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Additive equations system to estimate aboveground biomass by structural component and total of three giant Bamboo species in Mexico

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FOREST MANAGMENT

ABSTRACT

Background: Bamboo species have a high potential to produce biomass and stock carbon. However, biometric tools are not available to estimate biomass production for most giant bamboo taxa. The aim was to develop an additive equation system to estimate the aboveground biomass by structural component and the total of the three bamboo species. Destructive sampling was applied, and a sample of 101 mature bamboo specimens was collected. The nonlinear power allometric model was used to integrate two additive equations systems, which were formed by the structural components of biomass: culm, branches and leaves as well as aboveground biomass total. The predictor variables were: diameter at breast height (D) for the S1 system, and D in combination with the total height (D^2H) for the S2 system.

Results: It was determined that the SUR method in combination with the dummy variables technique and the correction of heteroscedasticity is an adequate fit strategy. Given that the additivity property is fulfilled, specific values of the parameters of each system and by taxon are identified. In addition, the variance of the error stabilizes. The aboveground biomass of the culm constitutes 86.40%, 90.48%, and 93.94% for *Bambusa oldhamii* Munro, *Guadua aculeata* Rupr., and *Guadua angustifolia* Kunth, respectively. The S1 system was selected, and its statistics regarding the total aboveground biomass were 0.92, 4.9 kg, -0.35 kg, and 0.05 for the fit statistics R^2_{adj}, RMSE, S, and E, respectively.

Conclusion: This biometric tool will easier to carry out aboveground biomass inventories, as well as to infer the carbon content and CO_2 equivalent at the specimen level.

Keywords: Additivity property; *Bambusa oldhamii* Munro; *Guadua aculeata* Rupr; *Guadua angustifolia* Kunth; SUR method.

HIGHLIGHTS

Additive equation system estimates the biomass of culms, branches, leaves, and total aboveground biomass.
Power allometric model, SUR method, and dummy variables technique were appropriate.
The S1 system that uses diameter at breast height as a predictor variable is recommended.
Additive equations systems developed for *Guadua aculeata* stands are the first record in the literature.

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INTRODUCTION

Bamboo forests are widely distributed in tropical and subtropical areas; some species are adapted to temperate climates (Liu et al., 2018). Bamboos are grasses species belonging to the Poacea family and Bambusoideae subfamily (Liese and Köhl, 2015). Worldwide, 1642 bamboo species are reported, 435 of which are native species in America (Kaushal et al., 2022). Mexico has 61 bamboo taxa, 36 of which are endemic (Ruiz-Sanchez et al., 2022). Bamboos stand out from tree species because of their accelerated growth rate, high biomass production, and rapid generation of individuals (Huy et al., 2019; Abebe et al., 2021). They have a high potential for projects related to adaptation to climate change (Nath et al., 2020). Bamboo ecosystems are dynamic and highly productive; studies report that in plantations, they can produce from 30 to over 70 $Mg.ha^{-1}.year^{-1}$ of biomass (Darabant et al., 2014; Yuen et al., 2017).

Bamboo biomass can be transformed into a wide variety of products, including structures for construction, laminates, furniture, kitchen utensils, textiles, pharmaceutical products, food, among many others (van Dam et al., 2018; Nath et al., 2020). Bamboo industrialization allows to sequester carbon in products with long life cycles (Li et al., 2015; Xu et al., 2022); furthermore, the production and harvesting of mature culms stimulates the generation of new bamboo shoots, suggesting that these forests enter into a constant and dynamic production that can last up to 80 years (Castañeda-Mendoza et al., 2005; Nath et al., 2019).

In the northeastern region of the State of Puebla, Mexico, commercial plantations have been established with *Bambusa oldhamii* Munro and *Guadua angustifolia* Kunth; there are also natural forests of *Guadua aculeata* Rupr. The first two are species introduced from Asia and South America, while the latter is native to Mexico and Central America (Aguirre-Cadena et al., 2018). Based on Lobovikov et al. (2012), these three taxa are classified as giant bamboos because they can reach an H of 30 m and a D of up to 20 cm. These are used in the construction of houses, furniture, crafts, food, and paper manufacturing (Zaragoza-Hernández et al., 2015). Recently, studies have been conducted to characterize some attributes of these bamboo species in the region, highlighting their economic, ecological, and social importance (Zaragoza-Hernández et al., 2015; Aguirre-Cadena et al., 2018).

Biomass is an indicator of the productivity of bamboo ecosystems (Ceccon and Gómez-Ruiz, 2019). There are different tools for its quantification; the most commonly used are allometric equations (Fonseca-González and Rojas, 2016; Liu and Yen, 2021), which are generated from data obtained through destructive sampling (Singnar et al., 2017). Subsequently, from these data and through regression techniques, the relationship between the diameter at breast height and total height is studied with variables of interest such as volume, biomass, and carbon (Ouyang et al., 2022). These types of equations have been widely developed for tree species (Sileshi, 2014; Picard et al., 2015); in Mexico, they have been applied to different timber species with satisfactory results (Rojas-García et al., 2015; Cuevas-Cruz and Aquino-Ramírez, 2020). Using this regression technique can be extended to giant bamboo species because their morphology is similar to that of a tree; they have a main stem (culm), lateral branches, and leaves (Yiping et al., 2010; Fonseca-González and Rojas, 2016; Yuen et al., 2016; Camargo-García et al., 2023).

According to international literature, the number of allometric models available to estimate the biomass of bamboo taxa is limited. This is largely because of the number of species and their wide geographical distribution (Kuehl, 2015; Singnar et al., 2017; Huy et al., 2019; Nath et al., 2019; Nath et al., 2020). This information can contribute to the development of better strategies to mitigate climate change and global warming (Lobovikov et al., 2012; Kumar et al., 2022). In Mexico, studies on these topics are even more limited, so there is a need to develop biometric tools to accurately quantify the production of biomass and carbon storage. Based on these antecedents, the aim of this study was to develop an additive equation system to estimate the aboveground biomass by structural component and total of the three giant bamboo species from Puebla, Mexico.

MATERIAL AND METHODS

Study site

The study was carried out in bamboo plantations and natural forest stands in the municipality of Hueytamalco, Puebla, Mexico (Figure 1). The mean annual rainfall is 3153 mm, the mean annual temperature is 21 °C, and the maximum and minimum temperatures are 35 °C in the dry season and 8 °C in winter. These conditions favor a humid semi-warm climate (García, 2004). The orography comprises hills between 400 and 500 m in altitude with abundant water currents. The climatic conditions are optimal for the development of the rainforest and the establishment of bamboo plantations. The bamboo plantations studied correspond to the introduced species *G. angustifolia* and *B. oldhamii*, while the natural forest stands correspond to the native species *G. aculeata*.

The bamboo plantations are >8 years old, were established on land formerly used for livestock with a true-frame plantation design of 5 × 5 m plant spacing. Natural stands are distributed mainly along the banks of rivers and wetlands. The soils are characterized as Ultisols and Oxisols, with a clayey-sandy texture, light brown to dark brown; the pH is acidic at 4.5-5.5. At the landscape level, bamboos are associated with coffee, citrus, tropical forest vegetation, and mountain cloud forests (Ordóñez-Prado et al., 2023). Bamboo populations are made up of bamboos ranging from 2.5 to 16.5 cm in diameter at breast height. The total height ranged from 7 to 30 m. The population density ranged from 5250 to 9500 culms per hectare.

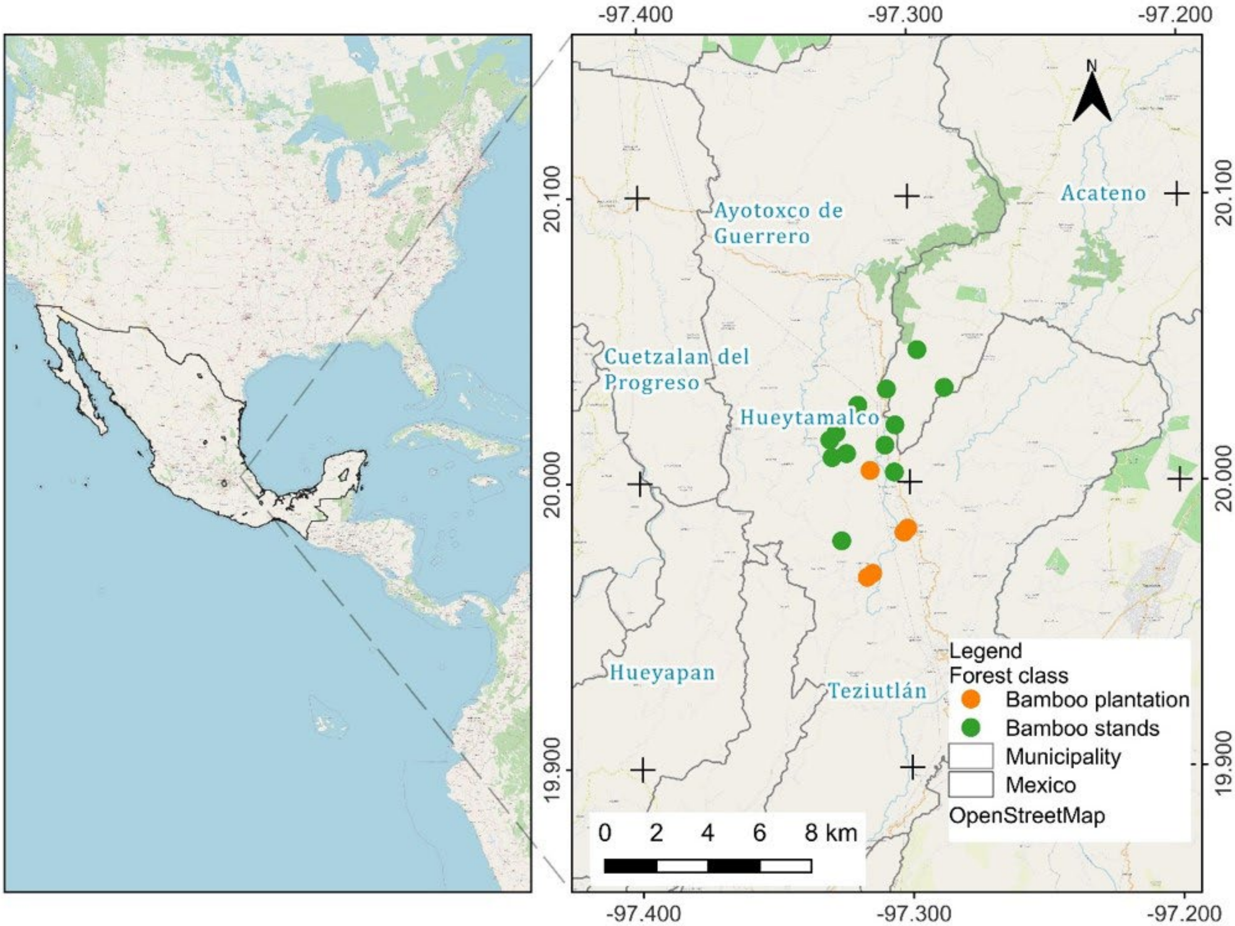

Figure 1: Geographical location of the study area with distribution of plantations and native bamboo forest stands.

Data collection and measurement

Through destructive sampling, a sample of 101 mature bamboo specimens was collected: 30 of *B. oldhamii*, 41 of *G. aculeata*, and 30 of *G. angustifolia*; randomly distributed in plantations and natural stands. A methodological procedure similar to that referred to by Guomo et al. (2013) and Huy and Long (2019) was used (Figure 2). Each standing specimen was measured for diameter at breast height with precision to the millimeter (*D*, cm) (1.3 m height from ground level) with a Forestry Suppliers model 283D/5m diameter tape. The selected specimens were complete culms, healthy, and without physical damage, including the culm, branches, and leaves; the aerial parts were stated as structural components of the aboveground biomass. The specimens were collected from the middle of the canopy. The sample was distributed to cover the range of diameter categories that exist as well as different growth conditions.

After cutting down each bamboo, the total height (*H*) was measured in meters, considering the stump, with a 30 m tape measure with cm precision. The biomass of the structural components culm (Bcu), branches (Bbr) and leaves (Ble) of each specimen were separated, and its fresh weight (*Pf*) was recorded. The weights were measured with a 200 kg capacity electronic scale with a precision of 0.01 kg.

Branches and leaves samples of 1000 g were taken, as well as a 10 cm long section of the base, middle part, and tip of the culm. All the samples were labeled with information about the species, structural component, and fresh weight in g. In the laboratory, the samples were dried with a forced-air oven at a temperature of 70 °C for foliage and 100 °C for culms until a constant dry weight was obtained. The dry weight of each sample was measured with a digital electronic scale with precision to the milligram.

The dry weight-fresh weight ratio was obtained by dividing the dry weight by the fresh weight. This ratio was used to calculate the total biomass per component, multiplying it by the total fresh weight of the culm, branches, and leaves. The total aboveground biomass (AGB) per specimen was obtained by adding the biomass of the three components.

The basic descriptive statistics of the variables analyzed by species are shown in Table 1. A database was formed with the information of the variables D, H, and dry biomass per component and total for each specimen, and it was audited to guarantee logical graphic behavior before the statistical analysis.

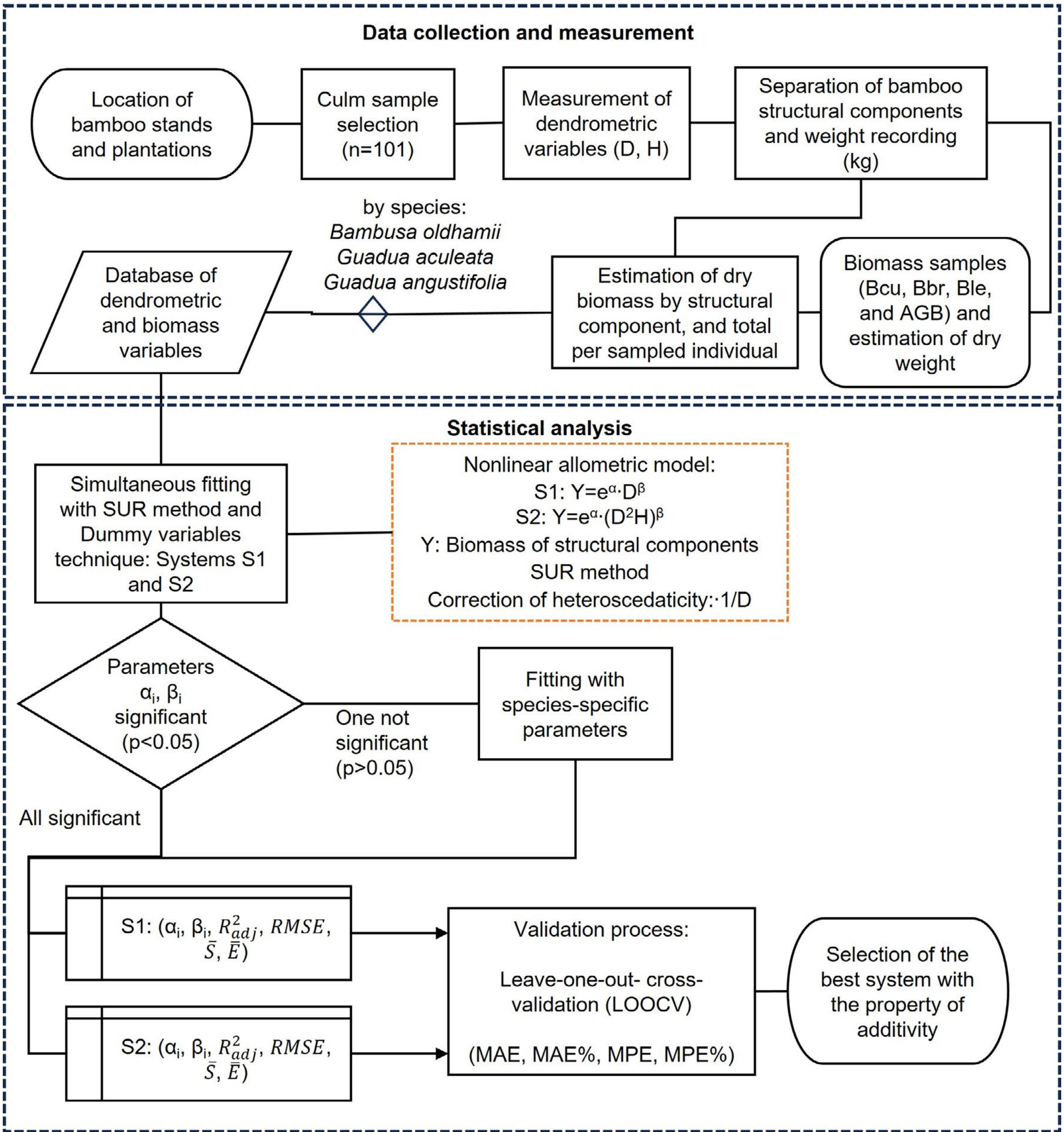

Figure 2: Flow chart with logical sequence illustrating the research process.

Models and biomass additive equations systems evaluated

Several nonlinear and linear allometric models, reported by Nfornkah et al. (2021) and Kaushal et al. (2022), were used to perform a previous analysis and identify candidate models and additive biomass equations to model the aboveground biomass of the bamboo taxa studied. The systems were made up of the explanatory variables *D* and *H* separately and combined so the forms *D*, D^2, *DH*, D^2H, and *H*, among others, were evaluated. This analysis led to the preselection of two additive equation systems labeled as S1 and S2, both of which presented the best performance in terms of predictive quality for the estimation of aboveground biomass by structural component and total for each bamboo species studied. The final base model that was used to make up each system corresponds to the nonlinear power function. The general mathematical structure is $Y=aX^b$, where *Y* is the aboveground biomass, *X* is the predictor variable, a and β are parameters to be estimated. For the S1 additive equations system, only *D* was used as a predictive variable (equation 1 to equation 4), whereas in the S2 system, *H* was added to obtain the combined variable (D^2H) as an explanatory variable (equation 5 to equation 8). where: B_{cu}, B_{br}, B_{le}, are the biomass of the culm, branches, and leaves; *AGB* is the total aboveground biomass of bamboo; *e* is the exponential function; D is the diameter at breast height; H is the total height; α_i, and β_i are parameters to be estimated; ε is the random error term.

S1 additive equations system

$$B_{cu} = e^{\alpha_0} \cdot D^{\beta_0} + \varepsilon \quad (1)$$

$$B_{br} = e^{\alpha_1} \cdot D^{\beta_1} + \varepsilon \quad (2)$$

$$B_{le} = e^{\alpha_2} \cdot D^{\beta_2} + \varepsilon \quad (3)$$

$$AGB = B_{cu} + B_{br} + B_{le} \quad (4)$$

S2 additive equations system

$$B_{cu} = e^{\alpha_0} \cdot \left(D^2H\right)^{\beta_0} + \varepsilon \quad (5)$$

$$B_{br} = e^{\alpha_1} \cdot \left(D^2H\right)^{\beta_1} + \varepsilon \quad (6)$$

$$B_{le} = e^{\alpha_2} \cdot \left(D^2H\right)^{\beta_2} + \varepsilon \quad (7)$$

$$AGB = B_{cu} + B_{br} + B_{le} \quad (8)$$

The dummy variable technique (Zeng, 2015; Montgomery and Runger, 2018; Gao et al., 2019) was applied to the complete database with the three bamboo species to identify if any of them required specific values in the parameters of equation systems. This technique expands the parameters of each function within each system by including parameters associated with an additive effect along with indicator variables. The significance of the associated parameters determines whether each species requires specific values; if the associated parameters are significant with a=0.05, it is concluded that statistically, the species involved in the indicator variables require specific values and vice versa. In the case of the non-significance of the associated parameter, a single value is sufficient for the parameter in question for all analyzed species (Montgomery and Runger, 2018).

The fitting of each system was done simultaneously with the MODEL procedure of SAS/ETS 9.3 (SAS Institute, 2011). After reviewing the significance of the parameters, when applying the dummy variable technique, only those that were significant ($p<0.05$) were identified and left in. Subsequently, each system was refitted using the nonlinear Seemingly Unrelated Regression (SUR) method, which minimizes the squares of the residuals. This method considers the correlation of the errors in the equations and ensures the full additivity property, where the sum of

Table 1: Basic descriptive statistics of the variables by bamboo species located in the northeastern of the State of Puebla, Mexico.

Species	Variable	Min	Max	Mean	SD	VC	Var
Sp1	D	4.50	12.40	9.14	2.26	24.77	5.13
	H	7.16	24.10	18.47	5.52	29.89	30.49
	B_{cu}	2.96	46.22	23.72	13.08	55.16	171.31
	B_{br}	0.92	4.57	2.10	0.92	43.95	0.85
	B_{le}	0.11	3.90	0.94	1.13	120.11	1.29
	AGB	4.02	49.77	26.77	14.19	53.00	201.37
Sp2	D	3.50	13.80	10.52	3.09	29.44	9.60
	H	7.17	30.12	20.91	6.14	29.35	37.70
	B_{cu}	2.12	63.80	32.86	17.89	54.44	320.29
	B_{br}	0.12	5.74	2.02	1.34	66.51	1.81
	B_{le}	0.03	5.96	1.73	1.51	87.26	2.29
	AGB	2.26	68.94	36.62	20.11	54.91	404.51
Sp3	D	3.85	13.45	8.66	2.93	33.89	8.61
	H	6.83	22.76	16.39	3.99	24.34	15.93
	B_{cu}	1.79	45.00	17.95	13.05	72.72	170.45
	B_{br}	0.04	2.35	0.88	0.66	75.38	0.44
	B_{le}	0.01	0.62	0.20	0.16	81.84	0.027
	AGB	1.84	47.95	19.04	13.72	72.07	188.39

Sp1: *B. oldhamii*; Sp2: *G. aculeata*; Sp3: *G. angustifolia*; D: diameter at breast height (cm); H: total height (m); B_{cu}: culm biomass (kg); B_{br}: branches biomass (kg); B_{le}: biomass of leaves (kg); AGB: total aboveground biomass (kg); SD: standard deviation; VC: variation coefficient (%); Var: variance.

the biomass component estimated is equal to the total biomass estimated (Huy et al., 2019; Mohan et al., 2020). Heteroscedasticity was corrected based on Dutcă et al. (2022), which means that different weighting factors were tested that were related to the variance of the error. The reciprocal of D (1/D) was the weighting factor that best corrected the heteroscedasticity of the residuals.

Model evaluation and validation

To evaluate the goodness of fit of the systems, the adjusted coefficient of determination (R^2_{adj}), the root mean square error (RMSE), the average bias ($\bar{S}$), and the average percentage relative error ($\bar{E}$), were applied. These statistics were estimated with equation 9 to equation 12, respectively. where: y_i = total observed biomass per specimen; $\hat{y}_i$ = total predicted biomass per specimen; $\bar{y}_i$ = total mean biomass per specimen; n = number of observations; and p = number of parameters of the model.

$$R^2_{adj} = 1 - \left[\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2 / (n-p)}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2 / (n-1)} \right] \quad (9)$$

$$RMSE = \sqrt{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2 / (n-p)} \quad (10)$$

$$\bar{S} = \sum_{i=1}^{n} (y_i - \hat{y}_i) / n \quad (11)$$

$$\bar{E} = \frac{100}{n} \left(\sum_{i=1}^{n} \frac{\hat{y}_i - y_i}{y_i} \right) \quad (12)$$

To examine the performance of systems S1 and S2, the leave-one-out cross-validation (LOOCV) method was applied (Dong et al., 2016; Cui et al., 2020). The mean absolute error (MAE), mean absolute error percentage (MAE%), mean prediction error (MPE), and mean percentage prediction error (MPE%) (equation 13 to equation 16) were the statistics calculated. where: W_i is the ith observed biomass value, $\hat{W}_{i,-i}$ is the predicted value of the ith observed value by the fitted model that was fitted by (n-1) observations and that excluded the use of the ith observation, $\bar{W}$ is the mean of observed biomass value.

$$MAE = \frac{\sum_{i=1}^{n} \left| W_i - \hat{W}_{i,-i} \right|}{n} \quad (13)$$

$$MAE\% = \frac{\sum_{i=1}^{n} \left(\frac{\left| W_i - \hat{W}_{i,-i} \right|}{W_i} \right)}{n} .100 \quad (14)$$

$$MPE = \frac{\sum_{i=1}^{n} \left(W_i - \hat{W}_{i,-i} \right)}{n} \quad (15)$$

$$MPE\% = \frac{\sum_{i=1}^{n} \left(\frac{W_i - \hat{W}_{i,-i}}{\bar{W}} \right)}{n} .100 \quad (16)$$

RESULTS

Aboveground biomass by structural component and total

Together, the three species showed an average biomass weight per specimen of 24.8, 1.6, 0.9, and 27.3 kg for culm, branches, leaves, and total, respectively. The culm had the highest proportion of aboveground biomass, with *G. angustifolia* having the highest value (93.94%), followed by *G. aculeata* with 90.49%, and *B. oldhamii* having the lowest value (86.40%). While the branches contribute 9.98%, 5.50%, and 4.98% of the biomass for *B. oldhamii*, *G. aculeata*, and *G. angustifolia*, respectively. Leaves contributed the least biomass, accounting for less than 5%; *G. aculeata* had the highest value of 4.02%, followed by *B. oldhamii* with 3.63%, and *G. angustifolia* with only 1.08% (Figure 3).

Additive equations systems for estimating aboveground biomass

The S1 additive equations system fitted through the nonlinear SUR method with dummy variables technique showed significance only in the parameters related to culm and branch biomass for *B. oldhamii* ($p<0.05$); therefore, this species requires specific parameters in these two structural components. On the other hand, the parameters associated with the respective indicator variables for *G. aculeata* and *G. angustifolia* were non-significant ($p>0.05$), implying that these are common and that it is possible to use the same values to quantify the aboveground biomass in the three components of both species.

The readjusting of the S1 system until only significant parameters were obtained ($\alpha=0.05$), allowed us to find the final values of the parameters (Table 2). The *D* variable used in the S1 system explained 93% of the biomass variability of the culm. In contrast, branches and leaves showed a less strong relationship, with R^2_{adj} values of 0.64 and 0.43, respectively. The RMSE values were low (<4.9 kg) (Table 2). Considering the additive effect of the dummy variable technique, the expression of the S1 system to calculate *AGB* for *B. oldhamii* is given in (equation 17), while for *G. aculeata* and *G. angustifolia* in (equation 18).

$$AGB = e^{-3.1236} \cdot D^{2.7754} + e^{-2.0540} \cdot D^{1.2523} + e^{-8.8281} \cdot D^{3.7639} \quad (17)$$

$$AGB = e^{-2.4401} \cdot D^{2.4462} + e^{-5.4065} \cdot D^{2.4942} + e^{-8.8281} \cdot D^{3.7639} \quad (18)$$

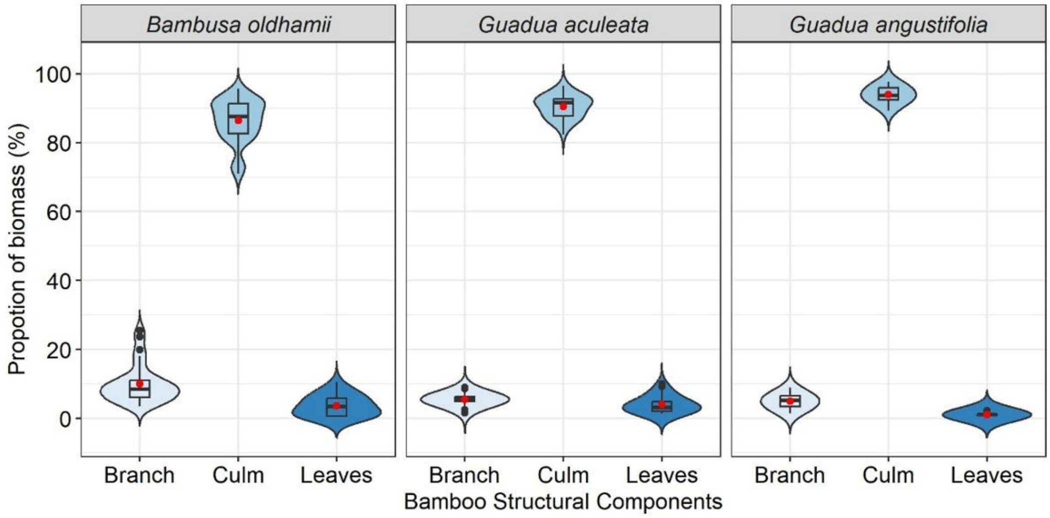

Figure 3: Proportion of aboveground biomass for culms (B_{cu}), branches (B_{br}), and leaves (B_{le}) by species.

Table 2: Parameters of S1 and S2 additive equations system for aboveground biomass estimation by structural component and total for bamboo species studied.

Species	Component	α ± SE	β ± SE	R^2_{adj}	*RMSE*	$\bar{S}$ (kg)	$\bar{E}$ (%)
S1 additive equations system							
SP1	Culm	-3.1236±0.3439	2.7754±1.5989	0.9314	4.2849	0.3930	-0.015
	Branch	-2.0540±0.1049	1.2523±0.6624	0.6357	0.7115	0.0318	0.272
	Leaves	-8.8281±1.4836	3.7639±0.5951	0.4272	0.9904	0.0637	1.240
	AGB	α_i, β_i		0.9268	4.9121	-0.0833	2.140
SP2 and SP3	Culm	-2.4401±0.1019	2.4462±0.0420	0.9314	4.2849	0.2788	0.050
	Branch	-5.4065±0.7213	2.4942±0.2930	0.6357	0.7115	0.0057	0.320
	Leaves	-8.8281±1.4836	3.7639±0.5951	0.4272	0.9904	0.0637	1.240
	AGB	α_i, β_i		0.9268	4.9121	-0.3531	0.060
S2 additive equations system							
SP1	Culm	-5.1658±0.0749	1.0932±0.0090	0.9678	2.9340	2.3335	-0.567
	Branch	-4.4653±0.1083	0.5452±0.1083	0.6165	0.7301	1.4494	-2.235
	Leaves	-15.7270±0.8374	1.8763±0.1068	0.4998	0.9255	0.7091	-1.304
	AGB	α_i, β_i		0.9673	3.2856	4.4831	-0.799
SP2	Culm	-3.0694±0.0548	0.8304±0.0067	0.9678	2.9340	0.0258	1.010
	Branch	-6.0014±0.8427	0.8473±0.1032	0.6165	0.7301	0.0151	13.740
	Leaves	-9.5667±0.7323	1.2643±0.0867	0.4998	0.9255	0.0731	13.040
	AGB	α_i, β_i		0.9673	3.2856	0.0972	0.930
SP3	Culm	-3.7936±0.0787	0.9127±0.0159	0.9678	2.9340	0.0301	-1.520
	Branch	-1.2939±0.8882	0.1590±0.1144	0.6165	0.7301	0.1244	22.030
	Leaves	-24.7872±5.4587	3.0519±0.6436	0.4998	0.9255	0.0968	-7.370
	AGB	α_i, β_i		0.9673	3.2856	-0.0172	1.010

Sp1: *B. oldhamii*; Sp2: *G. aculeata*; Sp3: *G. angustifolia*; α_i and β_i estimates parameters; SE: standard error; R^2_{adj}: adjusted coefficient of determination; *RMSE*: root mean square error; $\bar{S}$: average bias; $\bar{E}$: average percentage relative error.

The estimated biomass, by component and total, with the S1 system exhibited a congruent graphical performance regarding the observed values (Figure 4S1-a to Figure 4S1-d). When the weighting factor, defined by the inverse of the D, was related to the variance of the error, it had the best performance to correct the heteroscedasticity; the residuals graphically presented a pattern with a random distribution and homogeneous tendency (Figure 5S1-a to Figure 5S1-d).

For the S2 system, the dummy variables technique showed that all parameters were significant (α = 0.05) (Table 2), meaning that each bamboo species requires specific parameters in all equations per structural component. Equations 19, 20, and 21 correspond to the S2 system to estimate *AGB* for *B. oldhamii*, *G. aculeata*, and *G. angustifolia*, respectively.

$$AGB = e^{-5.1658} \cdot \left(D^2H\right)^{1.0932} + e^{-4.4653} \cdot \left(D^2H\right)^{0.5452} + e^{-15.7270} \cdot \left(D^2H\right)^{1.8763} \quad (19)$$

$$AGB = e^{-3.0694} \cdot \left(D^2H\right)^{0.8304} + e^{-6.0014} \cdot \left(D^2H\right)^{0.8473} + e^{-9.5667} \cdot \left(D^2H\right)^{1.2643} \quad (20)$$

$$AGB = e^{-3.7936} \cdot \left(D^2H\right)^{0.9127} + e^{-1.2939} \cdot \left(D^2H\right)^{0.1590} + e^{-24.7872} \cdot \left(D^2H\right)^{3.0519} \quad (21)$$

The S2 system exhibited a R^2_{adj} coefficient of 0.97 for culm biomass, which is 4% higher than the S1 system in this same component; however, for the branches and leaves, the R^2_{adj} was 0.62 and 0.50, respectively. Therefore, in this case, incorporating H did not improve this goodness-of-fit statistic for branches and leaves. The *RMSE* values were low (<3.3 kg) (Table 2); the graphic representation of the estimated vs. observed values by structural component and total for each species maintains a logical consistency in both systems (Figure 4). The heteroscedasticity correction with the weighting factor in S1 and S2 system fitting resulted in residual graphics that show a narrow variation and a distribution without a systematic trend in the structural components, indicating that error variance was stabilized (Figure 5).

Validation of S1 and S2 systems

The validation process showed that for the total aboveground biomass, the S2 system presented better values in the mean prediction error (MPE and MPE%) and also in the magnitude of the prediction error (MAE and MAE%) (Table 3). However, equations for the biomass of branches and leaves of the S2 system had less precise predictions (MAE%>153) than those of the S1 system. The magnitude of the error in these variables can be twice the actual biomass, however, as they are structural components that harbor little biomass (<10%), they do not significantly influence the estimation of bamboo AGB.

DISCUSSION

Aboveground biomass by structural component and total

The giant bamboo species generate a large amount of biomass; the studied species distributed it mainly in the culm. Their contribution is low compared to trees, but the high population density, both in forest plantations and in natural forest stands, allows the biomass accumulated per surface unit to become important. The bamboo forests of these taxa have sympodial and pachymorphous growth, so they form clumps, and the culms grow close to each other. These characteristics stimulate vertical growth to take better advantage of space and light and could explain why these species allocate the greatest biomass production to the culm (García-Soria and Del Castillo-

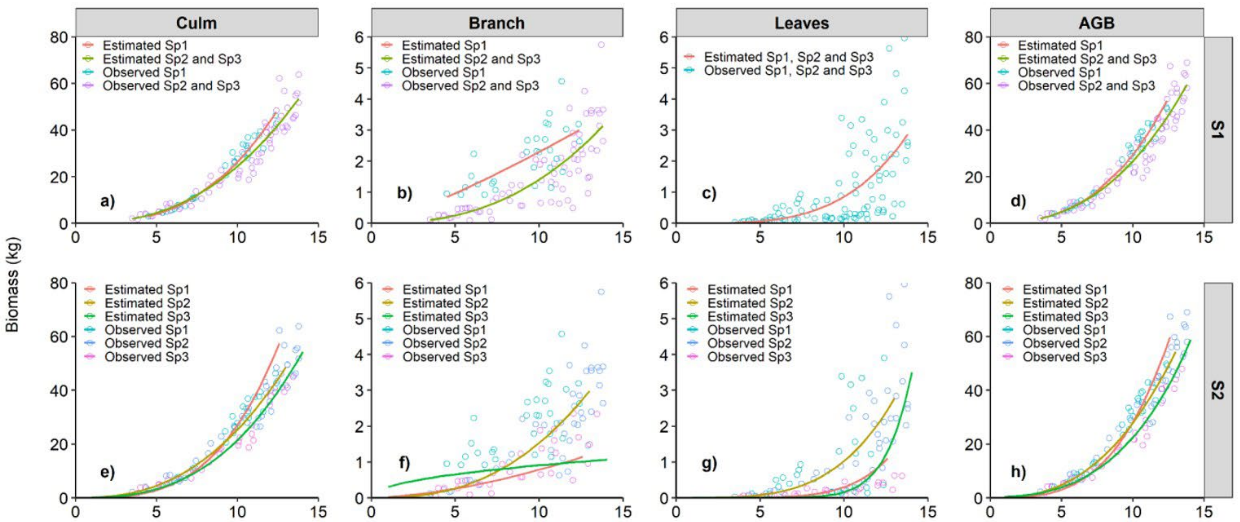

Figure 4: Graphic behavior of the trends generated by the S1 and S2 system regarding those observed; Sp1: *B. oldhamii*, Sp2: *G. aculeata*; Sp3: *G. angustifolia*.

Torres, 2013). The proportion of biomass estimated at culms of *G. aculeata* and *G. angustifolia* was higher than that reported by García-Soria et al. (2015) for *G. sarcocarpa* Londoño & P. M. Peterson from the Peruvian Amazon, who determined the distribution of 68%, 16.4%, and 15.6% for culms, branches, and leaves, respectively.

The existing differences in the distribution of aboveground biomass may be due to the dendrometric characteristics and environmental conditions in which the bamboo species grow; e.g., the culm biomass estimated in *G. aculeata* and *G. angustifolia* was higher than that reported by Yen and Lee (2011) for *Phyllostachys heterocycla* Matsum. in Taiwan, a bamboo that distributes its biomass in a proportion of 83% to 85% in its culm, while the biomass in the branches ranges from 12% to 17%, and the leaves have values similar to those of the present study, ranging from 3% to 5%. Meanwhile, *B. oldhamii* presents values like those reported for *P. heterocycla* by the same authors. In India Kaushal et al. (2016) reported for *Dendrocalamus strictus* Rosb. a biomass distribution of 65 to 70% for culms and branches of 20 to 25%, differing from that found in this study; but reported values lower than 10% for leaves, similar to all the studied species. Similar differences were found by Yen et al. (2010) for *Phyllostachys makinoi* Sieb. & Zucc. in Taiwan, a bamboo that distributes its aboveground biomass in proportions of 73 to 78% in the culm, 13 to 17% in branches, and 6 to 9% in the leaves.

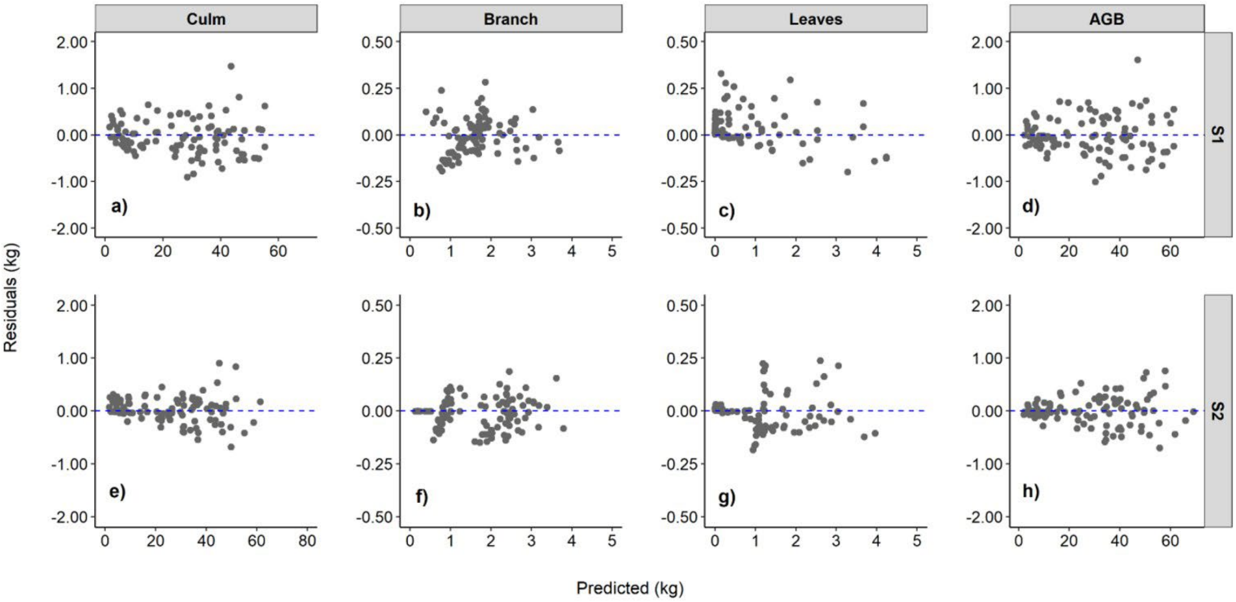

Figure 5: Graphic behavior of residuals generated by the S1 and S2 system for each structural component of biomass.

Table 3: Validation of the additive equations to predict aboveground biomass in three bamboo species using the leave-one-out cross-validation method.

System	Component	MPE	MPE%	MAE	MAE%
S1	Culm	-0.0965	-0.3750	3.0875	13.4788
	Branch	0.0038	0.2250	0.5244	47.3807
	Leaves	0.0032	0.3111	0.6873	150.3822
	AGB	-0.0892	-0.3757	3.6294	14.4519
S2	Culm	0.1315	0.5113	2.0611	8.9064
	Branch	-0.0592	-3.4632	0.6447	208.8521
	Leaves	-0.1135	-10.8556	0.6912	153.7984
	AGB	-0.0411	-0.1443	2.3570	11.0071

S1, S2: additive equation systems; MPE: mean prediction error; MPE%: mean percentage prediction error; MAE: mean absolute error; MAE%: mean absolute error percentage.

Estimation of aboveground biomass by structural component and total

The implementation of the SUR method, dummy variables technique, and heteroscedasticity correction allowed both additive equation systems to provide an accurate estimate of aboveground biomass by structural component and total. This result suggests that the S2 system, which includes the total height variable, is more sensitive than the S1 system with only the D variable; this characteristic of the S2 system results in taxon-specific allometric relationships.

The SUR method has ample benefits owing to its compatibility in the equations developed (Nord-Larsen et al., 2017). Besides, its simultaneous fitting provides better values in the goodness of fit statistics, significantly decreasing the standard errors and reducing confidence and prediction intervals for the estimates (Mohan et al., 2020), as shown in this study. This method achieves a high statistical efficiency in the estimation of parameters by a logic consistency reached with the complied additivity property between the structural and total components per specimen (Huy et al., 2019), which is a highly desirable characteristic. Additionally, the predictor variables D and H in the system equations were measured directly, fulfilling the assumption of making measurements without errors (Fu et al., 2016). Therefore, the use of these variables to predict aboveground biomass by component and total avoids biased values. This means that the generated systems are statistically efficient at making highly accurate estimates.

The S1 and S2 systems have similar aboveground biomass predictions, which is consistent with Xayalath et al. (2019), who reported small differences between the estimations using D or D combined with H. The S1 system would be the most appropriate, using only D as an explanatory variable that is easy, fast, and cheap to measure in the field. Gao et al. (2016) indicated that a high density of culms and foliage per clump creates closed canopy conditions, adding to the curvature as a natural fall to the upper end of commercial culms. This natural situation, created by genotype and climate conditions, complicates the measurement of the total height used in the S2 system. Singnar et al. (2017) determined that D and H together form a composite variable that is comparatively a better predictor of the aboveground biomass. We consider that it is only possible to use the S2 system in combination with an allometric height-diameter model for each bamboo taxon studied. However, Nath et al. (2009) argued that the best practical option is to have simple models that use a single independent variable, implying less effort and time in field measurements. These reasons led to the selection and recommendation of the use of the S1 system, which is parsimonious and robust by doing statistically acceptable estimations of the aboveground biomass per component and total with less field effort.

The values of the R^2_{adj} fitting statistics were similar for both systems of equations (Table 2). Yen et al. (2010) studied *P. makinoi*, finding R^2_{adj} values of 0.54, 0.92, and 0.62 for leaves, culms, and branches, close to those found in this study, but for the total biomass, they show a value of 0.88 below that reported in the three species in this study. For the species *D. strictus*, Kaushal et al. (2016) found values of this statistic of 0.13, 0.95, 0.79, and 0.98 for culms, branches, leaves, and total, the first value being lower and the others similar to those found in the present work. Likewise, Huy et al. (2019) studied *Bambusa procera* (A. Chav. and A. Camus) and found values for R^2 of 0.53, 0.62, 0.56, and 0.65 for leaves, stems, branches, and total, the values for culms and the total being lower than those of both systems in this study.

Estimates of the aboveground biomass total for *B. oldhamii* done by the S1 system are similar to the non-linear model developed by Castañeda-Mendoza et al. (2005) for the same species with three-year-old culms in Veracruz, Mexico. The similarity is maintained at a D interval of 4 to 9 cm; the S1 system comparatively makes slightly higher predictions. However, the estimates of the S1 system are lower up to a D of 9 cm compared to those of a linear model generated by Sanquetta et al. (2015) for the same taxon that grows in Brazil; after 9 cm of *D*, the predictions of the S1 system are higher and better adhere to the biomass values observed.

Model estimates for total aboveground biomass in *G. angustifolia* reported by Aguirre-Cadena et al. (2018) in Mexico and Briceño-Elizondo (2019) in Costa Rica show differences in the expected logical behavior regarding the increase in *D*, while the S1 system for this same species is consistent under the same criteria. For *G. aculeata,* the S1 additive equation system that is reported in this study is the first that is registered in the specialized international literature.

Regarding the validation statistics (MPE, MPE%, MAE, and MAE%) are consistent with what was reported by Camargo-García et al. (2023) for *Guadua angustifolia* in Colombia; in their research, they reported an MAE% >100% for the estimation of the biomass in the leaves, and they mentioned that the error in the proportion of leaves and branches can vary depending on the state of maturity and the density or number of culms. This effect is also present within the bamboo strains, where the central culms have lower biomass than the culms on the banks, mainly in *B. oldhamii,* since their culms are very close to each other.

The additive equation systems for aboveground biomass, generated by structural components and bamboo species, constitute a fundamental biometric tool since they have direct and immediate application to carrying out biomass inventories. These tools allow us to determine the aboveground biomass production potential and to infer and quantify the carbon capture and storage potential of bamboo forests as ecosystems. In particular, based on Barnabas et al. (2020) to estimate the amount of carbon dioxide (CO_2) per hectare that is fixed by a bamboo species, the following relationship should be applied: CO_2 = AGB . CC . PF, where AGB is the total aboveground biomass, CC is the proportion of carbon in AGB, and PF is the proportionality factor and that takes the value of 3.67. Abebe et al. (2021) carried out a procedure in Ethiopia that included giant bamboos in the REDD+ mechanism; this action might be lobbied for Mexico as an additional strategy to contribute to the international environmental policy effort aimed at mitigating the effects of global climate change. These equation systems could also be used to determine bamboo biomass as a raw material in industrial applications such as bioenergy, biorefinery, and bioproducts. In further studies of biomass in bamboo species, it is important to determine other compartments of these ecosystems, such as litter aboveground and biomass belowground, including rhizomes and roots.

CONCLUSIONS

To estimate the aboveground biomass by structural component and total of *B. oldhamii*, *G. aculeata*, and *G. angustifolia*, the use of the S1 additive equations system is recommended, which only uses diameter at breast height as a predictive variable. The S2 system can only be used when reliable information on the total culm height is available, e.g., when using a height-diameter allometric model. The additive equation systems generated with the SUR method combined with the dummy variables technique and heteroscedasticity correction are regional and specific to the taxa studied; this fitting strategy combined with the LOOCV validation technique can be applied to generate biomass equation systems in other bamboo species from other parts of the world. Although the three bamboo species are classified as giant bamboos, they produce slightly different amounts of biomass, with *G. aculeata* being the greatest aboveground biomass producer. The type of growth and cultivation are aspects that can influence biomass production in branches and leaves, as well as the average dimensions of mature commercial culms, which may explain these differences observed. The biomass contribution of the branch and leaves components is minimal; however, its estimation is important to know its contribution to carbon capture and for their marketing as a wood energy product and as forage, respectively.

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AUTHORSHIP CONTRIBUTION

Project Idea: COP, JCTU;

Funding: COP;

Database: COP, JCTU, MRA;

Processing: JCTU, ANN, MRA;

Analysis: COP, JCTU, ANN;

Writing: COP, JCTU;

Review: COP, JCTU, ANN, MRA.

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