized PALSAR image of the study area taken on 25 July 2010 (R: HH, G: HV, B: HH-HV; Light Green: Forest) with location of plots (black circles).
where \( I \) correspond to the node value, \( n \) is the source space dimension or number of input data \((x_i)\), \( w_i \) is the weight of an input signal, and \( b \) is the bias associated with the target scalar (node).

The model parameters and bias term for each node were then optimized using a network activation function, and then these optimal model parameters and biases minimized the error between the desired output and the actual one for all training patterns. Finally, the output layer provided the response of the neural network to the pattern vector submitted in the input layer (Mas and Flores, 2008).

In this research, the multitemporal ALOS PALSAR backscatter values were used as a source to estimate the AGB as a target space, and the number of hidden layers and iterations were set to 2 and 1000, respectively.

The Support Vector Machine is a nonlinear kernel-based technique for classification, regression, and function approximation in the multidimensional space of the data (Mountrakis et al., 2011). The SVR function for biomass estimation is defined as:

\[
AGB = \sum_{i=1}^{n} \alpha_i k(x_i; x) + b 
\]

where \( k(x_i; x) \) is a kernel function with the training vector \( x_i \), and \( \alpha \) is Lagrange multiplier.

A radial basis function (RBF) kernel is typically chosen as a kernel function:

\[
K(x, x) = \exp \left( \frac{(x - x_i)^2}{\sigma^2} \right)
\]

where \( \sigma \) is a scale parameter chosen based on the training data, and a unit vector could be concatenated with kernels as the intercept (further details can be found in Rabe et al., 2009).

Although SVR parameters are specified to be fixed for any predefined numbers, they should be defined using a cross validation approach. Further, because SVR is very sensitive to parameters, it is very important to define them properly. Hence, the accuracy of the SVR model can be significantly improved by choosing the correct bias for the parameters. As previously stated, the input vectors for MLPNN, SVR, and MVRVR in this paper are the multitemporal ALOS PALSAR backscatter values.

Estimation of AGB Using the MVRVR Method

As described in the Introduction, in this study we applied an MVRVR model to estimate the forest AGB. It is important to mention that MVRVR is a multivariate regression approach, which means that a MVRVR model can also be used to find the non-linear mapping function among input (source) and output (target) data, even if their (input and output) dimensions are greater than one. The simplified MRVM model for the target point, for example AGB values, with one dimension is defined as:

\[
AGB = W\Phi(x) + \varepsilon
\]
where the posterior on $W$ is proportional to the product of the Gaussian distribution of weight vectors, which correspond to each target element as follows:

$$p(W|AGB, S, A) \propto p(AGB|W, S)p(W|A) \propto \prod_{i=1}^{n} p(w_{i}|\mu_{i}, \Sigma_{i})$$ (11)

where $\mu = \sigma_{A}^2 \Sigma_{A}^{T} AGB_{i}$ and $\Sigma = (\sigma_{A}^2 \Sigma_{A}^{T} \Phi + A)^{-1}$ are the model parameter ($w$) mean and the covariance of distribution, respectively. The optimum values for the hyperparameters, $\hat{A} = \text{diag}(\hat{a}_{1}^{opt}, \hat{a}_{2}^{opt}, \ldots, \hat{a}_{m}^{opt})$, are then used to obtain the posterior mean and covariance, as follows (Thayananthan et al., 2006):

$$\mu_{i}^{opt} = (\sigma_{A}^2)^{-1} \Sigma_{opt}^{T} \Phi^{T} AGB_{i}$$ (13)

$$W_{opt} = \text{diag}(\mu_{1}^{opt}, \mu_{2}^{opt}, \ldots, \mu_{m}^{opt})$$ (14)

The coefficient of determination ($R^2$), the root mean square error (RMSE), the mean absolute error (MAE), and the mean error (ME) are calculated as the accuracy statistics. The predicted AGB is underestimated when ME is negative and overestimated when ME is positive (Englhart et al., 2012):

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(f_{i} - y_{i})^2}{n}}$$ (15)

$$\text{MAE} = \frac{\sum_{i=1}^{n}|f_{i} - y_{i}|}{n}$$ (16)

$$\text{ME} = f_{i} - y_{i}$$ (17)

where $f$ is predicted AGB, $y$ is measured AGB, and $n$ is number of predicted AGB

### Results

The models were implemented using Matlab 2013, and the results were averaged from the results of ten iterations. The estimation of AGB from SAR data using the MLR model resulted in Equation 18:

$$AGB = 64.4 + 47.76 \times 10^{3}\exp(\sigma_{F1H}) + 4.21 \times 10^{3}\exp(\sigma_{F1W})$$ (18)

where $\sigma$ is the average of multi-temporal backscattering coefficients.

In the MLPNN model, the actual multitemporal backscatter values of the input layer were converted to the corresponding output values with the assumption that the number of hidden layers is two. In addition, the SVR model was used to estimate the AGB with a kernel function parameter, $g$, equal to 1.5 and a regularization parameter, $C$, equal to 50. The error tolerance was set to 0.001, and the number of support vectors was 88. The MVRVR model was modified using the Gaussian kernel function with a scale parameter, $\sigma$, equal to 1.85, where the number of relevance vectors was approximately 12 percent of training data. In this model, non-zero columns of the optimized weight matrix correspond to the training data.

The results of validation are shown in Table 2, where it can be seen that the MVRVR model has both the highest $R^2$ value ($R^2 = 0.9$) and the lowest error measures (RMSE = 32.05, MAE = 24.20, and ME = 32.08). In the MVRVR model, the training data were pruned to a few relevance vectors, in contrast to the approach used in other models. The overfitting problem can be solved by reducing the impact of outliers (Tipping, 2001) and the MVRVR model achieved better results using only 12 percent of training data (after reducing the impact of outliers) compared to other models. Also, the use of fewer observations can lead to reduction of both the time and cost involved in collecting ground data. In addition, the results of the MVRVR shows the lowest overestimation in the biomass range between 0 and 200 Mg/ha and the lowest underestimation in the biomass range between 0 and 400 Mg/ha.

The SVR model showed reduced errors in relation to MAE measurements than the MLPNN, due to the proper estimations made before the saturation point (224.75 Mg/ha), while its ME was greater than that of other models because of its lower saturation point. Despite the lower ME and higher saturation point, the MLPNN model showed random behavior in comparison with the SVR and MVR models. Utilizing the MLR model resulted in the lowest $R^2$ ($R^2 = 0.47$) value, and the highest error measures (RMSE = 75.35, MAE = 68.61, and ME = 78.11), which led to an underestimation of AGB because of the negative ME.

Figure 2 shows a comparison of the different estimation approaches used in AGB estimation, and it can be observed that the highest saturation point were recorded for the MVRVR model (297.81 Mg/ha). Because the selection of relevance vectors in the MVRVR model is aimed at minimizing the whole approximation errors, this model followed the trend of ground data for the whole range of biomass, unlike the SVR model. In addition, the over- and under-estimation of validation data are evident in MLPNN and MVR, respectively.

Figure 3 shows scatterplots of the observed versus predicted values of AGB. The scatterplots for MVRVR show that the results are scattered over the whole biomass range. In addition, as the MVRVR tries to minimize the whole error before saturation point, the scatters tend to lie near the line one to one. It is possible to see that the real biomass value before 200 [Mg/ha] is extremely underestimated using MLR, but after saturation points it is underestimated using all models.

Plate 2 shows a biomass map of the study area produced by the MVRVR model. All four models have the ability to estimate biomass when it has a value of under 200 Mg/ha. The biomass range between 250 Mg/ha and 300 Mg/ha emphasizes the importance of increasing the saturation point in biomass estimation. This is the area in which the MVRVR model is better than the other three models; in these cases, it is the only model that can accurately estimate biomass.
The saturation point improved by 32 percent when using the MVRVR model, compared to the best previous model (SVR). Furthermore, 15 percent of the study area has biomass that falls between the saturation point of MVRVR and the saturation point of SVR. The MVRVR model reached saturation point at over 300 Mg/ha, and thereafter the estimation accuracy was reduced. However, all four models were shown to have a lower accuracy in this range of biomass, and none of the
models were able to estimate the biomass of the area accurately. These results show that estimation of the biomass of dense forests (up to 300 Mg/ha) is possible using radar remote sensing data, and such results can be used to enable management and monitoring of wide areas of forest.

**Discussion**

This research compares the capabilities of MLR, ANN, SVR, and MVRVR in relation to modeling AGB using multi-temporal ALOS PALSAR data. Forest inventories provided AGB reference data, and these were used to reduce the source of the errors presenting a suitable basis in the modeling process. AGB values of the entire area are mostly in the medium biomass range (74 to 129 Mg/ha) in forested areas.

The results from the models were as follows. Validation results of the MLR model showed that it had the lowest $R^2$ and the highest errors. The saturation point of the MLR model was determined at 255.66 Mg/ha, and the ME indicated that the real biomass was extremely underestimated in the biomass range between 0 and 200 Mg/ha. The SVR method was found to be appropriate for use in estimating the AGB from multi-temporal SAR data under a density of 200 Mg/ha and the saturation point of SVR model was determined at 224.75 Mg/ha. The limitation of the MLPNN model lies in the fact that it does not reveal the mathematical relationship between the SAR signals and AGB. However, the highest saturation point, after that of the MVRVR, was seen in the MLPNN (264.69 Mg/ha). In contrast, the validation of the MVRVR model concludes that this is the most superior method for use in calculating AGB. It featured the lowest errors and highest $R^2$ and used fewer training data. However, the range between 0 and 150 Mg/ha was not sufficiently represented to consider that the MVRVR should be selected as the best method for use in estimating AGB, because in this respect, the SVR has similar behavior. However, the MVRVR was able to predict the AGB at higher biomass levels, which led to a higher saturation point (297.81 Mg/ha), and this affected the error measured. Although the error values were low because of the low maximum AGB value; however, in total, the real biomass is underestimated.

It is considered that the comparison of methods in this study is extremely valuable, as most studies have only assessed the use of one method, making it difficult to compare various approaches using different data in diverse ecological environments. However, a number of previous studies have compared different methods to retrieve ecological parameters from remotely sensed data. In such studies, neural network models were found to be superior to MLR models according to the results achieved (Englhart et al., 2012). Other studies have stated that the SVR is able to outperform neural network models (Camps-Valls et al., 2006), or that similar results can be obtained using a regression model (Monnet et al., 2011). Such findings are comparable to those of this study, where the neural network model outperformed the MLR model. However, in contrast to the results of Englhart et al. (2012), and in agreement with the findings of Camps-Valls et al. (2006), we found that the SVR out-performed the neural network model in relation to making better AGB estimations, even if some of the validation of the SVR model was less accurate. In agreement with Englhart et al., 2012, this study revealed that the SVR had a better performance compared to the MLR model.

According to these results, the MVRVR model has two major advantages compared to the other models considered. For example, it operates without the need for a large amount of ground data, and it has a higher saturation point, which leads to the ability to estimate larger amounts of biomass (i.e., the biomass estimation of dense forests). The forests in Iran were selected as the study area, as they are the most important forests in the country and play a critical role in the carbon sequestration of northern Iran. As such, they are key to reducing the effects of climate change. More than half of these forests have a high density and biomass of more than 250 Mg/ha, which can be well-estimated using the MVRVR model. In addition, the estimation accuracy of this model is better than that of the best previous method. Furthermore, the MVRVR model has a higher saturation point, which enables coverage of a wider for the estimation of biomass. Finally, use of the MVRVR method reduces both the time and cost involved in collecting ground data, because it requires fewer observations. These factors have a significant impact on enabling better and faster...
monitoring of forest biomass, which will ultimately result in the production of accurate and comprehensive information for use in forest management.

Conclusions
This study proposed the use of a MVRVR model for AGB estimation. In addition, to validate the use of multi-temporal ALOS PALSAR FBD data, a comparison of MLR, MLPNN, SVR, and MVRVR models was performed. AGB values were obtained from forest inventories which were in the range of 11 to 392 Mg/ha. The results from the various models showed that the MVRVR model featured the highest R2 value and the lowest errors; the MLR model had the lowest R2 value and the highest errors with a high overestimation in the biomass range between 0 and 200 Mg/ha. It was also indicated that the MLPNN model had a relatively good saturation point, but the results was not able to follow the trend of validation data. The superior performance of the MVRVR model is related to the fact that it is able to follow the trend of validation data using limited ground data. In addition, the output values of the validation data were synthesized using only a limited number of relevance vectors (12 percent of training data). Furthermore, the MVRVR model has the highest saturation point (297.81 Mg/ha) in comparison with those of the MLPNN (264.69 Mg/ha), MLR (255.66 Mg/ha), and SVR (224.75 Mg/ha) methods. It is evident that although each approach has positive properties, none of them is able to thoroughly solve the problem of underestimation. In future work, we will focus on machine learning techniques, such as deep learning algorithms, in an attempt to capture all the details relating to AGB data, with the aim of avoiding the problem of underestimation at higher levels.

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References


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* For purposes of this form, a color plate is considered to be a plate that is numbered, even if it contains several parts, e.g. (a), (b), and so on.

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