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Review

Forest Biometric Systems in Mexico: A Systematic Review of Available Models

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Abstract: Biometric systems are the basis of forest management and consist of a set of equations that describe the relationships between forest attributes and dendrometric variables. A systematic review of the state of the art of biometric systems in Mexico was carried out by a Mexican consortium (10 researchers), covering a period of 50 years ca (1970–2019), using the main scientific literature delivered by a systematic search (WoS, Scopus, Scielo, Redalyc) and a targeted search (theses, technical reports, etc.). A single selection criterion was established for the inclusion of information in the analysis: the document had to present at least one of the equations of interest. We found 376 documents containing 2524 equations for volume (69%), diameter (11%), height (9%) and site index (11%). These equations were developed for forest species mainly from temperate regions (88%), such as pine (66%) and oak (9%). Consequently, the Mexican states with the highest number of equations were Durango (28%), Chihuahua (17%), Hidalgo (13%) and Oaxaca (8%). Although large, the number of equations identified concentrated on a relatively small number of models: Schumacher & Hall and Fang et al. for volume; Chapman-Richards and Schumacher for site index and diameter; and Chapman-Richards and the allometric equation for height. An analysis of model fit, measured through R^2, showed that, on average, the volume, diameter and site index models show high fit (R^2 = 0.96), although this pattern was more consistent in the volume models. Publication bias was evaluated by means of a funnel plot analysis, with no apparent bias identified. A limitation of our study is that the information obtained is not updated to the present year; however, the 50-year trends allow us to assume that no recent significant changes in the patterns exist. Finally, we highlight the need to assess the predictive ability of the models to ensure accurate estimates to support better forest management decisions.

Keywords: forest ecosystems; goodness-of-fit; growth models; static models; systematic review

Citation: López-Martínez, J.O.; Vargas-Larreta, B.; González, E.J.; Corral-Rivas, J.J.; Aguirre-Calderón, O.A.; Treviño-Garza, E.J.; De los Santos-Posadas, H.M.; Martínez-Salvador, M.; Zamudio-Sánchez, F.J.; Aguirre-Calderón, C.G. Forest Biometric Systems in Mexico: A Systematic Review of Available Models. *Forests* **2022**, *13*, 649. https://doi.org/10.3390/f13050649

Academic Editor: Karol Bronisz

Received: 26 February 2022
Accepted: 19 April 2022
Published: 22 April 2022

1. Introduction

One of the paradigms for the conservation of forest resources is their sustainable use. To this end, it is necessary to determine the status of forest resources and to plan strategies for their use [1]. The state of the resources is established from the quantification of various attributes of the forest, such as volumetric stocks, growth and harvesting intensities. To estimate them, we need to understand the relationship between these and easily measurable variables such as diameter and height [2,3]. These relationships are described through mathematical models that together constitute forest biometric systems [4]. Efficient forest management requires accurate, robust and parsimonious biometric systems; systems lacking these characteristics jeopardize the conservation of natural resources and the ecosystem processes that maintain them.

Historically, biometric systems can be traced to the late 18th century in Germany, where the practice of building region- and species-specific models by generating production tables began [5]. In Mexico, the first documented records of biometric systems date back to the 1970s. From this date onwards and because of environmental heterogeneity (e.g., tree age, nutrient availability, competition and density of individuals) and the high diversity of forest species, a plethora of models to account for this variability have been developed. Additionally, Mexican environmental legislation demands the use of equations at the species level [6].

In recent decades, due to the increase in computing power, more complex models, both in their structure and number of parameters, have been generated to increase their descriptive and predictive power [7]. However, model complexity does not guarantee an increase in model fit to the data [8] nor a higher accuracy in prediction. On the one hand, fit has been assessed through a variety of statistical metrics, such as the coefficient of determination (R^2), root mean square error (RMSE) and average bias (e), among others, being the first the most commonly used due to its ease of interpretation and its model intercomparability. On the other hand, prediction accuracy has been assessed through model validation in which the model is used to predict the forest attribute of interest on a new set of data and fit is evaluated on these predictions.

For all these reasons, and after 50 years of generating biometric systems for forest management in Mexico, it is important to integrate and evaluate the state of the art on these systems. For this purpose, a systematic review of the available volume, diameter, height and site index models, the main types of equations that integrate forest biometric systems, was carried out. In addition, to identify those models with the highest descriptive capacity we recorded the most commonly reported goodness-of-fit metric (R^2).

2. Materials and Methods

2.1. Information Search

The search for information focused on volume, height, site index and diameter equations constructed from individual trees or stands data, and published before 2020. The review was conducted based on two strategies: (1) systematic search and (2) targeted search.

The systematic search aimed at compiling the literature published in national and international scientific journals, for which all combinations of terms considered relevant for the analysis were identified. A search string (Supplementary Material S1) was designed, in which the search terms were specified (in English and Spanish), as well as the species and states included in the study. Terms were grouped around the concepts of model, variable, region, and species. Thus, to identify an article as relevant, it had to contain at least one element from each group of terms in the title, abstract or keywords. All these combinations of terms were entered into the search engines Web of Science, Scopus, Scielo and Redalyc.

The references found by the search engines were integrated into a list for review, eliminating duplicate publications. Those references that, based on the title, were clearly outside the scope of interest of the study were discarded. Finally, the documents associated with each reference were obtained and the relevance of each to the objectives of the study was assessed based on a single inclusion criterion; it should include at least one of the models of interest.

A large part of the literature on the subject is not published in scientific journals, so a targeted search was carried out to explore the existing grey literature. This search entailed the review of documents available in printed or digital media in national journals not indexed or refereed, as well as theses, brochures, manuals, technical reports, conference proceedings and timber forest management programs produced by academic institutions (universities and research institutes), as well as government agencies in the forestry sector (e.g., SEMARNAT, CONACYT, CONAP, CONAFOR, etc.).

Information was sought, registered, and validated by a forest consortium of collaborators (the 10 authors) located in different regions of Mexico and integrated into a single database for assessment and depuration by three authors (J.O.L.-M., B.V.-L. and E.J.G.).

2.2. Metadata

From each document we extracted the following information: (a) location: state, municipality, regional forest management unit (UMAFOR; if applicable) and place where the study was carried out; (b) variable estimated by the model: volume [total tree volume with bark (vtacc, includes branch volume), total tree roll volume with bark (vrtacc), total tree roll volume without bark (vrtasc), branch volume (vbranches), bark volume (vbark), volume growth (Δv) and taper-volume (a-v)]; height [height growth (Δh), merchantable height (hcom) and height-diameter ratio (h-d)]; site index; and diameter [diameter growth (Δd), basal area growth (Δab), normal diameter (d)]; (c) species (scientific name); (d) name associated with the model; (e) model goodness-of-fit measure; (f) assessment of model predictive capacity; (g) sample size; and (h) reference. The database with these metadata is presented in Supplementary Material S2.

2.3. Analysis

With the database completed, we carried out a descriptive analysis of the number of cases generated per response variable, equation, species, and state.

For those cases in which data on the R^2 value and the sample size were provided, further analyses were performed. First, the empirical distribution of the R^2 values per response variable was constructed to detect those variables best modeled in general through mathematical equations. Second, for each response variable, we estimated mean R^2 values and their associated confidence intervals through the metafor package [9] in R [10]. To achieve normality, R^2 values were normalized through the equation:

$$Z = \tanh^{-1}((R^2)^{1/2}). \quad (1)$$

With these Z values, we constructed a weighted null model and weighted models that incorporated the explanatory variables (e.g., equation, species, state). Weights were set as the inverse of the sample size associated with each case, to reflect the distinct confidence we have on the model associated with the case. Model comparisons were performed through the sample corrected Akaike Information Criterion (AICc; [11]).

To evaluate the risk of publication bias, i.e., a tendency to favor overparameterized models that translate into high R^2 values, funnel plots were constructed between the normalized R^2 values and their corresponding mean (estimated from the weighted models), and their standard error. Publication bias can be detected from these plots through an asymmetry along the x-axis.

In these analyses we favored the R^2 over other goodness-of-fit measures, since this was the most frequently reported measure (see Section 3.4 in Results).

3. Results

3.1. Information Sources

The search yielded 376 documents, including scientific papers, theses, technical reports, brochures, books, conference proceedings and timber forest management programs.

After the elimination of duplicates and relevance evaluation, a list of 209 documents considered relevant for the analysis was compiled (Supplementary Material S2), which included scientific articles (52), brochures or technical reports (41), books (3), theses (23), proceedings (2) and timber forest management programs (83); 5 equations were obtained from photocopied material, for which the source could not be determined.

3.2. Types of Models

Out of 2810 equations gathered, 2524 (1116 and 1408 in the first and second searches, respectively) met the requirements of referring to a species, state and output variable of interest. The equations with the highest number of cases were volume (69%) and site index (11%), followed by diameter (11%) and height (10%) (Figure 1).

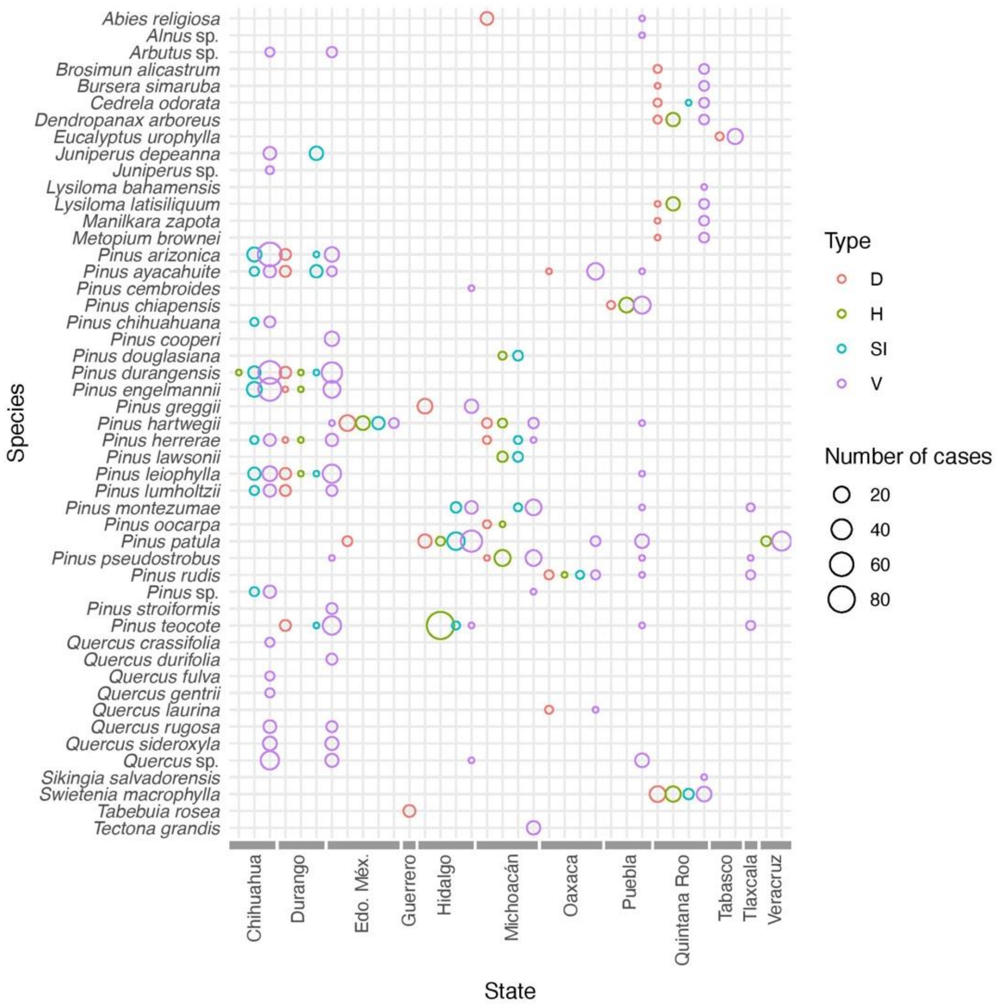


Figure 1. Distribution of the number of cases per tree species, state and type of equation (color) obtained from the search of existing biometric systems.

Volume models were mainly distributed in the following subtypes (Supplementary Material S2): 673 taper-volume equations, 464 stem volume with bark, 314 total tree volume (including branches) and 75 growth volume equations; branch volume, stem volume without bark, total tree volume without bark, bark volume and stand level volume equations accounted for 209 cases (10%).

Diameter models included as output variables: diameter at breast height (DBH), basal area (49), diameter-stump diameter relationship (32), growth basal area (46), and growth diameter (146). Finally, in the group of height models, 142 cases were of a height-diameter relationship, 23 cases of height increment and 22 cases of merchantable height.

3.3. Geographical Distribution of the Models

States with the largest number of equations reported were Durango (700), Chihuahua (419), Hidalgo (325), Oaxaca (212) and Quintana Roo (132). On the other hand, Veracruz and Tlaxcala were the states with the smallest number of equations (74 and 20, respectively). The states for which equations were found represent about 90% of the country's timber production (10.3 million m^3) [12].

Guerrero, with 132 cases out of 464, is the state with the highest number of stem volume with bark equations; however, all the cases were obtained from timber forest management programs, in which the goodness of fit of the models could not be verified. After Guerrero, Chihuahua (83) and Durango (69) are among the states with the highest number of stem volume with bark equations, which is the result of initiatives promoted by the National Forestry Commission to validate the biometric systems used in forest management programs in both states [4]. In all states except Puebla, more than 10 cases of this type of model were recorded. Similarly, of the 314 cases of total tree volume with bark, 153 were developed in Durango.

Only 52 equations of total tree volume without bark were collected; most of them reported for Durango (14), Michoacán (16) and Chihuahua (8) (Figures 1 and 2).

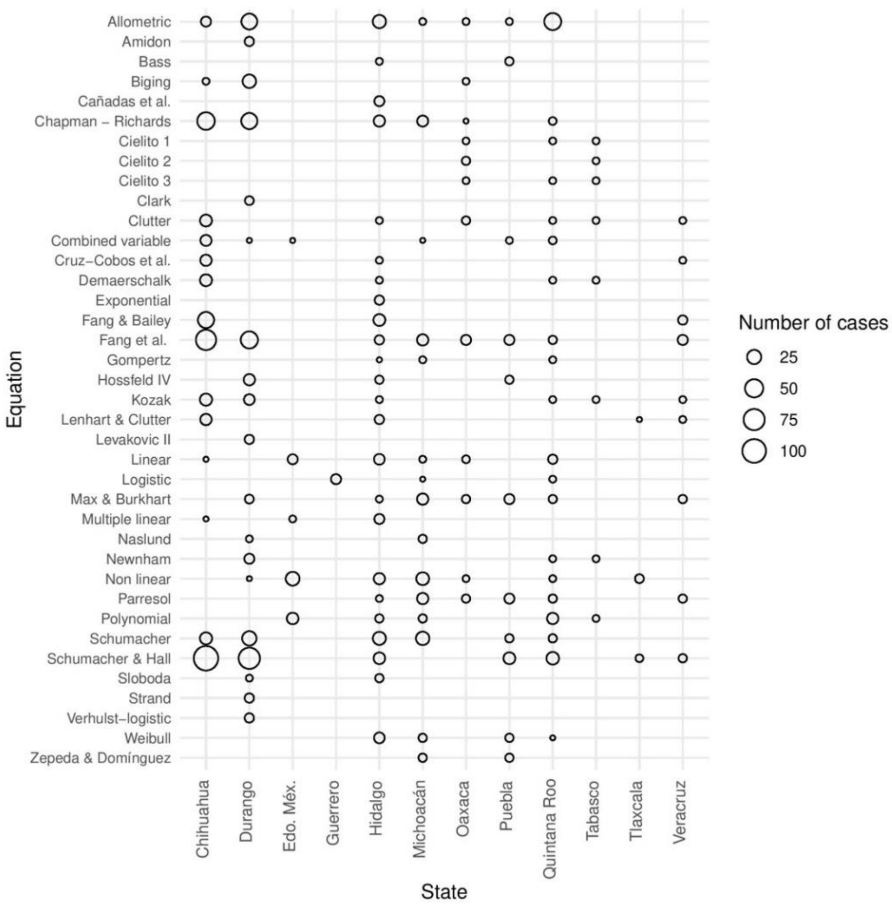


Figure 2. Distribution of the number of cases per model name and state obtained from the search of existing biometric systems.

The largest number of growth diameter and growth basal area models were recorded in Oaxaca (63), Hidalgo (51), Durango (36) and Estado de México (17). Twenty-eight models for the estimation of diameter from total tree height or stump diameter were found in Quintana Roo.

Most of the reported taper-volume equations were classified as simple taper-volume models, segmented models and variable-form taper models. These compiled equations have been developed for particular species and regions of the country, mainly for *Pinus* species, although in states such as Chihuahua and Durango these equations were found for *Quercus* species. Most of these equations were reported for the states of Chihuahua, Durango, Hidalgo, Oaxaca and Michoacán (Figure 1).

3.4. Reported Models by Species

The largest number of cases corresponded to temperate forest species (88%); the rest of equations (12%) were found in tropical forests. Equations for pine species were the most frequent (75%), while equations for oak species accounted for only 10% of the cases in temperate forests (Figure 3).

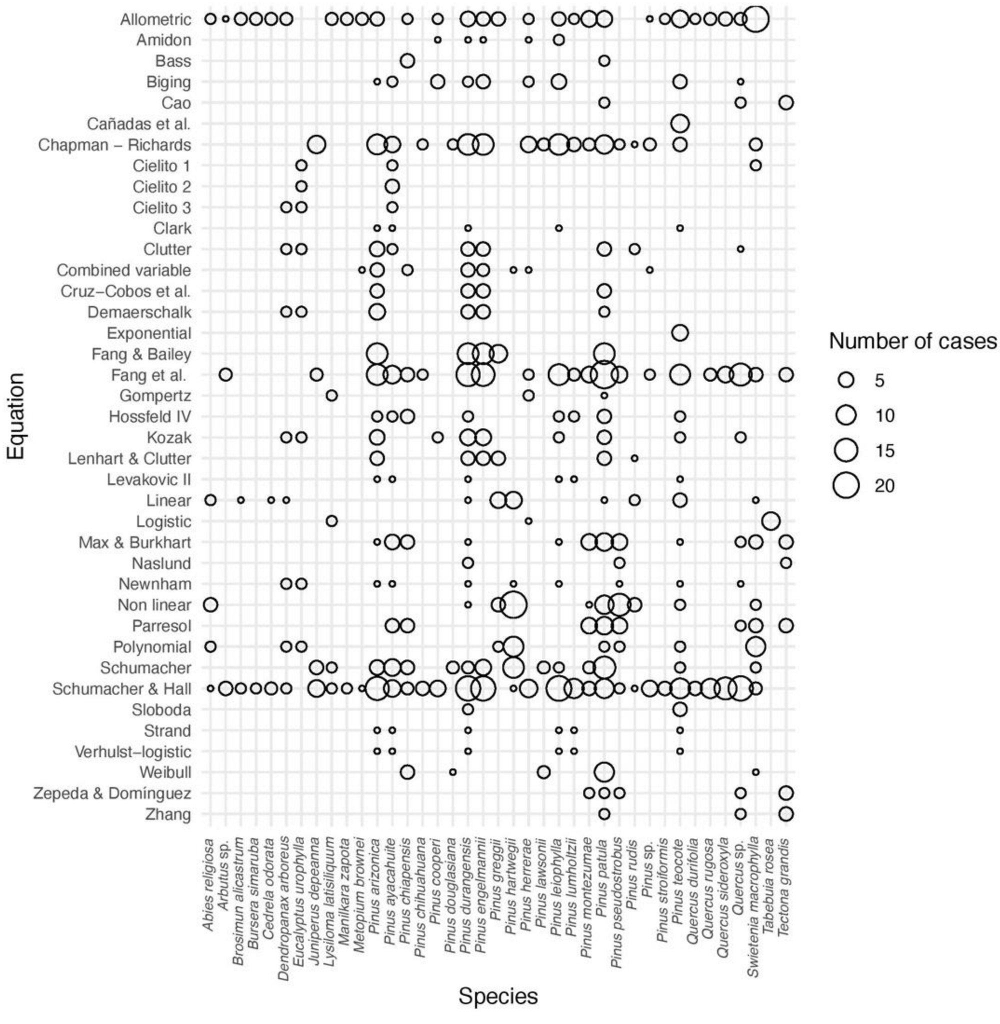


Figure 3. Distribution of the number of cases per model name and species obtained from the search of existing biometric systems.

The most studied species are those of *Pinus*, of which *P. patula* (254), *P. teocote* (168), *P. durangensis* (167), *P. arizonica* (138) and *P. engelmannii* (126) stand out. Regarding oak species, *Quercus sideroxyla* is the most studied one (32), followed by *Q. rugosa* (22) and the *Quercus* sp. group (143). In turn, the tropical species with the highest number of models were *Swietenia macrophylla* (60: 20 diameter, 18 height, 17 volume and five site index equations) and *Tectona grandis* (54) (Figure 3).

The species with the most site index models in the country is *P. arizonica* (44), followed by *P. durangensis* (38), *P. patula* (36), *P. douglasiana* (23), *P. engelmannii* (16) and *P. ayacahuite* (14). In addition, 20 equations were found for the *Pinus* sp. group. The species with the highest number of height models were *P. hartwegii*, *P. pseudostrobus*, *P. patula* and *P. durangensis*, respectively, while most diameter models were recorded for *P. patula*, *P. hartwegii*, *P. montezumae*, *P. pseudostrobus*, *P. douglasiana* and *S. macrophylla* (Figure 1). The species with the highest number of taper-volume equations were *P. patula* (77), *P. durangensis* (69), *P. arizonia* (61), *P. engelmannii* (65) and *P. leiophylla* (37); with available equations for the remaining species ranging from 1 (*P. cembroides* and *P. hartwegii*) to 35 (*P. ayacahuite*).

Timber species, or species of conservation interest in temperate forests, for which no equations were found were *Abies concolor*, *Clethra mexicana*, *Liquidambar* sp., *Pinus caribaea*, *Pseudotsuga* sp. and 17 oak species. Tropical timber species included in the search for which no equations were found were *Metopium brownei*, *Vitex gaumeri* and *Swartzia cubensis.*

3.5. Most Frequently Used Models

The most frequently used models are those by Schumacher and Hall [13] for volume estimation (503 cases); Fang et al. [14] for taper-volume (301); Chapman-Richards [15] and Schumacher [16] for site index (151 and 78, respectively) and diameter (34 and 41, respectively). Other models, such as geometric (128), allometric (179), and combined variable (72), are frequently used to model forest volume, while the models by Max and Burkhart [17] (41), Kozak [18] (31) and Biging [19] (24) are used as merchantable volume models. The most commonly used height models are Chapman-Richards [15] (17) and the allometric equation (14 cases), and Schroeder and Alvarez [20]. Other models used to estimate tree height are those by Schumacher [16], Weibull [21] and Gompertz [22] (Figure 3).

3.6. Analysis of Model Fit

The most frequently used criteria for the selection of the best models were the determination coefficient (R^2; 1604 cases) and the root mean squared error (RMSE; 609 cases, with an overlap with R^2 of 589 cases). Average bias, number of independent variables, and parameters significance are reported as secondary criteria. Output variables showed different capacity trends of mathematical models to describe them (Figure 4). Volume was the best forest attribute described through an equation as its frequency density displayed its mode at the highest R^2 value (0.96) and the smallest dispersion around this mode. Site index and diameter displayed similar modes in the distribution of their R^2 values but showed larger dispersions. In turn, height had a dispersion similar to that of volume, but with a mode at a lower R^2 value.

In the case of volume, the most frequently reported model was that by Schumacher and Hall [13], with a weighted average R^2 = 0.96. Volume models such as that by Clark et al. [23], Kramer and Akça [24] and Meyer [25] recorded R^2 values up to 0.99; however, their application is sporadic. The compatible taper-volume model by Fang et al. [14] showed a high average fit (R^2 = 0.98), similar to that observed for Biging's model [19], with R^2 values between 0.93 and 0.99 (weighted average of 0.96). For the most used site index models (Chapman-Richards and Schumacher), the range of R^2 was 0.75 to 0.99 (average of 0.97), and 0.63 to 0.99, respectively, and are surpassed in goodness-of-fit quality by models such as Weibull's model [26] with a narrower range of R^2 (0.91–0.99) (Figure 5a). For diameter, the logarithmic model was the only one that produced a weighted average R^2 value (0.99) above the global mean (0.93). Finally, linear models were the best option for modelling total tree height (average R^2 = 0.96).

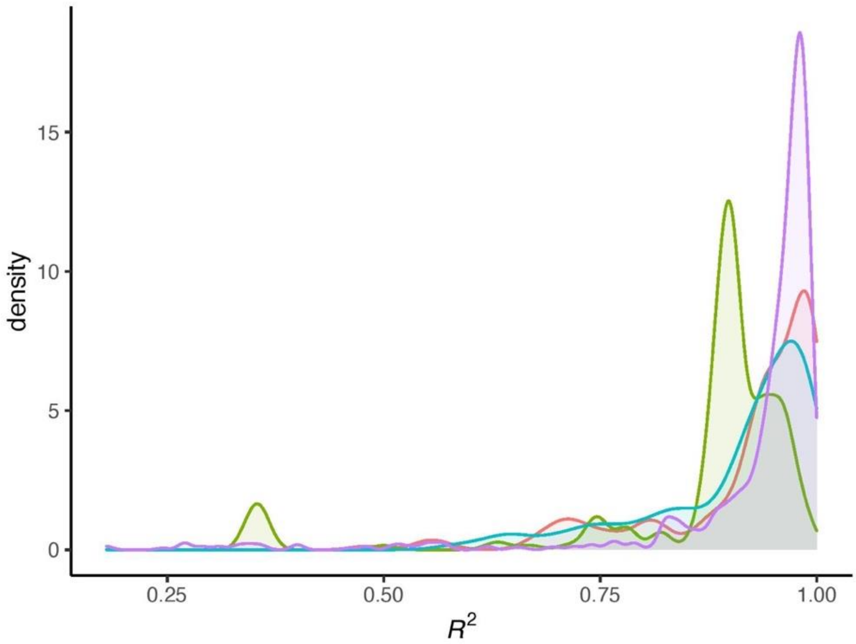
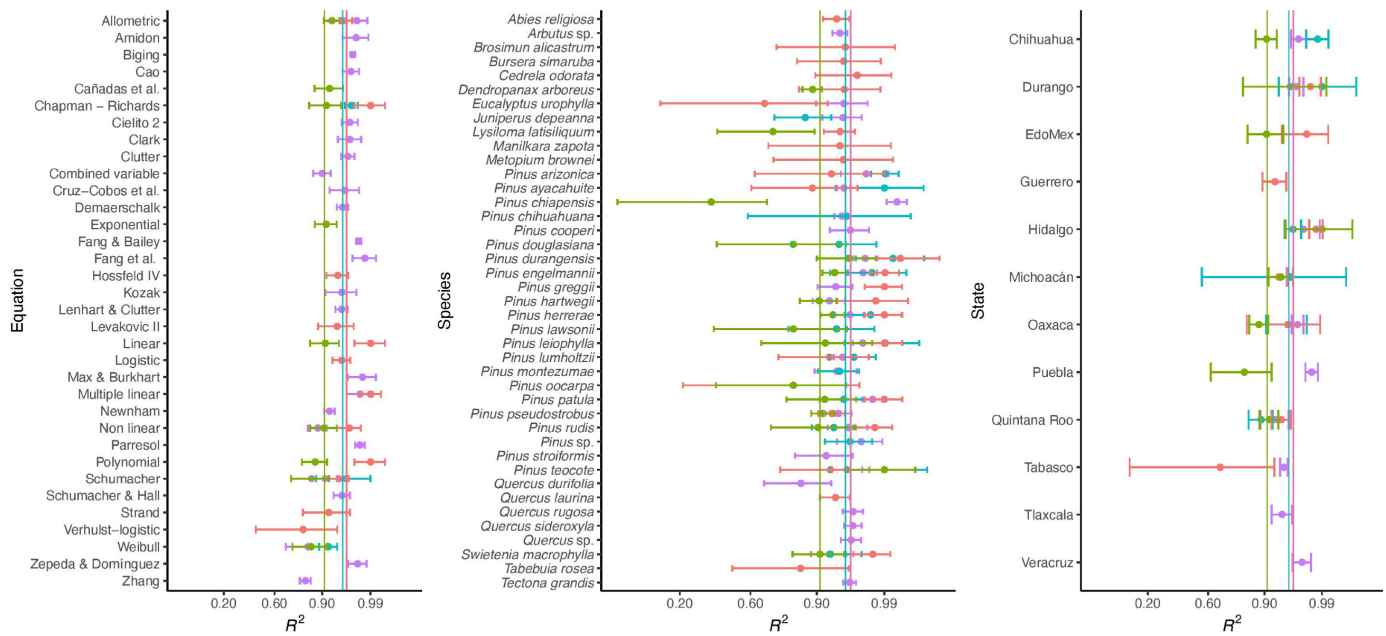


Figure 4. Distribution densities of the coefficient of determination (R^2) values obtained after fitting models to different forest attributes (D: diameter, H: height, SI: site index, and V: volume).



(**a**) (**b**) (**c**)

Figure 5. Mean estimates of the coefficient of determination (R^2) values obtained after fitting models to different forest attributes (volume: purple, height: green, diameter: red, site index: cyan), along with their confidence intervals, according to the model used (**a**), studied species (**b**) and Mexican state where the study was performed (**c**). Vertical lines are general mean estimates per forest attribute. The R^2 axis is presented in the probit scale to emphasize those values close to 1.

Volume is easier to model in pine species, compared to oak and tropical species, as they had the lowest R^2 dispersion around the global mean for this equation type (Figure 5b). Species with acceptable goodness-of-fit, but have been little studied were *P. herrerae*, *P. rudis*, *P. ayacahuite*, and *P. chihuahuana.* Most studied species, such as *P. patula*, *P. durangensis* and *P. arizonica*, showed moderate fits (0.95–0.96), not significantly different from the global mean.

Similar goodness-of-fit for site index equations were reported for most species; however, *P. chihuahuana* stands out as one of the species for which it is most difficult to model this variable, as it presented the largest R^2 values dispersion. For diameter models, the only species that presented goodness-of-fit above the global mean was *Bursera simaruba*, with R^2 values greater than 0.94 (Figure 5b).

Differences in the goodness-of-fit of the models were also assessed as a function of the study region (state; Figure 5c). This decision assumed that differences in the fit could be because of environmental conditions on tree shape, but also to the quality of data capture in different states. For volume and diameter equations, the state had no effect on the R^2 values, as all confidence intervals included the overall global mean (Figure 5c). For the site index models, Michoacán was the state with the largest number of site index models and fit levels above the global mean. For height models (Figure 5c), Oaxaca was the state with the best fits, with values above 0.95 and a weighted mean of 0.99.

The bias analysis showed no clear publication bias in the distribution of R^2 values as a function of the sample size used in the construction of each model (Figure 6).

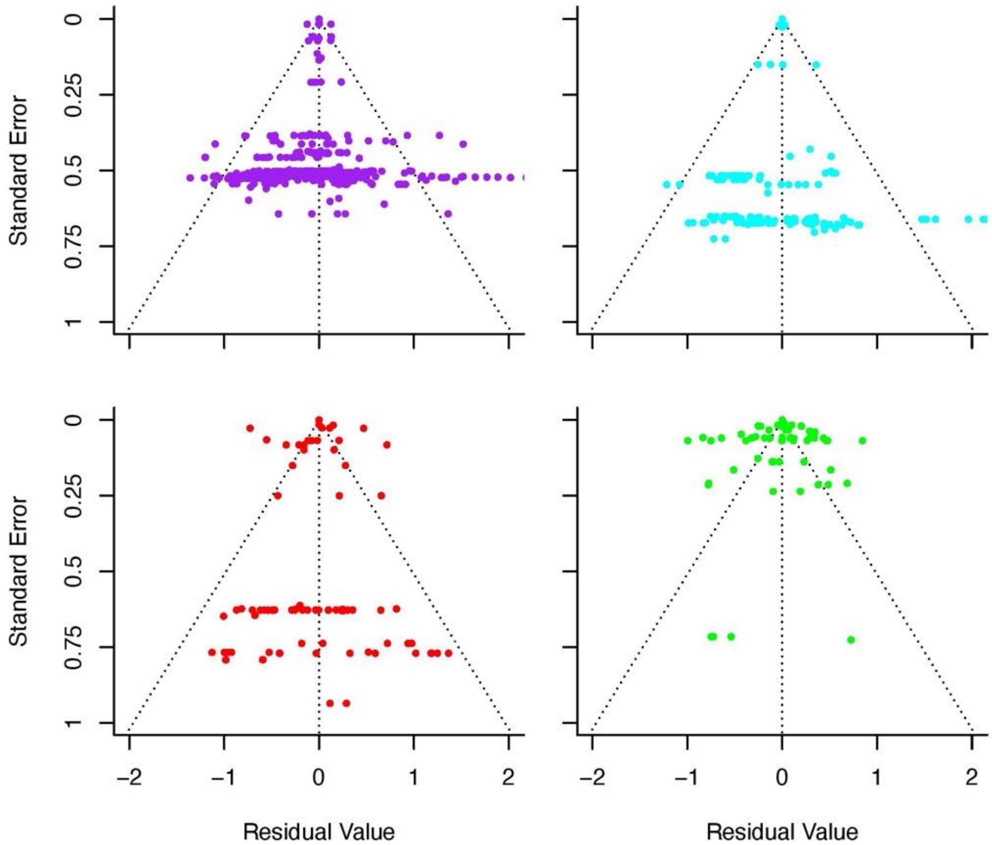


Figure 6. Funnel plots of the residuals between the normalized coefficient of determination (R^2) values and their corresponding means according to the forest attribute modeled (volume: purple, height: green, diameter: red, site index: cyan).

Finally, concerning the assessment of the prediction capacity of the models, only in 56, out of the 2524 cases that were identified in this study, a validation procedure was performed.

4. Discussion

Our results show that in Mexico there is a plethora of mathematical models developed for a large number of species and regions, which describe relationships between forest attributes based on relatively easy to measure variables, such as diameter and height. We found that, of a large number of models available, only a small fraction is used by researchers and forest managers. Also, the generation of models has focused on temperate forest species compared to other those from other ecosystems (e.g., tropical forests). Finally, the evaluation of the fit allowed concluding that most of the reported models present good fits; however, there was a clear tendency of the authors to recommend those models that present the highest R^2 values, without considering other criteria such as the parsimony of the model or their predictive power.

Advances in forest modeling, specifically in the evaluation of the response of trees and stands to silvicultural treatments, are still incipient. No dynamic models were found that evaluate forest productivity under the framework of global change, neither crown models, which are important in the evaluation of the wood quality and for the development of models of forest fuels and fire risk [27–29], nor incorporation models natural regeneration or mortality models. An area of opportunity for the development of these types of models would be to use information collected from forest inventories, as well as databases resulting from forestry research projects.

Concerning model fit, it was observed that the criteria used by the authors to evaluate this model characteristic were mainly the coefficient of determination and the root mean squared error. Other criteria that have been used for the evaluation of the models are Furnival's index [30], PRESS statistic [31], root mean squared error, and mean absolute error. We should emphasize that these criteria are only useful for the evaluation of fit, not for model selection, since they do not take into account the complexity of the model and, therefore, favor the choice of complex and, potentially, over-fitted models. Criteria such as the Akaike Information Criterion (AIC; Akaike [32]) seek to include this complexity to select more parsimonious models [11,33], ultimately selecting models that will make more biological sense.

Notwithstanding the above, it is important to emphasize that both sets of criteria only evaluate a model's ability to describe the data used to generate it, and not its ability to predict the response variable with an independent set of data [34]; given the interest of forest managers in applying models to make predictions, model selection should be performed based on the predictive, rather than the descriptive ability of the models [35,36].

Although the advances in the development of biometric systems in Mexico have been important over the last decades, these have not been coupled with the evaluation of their predictive capacity, which is achieved through validation. Less than 1% of the models we found reported results of some type of validation. Barrio-Anta and Diéguez-Aranda [37] suggest that an acceptable validation process may be cross-validation, although studies such as that of Kozak and Kozak [38] consider that the models should be validated using an independent sample. This may be one of the reasons why forestry models in Mexico are not validated since having independent samples is usually considered to increase costs and time for the development of validated models.

Finally, although the review does not include the last two years of forest modeling research, we believe that the 50-year trends detected in this study are strong enough to allow us to assume that no recent significant changes in the patterns will exist.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13050649/s1, Supplementary Material S1: List of terms, in English and Spanish, used in the search string grouped by concept. Supplementary Material S2: Database with the compiled equations. Supplementary Material S3: PRISMA checklist for the systematic review performed. Reference [39] is cited in supplementary material.

Author Contributions: J.O.L.-M., B.V.-L. and E.J.G. conceived the idea, research design, conducted the data collection, analysis, and wrote the manuscript. J.J.C.-R., O.A.A.-C., E.J.T.-G., H.M.D.l.S.-P., M.M.-S., F.J.Z.-S. and C.G.A.-C. provided data and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CONAFOR-CONACYT Fondo Sectorial, grant number 2013-C01-209772.

Data Availability Statement: The data used for this systematic review are available in the supplementary materials.

Acknowledgments: We thank our respective academic institutions for the facilities for the development of this study, and to SEMARNAT for information provided on forest management programs in Mexico, as well as to all those forest managers who shared their programs with us.

Conflicts of Interest: The authors declare no conflict of interest.

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