Challenges and solutions for reducing bias in Forest inventory-based estimates of aboveground biomass in arid zones

Luis A. Hernández-Martínez
Centro de Investigación Científica de Yucatán (CICY)
José Luis Hernández-Stefanoni
Centro de Investigación Científica de Yucatán (CICY)
Alfonso Medel-Narváez
Centro de Investigaciones Biológicas del Noroeste (CIBNOR)
Carlos Portillo-Quintero
Texas Tech University
Carlos A. Cabada-Tavares
Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP)
Carlos Lim-Vega
Rancho Cacachilas
Juan Manuel Dupuy-Rada
jmdupuy@cicy.mx

Centro de Investigación Científica de Yucatán (CICY)

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Abstract

Forest inventories are fundamental instruments for estimating the aboveground biomass density (AGBD) of forests and for assessing their contribution to climate change mitigation. However, inventories may entail errors that generate uncertainty in the estimates, the magnitude of which varies according to vegetation type. Few studies have addressed the sources of error and bias in AGBD estimates based on forest inventories in arid zones. In this study, three major sources of error or bias were analyzed: the selection of inadequate dendrometric variables during sampling, the omission of small trees and shrubs due to inclusion criteria, and the lack of allometric equations for some of the most abundant species, such as columnar cacti. The results reveal an alarming level of underestimation due to the omission of smaller individuals in xeric shrubland and tropical dry forest, whose contribution can increase the average AGBD value by up to 307% and 180%, respectively. In this study, we propose a methodology to mitigate such underestimation and provide new allometric equations to estimate the biomass of the columnar cactus *Pachycereus pringlei*. Improvements of this kind are essential to determine the actual contribution of arid and semiarid vegetation to carbon storage, which appears to be seriously underestimated.

Introduction

Forest inventories are important instruments for ecosystem monitoring. They provide useful information both for the sustainable use of forest resources and for the design and implementation of biodiversity conservation strategies. Moreover, they offer information that allows the quantification of ecosystem services provided by forests, such as atmospheric carbon sequestration (Breidenbach et al. 2021). This is crucial for climate change mitigation, due to the central role of forests in the absorption and emission of greenhouse gases (Pan et al. 2011; Friedlingstein et al. 2022). Among other variables, forest inventories allow for the estimation of aboveground biomass density (AGBD), which constitutes one of the most important components of the total carbon stock in terrestrial ecosystems (Kumar and Mutanga, 2017).

National Forest Inventories have made it possible to quantify AGBD and the carbon stored in forests. Because they are conducted periodically, they also enable the estimation of temporal changes in AGBD, a key component of forest productivity. Reporting the level of uncertainty in these estimates is a requirement for national reports to the United Nations Framework Convention on Climate Change (UNFCCC) and international mitigation programs such as the strategy for Reducing Emissions from Deforestation and Forest Degradation (REDD+) (Yanai et al. 2020). In addition to sampling design issues (Magnussen et al. 2020), numerous sources of uncertainty have been identified in estimates derived from inventories, such as errors in species taxonomic identification, problems associated with plot size and shape, minimum size criteria for individuals included in measurements, lack of information on wood density, and errors in height measurement or estimation (Réjou-Méchain et al. 2019; Yanai et al. 2023; Sæbø et al. 2022; Ma et al. 2024). The lack of species-specific allometric equations is an additional source of uncertainty in aboveground biomass (AGB) estimates at both the individual and species level (Conti et al. 2013; Návar et al. 2013).

In Mexico, the National Forest Inventory (NFI), coordinated by the National Forestry Commission (CONAFOR), represents a significant effort to monitor the state of its forest resources since 2004. It is carried out every five years and includes variables such as plant height, diameter at breast height (DBH), basal area, tree height and species identity, among others (CONAFOR, 2017). The NFI has played a central role in estimating AGBD in Mexico and has been used to generate modeled estimates using remote sensing (Cartus et al. 2014; Rodríguez-Veiga et al. 2016; Urbazaev et al. 2018). However, reported sources of error and bias include the lack of sample representativeness due to the spatial distribution of sampling units, the lack of allometric equations (Rodríguez-Veiga et al. 2016), and failing to account for the contribution of small trees, particularly in tropical dry forests and secondary vegetation (Hernández-Stefanoni et al. 2020), since the NFI does not measure dendrometric variables of individuals with DBH < 7.5 cm. Another unexplored potential source of error is the use of DBH as the only measure of stem diameter, even though many allometric equations for shrub species use basal diameter (BD) as a predictor of AGB (Conti et al. 2019; Návar et al. 2013). Similarly, in arid zones, AGBD estimates derived from the NFI may be subject to errors and biases due to low sampling density. Arid zones are characterized by high structural and vegetation cover heterogeneity, which requires an appropriate sampling design to capture this variability. Paradoxically, the NFI has the lowest density of systematic sampling units in arid zones, which adds to the biases stemming from inclusion criteria and diameter measurements. Notably, some arid regions contain high densities of small individuals with thick stems branching below DBH, which are omitted during NFI measurements, resulting in underestimation of AGBD. Additionally, columnar cacti represent a special problem due to the lack of specific allometric equations and the perception that they are of little relevance for carbon storage. Although some studies estimate that they may account for up to 11% of the AGBD in arid zones (Búrquez et al. 2010), the contribution of columnar cacti has been little studied (Briones et al. 2018).

Even though arid zones are perceived as areas of low importance for carbon storage, these regions cover approximately one-third of the planet's surface (Zhang et al. 2023) and are associated with up to 39% of the interannual variability of global carbon balances, a value higher than that of tropical forests (19%; Ahlström et al. 2015). In Mexico, arid and semi-arid zones cover more than half of the territory, highlighting the need to improve the quality of AGBD estimates in these areas. Better estimates are key for evaluating their contribution to carbon storage (Briones et al. 2018) and for enhancing the accuracy of national reports to UNFCCC and international mitigation programs such as REDD+ (Yanai et al. 2020).

In this study, we evaluated various sources of error or bias in AGBD estimates in an arid and semi-arid zone located in the Cape Region of Baja California Sur, Mexico, which constitutes a transition zone between xeric shrubland, tropical dry forest, and temperate forests. First, using a dataset of sampled plots, we estimated the effect of using BD instead of DBH (both ≥ 7.5 cm) as the inclusion criterion, as well as the effect of including smaller individuals (BD ≥ 2.5 cm) in AGBD estimates. With these data, correction factors for small individuals were also developed to estimate their contribution to AGBD. Subsequently, we evaluated the correction of two sources of error in NFI-derived data: (1) the lack of specific allometric equations for columnar cacti (*Pachycereus spp*.), for which new equations were developed; and (2) the omission of small individuals, which was corrected using correction factors derived from the sampled plots. In both cases, the effect of the corrections on plot-level AGBD estimates from the NFI was evaluated by comparing the results with a reference value. Our research questions were threefold: 1) what is the magnitude of underestimation of AGBD due to the use of DBH instead of BD and to the exclusion of small trees and shrubs (BD > 2.5 cm) in four vegetation types (xeric shrubland, tropical dry forest, broadleaf forests and coniferous-broadleaf forests)? 2) How does using an allometric equation developed for the most abundant species of columnar cacti (*Pachycereus pringlei*) affect the estimation of AGBD in xeric shrublands and tropical dry forests? 3) To what extent does using such allometric equation and correction factors for the NFI inclusion criterion (DBH ≥ 7.5 cm) compensate these biases in AGBD estimation in xeric shrublands and tropical dry forests? We propose the following hypotheses and predictions: H1. Xeric shrubland and tropical dry forest differ from broadleaf and coniferous-broadleaf forests in the predominance of shrubs and trees with thick stems branching below DBH in the former. P1. Therefore, we expect that the effect of the plant-size inclusion criteria used in the NFI on the underestimation of AGBD will be much greater in these two vegetation types than in broadleaf and coniferous-broadleaf forests. H2. Larger plants contribute disproportionately more to AGBD than smaller ones (Ali and Wang, 2021; Yang et al. 2022). P2. Consequently, we expect that using BD (≥ 7.5 cm) instead of DBH will result in a greater reduction in AGBD underestimation than including smaller plants (2.5 cm ≤ BD < 7.5 cm). H3. Given the important contribution of columnar cacti to AGBD in Xeric shrubland and the tropical dry forest in the study region, the lack of specific allometric equations for dominant species, such as *Pachycereus spp*. represents an important source of error in AGBD estimates in these vegetation types. P3. Therefore, we expect that applying a species-specific allometric equation for *Pachycereus pringlei*, a dominant species in the study region, will significantly reduce the error in NFI plot-level AGBD estimates.

Methods

Study area

The study was conducted in the Cape Region, located in northwestern Mexico in the southern part of the state of Baja California Sur, between 22° and 25° N latitude and -108° and -111° W longitude (Fig. 1). The lowlands of the Cape Region present warm and dry conditions, with mean annual temperature of 23° and mean annual precipitation of 200 mm. In Sierra de la Laguna in the central part of the Cape Region, there is an ecological and environmental transition linked to the orography, resulting in a more temperate and humid climate with rainfall reaching 700 mm annually in the highest parts (2090 m a.s.l.; León-de la Luz et al. 2000; González-Abraham et al. 2010). Rainfall occurs between July and January, with a strong influence from tropical cyclones that occasionally enter from the Pacific Ocean between September and November. In the study area, xeric shrublands dominate up to 500 m a.s.l., tropical dry forest occurs between 500 and 1000 m a.s.l., and broadleaf and coniferous-broadleaf forests predominate above 1000 m a.s.l. (González-Abraham et al. 2010).

Fig. 1 Location of the Cape Region in Baja California Sur, Mexico (a), main vegetation types, field-sampled plots (blue circles), and National Forest Inventory plots (black diamonds) (b)

Field data

Sampling and evaluation of the effect of NFI inclusion criteria

During 2022, field data were collected for four vegetation types: xeric shrubland, tropical dry forest, broadleaf forest, and coniferous-broadleaf forest. Although the focus of this study is on drier vegetation types, namely Xeric shrubland and tropical dry forest, results for broadleaf and coniferous-broadleaf forests are reported for comparative purposes. Following the NFI sampling design (CONAFOR, 2017), the primary sampling unit (hereafter “plot”) was a circular area of 1 hectare (radius = 56.42 m), composed of four circular subplots of 400 m² (radius = 11.28 m) distributed in an inverted “Y” shape. The NFI uses as its inclusion criterion for measuring dendrometric variables for individual stems a diameter at breast height (DBH: measured at 1.3 m above the ground) ≥ 7.5 cm. However, in Xeric shrubland and tropical dry forest, trees and shrubs with thick stems branching below 1.3 m predominate. Therefore, in our sampling we used basal diameter (BD) instead of DBH as a measure of diameter. Additionally, unlike the NFI, in each plot we established a concentric sub-subplot of 80 m² (radius = 5.04 m) to include smaller individuals (BD ≥ 2.5 cm). For each individual we recorded total height (H in m), stem height (cm), crown diameter (CD; average of two perpendicular measurements in m), BD (cm), and DBH (cm) of stems that met our inclusion criteria (BD ≥ 2.5 cm in 80 m² subplots, BD ≥ 7.5 cm in 400 m² subplots). Measurements were carried out after the rainy season, between September and December, yielding a sample size of 46 plots, in which a total of 5,025 individuals were measured. The sampling included 14 plots in xeric shrubland, 14 in tropical dry forest, 6 in broadleaf forest, and 12 in coniferous-broadleaf forest. In most cases, taxonomic identification of individuals was performed during field measurements; when this was not possible, photographs were taken and later used for identification by expert taxonomists at the Annetta Mary Carter Herbarium of the Centro de Investigaciones Biológicas del Noroeste.

Aboveground biomass (AGB) per individual was calculated using allometric equations primarily developed in arid zones, as well as equations that allowed AGB estimation using dendrometric variables beyond those considered by the NFI (e.g., BD or CD; see Table S1). In the case of columnar cacti, specific allometric equations for *Pachycereus pringlei* were developed as part of this study, following the methodology described below. Subsequently, AGB density per unit area was calculated at the plot level (AGBD in Mg ha^{-1}).

To evaluate the effect of the NFI diameter criterion (DBH instead of BD) and the exclusion of smaller individuals (2.5 cm ≤ BD < 7.5 cm), we used the data from the sampled plots in this study to perform three AGBD estimates: (1) considering only individuals with DBH ≥ 7.5 cm (as the NFI would); (2) using BD instead of DBH (BD ≥ 7.5 cm); and (3) including small trees and shrubs (2.5 cm ≤ BD < 7.5 cm).

NFI data

We used the NFI database from 2015–2019, which includes 31 plots of 1 ha distributed throughout the study area (Fig. 1). The NFI provides estimated AGB for each individual, from which total AGB per plot and subsequently AGB per unit area (AGBD in Mg ha^{-1}) were calculated.

Correction of NFI AGBD estimation

Development of allometric equations for Pachycereus pringlei

Two corrections were applied to the NFI AGBD estimation. First, due to the lack of allometric equations for estimating AGB of columnar cacti and their predominance in xeric shrubland and tropical dry forest, we developed species-specific allometric equations for *Pachycereus pringlei*, a dominant species in the study area. For this purpose, dendrometric variables of 40 individuals ranging in DBH from 19 to 43 cm were measured, recording the diameter and length of all their stems (main stem and branches), considering only uniform sections (cylindrically-shaped) and ignoring deformations. To estimate individual AGB, the volume of each stem was calculated and multiplied by the wood density reported by Romero et al. (2020) for *P. pecten-aboriginum*. Subsequently, biomass of all stems was summed to obtain total AGB per individual.

For equation development, total AGB was used as the dependent variable and dendrometric variables such as total height (H), basal diameter (BD), diameter at breast height (DBH), and crown diameter (CD) as independent variables. Sample characteristics are presented in supplementary information (Table S2). Linear and nonlinear models were fitted and validated using both individual variables and synthetic variables commonly used in allometric models (e.g., BD^2*H). Cross-validation was conducted (Picard and Cook, 1984), and the best model was selected based on the coefficient of determination (R^2), calculated from linear regression between observed and predicted values, as well as root mean square error in kg (RMSE) and percentage (%RMSE).

Using the best allometric equation, individual-level AGB was estimated for the two species of *Pachycereus* (*P. pringlei* and *P. pecten-aboriginum*) present in the study area in the NFI database. Although the equations were developed only with *P. pringlei* data, corrections were applied to both species considering that *P. pecten-aboriginum* was scarcely represented in the NFI sample, with only 38 individuals (equivalent to 2% of *Pachycereus spp*.). Likewise, the AGB of recorded individuals without branches was calculated, multiplying their volume by their wood density. Finally, plot-level AGBD was calculated after the correction (hereafter, *Pachycereus* correction).

Size correction

For the second correction, the contribution of shrubs and small individuals (BD ≥ 2.5 cm and DBH < 7.5 cm), which are not considered in NFI AGBD estimates, was estimated, and their proportion per AGBD quartile in each vegetation type was calculated using the dataset from the sampled plots. This proportion was then used as a correction factor for NFI data. To do so, NFI AGBD values were multiplied by these factors according to their distribution within quartile ranges. This correction (hereafter, size correction) was applied to take into account the contribution of shrubs and small individuals that were not measured in NFI sampling. It is worth noting that this correction included both the effect of using BD instead of DBH for stems ≥ 7.5 cm, and of considering smaller individuals (2.5 cm ≤ DB < 7.5 cm).

To evaluate the effect of both corrections (*Pachycereus* and size corrections) applied to NFI AGBD estimates, the distribution of observations was compared (without corrections, *Pachycereus* correction and both *Pachycereus* and size corrections). After checking for normality assumptions, statistical tests were conducted to assess whether significant differences existed among the estimates following the corrections. This comparison was carried out only for xeric shrubland and tropical dry forest, which showed sizeable correction factors compared to broadleaf and coniferous-broadleaf forests. To compare mean values of uncorrected and corrected estimates, an analysis of variance (ANOVA) was used for tropical dry forest, while a non-parametric Kruskal–Wallis test was applied for xeric shrubland, since it did not meet ANOVA assumptions.

Finally, AGBD estimates from the NFI (mean ± 95% CI for uncorrected and corrected values) were compared with the mean value of each quartile by vegetation type, which was estimated using the field data generated in this study; this dataset was assumed to represent an independent reference value for each vegetation type.

Results

Evaluation of the effect of NFI inclusion criteria

The AGBD values by vegetation type obtained from field sampling (including small individuals) showed the expected pattern, with an increase in biomass from the lowland xeric shrubland (mean = 35.94 Mg ha^{-1}) and tropical dry forest (mean = 32.78 Mg ha^{-1}) to the broadleaf forest (mean = 42.62 Mg ha^{-1}) and the conifer–broadleaf forest (mean = 146.29 Mg ha^{-1}) (Table 1; Fig. 2). The results also showed considerable variability within each vegetation type: AGBD values ranged from 17.08 to 63.47 Mg ha^{-1} in xeric shrubland, 11.69–60.14 Mg ha^{-1} in tropical dry forest, 10.61–61.46 Mg ha^{-1} in broadleaf forest, and 91.28–200.66 Mg ha^{-1} in conifer–broadleaf forest.

Noteworthily, compared to AGBD estimated following the NFI sampling methodology, the mean AGBD values in xeric shrubland and tropical dry forest increased by 220% and 99%, respectively, when BD was used instead of DBH as diameter measurement criterion (Table 1). When small individuals were included, the mean values for xeric shrubland and tropical dry forest showed additional increases of 27% and 41%, respectively. The total estimated increase, based on the difference between the AGBD estimated as in the NFI (DBH ≥ 7.5 cm) and that including small individuals and BD instead of DBH (BD ≥ 2.5 cm), was 307% and 180% in xeric shrubland and tropical dry forest, respectively. This highlights the huge underestimation of AGBD in these vegetation types when DBH is used as the inclusion criterion and when small trees and shrubs are omitted from measurements. In contrast, in broadleaf and conifer–broadleaf forests the increases were only 3.2% and 0.06%, respectively, when BD was used instead of DBH, and 1.2% and 0.3% when small individuals were included (Table 1).

In xeric shrubland, significant differences were found in the mean AGBD value between the sample estimated using the NFI approach and the one using BD instead of DBH, but no differences were observed between the latter and the one including small individuals. In tropical dry forest, a significant difference was found between the NFI-based estimate and the sample that included small individuals (BD ≥ 2.5 cm) (Fig. 2).

Table 1 Sample size and descriptive statistics of AGBD estimates derived from 46 field plots using different inclusion criteria

		AGBD Mg ha^{-1} *estimated as NFI* (DBH ≥ 7.5 cm)	AGBD Mg ha^{-1} *using BD* (BD ≥ 7.5 cm)		AGBD Mg ha^{-1} *including all* (BD ≥ 2.5 cm)	
Vegetation type	**ss**	**mean (min-max)**	**mean (min-max)**	**Inc**	**mean (min-max)**	**Inc**
XS	14	8.83 (2.94 – 20.10)	28.27 (15.61 – 55.75)	220%	35.94 (17.08 – 63.47)	27%
TDF	14	11.67 (0.83 – 32.35)	23.25 (6.04 – 48.29)	99%	32.78 (11.69 – 60.14)	41%
BLF	6	40.74 (10.04 – 58.96)	42.08 (10.05 – 61.46)	3%	42.62 (10.61 – 61.46)	1%
CBLF	12	145.72 (90.39 – 200.42)	145.82 (91.41 – 200.59)	0%	146.29 (91.28 – 200.66)	0%

ss = sample size; min = minimum; max = maximum; Inc = Increase of mean AGBD relative to the previous estimate (column); XS = Xeric shrubland; TDF = Tropical deciduous forest; BLF = Broad-leaved forest; CBLF = Conifer–broad-leaved forest.

Fig. 2 Mean values and 95% confidence intervals of AGBD by vegetation type, using three estimation methods applied to field plots sampled in the Cape Region, Baja California Sur, Mexico

NFI corrections

Allometric equations and results of the Pachycereus correction

The best AGB prediction model for *Pachycereus pringlei* was obtained using DBH, H, and CD as predictors (R^2 = 0.90), which also showed the best model validation performance (R^2 = 0.89, RMSE = 41.52 kg, and %RMSE = 17) (Table 2; Fig. 3a). However, columnar cacti vary in structure, and in some cases, individuals bifurcate below 1.3 m. Therefore, a model fitted with BD was also reported, using the variables BD^2*H and CD, which also performed well (R^2 = 0.80) but with lower validation parameters than the previous model (R^2 = 0.76, RMSE = 60.59 kg, and %RMSE = 24.81) (Table 2; Fig. 3b). Finally, considering that BD is not measured in the NFI and that CD measurements are sometimes absent or inconsistent (as detailed later), a third model including only DBH and H was reported. This last model showed a slightly lower fit than the previous one (R^2 = 0.76) and similar validation parameters (R^2 = 0.73, RMSE = 63.95 kg, and %RMSE = 26.18) (Table 3; Fig. 3c). Although the two additional models had lower fits than the first one, they may serve as valuable tools for estimating AGB in *Pachycereus spp*. individuals with different structural conditions and under different scenarios of dendrometric variables availability in forest inventories.

Table 2 Statistics of the allometric models fitted to predict aboveground biomass (AGB in Kg) of *Pachycereus pringlei* and cross-validation results

Calibration				**Validation**		
Model	**Parameter**	**β**	R^2	R^2	**RMSE**	**%RMSE**
	Intercept	-493.52	0.90	0.89	41.52	17.00
1)	DBH	16.78				
	H	23.07				
	CD	122.60				
	Intercept	-89.50	0.80	0.76	60.59	24.81
2)	BD^2*H	0.04				
	CD	128.91				
	Intercept	-475.76				
3)	DBH	22.00	0.76	0.73	63.95	26.18
	H	22.46				

Fig. 3 Cross-validation results of three allometric models fitted to predict AGB of *Pachycereus pringlei*. The dashed line represents the 1:1 relationship, and the green line indicates the regression line

During the exploration of NFI data, numerous dubious values were found (see Fig. S1), especially in CD measurements. Therefore, since models 1 and 2 both include CD as a predictor, model 3, which uses DBH and H as predictors, was applied to estimate individual-level AGB. At the plot level, the effect on AGBD values in xeric shrubland and tropical dry forest was moderate, with increases of 3% and 4%, respectively, after applying the *Pachycereus* correction (Table 3). In both vegetation types, no statistically significant differences were observed in mean values following the application of the *Pachycereus* correction ($p > 0.05$) (Fig. 4). However, branches were reported for only to 15% of the *Pachycereus spp*. individuals recorded in the NFI database (277 individuals), compared to 32% (103 out of 318 individuals) in our sampled plots. The remaining 85% (1546 individuals) in the NFI database corresponded to unbranched single-stemmed individuals. Although no significant differences in AGB were found between uncorrected and corrected values (Fig. 5b) overall and for single-stemmed individuals, a significant increase was found for branched individuals when AGB was corrected using the allometric equation (Fig. 5a).

Fig. 4 Distribution of NFI AGBD values without correction, with the *Pachycereus* correction, and with both *Pachycereus* and size corrections in (a) xeric shrubland and (b) tropical dry forest. Different letters indicate statistically significant differences ($p < 0.05$) between groups

Fig. 5 Effects of correcting *Pachycereus sp.* AGB estimates at the individual level using the species-specific allometric equation for branched individuals (a) and volume and wood density for unbranched individuals (b). The 95% confidence intervals are shown (whiskers) along with the mean values (points)

Effects of Pachycereus and size corrections

The AGBD correction factors showed an important contribution of small individuals in xeric shrubland and tropical dry forest, where they accounted for up to 36% and 81%, respectively. Correction factors were much lower in broadleaf forest, remaining below 4% in all cases, and even lower in conifer–broadleaf forest, where they represented less than 1% across the four AGBD quartiles. The correction factors estimated by quartile are presented in the supplementary information (Table S3). Since only xeric shrubland and tropical dry forest had a sufficient NFI sample size and only these vegetation types showed sizable correction factors (compared with broadleaf and conifer–broadleaf forests), the correction results are presented exclusively for these vegetation types.

Relative to the *Pachycereus* correction, the size correction increased the NFI mean AGBD value by 21% in xeric shrubland, and by 56% in tropical dry forest (Table 3). Although in xeric shrubland this percentage increase represents a considerable amount of AGBD, no significant differences were observed between corrected and uncorrected mean values ($p > 0.05$) (Fig. 4a). In contrast, tropical dry forest showed significant differences after applying both corrections ($p < 0.05$) (Fig. 4b).

Table 3 Descriptive statistics of NFI-based AGBD estimates, uncorrected and after applying *Pachycereus* and size corrections

			Mean AGBD Mg ha $^{-1}$ un corrected	Mean AGBD Mg ha $^{-1}$ *Pachycereus* correction		Mean AGBD Mg ha $^{-1}$ size + *Pachycereus* correction	
Vegetation type	**ss**	**# Ind**	**mean (min-max)**	**mean (min-max)**	**Inc**	**mean (min-max)**	**Inc**
XS	31	2513	9.98 (0.29 – 46.97)	10.27 (0.25 – 49.08)	2%	12.44 (0.29 – 67.63)	21%
TDF	19	2047	18.89 (2.75 – 40.94)	19.64 (2.73 – 40.84)	3%	30.62 (4.93 – 57.99)	56%

ss = sample size; # Ind = number of individuals measured; min = minimum; max =maximum; Inc = increase of mean AGBD relative to previous estimate (column); XS = xeric shrubland; TDF = tropical deciduous forest.

The analysis of quartile-based estimates relative to the reference value (estimated from our sampled plots) in xeric shrubland showed that for the first quartile (17–26 Mg ha^{-1}), the *Pachycereus* correction had a minimal effect on the underestimation. However, when both corrections were applied, the estimate did not differ significantly from the reference value, although it also did not differ significantly from the uncorrected value (Fig. 6a). Since the NFI had no estimates between 26–30 Mg ha^{-1} (second quartile), no comparison was possible for this range. Furthermore, above 26 Mg ha^{-1}, the NFI sample size was insufficient to allow a statistical comparison (only one observation between 30–45 Mg ha^{-1} and one >45 Mg ha^{-1}). In both cases, AGBD increased slightly after the *Pachycereus* correction and exceeded the reference value after applying both corrections (Fig. 6a). Due to the limited NFI sample available in the Cape Region, a comparative analysis of correction effects was carried out at the state level (entire State of Baja California Sur), where the NFI includes 249 additional sampling sites beyond the Cape Region. This comparison showed a similar effect to that observed in the Cape Region sample, except that the corrections did not eliminate the AGBD underestimation for the upper quartile (Fig. S2).

In tropical dry forest, the *Pachycereus* correction did not significantly reduce underestimation. However, a marked effect was observed when both corrections were applied; in the first three quartiles (10–40 Mg ha^{-1}), estimates with both corrections did not differ significantly from reference values. In the upper quartile (>40 Mg ha^{-1}), corrections considerably reduced underestimation but did not eliminate it (Fig. 6b).

Fig. 6 Comparison of mean AGBD estimated from NFI data without correction, with the *Pachycereus* correction, and with both *Pachycereus* and size corrections in (a) xeric shrubland and (b) tropical dry forest of the Cape Region. The mean and quartile-based 95% confidence intervals are compared with the reference value obtained from our sampled plots (dashed line). Note that no values are shown for the second quartile (26–30 Mg ha^{-1}) in shrubland, as there were no NFI samples within this range, and no confidence intervals are shown for the 30-45 Mg ha^{-1} and the > 45 Mg ha^{-1} quartiles since the NFI had only one sample in each of these biomass density quartiles

Discussion

Research on uncertainty in AGBD estimates has mainly focused on tropical and temperate forests, addressing aspects such as allometric equations (Molto et al. 2013, Bojórquez et al. 2020), sampling design (Magnussen et al. 2020), and errors in height and DBH measurements (Hill et al. 2013; Yanai et al. 2023). However, few studies address this problem in arid and semiarid zones. Búrquez and Martínez-Yrízar (2011) and others (Muturi, 2011; Návar et al. 2013) highlight the importance of considering statistical errors in AGBD estimates from allometric equations, but do not analyze errors associated with sampling methodology. Investigating these errors is highly relevant since arid zones cover approximately one-third of the Earth's surface (Zhang et al. 2023). Although they were formerly considered less important compared to tropical or temperate forests, their relevance in carbon storage (Búrquez et al. 2010; Hernández-Martínez et al. 2025) and as regulators of the carbon cycle (Ahlström et al. 2015) has been documented. In this study, we evaluated three sources of error that affect AGBD estimates in forest inventories in an arid and semiarid zone of Mexico: (1) the use of DBH instead of BD, which excludes trees with bifurcated stems below 1.3 m; (2) the omission of shrubs and small trees (BD > 2.5 cm, DBH < 7.5 cm); and (3) the lack of allometric equations for columnar cacti of the genus *Pachycereus*.

Evaluation of the effect of NFI inclusion criteria

The evaluation of diameter measurement criteria and the inclusion of small individuals in our sampled plots revealed the magnitude of AGBD underestimation when DBH is used instead of BD and when small individuals are omitted. In line with our first hypothesis (H1) and prediction (P1), we found that the effect of modifying NFI plant inclusion criterion on AGBD estimates was much greater for xeric shrubland and tropical dry forest than for broadleaf and mixed conifer-broadleaf forests. Mean AGBD values estimated in our sampled plots, which included small plants (BD ≥ 2.5 cm), were 307% and 180% higher than those estimated using NFI criterion (DBH ≥ 7.5 cm) for tropical dry forest and xeric shrubland, respectively. In contrast, including small plants in broadleaf and conifer-broadleaf forests increased estimates by only 3.2% and 0.06%, respectively. These marked differences between vegetation types clearly reflect the predominant role of small plants in xeric shrubland and tropical dry forest, where low stature and branching below DBH are strategies to tolerate or resist drought and create more favorable microclimates for seedling establishment (Mohanta et al. 2024). By contrast, in forests, where micro-environmental conditions are more favorable for establishment and growth, small plants play a much smaller role in AGB stock (Nilsson et al. 2005). Thus, it is possible that the plant inclusion criterion used by the NFI reflects a bias toward temperate forests, which have traditionally been the focus of forest management in Mexico. Our results show that these criteria do not strongly affect AGBD estimates in those forests, but are clearly inappropriate for xeric shrubland and tropical dry forest.

The average AGBD obtained in sampled xeric shrubland plots including small individuals (35.94 Mg ha^{-1}) was similar to previous reports for thornscrub in Tamaulipas, Mexico (31.08 Mg ha^{-1}; Briones et al. 2018) and more than double the average reported by Búrquez et al. (2010) for shrublands in Sonora, Mexico (15.99 Mg ha^{-1}). However, the mean estimated with corrected NFI data was closer to the latter, at 12.4 Mg ha^{-1}. Our results differ from the national average reported by Briones et al. (2018) for arid zones (23.2 Mg ha^{-1}), though that value includes the broad variability of arid vegetation types in Mexico. Our findings suggest that xeric shrublands in the Cape Region store more carbon than previously reported for this vegetation type in Mexico (except for Tamaulipas) and highlight the need to revise how this and other arid and semi-arid vegetation types are sampled in Forest Inventories.

A substantial difference was found between the average xeric shrubland AGBD in our sampled plots including small individuals and in NFI data, even after applying corrections (35.94 vs. 12.4 Mg ha^{-1}, respectively). This may be partly explained by differences in sampling design. While the NFI methodology employs a widely spaced systematic sampling (10 × 10 km grid; CONAFOR, 2017), our sampled plots were established empirically to capture the full range of vegetation density and cover conditions (low, medium, and high AGBD). This could explain the substantial difference in the minimum values between our sampled plots and NFI plots (17.08 vs. 0.29, respectively), since the NFI's systematic sampling includes mainly sites with scant vegetation cover. Nevertheless, when we estimated AGBD using NFI criteria in our sampled plots (DBH ≥ 7.5 cm), we obtained a minimum of 2.94 Mg ha^{-1}, closer to but still an order of magnitude greater than the NFI's minimum, suggesting we did not sample areas with very low vegetation cover/density (and extremely low values of AGBD). Additionally, although the maximum values of AGBD from both datasets were similar (63.47 in our sampled plots and 67.63 Mg ha^{-1} in NFI plots) the NFI sampling contains very few plots with high AGBD values (only two plots above 26 Mg ha^{-1}), which may partly explain the much lower NFI mean value.

Overall, and consistent with our second hypothesis (H2) and prediction (P2), results showed greater underestimation when using DBH as the measurement criterion compared to omitting small individuals. This is likely due to the disproportionately greater effect of larger plants (BD ≥ 7.5 cm and DBH < 7.5 cm) on aboveground biomass relative to smaller plants (2.5 cm < BD < 7.5 cm), as reported in general (Ali and Wang, 2021) and in arid zones in particular (Yang et al. 2022). Again, the NFI diameter criterion led to huge AGBD underestimation in xeric shrubland and tropical dry forest, but only slight underestimation in broadleaf and coniferous-broaleaf forests, highlighting the need for more appropriate inclusion criteria for NFI samples in arid and semi-arid vegetation.

Underestimation due to omission of small individuals was greater in sites with lower AGBD, consistent with previous studies in Yucatán forests (Hernández-Stefanoni et al. 2020), where small individuals account for a higher proportion of AGBD in early successional stages of dry forests compared to later successional stages (see also Read et al. 2003). However, in this study we did not consider successional age and most plots were established in old-growth or mature vegetation. Size correction factors exceeded 35% and 80% in xeric shrubland and tropical dry forest, respectively. In tropical dry forest, the highest factor (80.6%), estimated for AGBD ≤ 23.0 Mg ha^{-1}, was higher than factors reported for Yucatán (up to 56% for < 37.5 Mg ha^{-1}; Hernández-Stefanoni et al. 2020). We found no previously published correction factors for xeric shrublands.

Effect of corrections on NFI AGBD estimates

We developed three original allometric equations to estimate AGB of *Pachycereus pringlei*. These equations had low error levels (17.00–26.18%) compared to others developed for arid vegetation. For example, Návar et al. (2013) reported a general equation for trees and shrubs with 74% error, and Hernández-Martínez et al. (2022) reported an equation for mesquite (*Prosopis spp*.) trees with error values of 30–34%.

Contrary to our third hypothesis (H3) and prediction (P3), however, applying the *Pachycereus* correction did not significantly affect NFI AGBD estimates in xeric shrubland and tropical dry forest (Fig. 4 and Fig. 6). This could be due to the low percentage of branched individuals (for which the allometric equation was developed) in the NFI plots (15% compared to 32% in our sampled plots), since only branched individuals showed a significant increase in AGB estimates when the *Pachycereus* correction was applied (Fig. 5). Three alternative potential explanations for this minimal effect are, first that our assumption of bias in columnar cacti AGB estimation in NFI may be unfounded —there may be an appropriate equation, specific or general, not reported in NFI's equation database. Second, that the NFI may have applied the same method we used (volume × wood density) for single-stemmed individuals, which accounted for 85% of *Pachycereus* individuals in the NFI database. None of the NFI reports provide details on the methodology used to estimate AGB in cacti. Third, there are multiple errors or inconsistencies in H and CD measurements in the NFI database (see Fig. S1). We also found NFI records for single-stemmed individuals with high CD values, likely corresponding to branched individuals. Such errors cannot be corrected, even with more suitable allometric equations such as the ones developed here.

Although the size correction increased the mean NFI AGBD values in xeric shrubland and tropical dry forest, the effect was significant only for the latter (Fig. 4). The smaller effect in xeric shrubland may be due to at least two factors. First, as noted earlier, our field sampling did not include sites with very low vegetation cover, while most NFI samples corresponded to such conditions. Thus, the correction factor for the lowest quartile in this study may not be appropriate and may underestimate true AGBD values for most NFI samples. Second, NFI sampling may not sufficiently represent xeric shrubland areas with greater cover and biomass. In fact, NFI contained no plots with values corresponding to our second quartile and only one sample for quartiles 3 and 4 (see Fig. 6). These upper three quartiles (especially the second and fourth) had the highest correction factors, so their underrepresentation in NFI helps explain why corrected and uncorrected estimates did not differ. This disparity in AGBD value distribution between NFI and our sampled plots prevented a proper comparison of corrected NFI quartiles with the xeric shrubland reference sample (Fig. 6a), compared to tropical dry forest, where the size correction effectively addressed AGBD underestimation in the first three quartiles (Fig. 6b).

Recommendations to reduce bias in AGBD estimates in arid and semiarid zones

The lack of allometric equations for arid species is a recurring problem (Návar et al. 2004, 2013; Muturi et al. 2011). Although we developed a species-specific equation for the most abundant species of columnar cacti with relatively small estimation error (%RMSE = 17), the lack of information on AGB estimation methodology along with inconsistencies in the NFI measurements of dendrometric variables (DBH, H CD) hindered the evaluation and adequate correction of errors. We searched for allometric equations for arid-zone species in scientific literature and public databases, including the Comisión Nacional Forestal equation database, and failed to find any equation for columnar cacti. Moreover, we were unable to obtain information from the Commission on the estimation methodology, as no such equation had been reported to date. Clearly, there is a need to specify the process for individual-level AGB estimation by publishing the allometric equations and AGB calculation methodologies employed. Moreover, errors and inconsistencies in DBH, H, and CD values reported in the NFI likely limited the utility and accuracy of species-specific equations. Strengthening measurement quality-control, or establishing verification methods as done in other NFIs (Yanai et al. 2023), is also necessary. Uncertainty in height measurements remains a major area of improvement in forest inventories in general (Jurjević et al. 2020; Saliu et al. 2021) and should be addressed in future studies.

Our results clearly show that AGBD is strongly underestimated in xeric shrubland and tropical dry forest, at least in the Cape Region of Baja California State, Mexico. To improve the quality of these estimates, the sampling methodology should be modified to include smaller trees and shrubs. Based on our results, we recommend using BD as the diameter measurement criterion in these vegetation types. This single change increased mean AGBD values by 220% and 99% in xeric shrubland and tropical dry forest, respectively, highlighting its relevance in reducing AGBD underestimation. Including small individuals had a much smaller effect, although it contributed to reduce underestimation. Since including small individuals would require additional sampling effort, we suggest that using BD (≥ 7.5 cm) instead of DBH could be a crucial first step toward improving NFI AGBD estimates in arid and semiarid zones.

Finally, considering the highly heterogeneous cover of xeric shrublands, we suggest modifying the NFI current 10 km grid systematic sampling design. A stratified systematic design could be applied, considering zones with greater vegetation cover (e.g., dense shrubland or gallery forests), where plot spacing could be reduced (i.e. 5 km grid), and areas with sparse vegetation, where larger spacing (10 km grid) could be maintained.

Conclusion

Arid zones occupy a vast area of the planet's terrestrial ecosystems. Therefore, given the lack of reliable information, it is necessary to reassess their contribution to global carbon storage. In this study, we demonstrated the strong underestimation of AGBD in the NFI xeric shrublands and tropical dry forests of the Cape Region, Baja California Sur, Mexico, especially in sites with lower AGBD, where a large proportion of small trees and shrubs are omitted during NFI sampling. Since underestimation can reach up to 180% and 307% of AGBD in xeric shrublands and tropical dry forests, respectively, strategies to improve estimates in arid and semi-arid zones should be a priority. In this regard, modifying the inclusion criteria of individuals based on their size, especially using BD instead of DBH, could greatly improve AGBD estimation. However, it is also necessary to improve the quality of measurements of height and crown cover, at least for columnar cacti of the genus *Pachycereus*. Moreover, studies such as the current one should encompass other arid regions of North-Central Mexico and North America. Finally, this study provides allometric equations to estimate the AGB of *Pachycereus pringlei*, which may contribute to improve estimates not only for this species, but also for columnar cacti in general.

Declarations

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this manuscript.

Data availability

The research data is available on request from the authors of this article.

Code availability

Not applicable

Authors' contributions

LAHM Writing – review & editing, Writing – original draft, Conceptualization, Formal analysis, Funding acquisition, Methodology. JLHS Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. AMN Data curation, Writing – review & editing, Methodology. CPC: Writing – review & editing, Methodology. CACT Writing – review & editing, Methodology. CLV Data curation, Writing – review & editing, Methodology. JMDR Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

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Figures

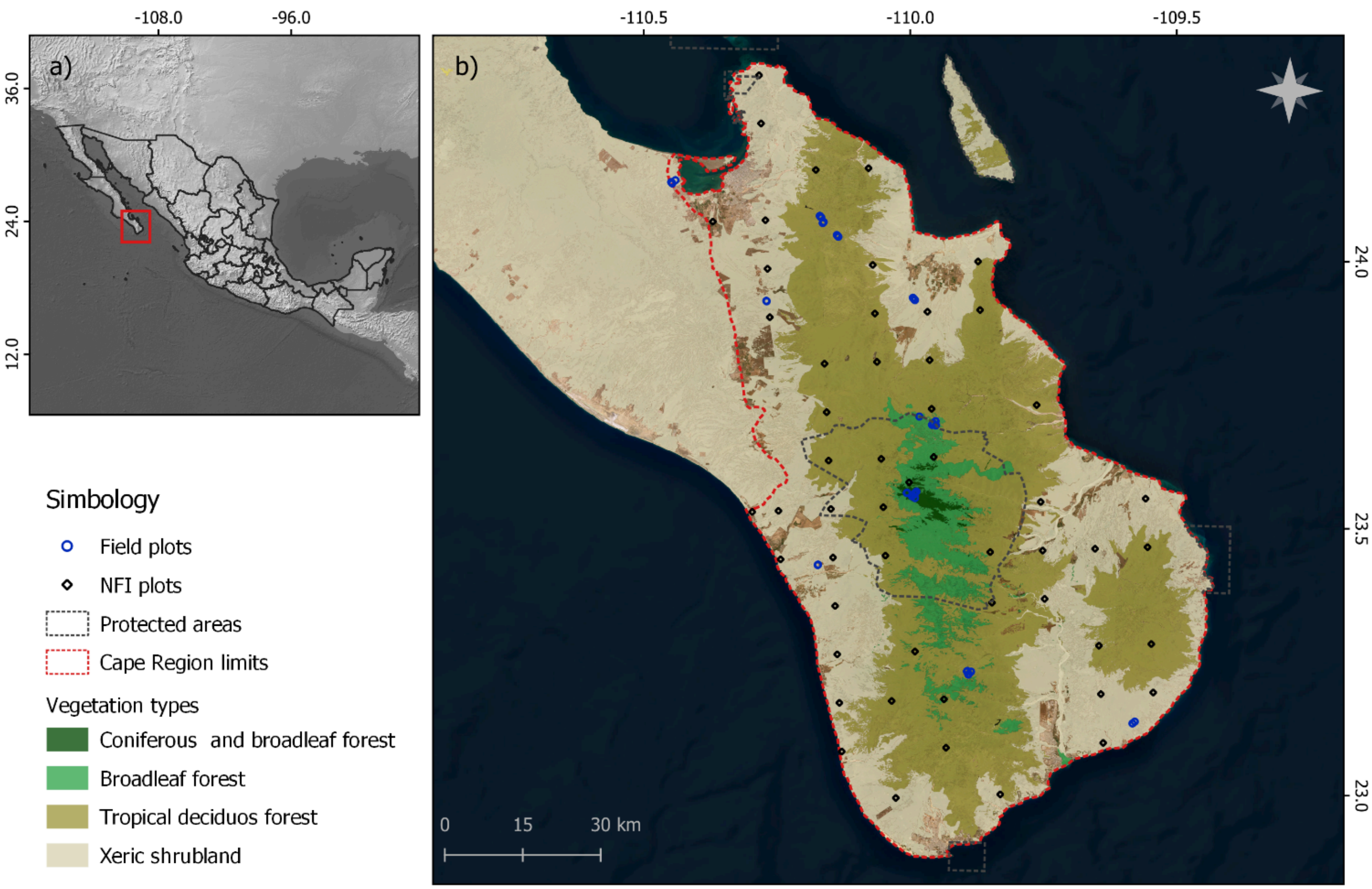

Figure 1

Location of the Cape Region in Baja California Sur, Mexico (a), main vegetation types, field-sampled plots (blue circles), and National Forest Inventory plots (black diamonds) (b)

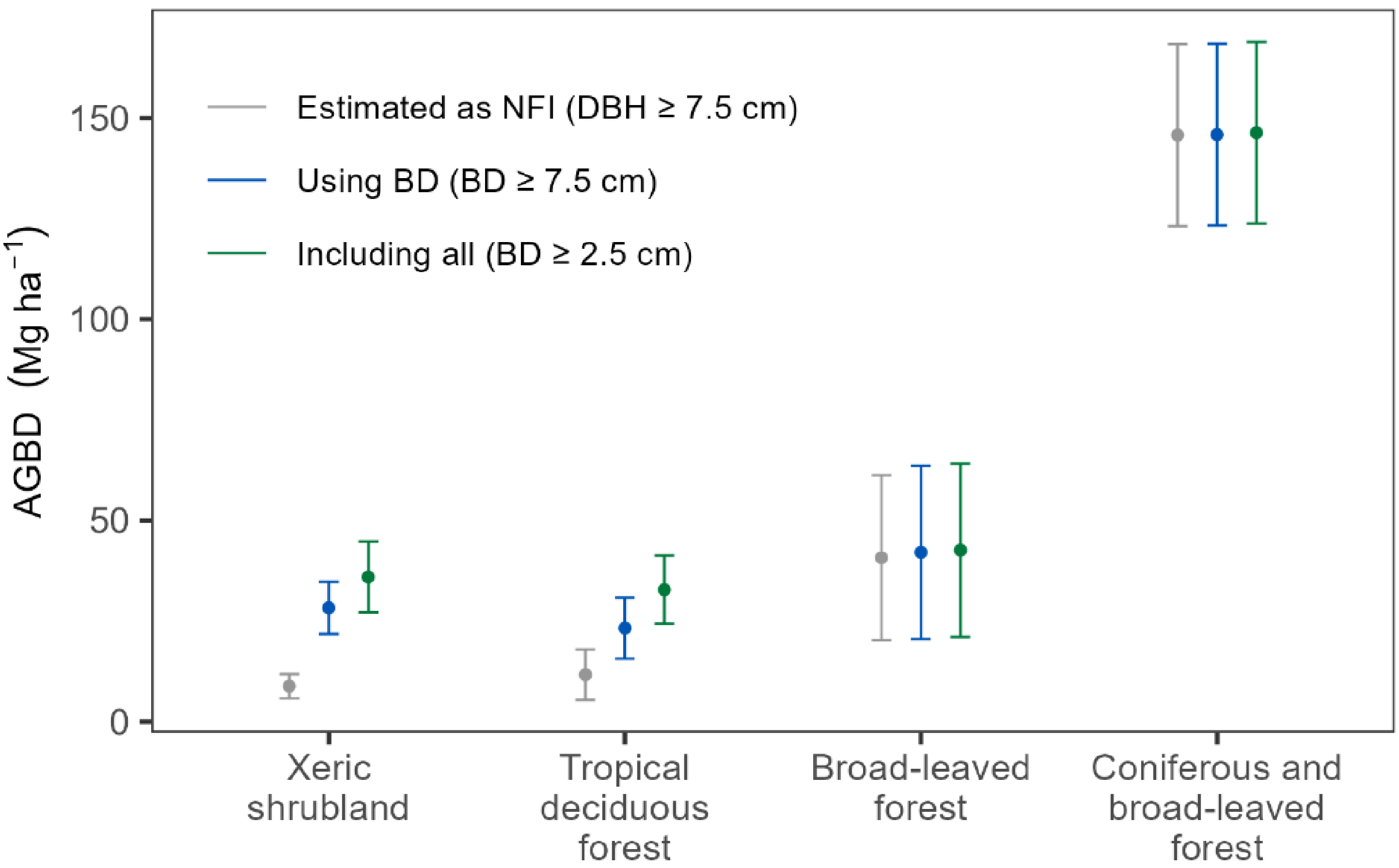

Figure 2

Mean values and 95% confidence intervals of AGBD by vegetation type, using three estimation methods applied to field plots sampled in the Cape Region, Baja California Sur, Mexico

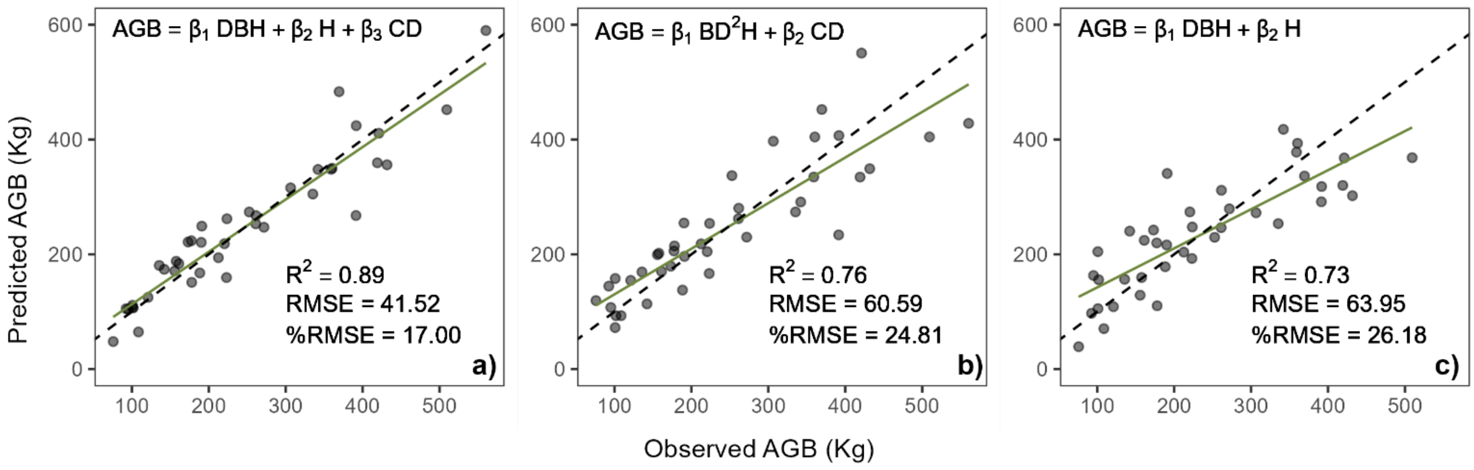

Figure 3

Cross-validation results of three allometric models fitted to predict AGB of *Pachycereus pringlei*. The dashed line represents the 1:1 relationship, and the green line indicates the regression line

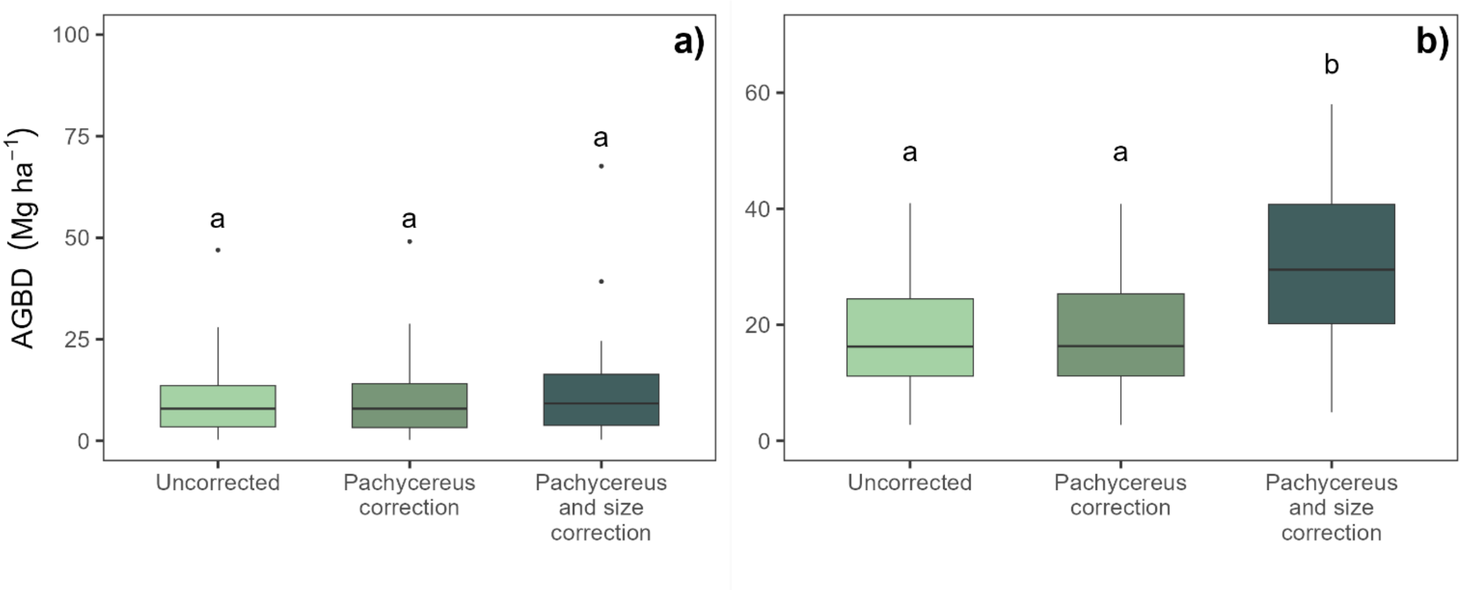

Figure 4

Distribution of NFI AGBD values without correction, with the *Pachycereus* correction, and with both *Pachycereus* and size corrections in (a) xeric shrubland and (b) tropical dry forest. Different letters indicate statistically significant differences ($p < 0.05$) between groups

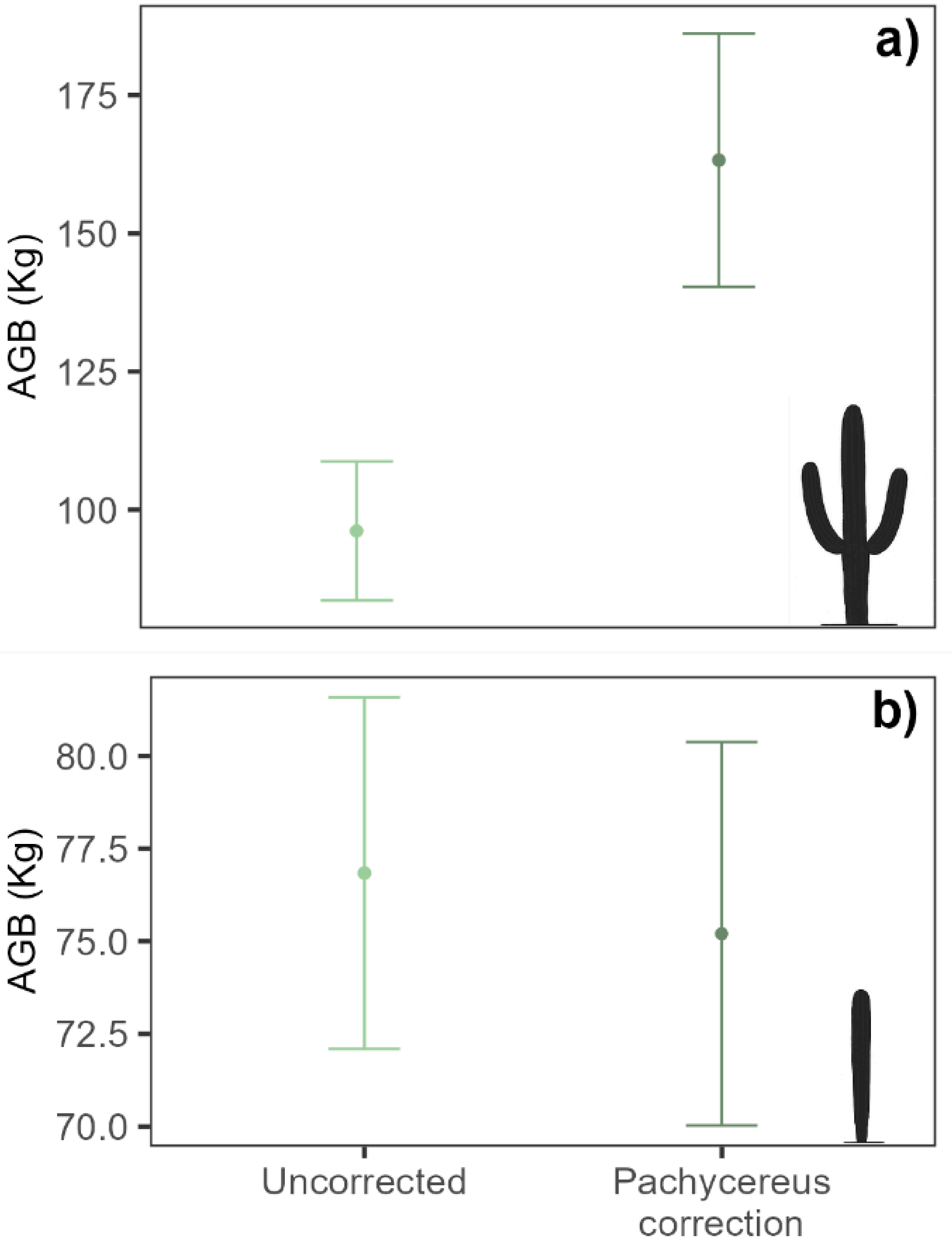

Figure 5

Effects of correcting *Pachycereus sp.* AGB estimates at the individual level using the species-specific allometric equation for branched individuals (a) and volume and wood density for unbranched individuals (b). The 95% confidence intervals are shown (whiskers) along with the mean values (points)

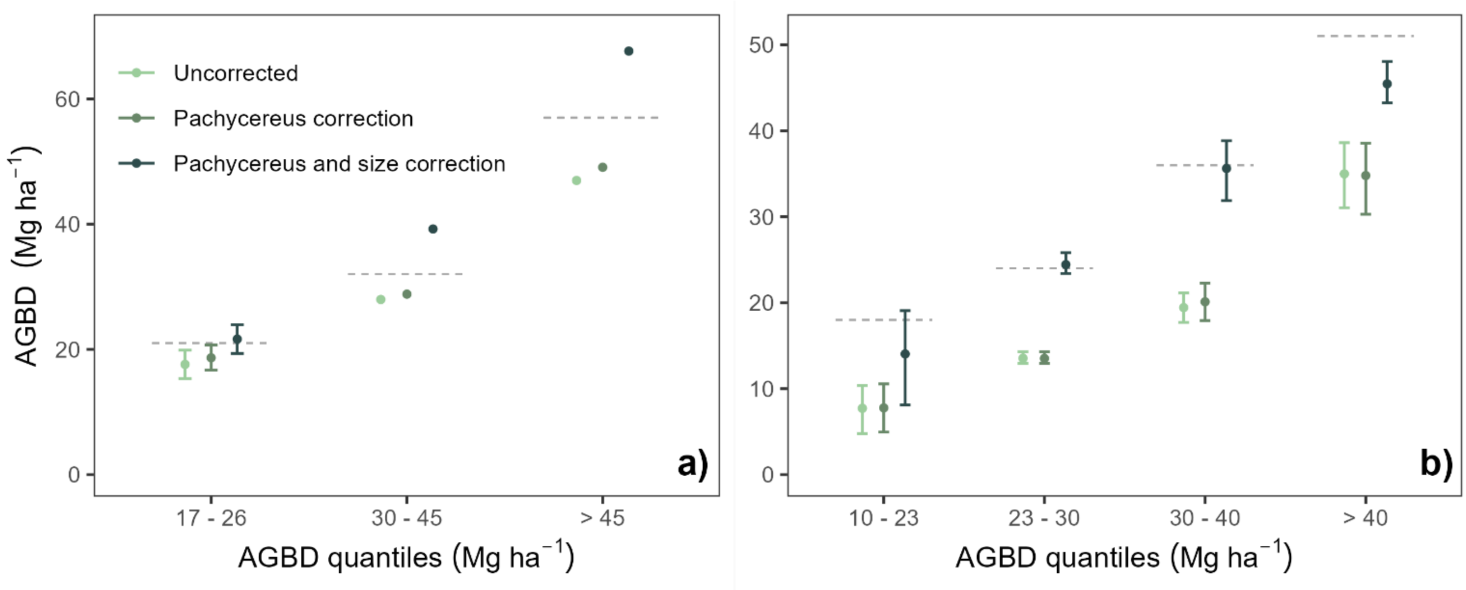

Figure 6

Comparison of mean AGBD estimated from NFI data without correction, with the *Pachycereus*correction, and with both *Pachycereus* and size corrections in (a) xeric shrubland and (b) tropical dry forest of the Cape Region. The mean and quartile-based 95% confidence intervals are compared with the reference value obtained from our sampled plots (dashed line). Note that no values are shown for the second quartile (26–30 Mg ha^{-1}) in shrubland, as there were no NFI samples within this range, and no confidence intervals are shown for the 30-45 Mg ha^{-1} and the > 45 Mg ha^{-1} quartiles since the NFI had only one sample in each of these biomass density quartiles

Supplementary Files

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