A Critical Review on Mathematical Descriptions to Study Flux Processes and Environmental-Related Interactions of Mangroves

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Abstract: Trees are resources that provide multiple benefits, such as the conservation of fauna, both terrestrial and marine, a source of food and raw material, and offering protection in storms, which makes it practical to understand their behavior against different phenomena. Such understanding may be possible through process modeling. Studies confirm that mangrove forests can store more carbon than other forests, influencing the fight against global warming. Thus, a critical and systematic review was carried out regarding studies focusing on mangroves to collect information on the models that have been applied and the most influential variables highlighted by other authors. Applying a systematic search for the most relevant topics related to mangroves (basic as well as recent information), it is possible to group models and methods carried out by other authors to respond to certain behaviors presented by mangroves. Moreover, possible structuring of a mathematical model applied to a species of interest thanks to the analyzed references could provide justified information to the authorities on the importance of these forests and the benefits of their preservation and regeneration-recovery.

Keywords: carbon storage; carbon dioxide sequestration; mangrove; mathematical model

1. Introduction

Over the years, concern about climate change has grown to the point where industries and any other activity are looking for ways to make themselves more efficient and environmentally friendly. The increase in the Earth's average temperature causes the modification of multiple ecosystems, affecting the species subsisting in it and the effect on the growth of multiple crops due to the carbon dioxide (CO_2) concentrations levels in the air [1]. In addition, the increase in the planet's temperature stimulates the melting of permafrost, causing the release of large amounts of trapped CO_2 and methane [2]. Trees play an essential role in the capture and retention of CO_2, the gas necessary to carry out part of its regeneration, growth, and maintenance processes during its life, having the possibility of increasing their CO_2 storage capacity, depending on the conditions of the tree (humidity, CO_2 concentration, nutrients, among others) [3].

This study aims to provide information on the equations that have been used recently to study the behavior of trees, specifically mangroves, providing information to other readers about the most relevant works in the determination of stored carbon and the most influential variables. The research focuses on the works presented in the last five years, including some works developed outside this limit, to then select the research focused on the retention of CO_2 in mangrove ecosystems, trying to show a better panorama of the variables involved than allowed by more comprehensive assessments of the importance of mangroves.

Trees near the coasts (in direct contact with salt and fresh water) are called mangroves. This kind of tree provides multiple benefits for the development of many species and the humans that live near these coastal areas [4]. These trees have the characteristic of capturing much more CO_2 than the species that are in contact with fresh water (much further from the coast) due to the characteristics of the soil, but they do not have the same number of studies due to the lack of accessibility to perform them [4,5]. Mangroves have managed to adapt to salt water and freshwater ecosystems thanks to the morphological adaptations they have developed, such as glands that allow them to expel excess salt, detachment of the seed once mature and ready to settle, and aerial roots for a greater fixation on their muddy soils, among others [4,6].

Mangroves also protect the coasts from strong winds and waves, dissipating the energy generated by their physical characteristics (such as their abundant roots and leaves) [4], also influencing the attenuation of cyclonic winds [7] and carbon fixation both in the soil and its biomass [8,9]. To survive the extreme environmental conditions, they developed unique ecophysiological characteristics [10–16] for functions such as leveling the salt concentration inside, water flow, and gas exchange [17]. In the following sections, various equations that characterize mangroves are evaluated. Through the evaluation, it was observed that in many cases, each species of tree has characteristics for which the equations developed for that species would not precisely give the same results if they were applied in another species with different configurations.

The text is divided into five main sections; Section 1 contains a brief introduction to the topic, Section 2 presents the methodology used, Section 3 contains the main results, and Sections 4 and 5 presents the discussions and conclusions of this research.

2. Methodology

2.1. Literature Search Strategy

This work was based on bibliographic research on the mathematical models that have been developed to explain specific processes in trees oriented towards mangrove species. A search was carried out on the research published from 2016–2021 to record updated information involving mangroves. Two codes were used to extract information regarding the mangroves to perform the analysis, "(Tree AND Mangrove) AND (Model OR Modeling)" and "(Tree AND Mangrove) AND (Model OR Modeling AND sequestration)", named C1 and C2, respectively, in Figure 1, obtaining a total of 2629 articles. These 2629 articles were obtained after searching for these keywords on the MDPI, IEEE Xplore, Elsevier, and Springer platforms (Figure 1), and then a more exhaustive review and evaluation of these articles was carried out as described in Section 2.2.
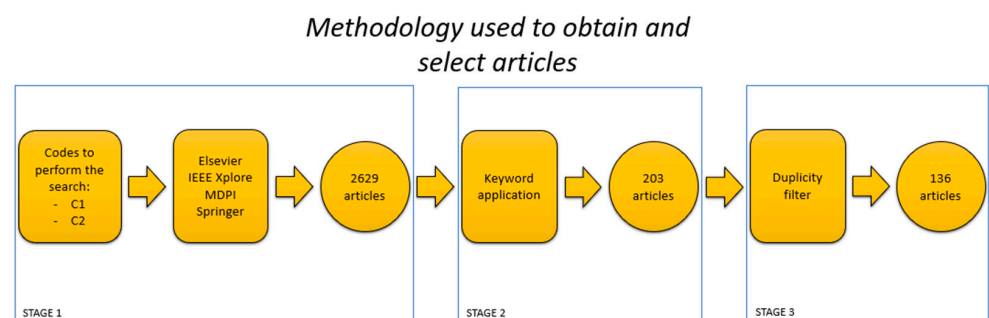
Figure 1. Methodology applied in the selection of articles. Source: Own elaboration.

2.2. Bibliometric Analysis

To structure stage 2, Software Rstudio (version 1.3.1093, Boston, MA, USA. Available online: https://www.rstudio.com/, accessed on 10 June 2021) was used, which, employing a code, extracted the articles mainly related to the topics of interest of the research such as: catchment, water flows, sap and/or carbon, carbon dioxide, regeneration, and flooding.

The code searched the topics of interest in the title, abstract, and keywords of the articles that were in the database. Among the packages used in the Software are "bib2df" and "ggplot2." Analyzing the results generated by the code, a distribution was observed that, for the most part, corresponds to issues related to CO_2, followed by catchment, and flows in mangroves, as shown in Figure 2. It was also possible to observe the number of publications that relate CO_2 to mangroves according to the database obtained since 2016 in Figure 3.
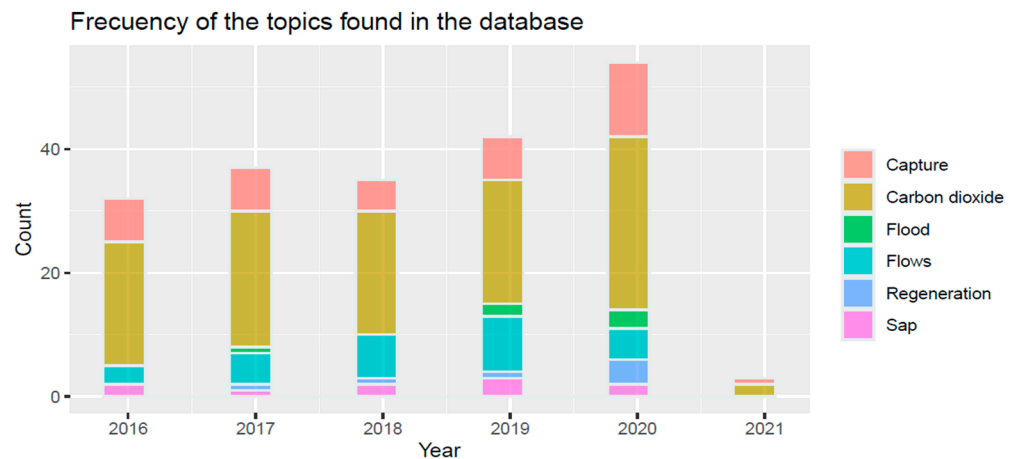
Frecuency of the topics found in the database

Figure 2. Frequency of the topics found in the database. Source: Own elaboration.

Publications linking carbon dioxide to mangroves
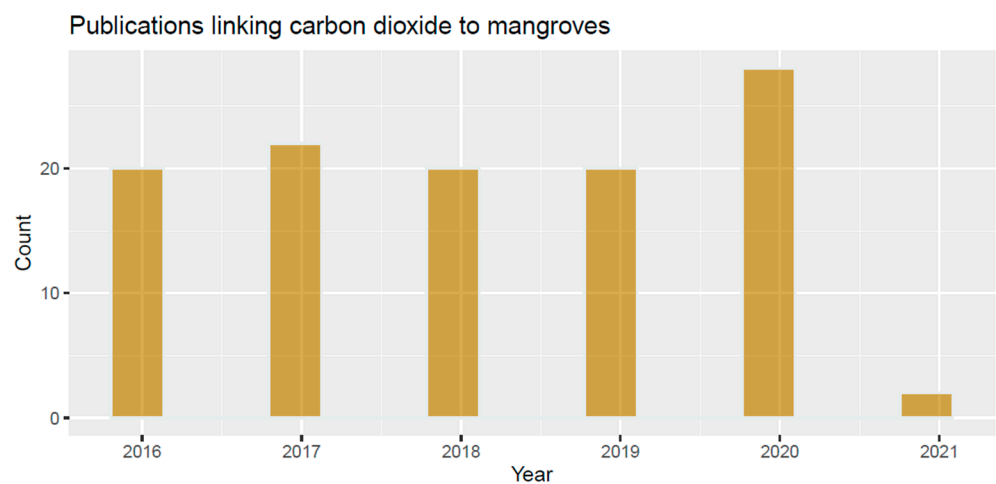
Figure 3. Publications on CO_2 and mangroves. Source: Own elaboration.

The topics most found in the resulting database are structured in Table 1, shown below.

Table 1. Topics found in the database.

Topics	Reference
Carbon stored by remote sensing/satellite images	[18–33]
Monitoring of stored carbon	[5,34–40]
Carbon quantification through literature	[41–45]
Mangrove flows	[46–49]
Filtration of heavy metals and pollutants	[50,51]

Source: Own elaboration.

3. Results: Relevance of Mangroves Modeling to Reap Their Benefits

This section presents the studies found regarding the mathematical modeling of mangroves' characteristics or aspects. Only four aspects regarding mangroves' habilities

or benefits were found and are classified as follows: depollution, biomass content, carbon sequestration, and rate of growth.

3.1. Depollution

Regarding depollution, only one reported study was found involving mathematical descriptions. The study developed by Ray et al. [50] analyzed the purification properties of the mangrove by performing tests in an empirical model to determine the uptake of vanadium, tantalum, and niobium in the soil, roots, and leaves of eight mangrove species by extracting samples from the Indian Sundarbans in the northeast of the Indian peninsula. Multiple types of equipment were used in the laboratory to transform the samples into data that could be used for the following equations (see Table A1 in Appendix A for nomenclature):

$$\log[metal] = b \times \delta 13C + a \tag{1}$$

$$BAF = metal_{leaf+wood+root} \ / \ metal_{sediment} \tag{2}$$

$$TF = metal_{leaf+wood} \ / \ metal_{root} \tag{3}$$

$$EF = \left\{ (metal \ /Hf)_{leaf+wood+root} \right\} \ / \left\{ (metal \ /Hf)_{sediment} \right\} \tag{4}$$

The results indicate that there is a retention of these elements in the different parts of its structure. Such results can be found in the author's article for the different mangrove species analyzed. Error or correlation data were not presented in the study.

3.2. Biomass Content

There are multiple studies focused on determining the biomass content in tropical forests to know the carbon storage capacity they possess, and with this, the importance they represent in the fight against global warming. Within the studies that focused on the calculation of biomass, there was a certain tendency regarding allometric models that involved measurements in the field for their use, mostly the product of correlations between the variables. Such is the case of Lozano [17], Mohd Zaki et al. [52], Da Motta et al. [53], Van Vinh et al. [54], Simpson et al. [55], and Chatting et al. [56], among others, who did not use the same equations but had variables in common (see Table 2).

Table 2. Allometric equations focused on the determination of aboveground biomass.

Author	Equation		Species	T (°C)	Mean Annual Rainfall (mm y⁻¹)
Mohd zaki et al. [52]	$AGB = exp[[-1.803 - 0.976 \times E + 0.967 \times ln(\rho_e) + 2.673 \times ln(DBH) - 0.0299 \times [ln(DBH)^2]]]$	(5)	L.t.t.s.	22.9–27.7	2178
Da Motta et al. [53]	$AGB = 0.251 \times \rho_e \times DBH^{2.46}$	(6)	L.r.—R.m. A.s.	-	1320
Van Vinh et al. [54]	$AGB = 0.38363 \times DBH^{2.2348}$	(7)	R.a.	27	1800
Simpson et al. [55]	$ln(AGB) = 1.63 \times ln(D_0) + 1.3545 \times ln(H) - 2.8853$	(8)	L.r.–A.g. R.m.	21–29	-
Chatting et al. [56]	$\log(AGB) = 2.14 \times \log(CD) + 0.20$ $CD = 0.3831 \times DBH + 0.6863$	(9)	A.m.	-	54
Kelleway et al. [57]	$AGB = \frac{h \times [0.214 \times (DBH \times \pi) - 0.113]^2}{10}$	(10)	A.m.	-	1084
Clough et al. [58]	$Log\,(AGB) = A + (B \times Log(DBH))$	(11)	R.s.–A.m.	35	1750
Prasanna et al. [59]	$V = \frac{h}{6} \times (A_{ba} + 4 \times A_m + A_t)$ $L_{db} = \sum_{j=1}^{i} n_j \times Lw_j \times N_j$ $B_{db} = \sum_{j=1}^{i} n_j \times bw_j$	(12) (13) (14)	A.m.	28–34.2	-
Makinde et al. [60]	$AGB = e^{(-3.1141 + 0.9719\ ln\,(DBH \times h))}$	(15)	T.g.–G.a. I.e.	-	1850

With: L.T.T.S. (lowland tropical tree species), L.R. (Laguncularia racemosa), R.a. (Rhizophora apiculata), A.g. (Avicennia germinans), R.m. (Rhizophora mangle), A.s. (Avicennia schaueriana), A.m. (Avicennia marina), R.s. (Rhizophora stylosa), T.g. (Tectona grandis), G.a. (Gmelina arborea), and I.s. (Indigenous species [60]). Source: Own elaboration.

Mohd Zaki et al. [52] presented equations that help reduce uncertainty when estimating carbon stored in forests, including equation (5) (Table 2), calculating the aboveground biomass (AGB) using remote sensing and non-linear regression equations in tropical lowland. The study was carried out in Hutan Simpan Ayer Hitam, a Malaysian forest reserve, which had information collected since 2013, and then the researchers carried out another more recent scan and thus completed the information necessary to apply the study. The equation used considers the density of tree species (ρ_e), as well as the diameter at breast height (DBH). Within the results, there were slightly low values in the determination coefficient ($R^2 = 0.453$) between the existence of carbon and the crown projection area, although its correlation turned out to be higher (0.671), attributing the values to the irregularities present in the canopy of the forest being studied.

Da Motta et al. [53] carried out a study in southeastern Brazil on the banks of the Piraquê-Açu river to determine the AGB and the carbon stored by the mangroves. They were able to obtain results by using allometric equations such as (6) (Table 2), taking measurements in the trees present in an area of 600 m^2 and soil samples to identify aspects such as humidity, permeability, and granulometry, among others. This study obtained 2.92 tons of AGB per hectare (t ha^{-1}) and 1.46 t ha^{-1} of carbon, with a coefficient of determination, for the mangrove species *Laguncularia racemosa*, which was satisfactory for the author ($R^2 = 0.89$). For the determination of AGB, an equation involving the density of the wood and the DBH was used, while for the stored carbon, the literature was used depending on the type and quantity of species found in the analyzed area.

Van Vinh et al. [54] focused their research on mangroves in Southern Vietnam, with the objective of determining the stored biomass through a proposed allometric equation (Equation (7)) that involves DBH, resulting in values between 59.7 and 230.9 mgC ha^{-1}. Additionally, distributions of carbon storage in biomass were assigned: 77.11% for the trunk, 11.87% for the branches, and 11.02% between roots and leaves with a coefficient of determination R^2 of 0.976 with a standard error value of 1.17. Simpson et al. [55] worked on the Atlantic coast of Florida, USA to identify the three-year changes concerning carbon storage due to the invasion of mangrove species in marsh areas thanks to Equation (8), using height of the tree in centimeters (H) and the diameter just after the soil surface (D_0). This work did not present correlation data or percentage of error. Chatting et al. [56] analyzed a mangrove area in Qatar, where the species *Avicennia marina* was prevalent, generating the Equation (9) used to determine the existing AGB by means of crown diameter (CD) and DBH. The equation used to determine AGB had a correlation coefficient of 0.94, while the equation used to convert DBH into CD had $R^2 = 0.53$.

The data collection for Mohd Zaki's work was carried out through non-destructive testing, unlike the study developed by Kusmana et al. [61], who conducted destructive tests on 30 tree samples in the mangroves of Cilacap, Indonesia. Within the study, the equations developed to obtain values of aboveground and underground biomass of the mangrove species *Sonneratia* spp. were observed, which required the DBH, height in meters (h), and density of the wood. For their part, Kelleway et al. [57] analyzed two mangroves located in marshes in southeastern Australia to quantify changes in mangrove migration to areas corresponding to salt marshes over 70 years. Aerial photographs from different years were used to make comparisons in vegetation, together with field measurements to determine AGB through allometric equations (Equation (10)) using height and DBH. The model was used in two places, obtaining a unified R^2 value of 0.603. Clough et al. [58] also provided experimental expressions for estimating AGB in mangroves on the north and west coast of Australia (Equation (11)) to determine the differences in the amount of biomass that exists due to environmental variations with DBH and height. The model used varied in the correlation coefficient depending on the species analyzed: for *Rhizophora stylosa*, there was an R^2 of 0.96 with a standard error of 0.090, while for the *Avicennia marina*, there was an R^2 of 0.969 with a standard error of 0.091.

Prasanna et al. [59] applied Equations (12)–(14) in the Karankadu mangrove swamp in southeastern India. These equations were sectioned in a tree to analyze each biomass

contribution and then summations were applied, taking into account the base, middle, and top areas of the trunk (A_{ba}, A_m, and A_t, respectively), dry leaf biomass (L_{db}), and dry branch biomass (B_{db}). A positive correlation was obtained between AGB and DBH ($R^2 = 0.960$), but it was not significant with respect to height ($R^2 = 0.349$).

Makinde et al. [60] applied geospatial techniques to determine the aboveground and underground biomass through the non-destructive method, interpreting the information provided by said method and applying Equation (15). In Table 2, it is possible to observe the allometric equations, mainly focused on the estimation of AGB.

The aforementioned works ([17,52–61]) used equations that estimate the AGB of a single tree. To determine the AGB of a forest, it will be necessary to carry out an inventory to obtain the measurements and then multiply by the number of trees. In Table 3, the parameters most used by the different authors for the determination of AGB can be observed.

Table 3. Parameters used in the equations to determine the AGB.

Parameter	Reference								
	[52]	[53]	[54]	[55]	[56]	[57]	[58]	[59]	[60]
DBH	*	*	*		*	*	*	*	*
D_0				*					
E	*								
ρ_e	*	*	*						
H				*					
CD						*			
V							*		
h								*	*

Source: our elaboration.

3.3. Carbon Sequestration

Thanks to an inventory developed by the Management Plan of the Guapi-Iscuandé Integral Management Unit (UMI) in Colombia, Lozano [17] managed to apply an empirical model to determine the CO_2 fixed in the selected mangrove, by means of Equation (18), shown in Table 4. For their part, Marchio et al. [62] selected two mangrove streams in southwest Florida, with the difference that one of these streams was hydrologically altered by human presence (dredging, channeling, polluted stormwater, compartmentalization of water flows, etc.) to determine the differences between carbon sequestration and the properties of sediments in mangroves once they are disturbed, thanks to Equation (17). As a result, it was possible to show the negative impact in terms of carbon sequestration as a result of the modification of its ecosystem. Neither paper presented had information on the percentage of error or correlation.

Table 4. Allometric equations focused on other objectives mangrove.

Author	Equation		Species	T (°C)	Mean Annual Rainfall (mm y^{-1})	Objective
Lozano [17]	$C_f = K \times A_b \times \left[B_i + \left(G_y \times t \right) \right]$	(16)	R.s.–A.m.	26	-	Carbon sequestration
Marchio et al. [62]	$C_{seq} = A_d \times BD \times C_{conc}$	(17)	A.g.–L.r. R.m.	23.6	1346	
Chatting et al. [56]	$\log(BGB) = 2.67 \times \log(CD) - 0.11$	(18)	A.m.	-	54	below ground biomass
Makinde et al. [60]	$BGB = 0.2 \times AGB$	(19)	T.g.–G.a. I.e.	-	1850	
Rodriguez et al. [6]	$AG = \frac{G_y \times DBH \times \left(\frac{1 - DBH \times H}{D_{Max} \times H_{Max}} \right)}{274 + 3 \times b_2 - 4 \times b_3 \times DBH^2} \times S \times n \times t_e \times r_{el}$	(20)	R.m.–A.g. L.r.	26.6	2300	Annual mangrove growth

Source: Own elaboration.

Table 4 presents the allometric equations applied to the determination of carbon storage in other sections of the mangrove, as well as an equation focused on the growth of mangroves.

3.4. Rate of Growth

Among the works focused on growth is Rodríguez et al. [6], which was developed in the Ciénaga Grande de Santa Marta mangroves in Colombia. A code written in "C" language was used with 16 years of information-gathering through monitoring. An individual-based model (IBM) was applied because it generates quite accurate results, taking into account how variable and complex mangrove ecosystems are according to the author, using Equation (20) (Table 4) analyzing three mangrove species: *Laguncularia racemosa*, *Rhizophora mangle*, and *Avicennia germinans*.

Once the model was applied in the selected areas, it was possible to observe how vulnerable the species were to high concentrations of salinity, unlike *Avicennia germinans*, which continued to grow and produce new seedlings over time. In the end, the model presented the increase in the basal area that would be expected in the following years, varying the concentration of salinity or maintaining them. The work did not present information on percentage of error or correlation.

In order to better understand the equations presented, dimensional analysis was used to verify dimensional homogeneity, as well as the interrelationships of the quantities that compose them. The Rayleigh method was applied to each of the equations as shown below:

$$AGB = exp[[-1.803 - 0.976 \times E + 0.967 \times ln(\rho_e) + 2.673 \times ln(DBH) - 0.0299 \times [ln(DBH)^2]]]$$

$$AGB = f(\rho_e, \, DBH)$$

with AGB (kg), ρ_e (g·cm^{-3}), and DBH (cm). Following the steps of the Rayleigh method, the fundamental dimensions were used:

$$AGB = \alpha \times \rho_e{}^a \times DBH^b$$

$$M = M^0 \times \left(ML^{-3}\right)^a L^b$$

where M is for mass, L for length, and t for time. Developing for M and L, we obtained $a = 1$ and $b = 3$.

Then:

$$AGB \propto \rho_e \times DBH^3$$

This procedure was carried out for each of the equations presented in Tables 2 and 4, but not all of them achieved a consistent result; however, it is to be expected that some expressions do not make physical dimensional sense among the variables they relate to. The results of the dimensional analysis are presented in Table 5.

Table 5. Dimensional analysis of equations.

Equation	Parameters	Fundamental Dimensions	Result Using Rayleigh's Method
(5) (6)	ρ_e, DBH	M, L	$AGB \propto \rho_e \times DBH^3$
(12)	h, A_{ba}, A_m, A_t	L	$V \propto \frac{h \times A_{ba} \times A_m}{A_t}$
(13)	Lw_j	M	$L_{db} \propto Lw_j$
(14)	bw_j	M	$B_{db} \propto bw_j$
(16)	A_b, B_i, t	M, L, t	$C_f \propto B_i$
(17)	A_d, BD, C_{conc}	M, L, t	$C_{seq} \propto A_d \times BD$
(19)	AGB	M	$BGB \propto AGB$

Source: Own elaboration.

4. Discussion

The conditions in which the works are carried out turn out to be influential when making comparisons or selecting a model to replicate it elsewhere. Precipitation, as well as

the temperature and fresh water that reaches the mangrove, help to stabilize the salinity of the environment, in this way the trees do not suffer from physiological stress, which would reduce the carbon retention capacity of the forest [62].

The authors agreed on the use of the variable DBH when determining AGB. However, all these expressions (Tables 2 and 4) result from experimental correlations and may limit their implementation in studies with different conditions and species. This means that each author who wishes to study or determine AGB for a certain mangrove species may have to carry out the process to obtain their corresponding regressions before estimating the total AGB in the mangrove. In fact, it could be said that only Equations (12–15) do not seem to depend strictly on a case study to obtain a way to estimate AGB. This is because they use common variables to any mangrove species and mangrove distribution. However, the foregoing does not exonerate us from the need to measure the diameter and height of the mangrove by incurring invasive studies of the mangrove ecosystem.

Moreover, most of the expressions indicated that the relationship between AGB and DBH is not linear. They show that the amount of AGB available increases exponentially when the DBH value increases, which leads us to infer a maximum amount of AGB; even if the DBH increases, the AGB available might not be significantly higher as one may expect. Moreover, these equations indicate that any amount of AGB cannot be obtained when DBH equals zero as expected, except for Equations (9), (12), and (17), but the resulting AGB value remains irrelevant.

The relationship between AGB and H (or h) seems to be less critical for the analyzed studies, except for Equations (8), (10), and (15). In the case of Equation (8), they used height to structure their equation because the species in the study area did not exceed 1.3 m in height to work with the DBH, so they decided to work with the diameter of the trunk right after the ground surface and its height. In Equation (10), the level of accuracy could be increased if the height of the tree was included since, in this study, there were trees above 2 m in height. It is not possible to say the same for Equation (15) because they did not work with mangroves. Instead, other morphologies and different dimensions were employed, and thus, the height could play a fundamental role in determining AGB.

The fact that CD is less considered in the estimation of AGB could indicate that the use of DBH considerably simplifies the calculations for obtaining the AGB. Such a selection could reduce the number of processes to be performed for the final determination of the AGB. This estimate would contribute greatly to show the importance of these forests in the fight against global warming through carbon sequestration and the benefits for marine fauna.

The structures of Equations (6) and (7) differ in the participation of the density of the tree species analyzed. For Equation (7), it is not important to consider density since they only focused on one mangrove species, in this case, *Rhizophora apiculata*, while Equation (6) was developed for three mangrove species. Hence, it would give a greater approximation of the aerial biomass if the density of the analyzed wood was considered.

Comparing the equations for carbon sequestration, it was observed that Equation (17) appears to be much more complete because it accounts for the carbon present in the soil C_{conc}, while Equation (16) focuses only on the AGB. However, if Equation (19) is considered, a less complicated approximation of the total uptake could be obtained by finding the AGB with Equation (17) and then assigning 20% to the soil carbon [60]. Equation (20) handles the same growth parameter as Equation (16). Such growth variable of the analyzed species focused mainly on determining the annual growth of mangroves and accounts for both the DBH and height.

The results in Table 5 indicate the proportionality of the dependent variables compared to the independent ones. For Equations (5) and (6), we saw that AGB is directly proportional to ρ_e and proportional to the cube of DBH. In Equation (12), we saw that V is proportional to h, A_{ba}, and A_m, but inversely proportional to A_t. For the case of Equations (13), (14), and (19) there is a proportionality with respect to the only parameter

that composes it. The result of Equations (16) and (17) show the proportionality between the most influential parameters that comprise it.

The models found do considered relevant parameters for AGB; however, they do not follow physical relationships entirely as suggested by the dimensional analysis. Most of the allometric equations found did not present dimensional homogeneity in terms of the dependent and independent variables. This leads to the conclusion that the authors did not seek a relationship that would first fulfil the physical dimensionality between dependent and independent variables, but rather functional relationships based purely on statistical foundations. The latter contradicts what Heusner stated in 1987: the physical dimensions of allometric expressions are of great importance, specifically the proportional coefficient relating the dependent and independent variables (alpha) [63]. In this regard, Morgado and Günther, in 1990, stated that "allometric equations only deals with two variables at a time, despite the fact that all biological processes are more likely to be of multivariate nature, and non-physical factors may influence the physical variables which are investigated"; however, it was stated years before (1984) by Schmidt-Nielsen that "dimensional analysis of physics can not be applied to the results of many biological measurements that are expressed in allometric form".

5. Conclusions

This investigation presents a critical and systematic review of the aspects considered when modeling mangrove flux processes and environmental interactions. A total of 15 studies were analyzed, where 1 was related to depollution, 11 to biomass content, 1 to a rate of growth, and 1 to carbon sequestration. Each of the models encountered was analyzed regarding mangroves' characteristics (i.e., linearity and similarities).

Among the analyzed studies, it is recommended to use the diameter of the crown instead of the DBH to have more accurate estimates, which represents a quite controversial assumption since most equations found for the determination of aerial biomass use the DBH in their calculations. In this case, it is necessary to consider the level of precision wanted to consider modifying the equation, depending on the diameter of the crown.

The variables necessary for structuring a complete model were identified, from simple measurements such as DBH to the determination of concentrations in the soil, density, and others. It will be necessary to reevaluate the variables that should be obtained, depending on the influence they have on the total value of AGB, in order to be more efficient in terms of equipment and time needed in the modeling processes.

The importance of complying with physical dimensionality lies in the fact that the models can be replicable for different species because they take into account intrinsic characteristics of each species such as its density, for example. Including volume, diameter, and height does not characterize a species. This can be achieved by combining the above with correlation analysis. Looking for relationships based solely on statistics indicates, among several things, that we are not concerned with knowing the complete physical relationship between these two variables. It is like a black box model.

It is possible to show the importance of studies to estimate CO_2 capture and storage, providing information to governments and other researchers to structure new analysis plans based on models, and not by the traditional invasive destruction method, seeking preservation and recovery of mangrove ecosystems while the information regarding these ecosystems continues to increase. In this way, mangrove forests can continue to mitigate the problems of global warming.

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Appendix A

Table A1 with information on parameters used in the different equations shown in this research.

Table A1. Parameters used in the equations presented.

Parameter	Definition	Units	Source
AGB	aboveground biomass	kg	-
AG	annual mangrove growth	-	[6]
A, B	constant	-	[58]
A_b	forest area	ha	-
A_d	accretion rate obtained by the radiometric system	$cm \cdot y^{-1}$	-
A_{ba}, A_m, A_t	base, middle, and top areas	m^2	-
b	trophic magnification slope	-	[50]
BD	average bulk density	$g\text{-soil} \cdot cm^{-3}$	-
BAF	bioaccumulation factor	-	[50]
BGB	below ground biomass	kg	-
b_2	growth constants of the species	-	[6]
b_3	growth constants of the species	-	[6]
B_i	initial biomass in the area	ton	-
B_{db}	dry branch biomass	kg	-
bw_j	average weight of the branches	kg	-
CD	crown diameter	m	-
C_{conc}	average concentration of carbon in the soil	$g\text{-C} \cdot g\text{-soil}^{-1}$	-
C_f	fixed carbon	ton	-
C_{seq}	carbon sequestration	$g\text{-C} \cdot cm^{-2} \cdot y^{-1}$	-
DBH	diameter at breast height	cm	-
D_0	diameter just above the soil surface	cm	-
D_{Max}	maximum diameter of the species	cm	-
E	bioclimatic variables	-	[52]
EF	enrichment factor	-	[50]
G	annual growth rate	-	[17]
G_y	growth constants of the species	-	[6]
h	stem height	m	-
H	stem height	cm	-
Hf	hafnium	-	[50]
H_{Max}	maximum height of the species	cm	-
K	carbon in biomass (45%)	-	-
L_{db}	dry leaf biomass	kg	-
Lw_j	average dry weight of extracted leaves	kg	-
n	effect of nutrients	-	[6]
n_j	number of branches in each tree	-	-
N_j	number of trees	-	-
r_{el}	effects of light intensity	-	[6]
S	effect of salinity	-	[6]
t	time	y	-
TF	translocation factor	-	[50]
t_e	temperature effects	-	[6]
V	volume of stem biomass	m^3	-
δ13C	stable carbon isotope	-	[50]
ρ_e	tree species density	$g \cdot cm^{-3}$	-

Source: Own elaboration.

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