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Individual Tree Attribute Estimation and Uniformity Assessment in Fast-Growing *Eucalyptus* spp. Forest Plantations Using Lidar and Linear Mixed-Effects Models

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1. Characteristics and descriptive statistics of the Eucalyptus sp. stands used in the study

Table S1. Descriptive statistics (mean ± standard deviation) of field measurements in the area of study. Ht = height; Dbh = diameter at 1.3 m above the ground; AGC = aboveground carbon.

Stand	Age	Plot	Species	Genotype	Ht (m)	dbh (cm)	AGC (Kg / tree)
S01	2.7	P1	SP05	GM01	15.3 ± 0.99	13.56 ± 1.44	31.43 ± 6.99
S02	3.7	P2	SP01	GM04	19 ± 2.05	14.92 ± 2.30	42.12 ± 11.23
S03	4.3	P3	SP05	GM05	18.9 ± 1.18	14.02 ± 1.22	36.56 ± 6.63
S04	3.8	P4	SP01	GM03	17.2 ± 0.79	11.61 ± 1.04	24.2 ± 4.62
S05	3.5	P5	SP01	GM03	20 ± 2.08	16.26 ± 2.67	51.39 ± 15.08
S06	3.8	P6	SP01	GM03	19.5 ± 1.21	13.81 ± 1.56	36.12 ± 8.32
S07	3.3	P7	SP03	GM08	13.2 ± 1.72	11.4 ± 2.17	21.57 ± 8.17
S08	1.8	P8	SP05	GM02	10 ± 0.6	8.83 ± 0.71	11.18 ± 1.81
S09	3.6	P9	SP04	GM06	20.2 ± 1.74	14.79 ± 1.48	41.86 ± 7.62
S10	1.8	P10	SP05	GM02	10.3 ± 1.01	9.42 ± 0.92	12.92 ± 2.67
S11	2	P11	SP05	GM02	11.9 ± 0.63	11.37 ± 0.92	19.76 ± 3.36
S12	2.8	P12	SP04	GM06	15.5 ± 1.19	13.97 ± 1.92	33.75 ± 8.63
S13	2.8	P13	SP04	GM06	15 ± 1.27	13.75 ± 1.8	32.18 ± 8.20
S14	1.8	P14	SP05	GM02	11.4 ± 1.23	12.09 ± 1.35	21.99 ± 4.77
S14	1.8	P15	SP05	GM02	11.2 ± 0.8	10.97 ± 0.88	17.9 ± 2.80
S14	1.8	P16	SP05	GM02	10.9 ± 1.08	10.72 ± 1.42	17.13 ± 4.62
S15	3.4	P17	SP02	GM07	18.3 ± 0.79	16.39 ± 2.34	49.62 ± 12.86
S16	3.3	P18	SP03	GM08	15.3 ± 1.48	13.72 ± 2.03	32.53 ± 9.88
S17	2.7	P19	SP03	GM08	16.1 ± 2.65	13.44 ± 1.75	31.91 ± 9.41
S18	3.6	P20	SP01	GM04	21.1 ± 1.83	16.38 ± 2.48	53.01 ± 15.72
S19	3.8	P21	SP01	GM03	21.3 ± 1.29	16.53 ± 1.39	53.12 ± 9.08
S20	1.7	P22	SP05	GM01	10.9 ± 0.74	9.79 ± 1.00	14.31 ± 3.01
S21	3.7	P23	SP01	GM04	20.8 ± 1.29	15.82 ± 2.00	48.68 ± 13.06
S22	2.2	P24	SP03	GM08	11.1 ± 1.48	9.77 ± 1.25	14.51 ± 4.30
S23	2.2	P25	SP05	GM02	12.7 ± 1.68	13.07 ± 1.63	27.01 ± 6.99

2. Aboveground carbon (AGC) equation for estimating the tree-level AGC in the study

The allometric model for AGC (kg/tree) was obtained based on the equation developed in [1]:

$$\ln AGC = -2.87 + 1.96 \, x \, ln \, dbh + 0.44 \, x \, ln \, H \tag{1}$$

Where: ln = neperian logarithm; AGC = aboveground carbon; dbh = tree diameter at 1.3 m above the ground; H = tree height.

3. Descriptive statistics of tree lidar-derived crown metrics calculated from the detected trees (accuracy = 96.6%) in the airborne lidar survey

Table S2. Summary statistics of lidar derived crown-metrics maximum height (HMAX), crown projected area (CPA), and crown volume (CV).

Crown metrics	Min	1st Qu.	Median	Mean	3rd Qu.	Max
HMAX	5.26	13.08	16.6	16.58	20.5	24.76
CPA	0.2	2.87	4.35	4.58	6.03	13.31
CV	1.08	17.51	26.27	27.54	35.51	106.15

4. Results of testing the selected random effect (Stand ID) in different variables and their combinations. The best model was obtained when applying the random-effect only in the intercept (b_{0j}) and the parameter associated to crown height (HMAX, b_{1j}).

Table S3. Statistics for the linear mixed-effect model (LME) using the Stand as random-effect variable considering intercept ($\boldsymbol{b_{0j}}$) and slope ($\boldsymbol{b_{1j}}$, $\boldsymbol{b_{2j}}$ and $\boldsymbol{b_{3j}}$) combinations. RMSE= root mean square error, R2 = Coefficient of determination; AIC = Akaike information criterion. We tested all the combinations using the random-effect variable in the intercept as this would represent the simplest mixed-effect model.

Attribute	Mixed effect parameter	RMSE	RMSE%	R²	AIC
Ht	u_0, u_1, u_2 and u_3	1.15	7.17	0.9019	5025.14
	u_0, u_1 and u_2	1.16	7.19	0.9013	4957.48
	$u_0, u_1$and u_3	1.16	7.18	0.9015	4955.92
	$u_0, u_1$and u_3	1.21	7.50	0.8925	5015.08
	$u_0$and u_1	1.16	7.21	0.9008	4952.01
	u_0 and u_2	1.21	7.51	0.8923	5009.14
	$u_0$and u_3	1.21	7.50	0.8925	5010.36
	u_0	1.21	7.52	0.8921	5009.17
dbh	u_0, u_1, u_2 and u_3	0.04	6.99	0.8732	4632.87
	u_0, u_1 and u_2	0.95	7.04	0.8715	4452.93
	$u_0, u_1$and u_3	0.95	7.04	0.8715	4453.35
	$u_0, u_1$and u_3	1.15	8.52	0.8120	4943.87
	$u_0$and u_1	0.95	7.05	0.8713	4447.46
	u_0 and u_2	1.16	8.60	0.8083	4945.88
	$u_0$and u_3	1.15	8.54	0.8110	4941.28
	u_0	1.16	8.65	0.8060	4959.16
AGC	u_0, u_1, u_2 and u_3	4.40	13.33	0.9091	9444.55
	u_0, u_1 and u_2	4.40	13.33	0.9091	9152.55
	$u_0, u_1$and u_3	4.43	13.40	0.9081	9140.09
	$u_0, u_1$and u_3	5.93	17.96	0.8349	9894.31
	$u_0$and u_1	4.44	13.44	0.9075	9119.29
	u_0 and u_2	5.98	18.11	0.8322	9896.69
	$u_0$and u_3	5.95	18.01	0.8339	9890.87
	u_0	6.02	18.22	0.8301	9911.42

LME: $Y_{ij} = (\beta_0 + b_{0j}) + (\beta_1 + b_{1j})\ HMAX_{ij} + (\beta_2 + b_{2j})\ CPA_{ij} + (\beta_3 + b_{3j})\ CV_{ij} + \varepsilon_{ij}$

Where: Yi is the response variable for the i-th tree of the j-th stand; $\boldsymbol{\beta_0}$, $\boldsymbol{\beta_1}$, $\boldsymbol{\beta_2}$, $\boldsymbol{\beta_3}$ are the fixed coefficients associated to the intercept, HMAX, CPA, and CV, respectively; $\boldsymbol{b_{0j}}$, $\boldsymbol{b_{1j}}$, $\boldsymbol{b_{2j}}$ and $\boldsymbol{b_{3j}}$, are the random coefficients for the j-th stand.e_{ij} ~N (0,s^2I) and b_j ~N (0, s^2D)

5. Predictions of the linear-mixed effect model parameters using genotype (GM), species (SP) and stand (SID) as random-effect variable.

Table S4. Parameters prediction for the models used to estimate tree height (Ht, m), diameter at 1.3 m aboveground (dbh, cm) and aboveground carbon (AGC, kg tree^{-1}). The standard deviation (sd) for the parameters $\boldsymbol{u_{2ij}}$ and $\boldsymbol{u_{3ij}}$ are not presented as the random-effect was considered only for the intercept and Hmax (see Table S3).

Attribute	Model	Random effect	Intercept	Hmax	CV	CPA	sd($\boldsymbol{u_{0ij}}$)	sd($\boldsymbol{u_{1ij}}$)
Ht	LME	GM	2.86783	0.783963	-0.011281	0.038298	4.31	0.22
		SP	3.84568	0.752109	-0.009068	0.028551	4.27	0.23
		SID	1.919593	0.825717	-0.007854	0.016937	4.58	0.26
		SID, SP, GM	1.919593	0.825717	-0.00785	0.016937	2.20	0.12
	LFE	-	3.1582663	0.790761	0.0006602^{ns}	-0.0430492^{ns}	-	-
dbh	LME	GM	-5.313682	1.023621	-0.003293	0.024358	12.22	0.58
		SP	-2.586625	0.887925	0.003487	0.007301	14.49	0.75
		SID	-11.1200	1.3560	0.0002021	-0.05065	14.62	0.68
		SID, SP, GM	-11.825177	1.396906	-0.002643	-0.035634	5.80	0.30
	LFE	-	5.334383	0.472429	-0.005097^{ns}	0.094923	-	-
AGC	LME	GM	-71.553130	5.604290	-0.015270	0.168020	74.23	3.63
		SP	-57.683290	4.979220	0.018890	0.072930	82.67	4.31
		SID	-97.263530	6.963557	-0.006557	-0.186658	94.22	4.44
		SID, SP, GM	-97.263529	6.963557	-0.006557	-0.186658	40.44	2.00
	LFE	-	-14.94518	2.79161	-0.03197^{ns}	0.5608	-	-

LFE: $Y_i = \beta_0 + \beta_1 \, x \, HMAX_i + \beta_2 \, CPA_i + \beta_3 \, CV_i + \varepsilon_i$;

LME: $\boldsymbol{Y_{ij}} = (\boldsymbol{\beta_0} + \boldsymbol{u_{0ij}}) + (\boldsymbol{\beta_1} + \boldsymbol{u_{1ij}}) \, \boldsymbol{Hmax_{ij}} + (\boldsymbol{\beta_2}) \, \boldsymbol{CPA_{ij}} + (\boldsymbol{\beta_3}) \, \boldsymbol{CV_{ij}} + \boldsymbol{\varepsilon_{ij}}$

LME = Linear mixed-effect models; LFE = Linear fixed-effect model; GM = Genotype; SP = Species; SID = Stand ID; sd = standard deviation; RMSE = Root Mean Square Error; R^2 = coefficient of determination; AIC = Akaike Information Criterion; ns p-value > 0.05 for the t-test

6. Linear-mixed effect model calibration for additional levels.

The linear mixed-effect models (LME) can be recalibrated when it is necessary to apply it to a new dataset without the same levels of the random-effect variable used during the fitting process. To demonstrate it we fitted the LME model removing from the dataset three stands, which correspond to the random-effect variable. The model is then recalibrated by calculating the best linear, unbiased predictor for the random parameters based on Equation (S2) [2,3]. The recalibrated model is then applied to the three removed stands.

$$\hat{a} = (Z'\hat{R}^{-1}Z + \hat{D}^{-1})^{-1}Z'\hat{R}^{-1}(y - \hat{\mu} \quad \text{(S2)}$$

Where: $\hat{a}$ = matrix of predicted random parameters; Z is the design matrix associated with random parameters; $\hat{R}$ = is the estimated variance-covariance matrix for residual errors of individual trees; $\hat{D}$ = estimate of the variance-covariance matrix for the random parameters of the mixed-effect models; y is the vector of observations of the dependent variable (i.e., tree attribute); $\hat{\mu}$ is the vector of estimated values using the model with fixed effect parameters only.

The results of the calibrated model were compared to a linear fixed-effect model (LFE) fitted using only the three levels removed to fit the LME. The LME yielded better results (Figure S1). This indicates that few samples might not yield robust LFE regression models while LME might benefit from the recalibration of a previously fitted robust model.

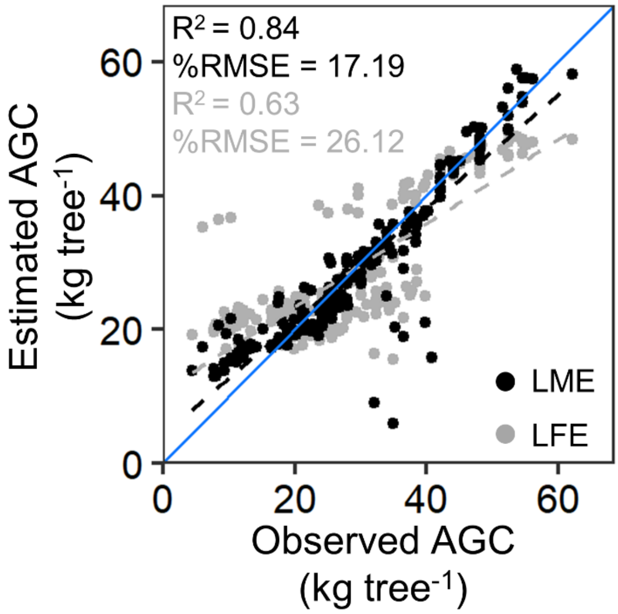

Figure S1. Scatterplot comparing recalibrated linear mixed-effect model and fixed-effect models (LME and LFE, respectively) for estimating aboveground carbon (AGC). R^2 = coefficient of determination; %RMSE = Root Mean Square Error.

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