COMBINING ALLOMETRY AND UNMANNED AERIAL VEHICLE TO ESTIMATE ABOVEGROUND BIOMASS AT THE INDIVIDUAL TREE LEVEL †

[COMBINANDO ALOMETRÍA Y VEHÍCULO AÉREO NO TRIPULADO PARA ESTIMAR LA BIOMASA AÉREA A NIVEL DE ÁRBOL INDIVIDUAL]

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SUMMARY

Background: Forest ecosystems are sources of environmental services, not least their considerable capacity to sequester large amounts of carbon. Accurate measurements of aboveground biomass (AGB) are therefore gaining importance in the models implemented by climate change mitigation initiatives. **Objective:** To estimate the aboveground biomass of individual trees using allometric and photogrammetric techniques, with total tree height (TH) as a predictor variable calculated from images obtained by unmanned aerial vehicles (UAV). **Methodology:** The experiment included a natural stand of mixed and uneven-aged forest (PAW) and a forestry plantation (REB) as strategic areas to contribute to refining the knowledge regarding AGB estimation. Combining field data with the use of a DJI Phantom 4 Multispectral UAV, we explored TH as a predictor variable of AGB using regression procedures. **Results:** In the PAW were classified four genera: *Pinus*, *Quercus*, *Arbutus*, and *Juniperus*, the first was the most abundant genus. On the other hand, the REB site is composed of *Pinus arizonica*. Consequently, the models of AGB were highly accurate ($R^2 > 0.85$, 0.90) for PAW and REB, respectively. **Implications:** To improve the estimates of AGB, we would not discount the future inclusion of more dasometric attributes, including spectral variables. It would also be advisable to refine these models by size and age ranges, as well as to apply other non-parametric statistical techniques. **Conclusion:** We argue that our methodology is useful for biomass estimation and acts to better facilitate the estimation of AGB compared to conventional techniques, as well as allowing subsequent calibration according to local conditions.

Key words: tree height; regression; tree attributes; airborne observations.

RESUMEN

Antecedentes: Los ecosistemas forestales son fuentes de servicios ambientales, entre ellos su considerable capacidad para secuestrar grandes cantidades de carbono. Por lo tanto, las mediciones precisas de la biomasa aérea (AGB) están ganando importancia en los modelos implementados por las iniciativas de mitigación del cambio climático. **Objetivo:**

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Estimar la biomasa aérea de árboles individuales utilizando alometría y técnicas fotogramétricas, con la altura total del árbol (TH) como variable predictora calculada a partir de imágenes derivadas de vehículos aéreos no tripulados (UAV). **Metodología:** El experimento incluyó un rodal natural de bosque mixto y de edades irregulares (PAW) y una plantación forestal (REB) como áreas estratégicas para contribuir a refinar el conocimiento sobre la estimación de AGB. Combinando datos de campo con el uso de un UAV DJI Phantom 4 multiespectral, exploramos TH como una variable predictiva de AGB mediante procedimientos de regresión. **Resultados:** En el PAW se clasificaron cuatro géneros: *Pinus*, *Quercus*, *Arbutus* y *Juniperus*, siendo el primero el género más abundante. Por otro lado, el sitio REB está compuesto por *Pinus arizonica*. En consecuencia, los modelos de AGB fueron muy precisos ($R^2 > 0.85$, 0.90) para PAW y REB, respectivamente. **Implicaciones:** Para mejorar las estimaciones de AGB, no descartaríamos la inclusión futura de más atributos dasométricos, incluidas variables espectrales. También sería recomendable afinar estos modelos por talla y rangos de edad, así como aplicar otras técnicas estadísticas no paramétricas. **Conclusión:** Sostenemos que nuestra metodología es útil para la estimación de biomasa y actúa para facilitar mejor la estimación de AGB en comparación con las técnicas convencionales, además de permitir la calibración posterior de acuerdo con las condiciones locales.

Palabras clave: altura de los árboles; regresión; atributos de árbol; observaciones aéreas.

INTRODUCTION

Aboveground biomass (AGB) is recognized as a key parameter in the delineation of policies and projects focused on assessing the capacity of forests to generate reliable models as an input to projections of carbon (C) and climate change flux dynamics (Lin *et al*., 2018). Its accurate quantification has a direct impact on international initiatives and policy instruments for mitigating carbon emissions, including strategies such as those included in the Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) scheme and mechanisms of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014; Wylie *et al*., 2016; Jones *et al*., 2020).

Composition and structure are crucial elements to consider in methods that recommend the use of precise measurements at specific sites to capture structural variability and improve our confidence in estimates of AGB and C (Shao *et al*., 2018). Such heterogeneity is reflected in the contrast offered by natural stands and forestry plantations, the characteristics of which are ideal for producing such estimates. These areas are therefore ideal as a natural laboratory in which to evaluate modern alternatives for AGB and C estimation.

The scientific community is constantly concerned with improving the accuracy of estimates through available technologies and progressively avoiding destructive methods without undermining statistical validity. Recent literature distinguishes, in the use of indirect methods (Lin *et al*., 2018), a reliable and modern alternative for the use of tree metrics that is associated with the use of airborne observations (Popescu *et al*., 2004; Itoh *et al*., 2008; Jucker *et al*., 2017; Machimura *et al*., 2021). In particular, UAVs and their ability to extract structural attributes at the individual tree level (Gallardo-Salazar *et al*., 2021) have acted to reduce uncertainty in estimation. The inclusion of total height (TH) has contributed significantly to the improvement of estimates (Vivar-Vivar *et al*., 2022). As has been demonstrated, this parameter is more easily obtained from above with UAV than at ground level in the field (Panagiotidis *et al*., 2017; Vivar-Vivar *et al*., 2022).

Traditional methods of AGB estimation have ranged from destructive procedures (Vargas-Larreta *et al*., 2017), including other inventory techniques that feature laborious field measurements (Powell *et al*., 2010), to modeling using allometric equations with acceptable levels of accuracy that can be scaled to the stand level. Furthermore, the international literature reports that, despite the various algorithms and technologies available for AGB estimation, there is still no universal procedure, and modeling of biomass remains poorly understood as a result (Lu *et al*., 2016). Above all, when using remote technologies associated with allometric techniques, uncertainties are systematically multiplied given the structural complexity of forests.

As shown by recent literature (Wang *et al*., 2018), the use of UAV yields a rapid and accurate biomass estimation of tree ABG. The ability to acquire TH from UAV potentially increase its application in forest inventories with the minimum effort on field work. Consequently, estimation of individual tree AGB based on these technologies remains operationally challenging, especially in diverse forests. The objective of this study was therefore to estimate AGB at the individual tree level using UAVs and allometry, testing TH as a predictor variable.

MATERIALS AND METHODS

Study area

The study was conducted in two neighboring sites (<2 km apart), located in forests of the western Sierra Madre, which extends from southwestern USA to western Mexico. The first corresponds to a forest plantation of *Pinus arizonica* Engelm. in the locality known as "El Rebaje" (REB) (27.143484° N, 107.111827° W; 2400 m asl). The plantation, which is fenced, was established in 2005 and covers one hectare. It comprises 117 individual trees, each with an alphanumeric identification code. The site is characterized by flat topography, with a maximum slope of 5%. The main climate types are semi-cold sub-humid with summer rains, semi-dry, and semi-warm. Mean annual precipitation is 540.4 mm and mean annual temperature is 10.8 °C. Minimum temperatures are 4.5-5 °C (recorded in January and December), while maximum temperatures are 16.5-17.5 °C (recorded in July). The dominant soils are haplic and luvic kastanozems of loamy textures, on broken slopes (Gallardo-Salazar *et al*., 2021). The second corresponds to an uneven-aged natural forest. located in the area known as "Mesa de Pawiranachi" (PAW) (27.149167° N, 107.111389° W; 2400 m asl). This site comprises a great variety of trees but is dominated by pine and oak forests (González-Elizondo *et al*., 2012). The dominant soils are regosols and leptosols of alluvial texture. The climate is predominantly semi-cold and semi-humid, with long cold summers, with monsoon rains and winter precipitation that present an annual average rainfall of 779 mm, with an annual mean temperature of 5-12 °C (Vivar-Vivar *et al*., 2022).

The strategy of studying two areas that contrast in terms of their structural diversity and tree spatial arrangement was employed to strengthen the modeling approach in both heterogeneous natural forests and plantations since the distribution and structure of vegetation affects the predictive capacity of drones (Gallardo-Salazar *et al*., 2021; Vivar-Vivar *et al*., 2022).

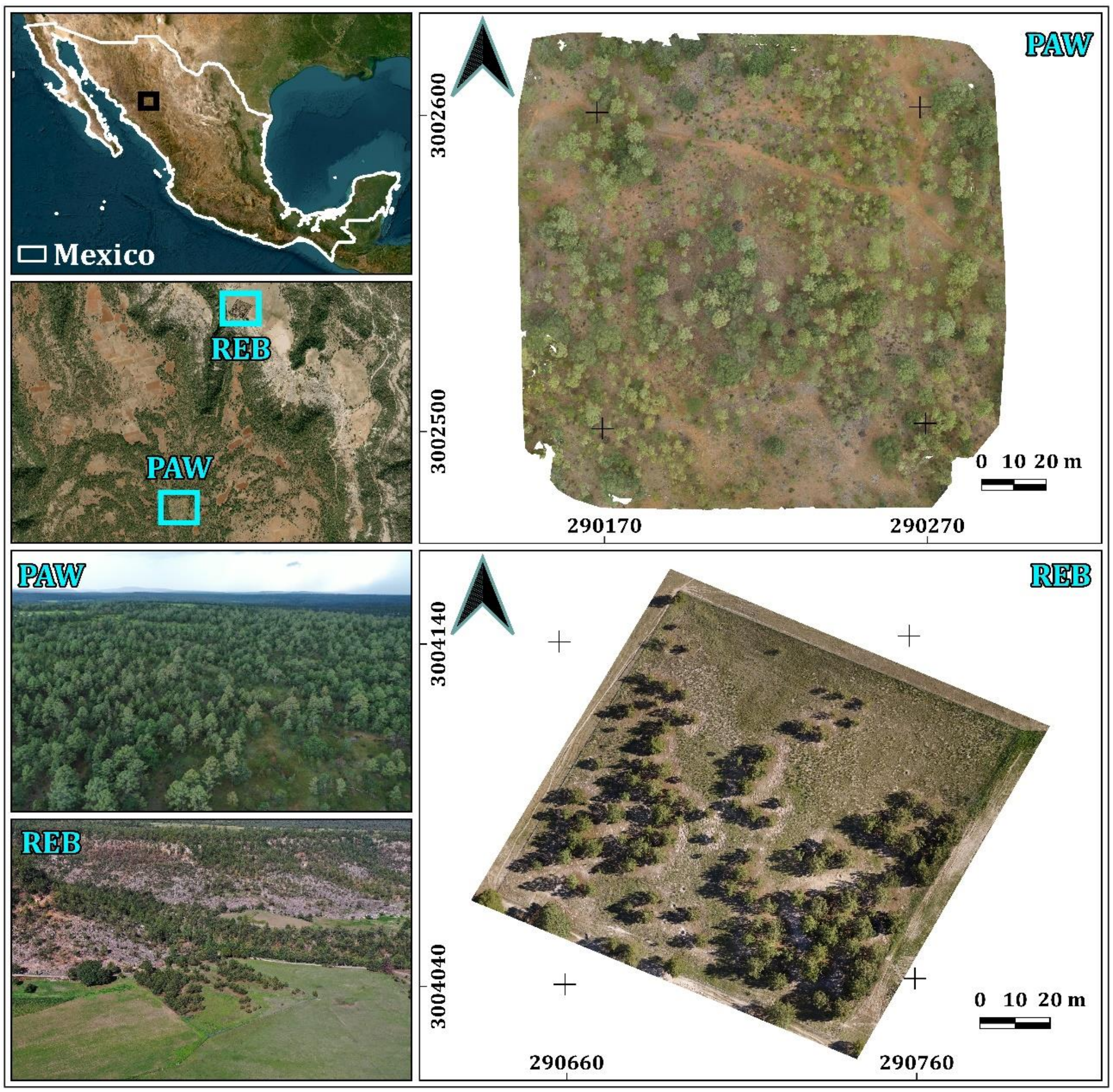

Figure 1. Study site locations. a) A natural mixed uneven-aged forest stand with the presence of four genera: *Pinus*, *Quercus*, *Juniperus*, and *Arbutus*, in the site "Mesa de Pawiranachi" (PAW), and b) a forestry plantation with 117 individuals of *Pinus arizonica* in the site "El Rebaje" (REB). Source: Own elaboration.

Data collection

To obtain field data during October 2022, each tree within both study areas was labeled with an aluminium plate fixed to the base and measured using two methods: 1) a conventional measurement field work census, recording diameter at breast height (DBH, cm) using a diametric tape, and 2) total tree height (TH, m), which was measured directly by climbing the trees and using a measuring tape (Figure 2). We also conducted a UAV flight, collecting 80 images from each study area. The flight altitude was set at 50 m, with overlaps between images and between flight paths of 80 and 75%, respectively. We used a DJI Phantom 4 multispectral quadcopter. The onboard P4M camera has a total of 6 imaging sensors: 5 multispectral sensors (blue, green, red, red-edge, and near-infrared bands) and 1 RGB sensor, all with an overall 2 MP shutter sensor. The focal length of the P4M camera was 5.74 mm and the image and sensor sizes were 1600 × 1300 and 4.87 × 3.96 mm, respectively.

Once the digital photogrammetry is processed, height is easily estimated using free software such as OpenDroneMap version 2.8.4 and QGIS Development Team (Vivar-Vivar *et al*., 2022) and can then be used as a predictive variable within the developed models.

Generation of individual models of AGB and C based on TH

Individual tree AGB was estimated through the specific species models developed by Vargas-Larreta *et al*. (2017) for the temperate forests of northwestern Mexico using the paired data set of DBH-height measured in the field. We then used a log-linear model to estimate tree AGB using the tree heights obtained by the UAV (Lin *et al*., 2018), thus normalizing the biomass error structure throughout the range of height values (Mascaro *et al*., 2011). The models were fitted using the statistical software R with the function “lm” for each group of species, i.e., *Pinus*, *Quercus*, *Juniperus*, and *Arbutus*. The mathematical formulation is given below:

$$log(AGB) = \alpha + \beta_1 * Height + \beta_2 * Height^2 + \varepsilon_i, (1)$$

$$\varepsilon_i \sim N(0, \sigma^2)$$

where log(AGB) is the tree AGB in ton in a logarithmic form, α is the intercept, β is the slope, and ε is the error term, assumed to be normally distributed. In addition, two goodness-of-fit statistics of tree AGB-height models were estimated: the coefficient of determination (R^2) and the root mean square error (RMSE).

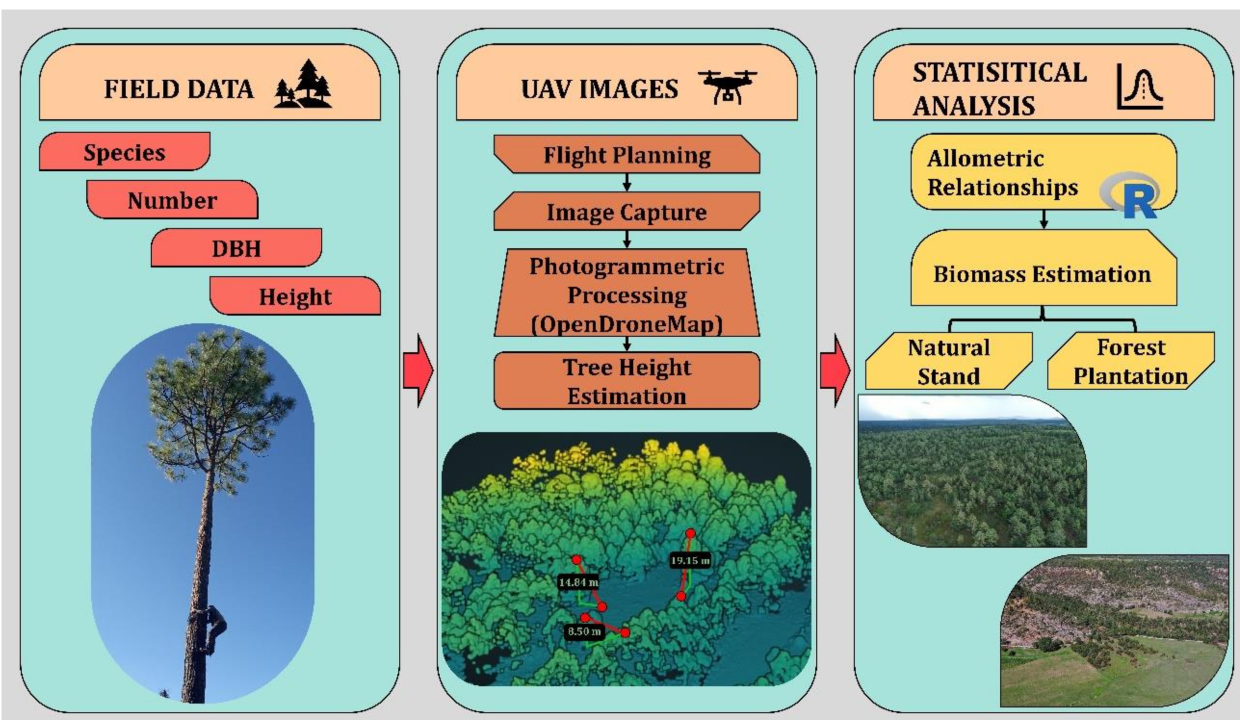

Figure 2. Workflow of the processing stages for AGB and C estimation. Source: Own elaboration.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \underline{y_i})^2} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n-p}} \quad (3)$$

where: y_i, $\hat{y}_i$, and $\underline{y_i}$ are the observed, predicted, and mean values of the dependent variable, respectively; n is the total number of observations, and p is the number of parameters used to fit the models. R^2 indicates the proportion of the variance of the dependent variable explained by the model, while RMSE indicates the precision of the estimates.

In addition, the distribution normality of the residuals and heteroscedasticity were evaluated using graphical analysis. Finally, we conducted a paired Wilcoxon rank sum test, a nonparametric test equivalent to an analysis of variance (ANOVA), to confirm whether the reference and estimated AGB differ statistically at the tree level. In case of statistical difference, a non-paired Wilcoxon test was conducted to assess whether the AGB estimations differ between methods at the sample level.

RESULTS

In the multispecies stand site (PAW), 2165 trees were sampled and classified into four genera: *Pinus*, *Quercus*, *Arbutus*, and *Juniperus*. *Pinus* was the most abundant genus, accounting for roughly 50% of the total. In addition, the sample shows showed a right-skewed distribution for both DBH and height. On the other hand, the REB site is composed of 117 trees of *Pinus arizonica*. Its population follows a normal size distribution comprising mostly small individuals. A summary of the two studies areas is presented below (Table 1).

Figure 3 gives the estimated parameters and the corresponding goodness-of-fit statistics of the models developed. All parameters were significant at the 5% level. Even though the models omit the DBH, they explain more than 85 percent of the total variance and their parameters were also significant at the 5% level. Similarly, Vargas-Larreta *et al*. (2017) achieved goodness-of-fit statistics with R^2 ranging from 0.82 to 0.95, although these models show different responses depending on the sample used (Temesgen *et al*., 2015).

On the other hand, the residuals show no evidence of heterogeneous variance over the full range of predicted values and a normal distribution for all genera evaluated. In addition, the reference AGB and the estimated values were statistically not different based on the paired Wilcoxon rank sum test, except for *Juniperus* spp. (Figure 4). We attributed this result to the lack of DBH data, thus losing the proportion of the variability explained by that variable. As is well known, the diameter variable contributes significantly to tree volume. Unfortunately, its estimation from drones remains a technological challenge unless more sophisticated and expensive technologies are used (e.g., LiDAR sensors). However, a non-paired Wilcoxon rank sum test indicated no difference in estimation between the two methods (Figures 5, 6 and 7).

DISCUSSION

Accurate estimation of AGB has economic, environmental, and social implications, for which reason the results of this study contribute to improving the conventional methods that use destructive sampling, causing disturbances or sometimes an increased amplitude of variables measured in the field (Basuki *et al*., 2009).

The use of remote sensing techniques with UAVs proved to be an excellent trade-off between resolution, scale, and sampling reduction in AGB estimation. Previous literature has documented various experiences in the contribution of remote sensing through the use of techniques featuring UAVs (Lu *et al*., 2016; Maesano *et al*., 2022). Our study is the first to include biomass estimates in both natural forest and forestry plantation plots, so the implications are of importance for forest inventories in areas of high biodiversity.

Table 1. Tree size attributes of the genera and species studied.

Site	N	DBH	Height field	Height UAV
Forest plantation (REB)				
Pinus arizonica	117	18.1 (6.7)	6.7 (1.9)	6.0 (2.0)
The uneven-aged mixed stand (PAW)				
Pinus	1105	14.3 (7.4)	6.6 (3.1)	6.5 (3.1)
Quercus	243	21.3 (16.7)	6.8 (3.8)	6.8 (3.9)
Arbutus	59	15.9 (9.0)	4.5 (1.7)	4.4 (1.7)
Juniperus	758	8.7 (4.8)	3.3 (1.4)	3.2 (1.5)

N: number of trees; DBH: Diameter at breast height; UAV: unmanned aerial vehicle.

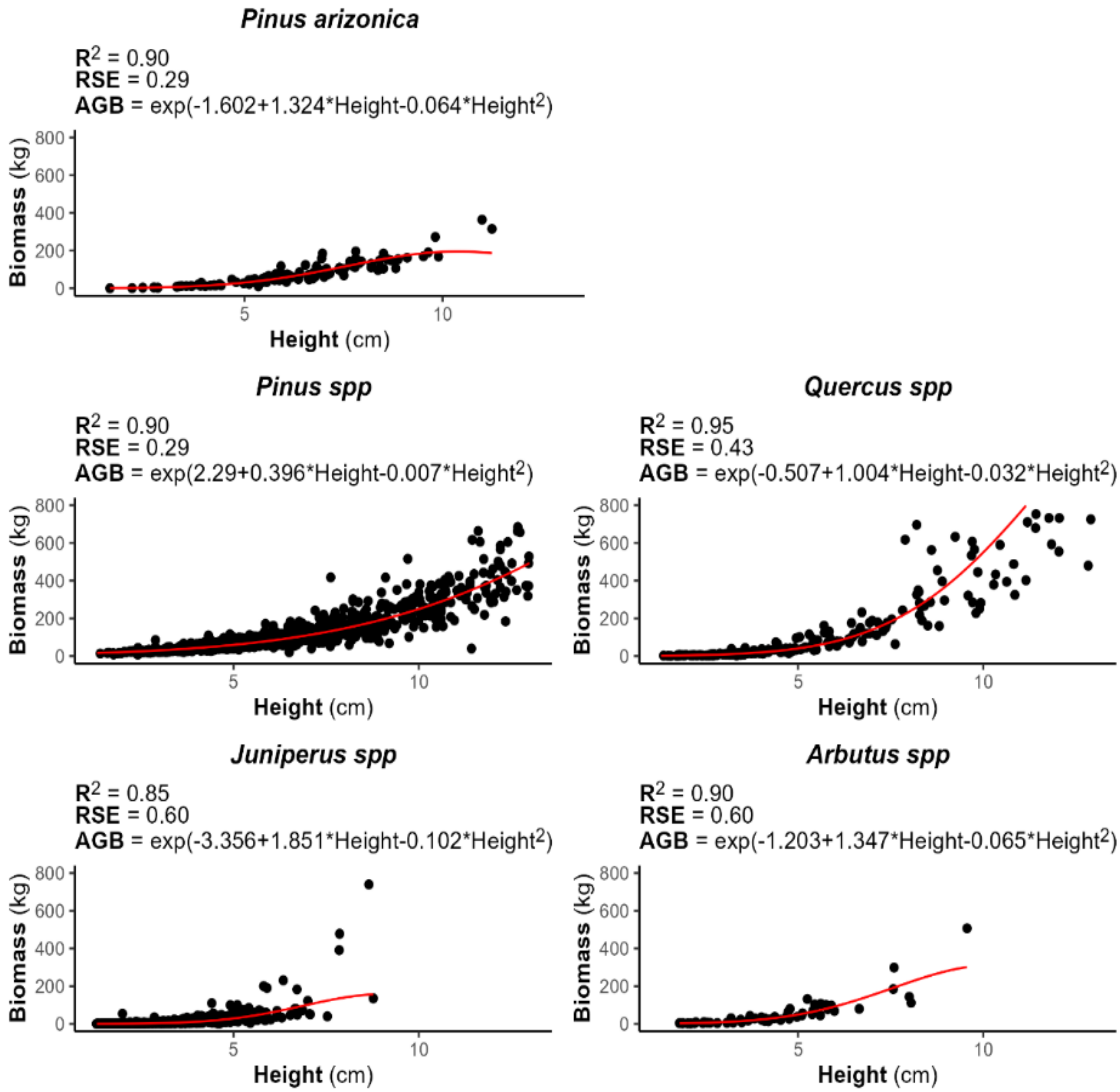

Figure 3. Estimate models for the studied genera.

The versatility of UAVs in terms of the ability to consistently monitor TH as a predictor variable in near real-time is one of the major advantages of our methodology for estimating AGB at the individual tree level, which confers major advantages to studies that use satellite information (Shang *et al*., 2019; Zhang *et al*., 2023). Flights can be as frequent and specific as necessary in their configurations to obtain the best perspective of the variable of interest, including in inaccessible areas, as well as experimental plots (Gallardo-Salazar *et al*., 2021) and smallholder forest areas (Di Lallo *et al*., 2016). It is well known that the quality of photogrammetric information relies on the quality of the point cloud, which in turn depends on the flight paths and altitude, among other parameters that configure the flight missions (Vivar-Vivar *et al*., 2022). Thus, AGB estimation at the individual tree level solves the critical problem of plot-level estimation (Maesano *et al*., 2022), as well as that of conventional destructive sampling (Ku and Popescu, 2019), making our methodology a sustainable tool.

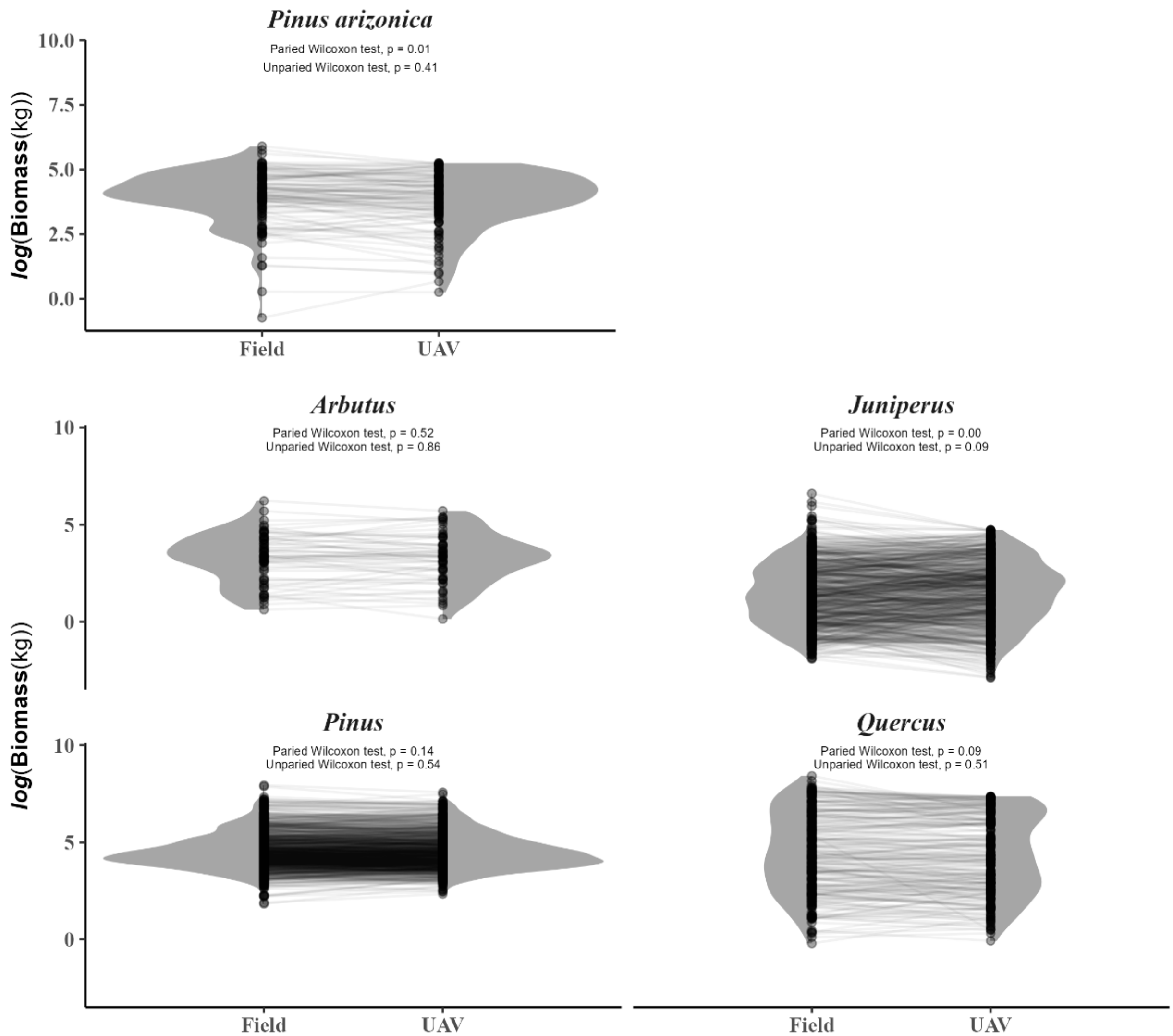

Figure 4. Mean test between field values and UAV values.

The parameter of TH was found to be a viable explanatory variable, supporting that found in other studies (Wang *et al*., 2018; Wang *et al*., 2021). The viability of obtaining this data in the field using UAVs has been demonstrated in various studies, highlighting the notable speed and accuracy of the estimations, which are even better than those estimated directly in the field (Gallardo-Salazar and Pompa-García, 2020; Vivar-Vivar *et al*., 2022). Moreover, tree height is an indicator of other associated variables of interest (i.e., site quality, volume, etc.), for which reason its use opens potential additional applications in the fields of ecology and forestry biometry (Yanli *et al*., 2019). We can therefore state that the equations of AGB estimated from TH constitute a reliable variable in the two different conditions studied here: plantation and natural forest. It is well known that biophysical complexity is an important factor of concern in experimentation involving techniques and algorithms for AGB estimation (Foody *et al*., 2003; Lu *et al*., 2016).

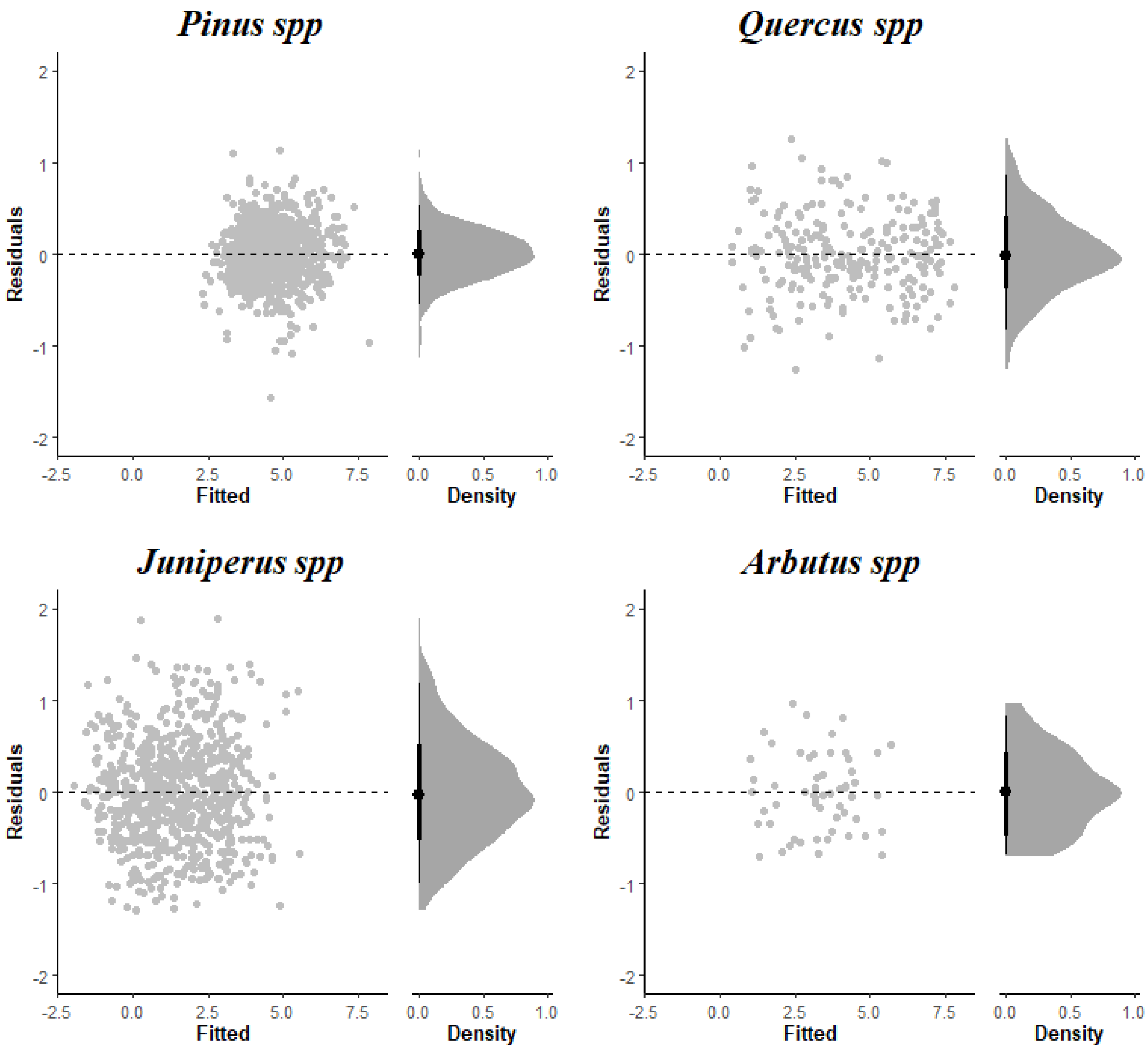

Figure 5. Graph of residuals.

The results in the mixed forest area (PAW) show good fits for the studied genera (Figure 3). The genus *Quercus* is prominent in terms of the coefficient of determination, explaining 95% of the variance for the model used; however, the RMSE of the genus *Pinus* is notable for its better precision in the estimators. The lower goodness of fit indicator presented by the individuals of *Juniperus* could be the result of alteration of their branch conformation, especially at greater heights since the trunk is straight and the branches are frequently pruned for later use of the trunks as poles. These trees are also much sought after by wildlife and the goats being grazed by the villagers. Modification of the branch structure in low-stature trees can therefore cause an imbalance in the estimates of AGB in undisturbed trees, compared to the rest of the species, the aerial structures of which appear to remain unmodified.

As an alternative to reducing bias, we suggest including an expansion factor calculated from non-disturbed trees, which are often difficult to find in natural habitats.

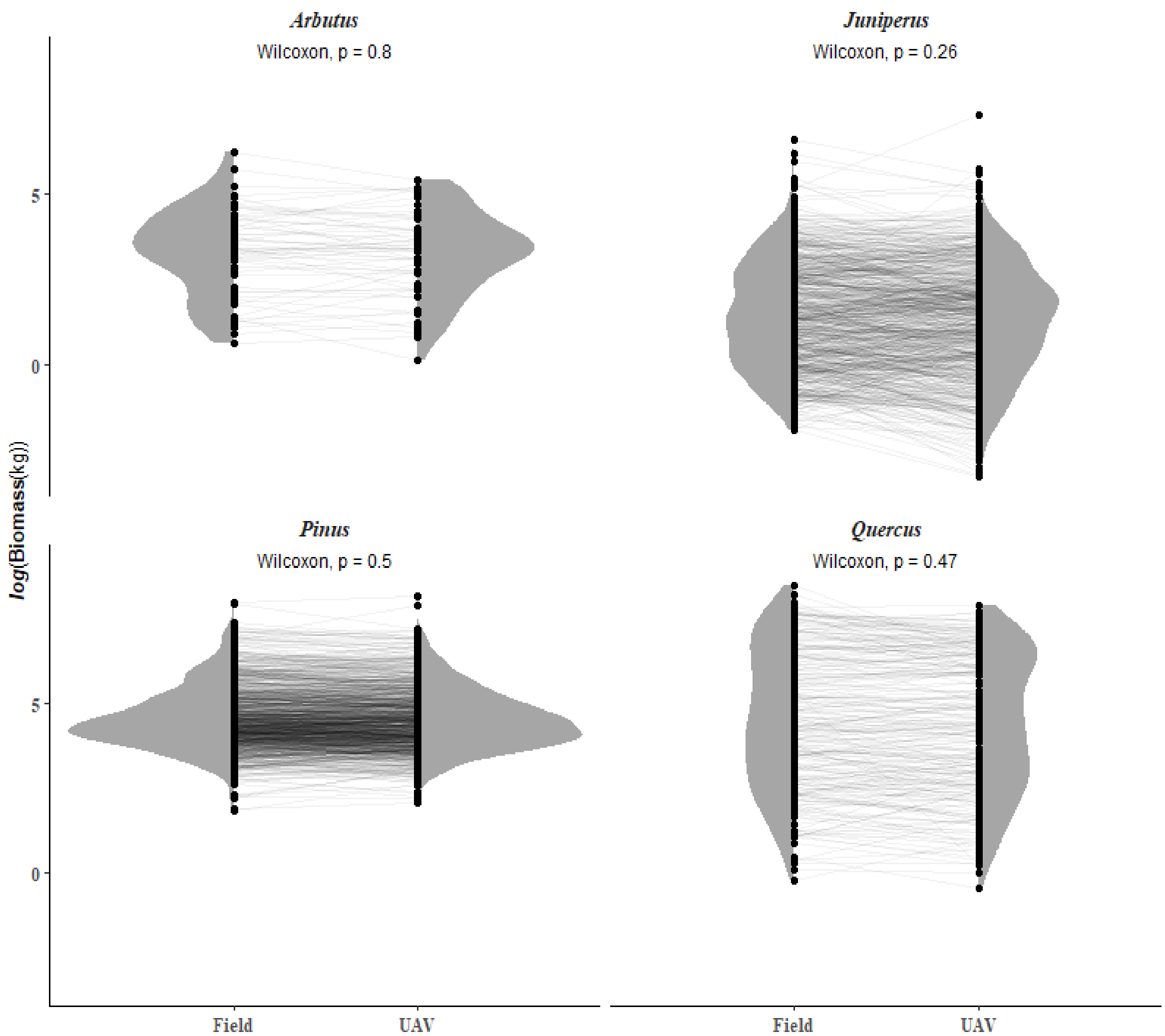

Figure 6. Mean comparison graphs using Wilcoxon method for genera from the REB site.

By comparison Shao *et al*. (2018) (R^2=0.67), our results ($R^2 \geq 0.85$) were better, and our study therefore has considerable potential for application in management program portfolios, particularly when forest inventories have been modernized by combining geomatics techniques to estimate AGB (Dang *et al*., 2019).

On the other hand, estimates made in the forest plantation (REB) did not show behavior that differed from that of the natural forest. The parameters of fit were very similar (R^2=0.90 and RMSE=0.29 vs. RMSE=0.33, respectively). Although it has been found in previous experiences that the occlusion of trees in natural forests prevents detection of the apexes of some individuals due to the overlap between them, we found no notable differences in the genus *Pinus* at both locations.

The best fits are presented for juvenile individuals, while the largest biases are generally presented for trees of heights greater than ~5 m (Figure 3). This is attributed to the phenotypic structure conformation. One strategy to reduce variation would be to broaden sampling and categorize by age class, as reported in similar literature, where errors of fit are proportional to the size of the individuals (Owers *et al*., 2018).

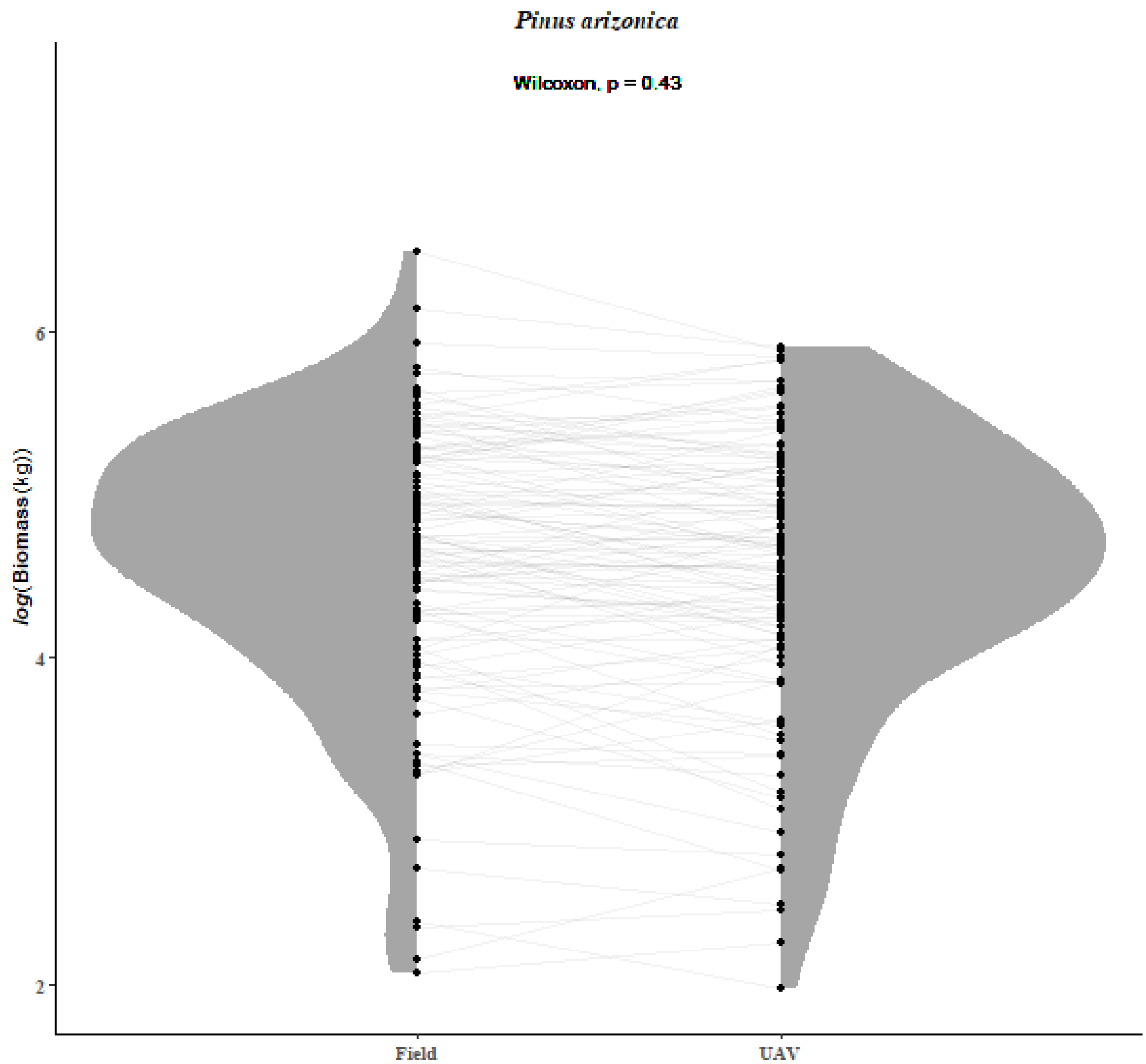

Figure 7. Results of the Wilcoxon test of means for the REB site species.

One limitation of our models is that their breadth only reaches the genus level since we do not have data to discern the tree species, except for in the forestry plantation area where all correspond to *P. arizonica*. Consequently, the generation of models at the species level and according to age ranges is highly recommended to improve the accuracy of the estimators. Some authors have found better results since the size conformation and phenotypes of the trees are directly related to the quality of the estimates (Lin *et al*., 2018). Particularly in the case of *Quercus* and *Arbutus*, some species have deciduous leaves throughout the seasons of the year, such that the estimation of height from a UAV would be disadvantageous in the dry season of the year. In the case of *Juniperus,* its lower values are recognized and it would therefore be convenient in future research to increase the sample size, given the importance that this species has acquired as a pioneer in disturbed areas (Miller *et al*., 2005; Hulet *et al*., 2014).

Although our sensor allowed us to meet our objectives, technologically better equipment has been reported to estimate AGB, most notably LIDAR (Lu *et al*., 2016), although its high cost may be a factor that restricts its viability in the field. In another aspect, it should be recognized that despite the good predictive capacity produced by the regression models, other statistical tools that have proven to be powerful, such as non-parametric algorithms (Vapnik *et al*., 1997; Moisen and Frescino, 2002; Ku and Popescu, 2019), remain to be tested. It should also be noted that the AGB estimation models are only appropriate for areas of influence or of similar characteristics to those where they were developed since environmental effects could have an influence on the results.

There are circumstances where trees are obscured by canopies due to the density of the forest, and therefore the heights of these suppressed trees cannot be extracted at least with our UAV here used. The cameras have limitations as poor penetrating capacity of sunlight in closed forests stands. Consequently, potential applications of under-canopy photogrammetry should be sought (Krisanski *et al*., 2018). Also, in future research more tree metrics could be included as branches and canopies (Aabeyir *et al*., 2020) by combining other regression techniques.

Although our methodology provides the use of a technology that is statistically sound and of high functionality (Karpina *et al*., 2016), a cost analysis is advisable to accurately determine economic feasibility. It is known that forestry administration must seek estimators of good accuracy, but the profitability of forestry activity must be achieved without financial risk.

In general terms, the equations are reliable for estimating AGB from height, which proved to be an accurate variable. Subsequent estimation of carbon is possible to influence current quantification and marketing schemes; however, the inclusion of diameter is highly desirable in volume equations due to its explanatory contribution (Chaturvedi and Raghubanshi, 2013), although the UAV used in this study is limited in terms of diameter determination.

CONCLUSIONS

Biomass estimation supported by UAV imagery and allometric techniques, using tree height as a predictor variable, was significant. Its contribution can refine the estimates given the requirements to improve the inputs of carbon flux modeling. For areas such as those studied here, the methodology can be replicated with robust results, provided that the point cloud allows the generation of a good DEM and tree height can be extracted accurately. The generation of equations per genus provides knowledge in heterogeneous forests. Regression equations continue to provide reliable statistical support for UAV models that use tree height as a high-capacity predictor variable.

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REFERENCES

Aabeyir, R., Adu-Bredu, S., Agyare, W.A. and Weir, M.J.C., 2020. Allometric models for estimating aboveground biomass in the tropical woodlands of Ghana, West Africa. *Forest Ecosystems*, 7(1), p. 41. https://doi.org/10.1186/s40663-020-00250-3

Basuki, T.M., van Laake, P.E., Skidmore, A.K. and Hussin, Y.A., 2009. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *Forest Ecology and Management*, 257(8), pp. 1684–1694. https://doi.org/10.1016/j.foreco.2009.01.027

Chaturvedi, R.K. and Raghubanshi, A.S., 2013. Aboveground biomass estimation of small diameter woody species of tropical dry forest. *New Forests*, 44(4), pp. 509–519. https://doi.org/10.1007/s11056-012-9359-z

Dang, A.T.N., Nandy, S., Srinet, R., Luong, N.V., Ghosh, S. and Senthil Kumar, A., 2019. Forest aboveground biomass estimation using machine learning regression algorithm in Yok Don National Park, Vietnam. *Ecological Informatics*, 50, pp. 24–32. https://doi.org/10.1016/j.ecoinf.2018.12.010

Di Lallo, G., Maesano, M., Masiero, M., Mugnozza, G.S. and Marchetti, M., 2016. Analyzing Strategies to Enhance Small and Low Intensity Managed Forests Certification in Europe using SWOT-ANP. *Small-scale Forestry*, 15(3), pp. 393–411. https://doi.org/10.1007/s11842-016-9329-y

Foody, G.M., Boyd, D.S. and Cutler, M.E.J., 2003. Predictive relations of tropical forest biomass from Landsat TM data and their transferability between regions. *Remote Sensing of Environment*, 85(4), pp. 463–474. https://doi.org/10.1016/S0034-4257(03)00039-7

Gallardo-Salazar, J.L., Carrillo-Aguilar, D.M., Pompa-García, M. and Aguirre-Salado, C.A., 2021. Multispectral indices and individual-tree level attributes explain forest productivity in a pine clonal orchard of Northern Mexico. *Geocarto International*, 37(15), pp. 4441–4453. https://doi.org/10.1080/10106049.2021.1886341

Gallardo-Salazar, J.L. and Pompa-García, M., 2020. Detecting Individual Tree Attributes and Multispectral Indices Using Unmanned Aerial Vehicles: Applications in a Pine Clonal Orchard. *Remote Sensing*, 12(24), p. 4144. https://doi.org/10.3390/rs12244144

González-Elizondo, M.S., González-Elizondo, M., Tena-Flores, J.A., Ruacho-González, L. and López-Enríquez, I.L., 2012. Vegetación de la Sierra Madre Occidental, México: una síntesis. *Acta Botanica Mexicana*, (100), pp. 351–403. https://doi.org/10.21829/abm100.2012.40

Hulet, A., Roundy, B.A., Petersen, S.L., Bunting, S.C., Jensen, R.R. and Roundy, D.B., 2014. Utilizing National Agriculture Imagery Program Data to Estimate Tree Cover and Biomass of Piñon and Juniper Woodlands. *Rangeland Ecology & Management*, 67(5), pp. 563–572. https://doi.org/10.2111/REM-D-13-00044.1

IPCC (Intergovernmental Panel on Climate Change), 2014. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [online] Switzerland: IPCC. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/Wetlands_Supplement_Entire_Report.pdf [Accessed 15 September 2024].

Itoh, T., Matsue, K. and Naito, K., 2008. Estimating forest resources using airbone LiDAR - Application of model for estimating the stem volume of Sugi (*Cryptomeria japonica* D. Don) and Hinoki (*Chamaecyparis obtusa* Endl.) by the tree height and the parameter of crown. *Journal of the Japan society of photogrammetry and remote sensing*, 47(1), pp. 26–35. https://doi.org/10.4287/jsprs.47.26

Jones, A.R., Raja Segaran, R., Clarke, K.D., Waycott, M., Goh, W.S.H. and Gillanders, B.M., 2020. Estimating Mangrove Tree Biomass and Carbon Content: A Comparison of Forest Inventory Techniques and Drone Imagery. *Frontiers in Marine Science*, 6. https://doi.org/10.3389/fmars.2019.00784

Jucker, T., Caspersen, J., Chave, J., Antin, C., Barbier, N., Bongers, F., Dalponte, M., van Ewijk, K.Y., Forrester, D.I., Haeni, M., Higgins, S.I., Holdaway, R.J., Iida, Y., Lorimer, C., Marshall, P.L., Momo, S., Moncrieff, G.R., Ploton, P., Poorter, L., Rahman, K.A., Schlund, M., Sonké, B., Sterck, F.J., Trugman, A.T., Usoltsev, V.A., Vanderwel, M.C., Waldner, P., Wedeux, B.M.M., Wirth, C., Wöll, H., Woods, M., Xiang, W., Zimmermann, N.E. and Coomes, D.A., 2017. Allometric equations for integrating remote sensing imagery into forest monitoring programmes. *Global Change Biology*, 23(1), pp. 177–190. https://doi.org/10.1111/gcb.13388

Karpina, M., Jarząbek-Rychard, M., Tymków, P. and Borkowski, A., 2016. UAV-based automatic tree growth measurement for biomass estimation. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B8, pp. 685–688. https://doi.org/10.5194/isprs-archives-XLI-B8-685-2016

Krisanski, S., Del Perugia, B., Taskhiri, M.S. and Turner, P., 2018. Below-canopy UAS photogrammetry for stem measurement in radiata pine plantation. In: C.M. Neale and A. Maltese, eds. *Remote Sensing for Agriculture, Ecosystems, and Hydrology XX*. SPIE. p. 11. https://doi.org/10.1117/12.2325480

Ku, N.-W. and Popescu, S.C., 2019. A comparison of multiple methods for mapping local-scale mesquite tree aboveground biomass with remotely sensed data. *Biomass and Bioenergy*, 122, pp. 270–279. https://doi.org/10.1016/j.biombioe.2019.01.045

Lin, J., Wang, M., Ma, M. and Lin, Y., 2018. Aboveground Tree Biomass Estimation of Sparse Subalpine Coniferous Forest with UAV Oblique Photography. *Remote Sensing*, 10(11), p. 1849. https://doi.org/10.3390/rs10111849

Lu, D., Chen, Q., Wang, G., Liu, L., Li, G. and Moran, E., 2016. A survey of remote sensing-based aboveground biomass estimation methods in forest ecosystems. *International Journal of Digital Earth*, 9(1), pp. 63–105. https://doi.org/10.1080/17538947.2014.990526

Machimura, T., Fujimoto, A., Hayashi, K., Takagi, H. and Sugita, S., 2021. A Novel Tree Biomass Estimation Model Applying the Pipe Model Theory and Adaptable to UAV-Derived Canopy Height Models. *Forests*, 12(2), p. 258. https://doi.org/10.3390/f12020258

Maesano, M., Santopuoli, G., Moresi, F., Matteucci, G., Lasserre, B. and Scarascia Mugnozza, G., 2022. Above ground biomass estimation from UAV high resolution RGB images and LiDAR data in a pine forest in Southern Italy. *iForest - Biogeosciences and Forestry*, 15(6), pp. 451–457. https://doi.org/10.3832/ifor3781-015

Mascaro, J., Litton, C.M., Hughes, R.F., Uowolo, A. and Schnitzer, S.A., 2011. Minimizing Bias in Biomass Allometry: Model Selection and Log-Transformation of Data. *Biotropica*, 43(6), pp. 649–653. https://doi.org/10.1111/j.1744-7429.2011.00798.x

Miller, R., Bates, J., Svejcar, T., Pierson, F. and Eddleman, L., 2005. *Biology, Ecology, and Management of Western Juniper*. Corvallis, OR, USA: Oregon state University, Agricultural Experiment Station.

Moisen, G.G. and Frescino, T.S., 2002. Comparing five modelling techniques for predicting forest characteristics. *Ecological Modelling*, 157(2–3), pp. 209–225. https://doi.org/10.1016/S0304-3800(02)00197-7

Owers, C.J., Rogers, K. and Woodroffe, C.D., 2018. Spatial variation of above-ground carbon storage in temperate coastal wetlands. *Estuarine, Coastal and Shelf Science*, 210, pp. 55–67. https://doi.org/10.1016/j.ecss.2018.06.002

Panagiotidis, D., Abdollahnejad, A., Surový, P. and Chiteculo, V., 2017. Determining tree height and crown diameter from high-resolution UAV imagery. *International Journal of Remote Sensing*, 38(8–10), pp. 2392–2410. https://doi.org/10.1080/01431161.2016.1264028

Popescu, S.C., Wynne, R.H. and Scrivani, J.A., 2004. Fusion of Small-Footprint Lidar and Multispectral Data to Estimate Plot- Level Volume and Biomass in Deciduous and Pine Forests in Virginia, USA. *Forest Science*, 50(4), pp. 551–565. https://doi.org/10.1093/forestscience/50.4.551

Powell, S.L., Cohen, W.B., Healey, S.P., Kennedy, R.E., Moisen, G.G., Pierce, K.B. and Ohmann, J.L., 2010. Quantification of live aboveground forest biomass dynamics with Landsat time-series and field inventory data: A comparison of empirical modeling approaches. *Remote Sensing of Environment*, 114(5), pp. 1053–1068. https://doi.org/10.1016/j.rse.2009.12.018

Shang, C., Treitz, P., Caspersen, J. and Jones, T., 2019. Estimation of forest structural and compositional variables using ALS data and multi-seasonal satellite imagery. *International Journal of Applied Earth Observation and Geoinformation*, 78, pp. 360–371. https://doi.org/10.1016/j.jag.2018.10.002

Shao, G., Shao, G., Gallion, J., Saunders, M.R., Frankenberger, J.R. and Fei, S., 2018. Improving Lidar-based aboveground biomass estimation of temperate hardwood forests with varying site productivity. *Remote Sensing of Environment*, 204, pp. 872–882. https://doi.org/10.1016/j.rse.2017.09.011

Temesgen, H., Affleck, D., Poudel, K., Gray, A. and Sessions, J., 2015. A review of the challenges and opportunities in estimating above ground forest biomass using tree-level models. *Scandinavian Journal of Forest Research*, pp. 1–10. https://doi.org/10.1080/02827581.2015.1012114

Vapnik, V., Golowich, S. and Smola, A., 1997. Support Vector Method for Function Approximation, Regression Estimation and Signal. In: M. Mozer, M. Jordan and T. Petsche, eds. *Advances in Neural Information Processing Systems 9*. Cambridge, Massachusetts, USA: The MIT Press. pp. 281–287.

Vargas-Larreta, B., López-Sánchez, C.A., Corral-Rivas, J.J., López-Martínez, J.O., Aguirre-Calderón, C.G. and Álvarez-González, J.G., 2017. Allometric Equations for Estimating Biomass and Carbon Stocks in the Temperate Forests of North-Western Mexico. *Forests*, 8(8), p. 269. https://doi.org/10.3390/f8080269

Vivar-Vivar, E.D., Pompa-García, M., Martínez-Rivas, J.A. and Mora-Tembre, L.A., 2022. UAV-Based Characterization of Tree-Attributes and Multispectral Indices in an Uneven-Aged Mixed Conifer-Broadleaf Forest. *Remote Sensing*, 14(12), p. 2775. https://doi.org/10.3390/rs14122775

Wang, M., Sun, R. and Xiao, Z., 2018. Estimation of Forest Canopy Height and Aboveground Biomass from Spaceborne LiDAR and Landsat Imageries in Maryland. *Remote Sensing*, 10(2), p. 344. https://doi.org/10.3390/rs10020344

Wang, Y., Zhang, X. and Guo, Z., 2021. Estimation of tree height and aboveground biomass of coniferous forests in North China using stereo ZY-3, multispectral Sentinel-2, and DEM data. *Ecological Indicators*, 126, p. 107645. https://doi.org/10.1016/j.ecolind.2021.107645

Wylie, L., Sutton-Grier, A.E. and Moore, A., 2016. Keys to successful blue carbon projects: Lessons learned from global case studies. *Marine Policy*, 65, pp. 76–84. https://doi.org/10.1016/j.marpol.2015.12.020

Yanli, X., Chao, L., Zhichao, S., Lichun, J. and Jingyun, F., 2019. Tree height explains stand volume of closed-canopy stands: Evidence from forest inventory data of China. *Forest Ecology and Management*, 438, pp. 51–56. https://doi.org/10.1016/j.foreco.2019.01.054

Zhang, L., Zhang, X., Shao, Z., Jiang, W. and Gao, H., 2023. Integrating Sentinel-1 and 2 with LiDAR data to estimate aboveground biomass of subtropical forests in northeast Guangdong, China. *International Journal of Digital Earth*, 16(1), pp. 158–182. https://doi.org/10.1080/17538947.2023.2165180