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Supplementary Materials for

Human impacts as the main driver of tropical forest carbon

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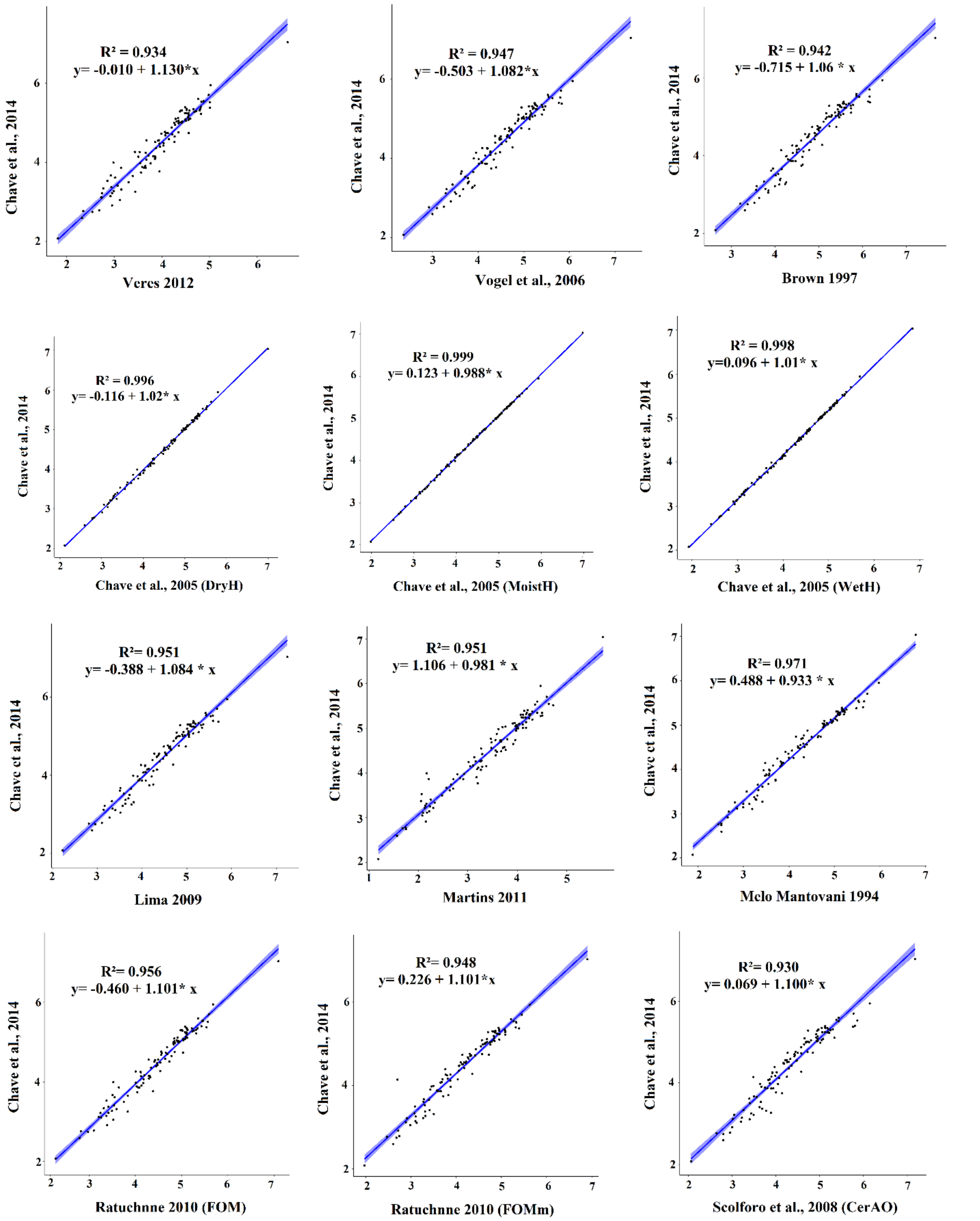
The PDF file includes:

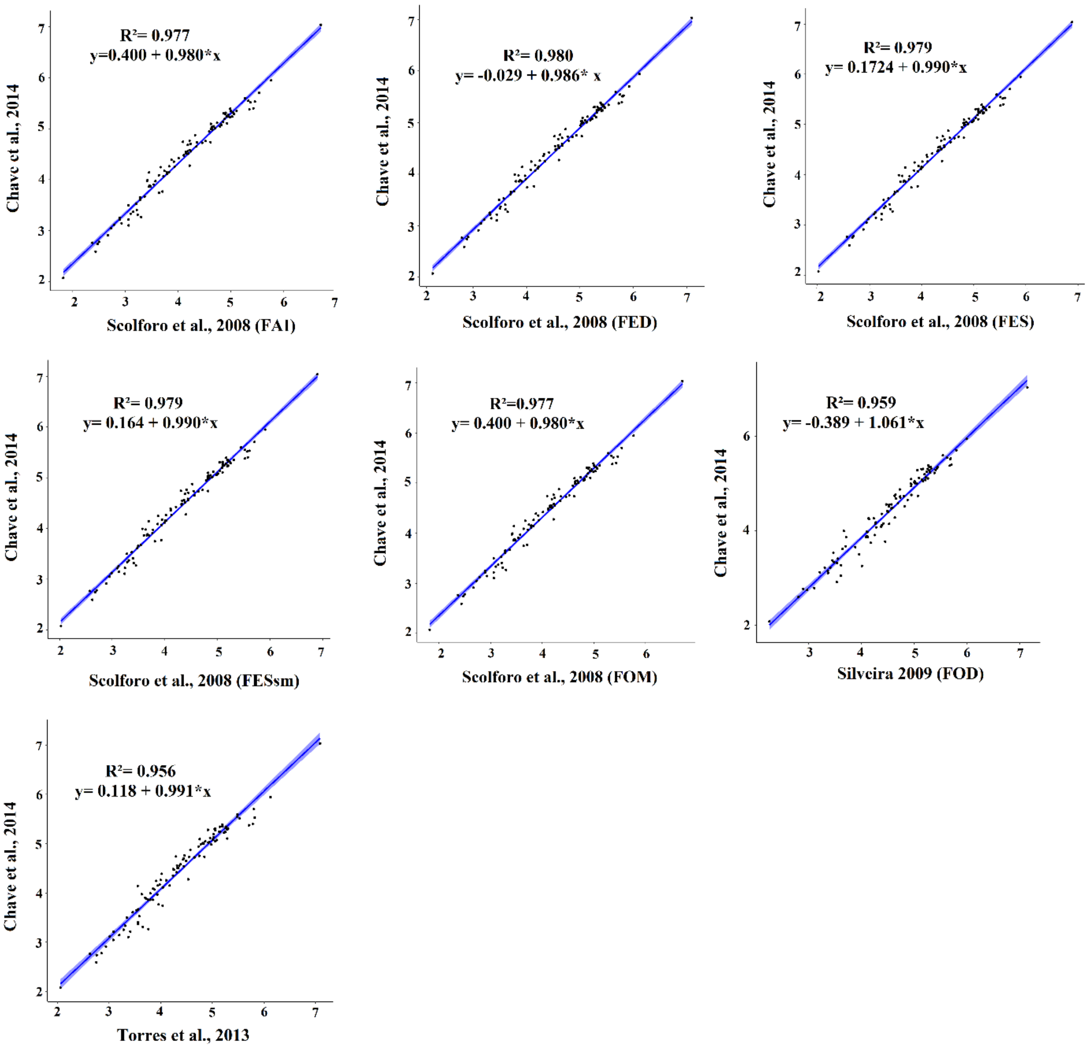
Supplementary Text
Figs. S1 to S7
Tables S1 to S6
Legend for data S1

Other Supplementary Material for this manuscript includes the following:

Data S1

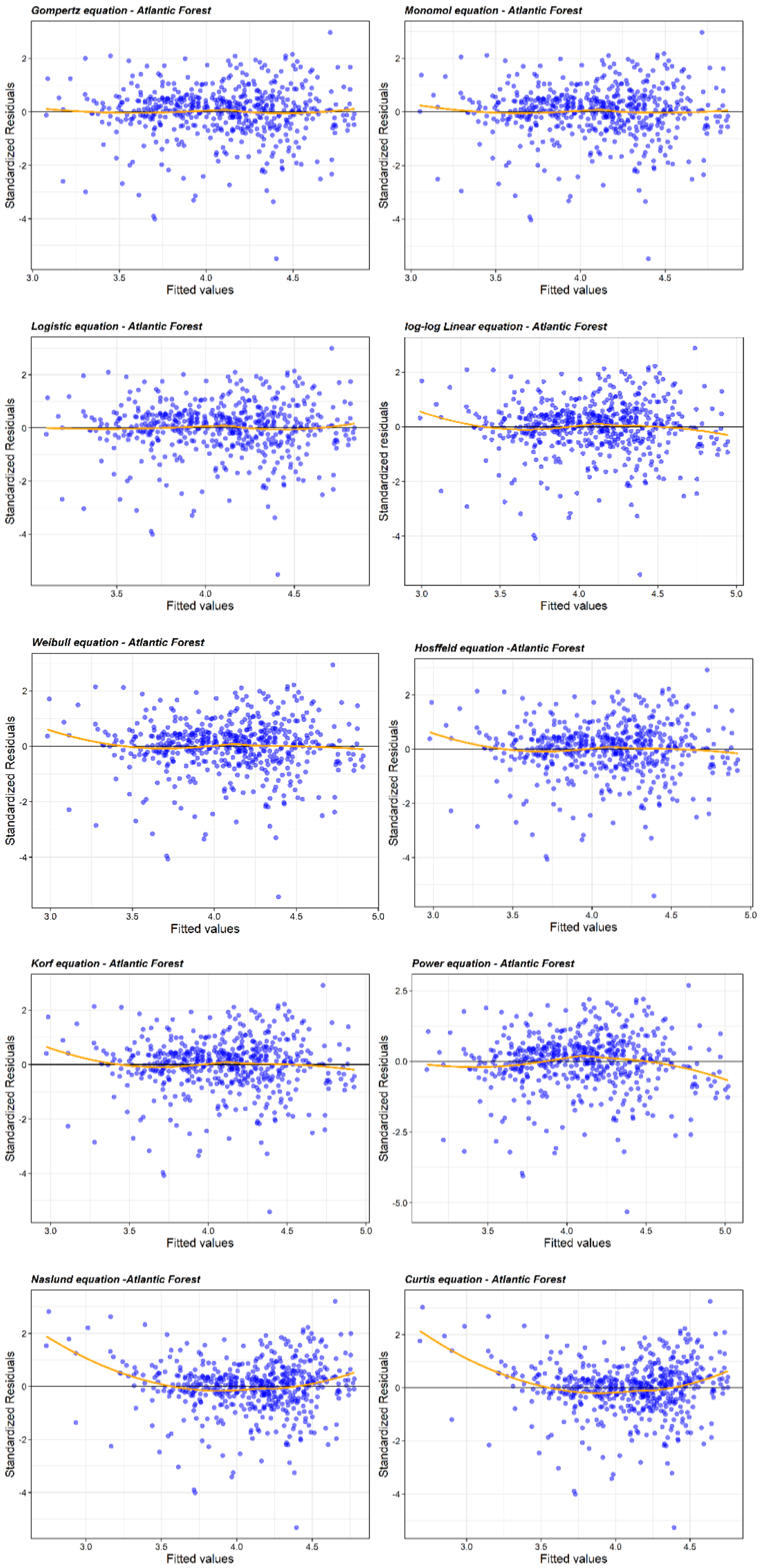
Fig. S1. The relationship between the 20 allometric equations found to estimate AGC (Table S1) and the one provided by ref. (1). The *y*-axis is the natural logarithmic of the estimate provided by ref. (1) formula and the *x*-axis is the natural logarithmic of the aboveground carbon of each allometric equation. We present the mean prediction of the linear regression model (in blue) and the associated R^2 of the model.

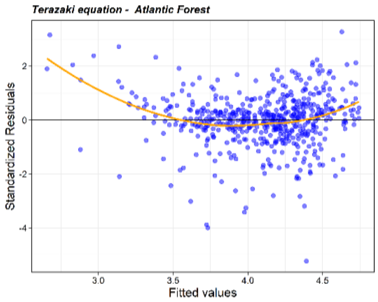


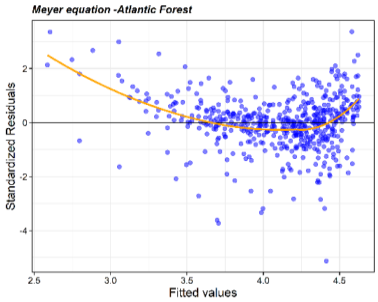


R²= 0.977
y=0.400 + 0.980*x
Chave et al., 2014
Scolforo et al., 2008 (FA1)
R²= 0.980
y= -0.029 + 0.986* x
Chave et al., 2014
Scolforo et al., 2008 (FED)
R²= 0.979
y= 0.1724 + 0.990*x
Chave et al., 2014
Scolforo et al., 2008 (FES)
R²= 0.979
y= 0.164 + 0.990*x
Chave et al., 2014
Scolforo et al., 2008 (FESsm)
R²=0.977
y= 0.400 + 0.980*x
Chave et al., 2014
Scolforo et al., 2008 (FOM)
R²= 0.959
y= -0.389 + 1.061*x
Chave et al., 2014
Silveira 2009 (FOD)
R²= 0.956
y= 0.118 + 0.991*x
Chave et al., 2014
Torres et al., 2013

Fig. S2. Carbon equations residual plots. Smoothers between residuals and fitted values from different models tested to find the best description of the relationship between above-ground carbon (AGC; estimated by ref. (1)) and basal area (BA) based on from 527 inventories reporting both AGC and BA estimates.




Terazaki equation - Atlantic Forest
Standardized Residuals
2
0
-2
-4
3.0
3.5
4.0
4.5
Fitted values


Meyer equation -Atlantic Forest
Standardized Residuals
2
0
-2
-4
2.5
3.0
3.5
4.0
4.5
Fitted values

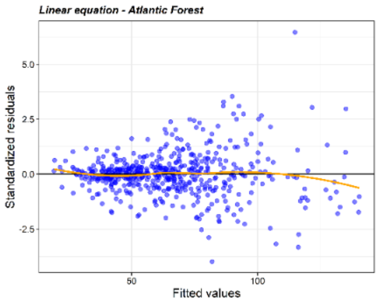

Linear equation - Atlantic Forest
Standardized residuals
5.0
2.5
0.0
-2.5
50
100
Fitted values

Fig. S3. The relationship between above-ground carbon and basal area for 527 forest inventories. Values of above-ground carbon were obtained from values of above-ground biomass estimated using the allometric equation provided by ref.(1)). The green line is the fit of the Gompertz equation, whose parameter estimates, explanatory power (R^2) and standard residual error (%) are provided. Points represents the values for each inventory**.**

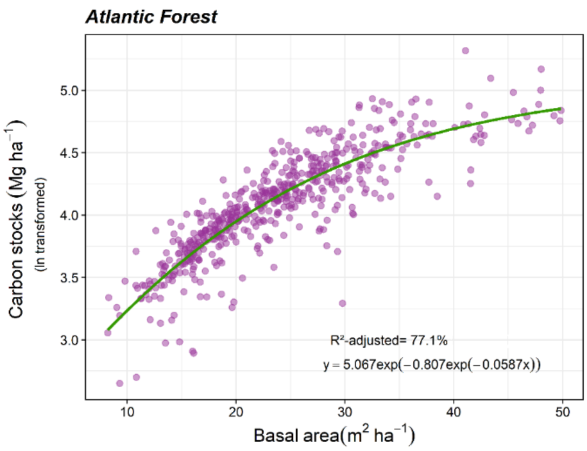


Figure S4: An a priori model of the causal relationships among climate, soil properties, topography, human impacts, tree community properties, and aboveground carbon storage (AGC) in Atlantic Forest. We hypothesize that effect of human impacts is negative, the soil properties is positive and the climate, slope declivity and field sampling methods can be positive or negative depending on the evaluated variable. Taller and hard wood species and taxonomic and functional diversity increases the carbon stocks.

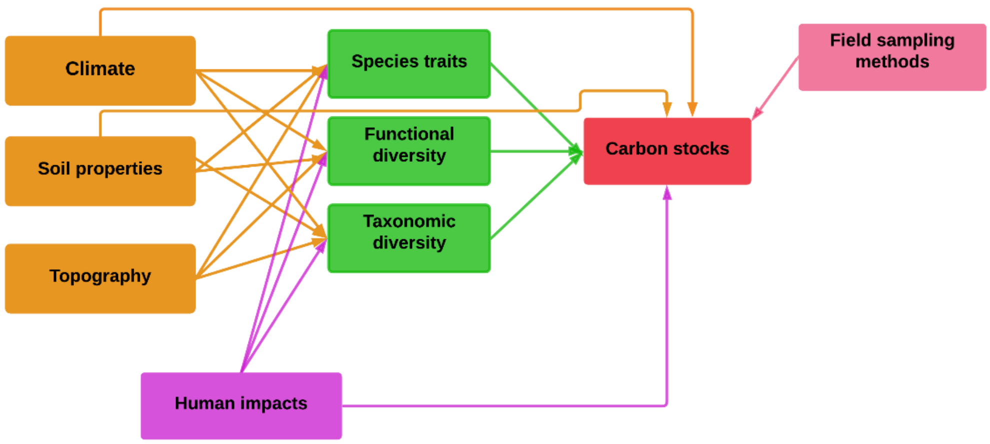


Figure S5: Correlation matrix between potential carbon stocks drivers. Wg_gcm3_log (CWM wood density log transformed), MaxHeight_m_log (CWM Maximum height log transformed), FEve.n (Functional evenness), FDiv.n (Functional divergence), FRic.n (Functional richness), PAR (perimeter area ratio), DBH_inclusion_c (Dbh cutoff criterion), Ridit_DL (Within fragment disturbance level), MAT (Mean annual temperature), ppt (Mean annual precipitation), CWD_T (Climatic water deficit -1 transformed), frag_area (Fragment size), mean.patch_area (Mean fragment size), DECLIV (Slope declivity), Soil.Quality_T (soil quality), LeafArea_log (CWM Leaf area log transformed) and SeedMass_g_log (CWD seed mass log transformed).

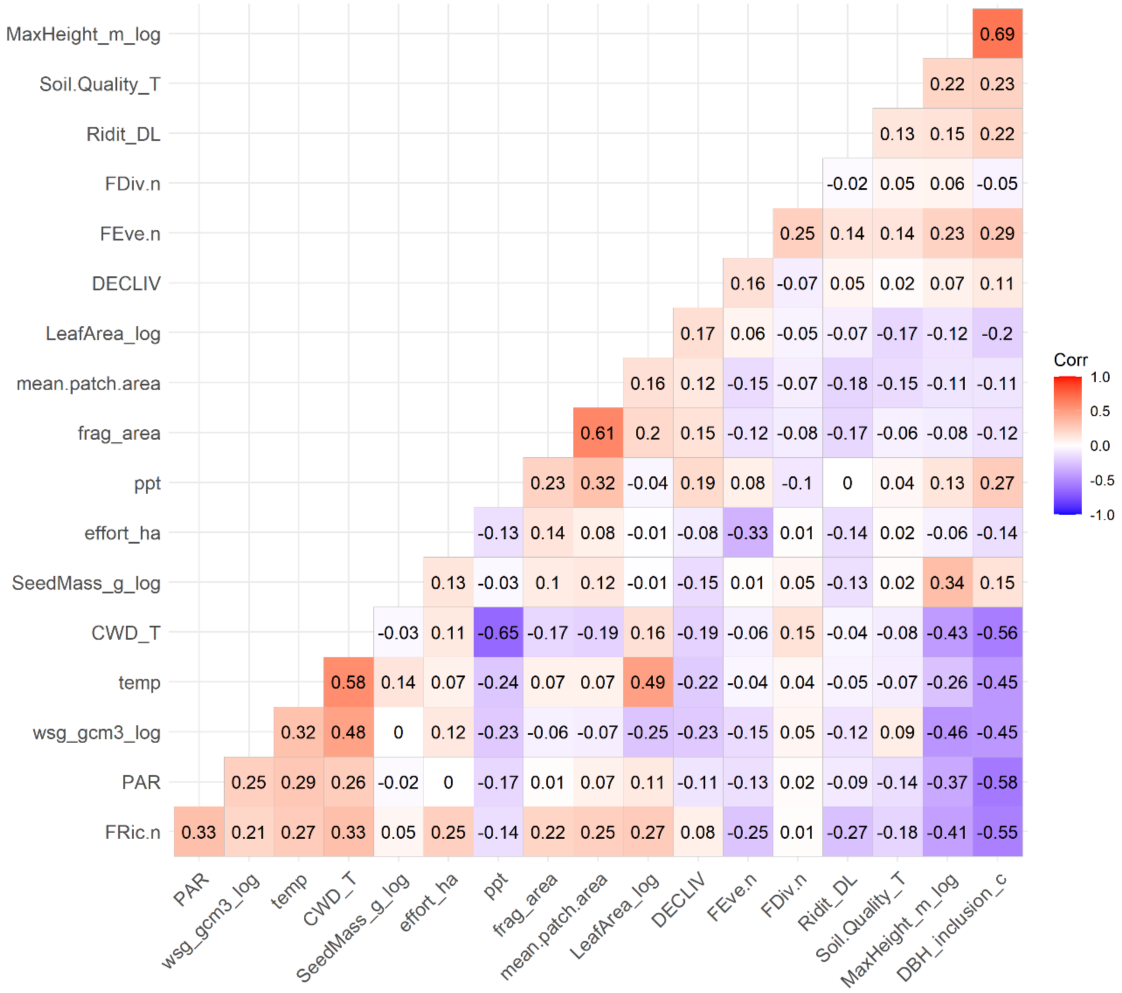


Figure S6: Causal mediation analysis in its simplest form. a' = effect of X on Y; b' = effect of X on M, b'c'= effect of X on Y mediated by M.

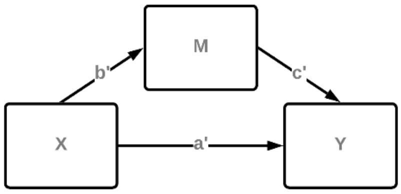


Figure S7: Residual plots. (A) AGC main drivers' model (Table S1 and Fig 1). (B-F) Causal mediation models (Table S4).

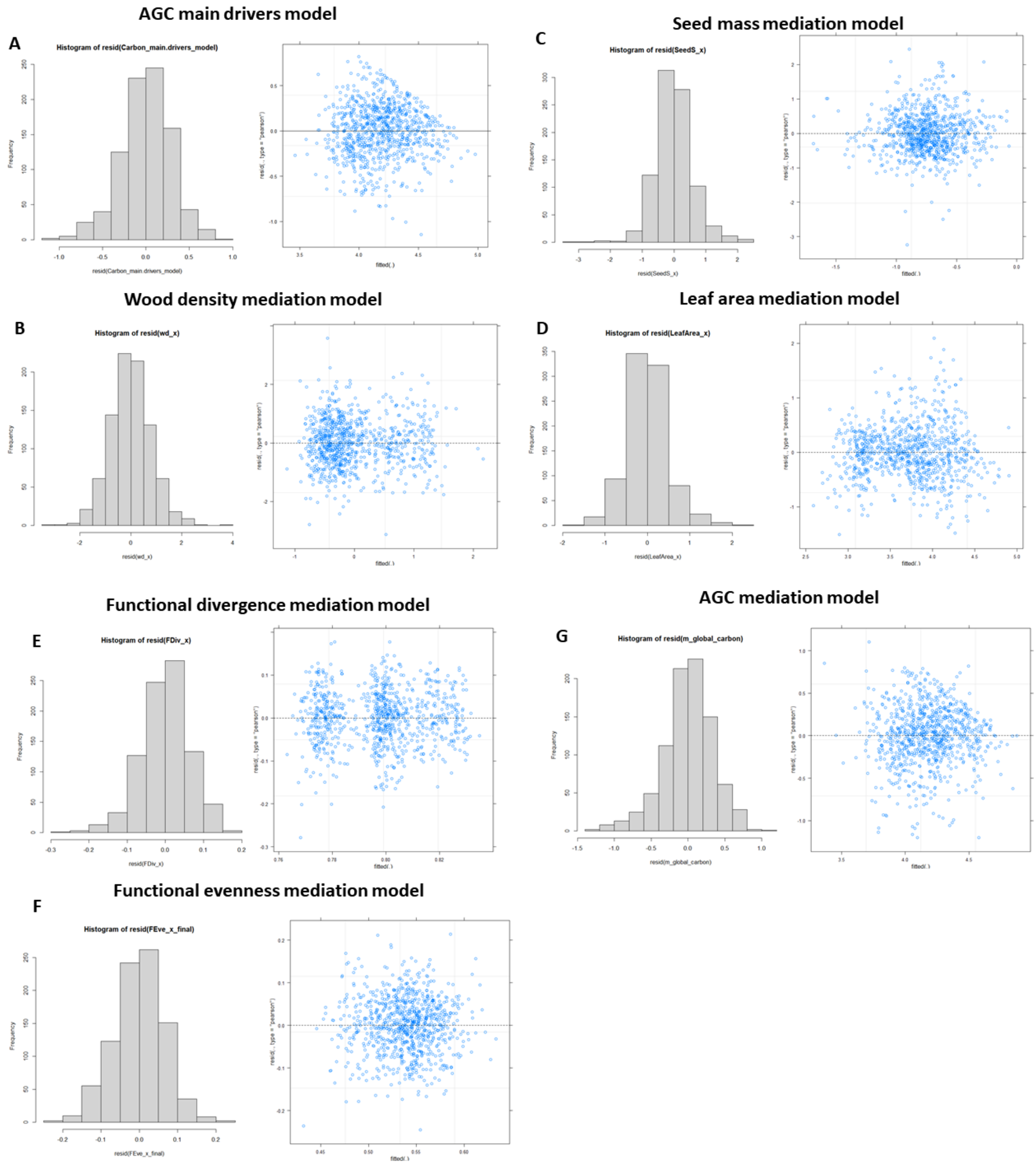


Table S1: Standardized coefficients and partial pseudo-R^2 of model-averaged of AGC main drivers model of Atlantic Forest. Model averaging was developed with all candidate models that presented ΔAICc ≤ 4. Note: AGC (Above-ground carbon stocks); SE (standard error).

Log(AGC)~scale(FRic.n)+scale(effort_ha)+scale(DBH_inclusion_c)+scale(PAR)+scale(log(LeafArea))+scale(FDiv.n)+scale(FEve.n)+scale(log(SeedMass_g))+scale(log(wsg_gcm3))+scale(log(MaxHeight_m))+scale(mean.patch.area)+scale(frag_area)+scale(Frag_Dist_L)+scale(CWD_T)+scale(temp)+scale(Soil.Quality_T)+scale(Slope)+(1|ecoreg)

Variable Code	**Drivers**	**Estimate**	**SE**	***p-value***	**partial pseudo-R^2 (%)**
	Intercept	4.132	0.054	<0.0001	
Frag_Dist_L	Within fragment disturbance level	-0.128	0.010	<0.0001	12.24
FEve.n	Functional evenness	-0.075	0.011	<0.0001	3.97
CWD_T	Climatic water deficit (-1 transformed)	-0.026	0.019	0.174	0.30
temp	Mean annual temperature	-0.098	0.015	<0.0001	3.97
DBH_inclusion_c	Dbh cuttoff criteria	-0.052	0.017	0.002	0.97
Soil.Quality_T	Soil quality	-0.017	0.010	0.110	0.25
Slope	Slope declivity	-0.001	0.011	0.921	0.00
FRic.n	Functional richness	0.016	0.013	0.234	0.15
SeedMass_g	CWM Seed mass	0.079	0.010	<0.0001	4.88
frag_area	Fragment size	0.029	0.011	0.007	0.73
FDiv.n	Functional divergence	0.044	0.010	<0.0001	1.71
mean.patch.area	Mean fragment size	0.033	0.011	0.002	0.90
LeafArea	CWM Leaf area	0.036	0.014	0.011	0.64
wsg_gcm3	CWM Wood density	0.054	0.013	<0.0001	1.56
PAR	Perimeter-area ratio	0.057	0.012	<0.0001	2.06
MaxHeight_m	Maximum tree height	0	0	0	0.00
effort_ha	Sampling effort	-0.020	0.010	0.059	0.35

Table S2: The carbon estimate ± standard error (SE) from optimum linear mixed model (Fig.2 and Table S1). Note: Within fragment disturbance level is shown here as a categorical variable (i.e., without Ridit score transformation).

Within Disturbance levels	**Estimate**	**SE**	**df**
Low	72.399	4.574	8.939
Medium	69.838	4.231	7.613
High	55.056	3.326	7.455
Heavy	48.241	5.225	75.295

Table S3: Tukey test results from generalized linear mixed models testing effects of within fragment disturbances on carbon stocks (AGC).

Within disturbances levels	***p- value***
Low - Medium	0.595
Low - High	<.0001*
Low - Heavy	<.0001*
Medium - High	<.0001*
Medium - Heavy	<.0001*
High - Heavy	0.445

"*" p-value > 0.05, significant values

Table S4: Causal mediation analysis models. The estimated coefficients ± standard error (SE) from multiple linear mixed models, testing the effects of human impacts (mean fragment size and forest degradation level) and environmental conditions (climate, slope declivity and soil quality) on functional traits (wood density -WD, Seed mass and Leaf area) and functional diversity (functional richness – FRic, functional evenness -FEve and functional divergence -FDiv). Note: MAT (Mean annual temperature), CWD (climatic water deficit), MEMs: Moran's eigenvector maps, spatial filters. Climatic water deficit was -1 transformed and AGC, WD, seed mass and leaf area were transformed in the natural logarithmic scale. All models were fitted with scaled drivers.

a) Wood density mediation model

	Estimate	SE	*p-value*
Intercept	-0.4869	0.0166	<0.0001
Within fragment disturbance level	-0.0091	0.0024	0.0002
Mean fragment size	0.0073	0.0026	0.0054
Slope declivity	-0.0092	0.0025	0.0002
Soil quality	0.0079	0.0025	0.0017
MAT	0.0061	0.0034	0.0750
CWD	0.0345	0.0046	<0.0001
Model R²	0.207		
Degrees of freedom	111.25		
Moran I statistic standard deviate			0.1791

b) Seed Mass mediation model

	Estimate	SE	*p-value*
Intercept	-0.7511	0.1159	0.0004
Within fragment disturbance level	-0.0885	0.0211	<0.0001
Mean fragment size	0.0487	0.0225	0.0308
Slope declivity	-0.0912	0.0215	<0.0001
Soil quality	0.0343	0.0217	0.1138
MAT	0.1611	0.0294	<0.0001
CWD	-0.1002	0.0387	0.0103
Model R²	0.088		
Degrees of freedom	111.25		
Moran I statistic standard deviate			0.4303

c) Leaf area mediation model

	Estimate	SE	*p-value*
Intercept	3.6961	0.1019	<0.0001
Within fragment disturbance level	-0.0120	0.0171	0.4833
Mean fragment size	-0.0246	0.0182	0.1771
Slope declivity	0.1545	0.0174	<0.0001
Soil quality	-0.0377	0.0175	0.0319
MAT	0.3129	0.0238	<0.0001
CWD	-0.0938	0.0317	0.0033
Model R²	0.208		
Degrees of freedom	111.25		
Moran I statistic standard deviate			0.9266

d) Functional divergence mediation model

	Estimate	SE	*p-value*
Intercept	0.7895	0.0072	<0.0001
Within fragment disturbance level	-0.0024	0.0021	0.2696
Mean fragment size	0.0001	0.0023	0.9634
Slope declivity	-0.0013	0.0022	0.5586
Soil quality	0.0012	0.0022	0.5864
MAT	0.0008	0.0030	0.7666
CWD	0.0073	0.0036	0.0468
Model R²	0.017		
Degrees of freedom	111.25		
Moran I statistic standard deviate			0.6942

e) Functional evenness mediation model

	Estimate	SE	*p-value*
Intercept	0.5245	0.0102	<0.0001
Within fragment disturbance level	0.0061	0.0022	0.0074
Mean fragment size	-0.0089	0.0024	0.0002
Slope declivity	0.0132	0.0023	<0.0001
Soil quality	0.0040	0.0023	0.0866
MAT	0.0102	0.0032	0.0015
CWD	-0.0069	0.0040	0.0870
MEM10	-0.0104	0.0022	<0.0001
MEM15	0.0071	0.0022	0.0017
MEM86	0.0072	0.0022	0.0010
MEM3	-0.0133	0.0030	<0.0001
MEM14	0.0075	0.0022	0.0008

f) AGC stocks mediation model

	Estimate	SE	*p-value*
Intercept	4.1420	0.0526	<0.0001
Within fragment disturbance level	-0.1272	0.0106	<0.0001
Mean fragment size	0.0329	0.0114	0.0040
Slope declivity	-0.0036	0.0111	0.7464
Soil quality	-0.0191	0.0108	0.0789
MAT	-0.0975	0.0164	<0.0001
CWD	-0.0253	0.0197	0.2008
Wood density	0.0642	0.0142	<0.0001
Tree Maximum Height	0.0265	0.0154	0.0863
Leaf area	0.0383	0.0147	0.0093
Seed mass	0.0721	0.0116	<0.0001
Functional richness	0.0193	0.0136	0.1546
Functional evenness	-0.0755	0.0118	<0.0001

				Functional divergence	0.0431	0.0105	<0.0001
				PAR	0.0552	0.0123	<0.0001
				DBH cutoff	-0.0614	0.0189	0.0012
				Sampling effort	-0.0211	0.0108	0.0516
Model R^2	0.144			Model R^2	0.367		
Degrees of freedom	68.461			Degrees of freedom	49.44		
Moran I statistic standard deviate			0.9111	Moran I statistic standard deviate			0.7696

Table S5. List of the all allometric equations reported in the forest inventories used for data analysis. AGB= Above-ground biomass, H= Height of the tree, DBH= diameter at breast height, WD= wood density and DW= Dry weight.

Allometric equations
AGB=0.0673*(WD*(DBH^2)*H)^(0.976)
AGB=0.033430*(DBH^2.397902)*(H^0.426536)
AGB=exp(-2.289+2.649*ln(DBH)-0.021*(ln(DBH))^2)
AGB=exp(-2.187+0.916*ln(WD*(DBH^2)*H))
AGB=exp(-2.977+ln(WD*(DBH^2)*H))
AGB=exp(-2.557+0.940*ln(WD*(DBH^2)*H))
DW=(59.321357)+(-12.28289)*DBH+(0.8396136)*(DBH^2)
AGB=0.04821*(DAP^1.34374)*(H^1.26829)
ln(AGB)=-4.15190+1.06068*ln((DBH^2)*H)
AGB=0.317*(DBH^2)+0.009*((DBH^2)*H)
AGB=-3.025*DBH+0.425*(DBH^2)+0.006*((DBH^2)*H)
AGB=exp(-10.8771683824+2.6359736325*ln(DBH)+0.0878059946*ln(H))/(0.4802)
AGB= exp(-11.319842099+2.1415723631*ln(DBH)+0.8134282561*ln(H))/(0.4833)
AGB=exp(-10.7501678493+2.0580637328*ln(DBH)+0.8604515609*ln(H))/(0.4860)
AGB=exp(-10.9520199234+2.0898526615*ln(DBH)+0.8096162241*ln(H))/(0.4839)
AGB=exp(-10.9520199234+2.0898526615*ln(DBH)+0.8096162241*ln(H))/(0.4802)
AGB=exp(-11.319842099+2.1415723631*ln(DBH)+0.8134282561*ln(H))/(0.4833)
AGB=25.87071+0.02909*(DBH^2)-0.21382*(H^2)+0.03189*(DBH^2)*H
AGB = 0.024530*(DAP^2.443356)*(H^0.423602) + 0.2596*(0.024530*(DAP^2.443356)*(H^0.423602)) + 0.0445*(0.024530*(DAP^2.443356)*(H^0.423602))
AGB=(-4.8639)+0.3981*DBH+0.2625*(DBH^2)
$\log_{10}$(AGB)=-0.88239023+2.40959057* $\log_{10}$ (DBH)

Table S6. Performance of carbon equations based on basal area. Comparison of the equations used to find the best description for the relationship between above-ground carbon (AGC; estimated by ref.1) and basal area (BA) based on from 527 inventories reporting both estimates. Best equation (i.e Gompertz equation) was selected based on the lowest AIC value and are shown in **bold.**

		Akaike value
Gompertz equation	**$\log_{10}$ (AGC) ~ A*exp(-c*exp(-k*BA))**	**-184.821**
Monomol equation	$\log_{10}$ (AGC) ~ A*(1-c*exp(-k*BA))	-184.783
Log-Log linear equation	$\log_{10}$(AGC)~$\log_{10}$(BA)	-183.039
Weibull equation	$\log_{10}$ (AGC) ~ A*(1- exp(-k*BA^c))	-182.772
Hosffeld equation	$\log_{10}$ (AGC) ~ A/ (1+c*exp(-k*ln(BA))	-182.287
Korf equation	$\log_{10}$ (AGC) ~ A*exp(-k/BA^c)	-181.787
Power equation	$\log_{10}$(AGC) ~ A* (BA^k)	-174.293
Naslund equation	$\log_{10}$ (AGC) ~ BA/ (A*BA+k)^2	-160.107
Curtis equation	$\log_{10}$ (AGC) ~ A*(BA/(1+BA))	-150.323
Terazaki equation	$\log_{10}$ (AGC) ~ A*exp(-k/BA)	-144.777
Meyer equation	$\log_{10}$ (AGC) ~ A*(1-exp(-k*BA))	-102.209
Linear equation	AGC ~ BA	4268.906

Supplementary Text

Indirect effect explanation in causal mediation analysis

Suppose you have Y as your response variable, T as your predictor (with levels 0 and 1) and M as a mediator variable (with levels 0 and 1). Mi(t) denotes the potential value of a mediator under the treatment status Ti = t. Yi(t, m) denote the potential outcome when T and M variables equal t and m, respectively. So the observed outcome, Yi, equals Yi(Ti,Mi(Ti)) where Mi(Ti) represents the observed value of the mediator Mi at Ti.

The indirect effect is represented by:
Indirect effect (t) ≡ Yi(t, Mi(1)) − Yi(t, Mi(0))

Thus, the indirect effect (causal mediation effect) is the expected change in Y when the mediator took the value that would realize under another level of T (Mi(Ti)) while T is hold constant (t).

The package use simulation to calculate confidence intervals around the coefficient. More details at the package documentation (https://cran.r-project.org/web/packages/mediation/vignettes/mediation.pdf) and in refs *(74,75).*

Supplementary data

Supplementary Data 1: Pre-selection of co-variables. The full co-variables and models used for selected the main drivers of carbon stocks.