Supplementary Material

Drivers of forest structure and biomass along a climatic gradient in the Soutpansberg, South Africa

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Content:

1. Plot design & Calculations

Finding, describing, and mapping forest sites across the study region and their potential plots in the field was done using the App Q-field running on an outdoor tablet. Nested rectangular plots were laid out with a 90° angle mirror, ranging rods, and measuring tapes.

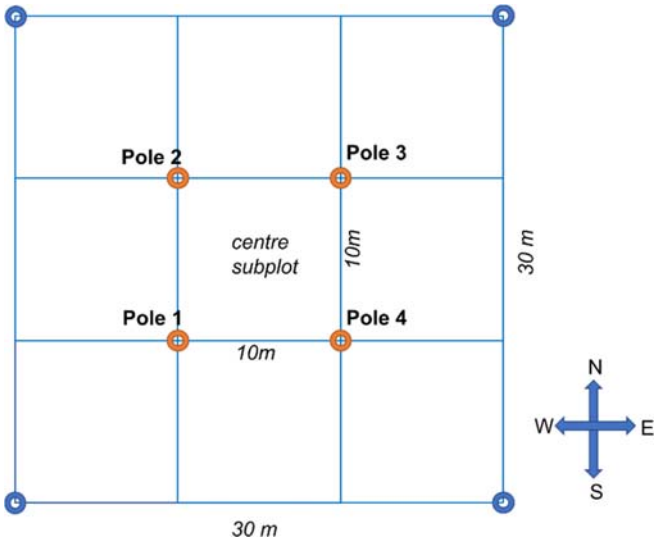

Figure S 1. Scheme of plot layout structure.

Crown projection area (CPA):

$$CPA = \left[\left(\sqrt{\frac{d_{NS}^2 \times d_{EW}^2}{2}}\right)/2\right]^2 \times \pi$$

(*Equation S 1*)

where $d_{NS}\ and\ d_{EW}$ are the crown diameter in north/ south and east/ west direction

Coefficient of Variance (CV):

$$CV = \frac{sd}{\bar{x}} \times 100$$

(*Equation S 2*)

Where sd is the standard deviation and $\bar{x}$ the mean value

Shannon Index (H):

$$H = -\sum_{i=1}^{S} p_i \times \ln(p_i)$$

(*Equation S 3*)

where S is the number of different species in the population and p_i the share of the i^{th} species on the total population

Standing deadwood:

$$deadwood_{standing} = G \times H \times 0.5 \quad \text{(Equation S 4)}$$

where G is the basal area at 1.3 m height and H the total height

Lying deadwood:

$$deadwood_{lying} = \frac{g_u + 4 \times g_m + g_o}{6 \times l} \quad \text{(Equation S 5)}$$

where $g_u, g_m and\ g_o$ are the minimum, the mean and the maximum basal area of the piece of deadwood and l the total length

de Martonne index (dMI):

$$dMI = \frac{MAP}{MAT + 10} \quad \text{(Equation S 6)}$$

where MAP is the mean annual precipitation and MAT the mean annual temperature

Aridity index (AI):

$$AI = \frac{MAP}{ET_{pot}} \quad \text{(Equation S 7)}$$

where MAP = mean annual precipitation and ET_{pot} the potential evaporation

Topographical wetness index (TWI):

$$TWI = \frac{\alpha}{\tan(\beta)} \quad \text{(Equation S 8)}$$

where α represents the upslope contributing area (or specific catchment area) per unit contour length, and β is the local slope angle.

Importance value index (IVI):

$$IVI = \frac{n_i}{\sum_{i=1}^{s} n_i} + \frac{f_i}{\sum_{i=1}^{s} f_i} + \frac{c_i}{\sum_{i=1}^{s} c_i} \quad \text{(Equation S 9)}$$

This index was determined for each species by summing the species relative density (number of trees), relative frequency (appearance in the different plots) and relative dominance (basal area), where n_i, f_i, c_i are the density, the frequency and the dominance respectively of the i^{th} species.

Table S 1. Forest and woodland type specific biomass equations chosen from literature. H = height, p = wood density, DBH = diameter at breast height

Forest type	Biomass equation	Reference
Mistbelt Forest	$\ln(AGB) = -2.69 + 0.69 \times \ln(\rho) + 0.95 \times \ln(DBH^2 \times H)$	(Mensah et al., 2016)
Mountain Woodland moist	$AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976}$	(Chave et al., 2014)
Mountain Woodland dry	$AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976}$	(Chave et al., 2014)
Ironwood Forest	$AGB = (0.000042 \times DBH^{1.9239} \times H^{1.1177}) \times 1050.4$	(Magalhães, 2017; Magalhães and Seifert, 2015)
Lowveld Woodland	$AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976}$	(Chave et al., 2014)
Mopane Woodland	$\ln(AGB_{stem}) = -2.882 + 0.904 \times \ln(DBH^2 \times H)$ $\ln(AGB_{crown}) = -3.343 + 0.927 \times \ln(DBH^2 \times H)$ $AGB = \ln(AGB_{stem}) + \ln(AGB_{crown})$	(Lisboa et al., 2024)

2. Variable selection

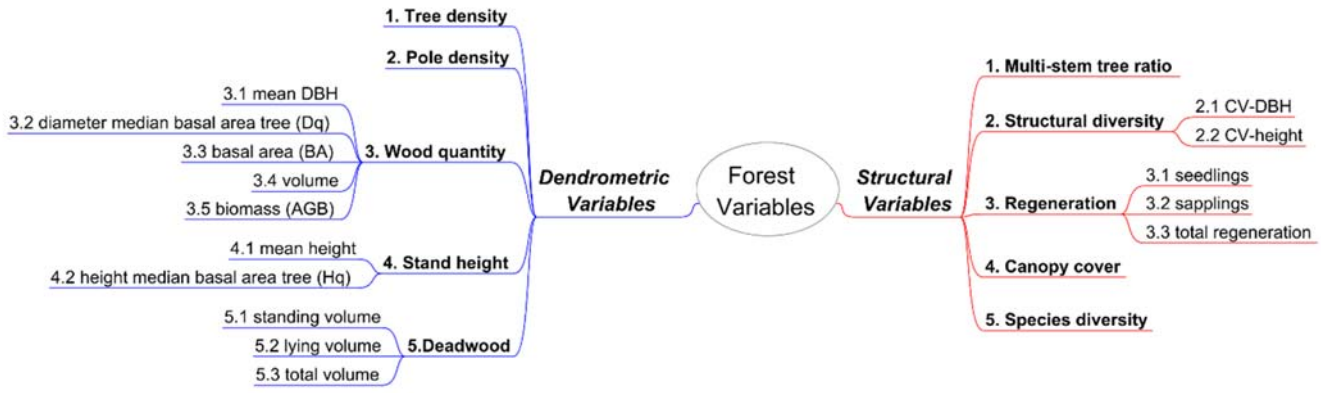

Figure S 2. Overview of 5 ecologically relevant dendrometric and structural variables (in bold). Groups were formed in case of similar ecological meaning of variables. Per group only one variable was selected.

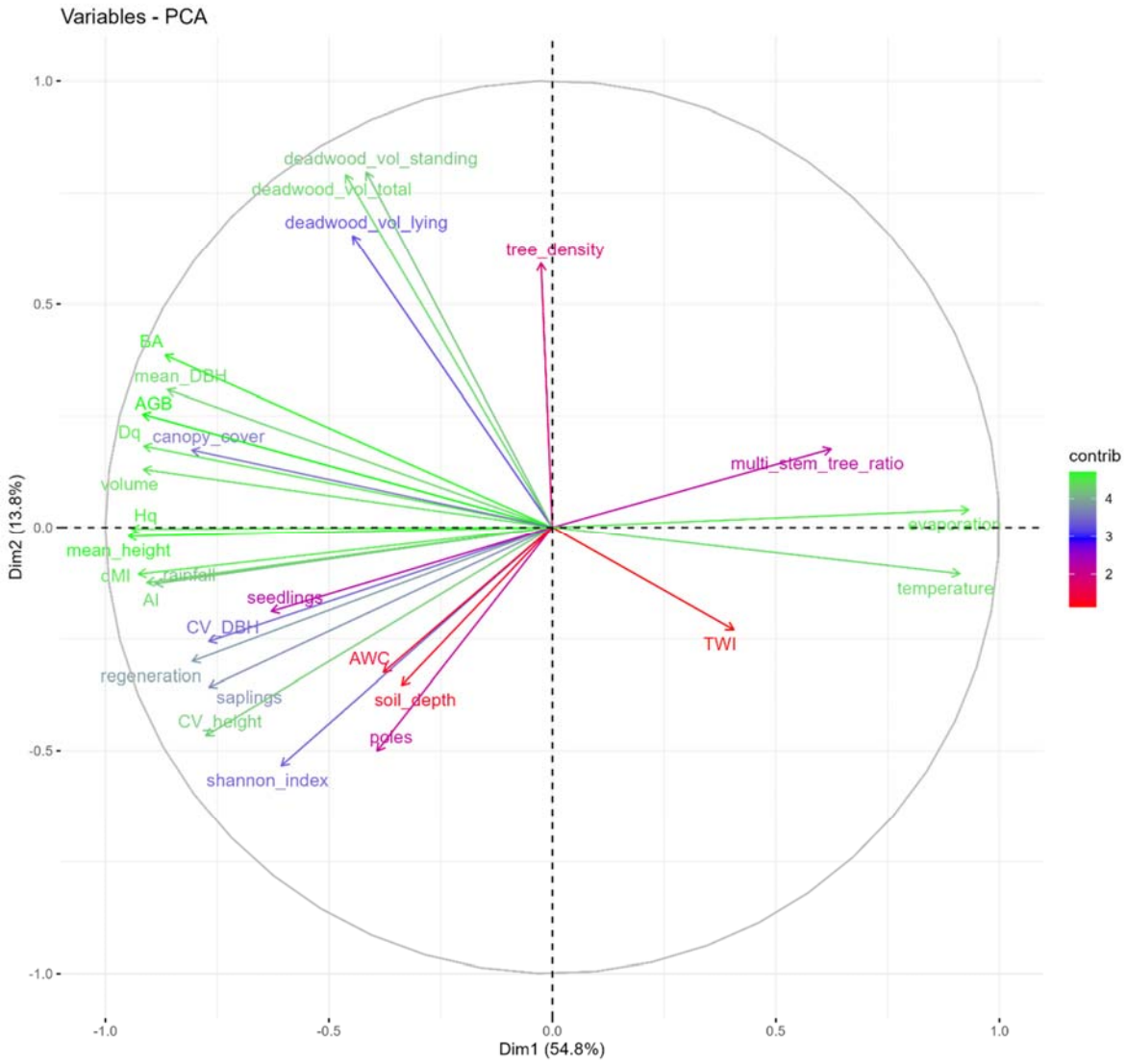

Figure S 3. Principal Component Analysis (PCA) of forest and environmental variables. Direction of arrows (proximity to one another) indicates their correlation (close to 0° would be highly positively correlated, 90° is without any correlation, 180° is highly negatively correlated). Colour and length of arrows signify the explanatory power of each variable (the longer, the more of the total data set can be explained by this variable)

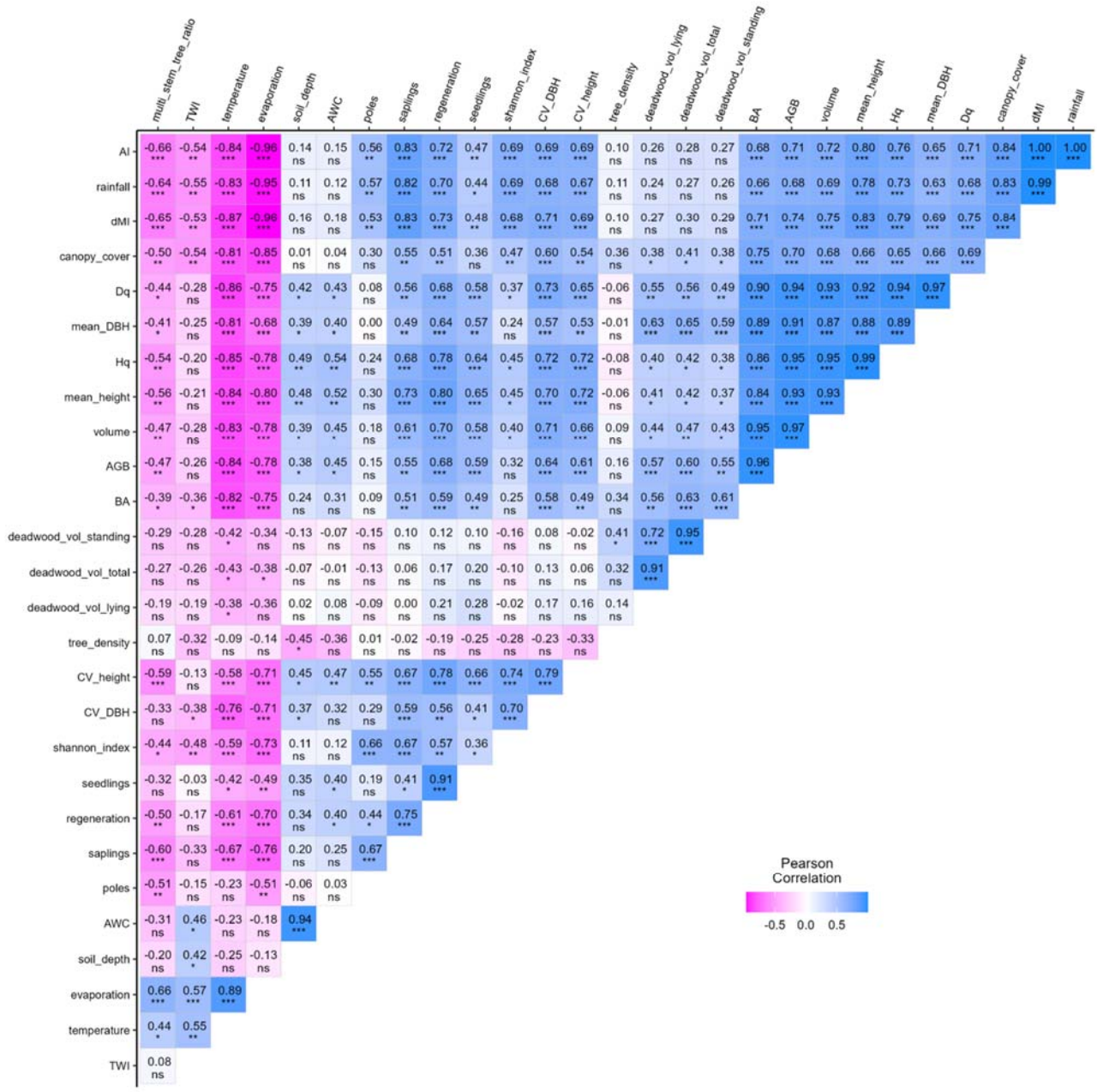

*Figure S 4. Pearson correlation matrix of all forest and environmental variables. Colour represents the correlation coefficient and significance levels are shown with stars (p < 0.05 = *, p < 0.01 = **, p < 0.001 = ***)*

3. Statistical results

*Table S 2. Results of **single effect models** for each of the 10 forest variables. Given are coefficient estimates of intercepts and predicting model variables (dMI, AWC and TWI). Standard errors are in brackets. Model parameters were standardized (z-score normalization) and logarithmized before. Significance levels are shown with stars (p < 0.05 = *, p < 0.01 = **, p < 0.001 = ***)*

	tree density	pole density	mean height	AGB	deadwood	multi-stem tree ratio	CV-DBH	regeneration	canopy cover	Shannon Index
Intercept	7.094*** (±0.060)	6.659*** (±0.261)	1.813*** (±0.025)	4.249*** (±0.110)	-0.292 (±0.534)	3.525*** (±0.068)	4.063*** (±0.032)	8.404*** (±0.159)	4.053***	0.043 (±0.165)
dMI	0.106 (±0.095)	1.080* (±0.415)	0.259*** (±0.039)	0.579** (±0.175)	2.066* (±0.848)	-0.441*** (±.108)	0.157** (±0.051)	1.034*** (±0.252)	0.274*** (±0.055)	0.584* (±0.262)
AWC	-0.178* (±0.075)	-0.164 (±0.327)	0.116*** (±0.031)	0.223 (±0.138)	-0.560 (±0.668)	-0.000 (±.085)	0.106* (±0.040)	0.200 (±0.199)	-0.024 (±0.044)	0.162 (±0.207)
TWI	0.001 (±0.102)	0.784 (±0.449)	0.063 (±0.043)	0.000 (±0.189)	-0.517 (±0.916)	-0.211 (±.116)	-0.051 (±0.055)	0.480 (±0.273)	-0.005 (±0.060)	-0.116 (±0.283)
R^2 Adj.	*0.215*	*0.133*	*0.790*	*0.499*	*0.392*	*0.414*	*0.585*	*0.473*	*0.667*	*0.320*
AIC	*449.4*	*512.0*	*79.9*	*315.5*	*137.7*	*242.8*	*230.5*	*586.8*	*234.6*	*87.4*
F	*3.643*	*2.489*	*37.389*	*10.616*	*7.228*	*7.827*	*14.652*	*9.663*	*20.347*	*5.558*
RMSE	*0.30*	*1.33*	*0.13*	*0.56*	*2.72*	*0.35*	*0.16*	*0.81*	*0.18*	*0.84*

*Table S 3. Results of selected models (based on Equation **Error! Reference source not found.**) for each of the 10 forest variables. Given are coefficient estimates of intercepts and predicting model variables (dMI, **AWC** and TWI), as well as their interactions. Standard errors are in brackets. Significance levels are shown with stars (p < 0.05 = *, p < 0.01*

*= **, p < 0.001 = ***). Equation terms of Equation* ***Error! Reference source not found.*** *are provided. Note that in this table all forest variables are* ***without scaling/ standardization, but in logarithmized form***

	Term	ln(tree density)	ln(pole density)	ln(mean height)	ln(AGB)	ln(dead wood)	ln(multi-stem tree ratio)	ln(CV-DBH)	ln(regeneration)	ln(canopy cover)	ln(Shannon Index)
Intercept	a_0	6.879*** (±0.437)	-5.854 (±5.207)	1.521 (±0.914)	37.539*** (±8.295)	-16.661*** (±3.787)	16.410*** (±4.395)	2.502*** (±0.240)	-5.172 (±3.209)	12.992*** (±3.044)	-4.574*** (±1.135)
dMI	a_1	0.228 (±0.130)	2.133* (±0.783)	-0.317 (±0.296)	-4.280** (±1.188)	5.191*** (±1.189)	-4.029* (±1.626)	0.419*** (±0.071)	2.512*** (±0.483)	-0.338 (±0.436)	1.464*** (±0.356)
AWC	a_2	-0.139** (±0.047)		-0.583* (±0.220)	-8.891*** (±1.872)			0.066* (±0.026)		-2.452** (±0.687)	
TWI	a_3		2.972 (±1.636)	0.505* (±0.183)	-10.793** (±3.289)		-5.213* (±2.273)		2.903** (±1.009)	-4.130** (±1.207)	
dMI × AWC	a_4			0.211** (±0.069)	1.332*** (±0.278)					0.225* (±0.102)	
dMI × TWI	a_5						1.642 (±0.863)				
AWC x TWI	a_6				2.539** (±0.696)					0.905** (±0.255)	
R^2 Adj.		*0.244*	*0.158*	*0.841*	*0.741*	*0.384*	*0.485*	*0.588*	*0.472*	*0.767*	*0.354*
AIC		*447.4*	*510.2*	*72.3*	*297.3*	*136.4*	*238.9*	*229.4*	*585.9*	*225.4*	*84.1*
F		*5.674*	*3.712*	*39.489*	*17.593*	*19.066*	*10.121*	*21.691*	*13.987*	*20.118*	*16.891*
RMSE		*0.30*	*1.34*	*0.11*	*0.39*	*2.84*	*0.32*	*0.17*	*0.83*	*0.14*	*0.85*

*Table S 4. Results of selected models (based on Equation **Error! Reference source not found.**) for each of the 10 forest variables. Instead of available water capacity (AWC) these models were fitted with **soil depth (SOD).** Given are coefficient estimates of intercepts and predicting model variables (dMI, SOD and TWI), as well as their interactions. Standard errors are in brackets. Significance levels are shown with stars (p < 0.05 = *, p < 0.01 = **, p < 0.001 = ***). Equation terms of Equation **Error! Reference source not found.** are provided. Note that in this table all forest variables are **without scaling/ standardization, but in logarithmized form**.*

	Term	ln(tree density)	ln(pole density)	ln(mean height)	ln(AGB)	ln(dead wood)	ln(multi-stem tree ratio)	ln(CV-DBH)	ln(regeneration)	ln(canopy cover)	ln(Shannon Index)
Intercept	a_0	6.337*** (±0.419)	-5.854 (±5.207)	-1.299* (±0.611)	-1.773 (±2.267)	-16.661*** (±3.787)	16.410*** (±4.395)	2.763*** (±0.226)	-5.172 (±3.209)	2.591** (±0.800)	-4.574*** (±1.135)
dMI	a_1	0.211 (±0.131)	2.133* (±0.783)	0.655*** (±0.082)	1.601*** (±0.303)	5.191*** (±1.189)	-4.029* (±1.626)	0.427*** (±0.071)	2.512*** (±0.483)	0.594*** (±0.107)	1.464*** (±0.356)
SOD	a_2	-0.223** (±0.078)		-0.753 (±0.386)	-13.694*** (±3.530)			0.112* (±0.042)		-3.466* (±1.245)	
TWI	a_3		2.972 (±1.636)	0.559** (±0.195)	0.441 (±0.738)		-5.213* (±2.273)		2.903** (±1.009)	-0.245 (±0.260)	
dMI × SOD	a_4			0.272* (±0.118)	2.050*** (±0.518)					0.289 (±0.183)	
dMI × TWI	a_5						1.642 (±0.863)				
SOD × TWI	a_6				3.875** (±1.228)					1.333** (±0.433)	
R^2 Adj.		*0.228*	*0.158*	*0.810*	*0.686*	*0.384*	*0.485*	*0.592*	*0.472*	*0.739*	*0.354*
AIC		*448.0*	*510.2*	*77.8*	*303.1*	*136.4*	*238.9*	*229.1*	*585.9*	*228.9*	*84.1*
F		*5.272*	*3.712*	*31.840*	*13.652*	*19.066*	*10.121*	*22.063*	*13.987*	*17.422*	*16.891*
RMSE		*0.31*	*1.34*	*0.12*	*0.43*	*2.84*	*0.32*	*0.17*	*0.83*	*0.15*	*0.85*

*Table S 5. Results of selected models (based on Equation **Error! Reference source not found.**)) for each of the 10 forest variable. Given are coefficient estimates of intercepts and predicting model variables (forest type, dMI, AWC and TWI), as well as their interactions. Standard errors are in brackets. Model parameters were standardized (z-score normalization) and logarithmized before. Significance levels are shown with stars (p < 0.05 = *, p < 0.01 = **, p < 0.001 = ***) and in superscript numbers (in case of close significance).*

	tree density	pole density	mean height	AGB	deadwood	multi-stem tree ratio	CV-DBH	regeneration	canopy cover	Shannon Index
Intercept	7.124***	8.427***	2.035***	5.517***	1.646	1.438**	4.434***	9.819***	4.397***	0.830**
	(0.104)	(1.289)	(0.092)	(0.132)	(1.069)	(0.405)	(0.063)	(0.308)	(0.159)	(0.266)
Ironwood Forest	0.474**	-19.315***	-0.256*	-0.585*	2.829	-0.579	-0.650***	-3.008***	-0.124	-2.313***
	(0.147)	(2.458)	(0.120)	(0.226)	(1.827)	(0.773)	(0.089)	(0.436)	(0.301)	(0.377)
Lowveld Woodland	-0.465**	-2.450 (0.081)	-0.272*	-2.059***	-6.466***	2.599***	-0.253**	-2.245***	-0.488**	-0.412
	(0.147)	(1.326)	(0.126)	(0.162)	(1.310)	(0.417)	(0.089)	(0.436)	(0.164)	(0.377)
Mopane Woodland	-0.294	-1.318	-0.031	-2.084***	-7.566***	2.798***	-0.678***	-1.576**	-1.119***	-1.863***
	(0.147)	(1.498)	(0.186)	(0.148)	(1.194)	(0.471)	(0.089)	(0.436)	(0.184)	(0.377)
Mount. woodl. Dry	0.098	-0.638	-0.359**	-1.729***	0.552	2.349***	-0.397***	-1.071*	-0.254	-0.121
	(0.147)	(1.376)	(0.095)	(0.220)	(1.784)	(0.433)	(0.089)	(0.436)	(0.168)	(0.377)
Mount. woodl. moist	0.005	-0.936	-0.417***	-1.149***	-0.978	1.811***	-0.247*	-0.590	0.051	-0.014
	(0.147)	(1.324)	(0.050)	(0.165)	(1.332)	(0.416)	(0.089)	(0.436)	(0.161)	(0.377)
dMI			0.244***							
			(0.062)							
AWC		-0.971	0.048*	0.230**	1.349*	1.506**			0.055	
		(1.239)	(0.019)	(0.080)	(0.651)	(0.390)			(0.151)	
TWI									0.091*	
									(0.042)	
AWC × Ironwood Forest		-13.006***				-4.098***			0.033	
		(2.231)				(0.701)			(0.274)	

	tree density	pole density	mean height	AGB	deadwood	multi-stem tree ratio	CV-DBH	regeneration	canopy cover	Shannon Index
AWC ×		0.569				-1.508**			-0.506**	
Lowveld Woodland		(1.327)				(0.417)			(0.162)	
AWC ×		0.403				-2.147***			0.122	
Mopane Woodland		(1.480)				(0.465)			(0.197)	
AWC ×		0.997				-1.229**			0.103	
Mount. woodl. dry		(1.292)				(0.406)			(0.158)	
AWC ×		1.135				-1.820***			-0.088	
Mount. woodl. moist		(1.328)				(0.418)			(0.162)	
R^2 Adj.	*0.605*	*0.811*	*0.964*	*0.926*	*0.748*	*0.812*	*0.736*	*0.670*	*0.939*	*0.706*
AIC	*430.3*	*471.2*	*29.7*	*260.6*	*113.6*	*213.8*	*218.6*	*574.3*	*188.8*	*63.9*
F	*9.902*	*12.317*	*112.851*	*61.189*	*15.346*	*12.364*	*17.151*	*12.753*	*38.339*	*14.903*
RMSE	*0.21*	*0.52*	*0.05*	*0.20*	*1.65*	*0.16*	*0.13*	*0.62*	*0.06*	*0.53*

*Table S 6. Anova results from comparisons between: Q-I/ Equation **Error! Reference source not found.** (without forest types) and Q-II/ Equation **Error! Reference source not found.** (with forest types as a fixed effect). RSS = Residual sum of squares, Res. Df = Residual degrees of freedom, Δ RSS = difference in RSS between the models, Δ F = difference in F-value between the models*

	tree density	pole density	mean height	AGB	deadwood	multi-stem tree ratio	CV-DBH	regeneration	canopy cover	Shannon Index
Global model 1										
RSS	*2.779*	*53.844*	*0.349*	*4.526*	*242.707*	*3.139*	*0.834*	*20.459*	*0.61*	*21.80*
Res. Df	*27*	*27*	*25*	*24*	*28*	*26*	*27*	*27*	*24*	*28*
Global model 2										
RSS	*1.289*	*8.050*	*0.069*	*1.245*	*81.543*	*0.795*	*0.475*	*11.391*	*0.113*	*8.513*
Res. Df	*24*	*18*	*22*	*23*	*23*	*18*	*24*	*24*	*17*	*24*
Comparison model 1 & 2										
Δ RSS	*1.490*	*45.793*	*0.280*	*3.281*	*161.16*	*2.344*	*0.359*	*9.068*	*0.497*	*13.283*
Δ F	*9.251*	*11.377*	*29.65*	*60.628*	*9.092*	*6.630*	*6.035*	*6.368*	*10.7*	*9.362*
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.01*	*<0.01*	*<0.001*	*<0.001*

*Table S 7. Model results of selected model for predicting **biomass** based on dendrometric and structural variables (RQ-III/ **Equation Error! Reference source not found.**)*

	Term	Estimate	SE	p-value
Intercept	α_0	4.111	0.204	<0.001
mean height	α_5	0.55	0.099	<0.001
CV-DBH	α_8	0.204	0.049	<0.001
canopy cover	α_6	0.204	0.051	<0.001
Ironwood Forest	α_{10}	1.037	0.269	<0.001
Lowveld Woodland	α_{10}	-0.248	0.263	0.356
Mopane Woodland	α_{10}	0.303	0.268	0.271
Mountain Woodland dry	α_{10}	-0.19	0.258	0.470
Mountain Woodland moist	α_{10}	-0.075	0.203	0.717
AIC		*221.385*		
R^2 Adj.		*0.981*		
RMSE		*0.099*		

Table S 8. Anova results from comparison of the biomass model from RQ-II/ Equation ***Error! Reference source not found.*** *(environmental drivers + forest type) and the biomass model used in RQ-III/ Equation* ***Error! Reference source not found.*** *(structural and dendrometric variables + forest type). RSS = Residual sum of squares, Res. Df = Residual degrees of freedom, Δ RSS = difference in RSS between the models, Δ F = difference in F-value between the models*

Global model 2	
RSS	*1.245*
Res. Df	*23*
Global model 3	
RSS	*0.295*
Res. Df	*21*
Δ RSS	0.95
Δ F	*33.828*
p-value	*<0.001*

4. Additional information

Table S 9. Overview of most dominant species (by basal area [m^2 ha^{-1}]) and important species (by important value index [IVI]) per forest and woodland type (see Equation S 10)

Forest type	Dominant species (by BA)	BA [m^2 ha^{-1}]	Important species (by IVI)	IVI
Mistbelt Forest	*Syzygium gerrardii*	15.96	*Syzygium gerrardii*	138.8
	Schefflera umbellifera	15.84	*Xymalos monospora*	130.3
	Nuxia floribunda	5.93	*Aphloia theiformis*	126.2
	Aphloia theiformis	5.75	*Robsonodendron eucleiforme*	105.8
	Xymalos monospora	3.74	*Nuxia congesta*	105.1
Mountain Woodland moist	*Parinari curatellifolia*	6.39	*Parinari curatellifolia*	142.4
	Combretum zeyheri	3.37	*Englerophytum magalismontanum*	118.8
	Albizia adianthifolia	2.09	*Combretum molle*	116.7
	Pterocarpus angolensis	1.67	*Combretum zeyheri*	112.5
	Combretum molle	1.62	*Xylopia parviflora*	105.4
	Englerophytum magalismontanum	1.42	*Albizia adianthifolia*	94.5
Mountain Woodland dry	*Pteleopsis myrtifolia*	3.7	*Pteleopsis myrtifolia*	166.9
	Pterocarpus angolensis	2.09	*Pterocarpus angolensis*	119.9
	Pseudolachnostylis maprouneifolia	1.21	*Xylopia parviflora*	117.5
	Xylopia parviflora	1.08	*Pseudolachnostylis maprouneifolia*	114.3
	Burkea Africana	0.94	*Parinari curatellifolia*	110.9
	Parinari curatellifolia	0.8	*Grewia microthyrsa*	87.5
Ironwood Forest	*Androstachys johnsonii*	31.8	*Androstachys johnsonii*	289.4
	Brachylaena transvaalensis	0.58	*Brachylaena transvaalensis*	85.1
	Combretum apiculatum	0.17	*Combretum apiculatum*	61.1
	Commiphora mollis	0.1	*Commiphora mollis*	60.6
	Vitex ferruginea	0.09	*Vitex ferruginea*	41.1
Lowveld Woodland	*Commiphora mollis*	3.05	*Combretum apiculatum*	110.4
	Kirkia accuminata	2.41	*Commiphora mollis*	98.8
	Combretum apiculatum	1.35	*Boscia albitrunca*	88.5
	Afzelia quazensis	1.32	*Kirkia accuminata*	83.5
	Boscia albitrunca	0.71	*Commiphora viminea*	65.3
Mopane Woodland	*Colophospermum mopane*	9.03	*Colophospermum mopane*	277.9
	Commiphora mollis	0.68	*Commiphora mollis*	90.3
	Boscia CF	0.14	*Commiphora edulis*	61.3
	Terminalia prunoides	0.13	*Terminalia prunoides*	43.8
	Combretum apiculatum	0.05	*Kirkia accuminata*	41.0

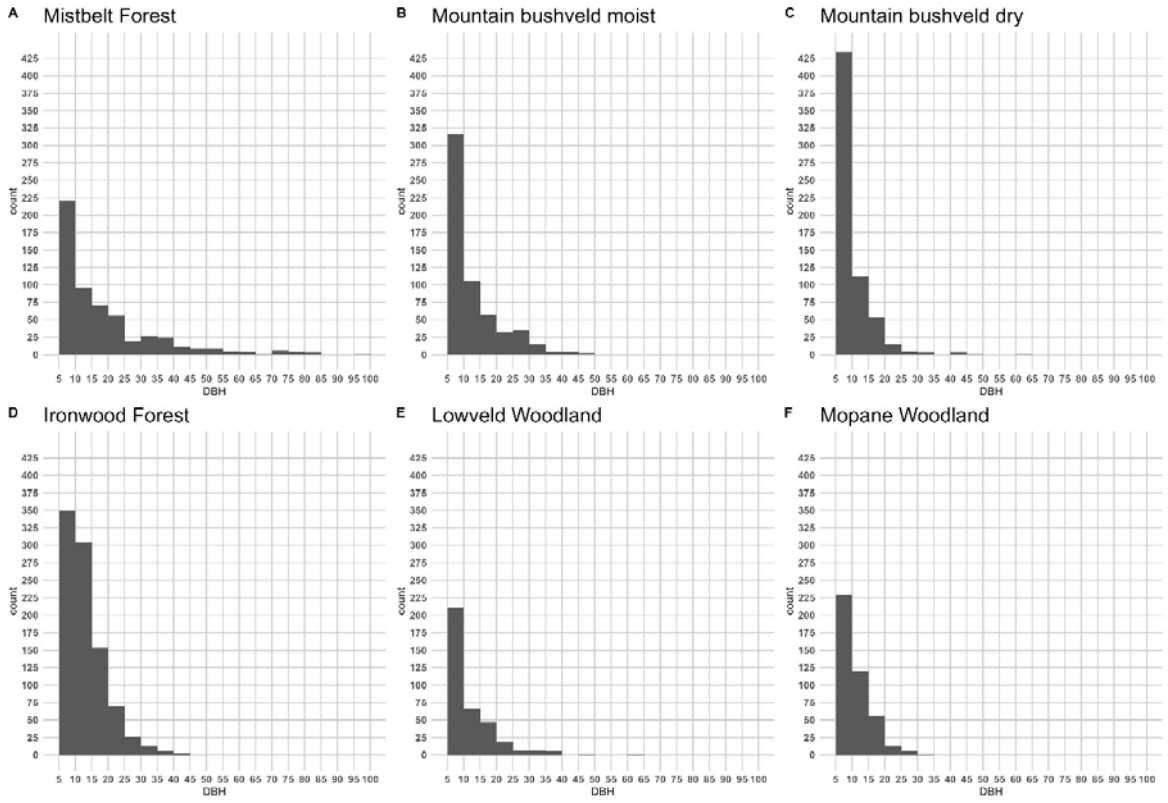

Figure S 5. Plot tree´s DBH class distribution per forest and woodland type. Counts per 4500 m^2 (= 30m x 30m x 5 plots)

Table S 10. Nomenclature of studied forest/ woodland types according to Mucina et al. (2014), names used in the text and land owning communities of our study sites

Names used in the text	**Vegetation atlas nomenclature**	**Abbreviation**	**Communities**
Mistbelt Forest	Northern Mistbelt Forest	FOz 4	Ha-Manyuwa
Mountain Woodland moist	Soutpansberg Mountain Bushveld	SVcb 21	Makwarani
Mountain Woodland dry	Soutpansberg Mountain Bushveld	SVcb 21	Gunda
Lowveld Woodland	Makuleke Sandy Bushveld	SVl 1	Gumela/ Musunda-B
Ironwood Forest	Ironwood Dry Forest	FOz 9	Musunda-B/ Gumela
Mopane Woodland	Musina Mopane Bushveld	SVmp 1	Ha-Mukununde

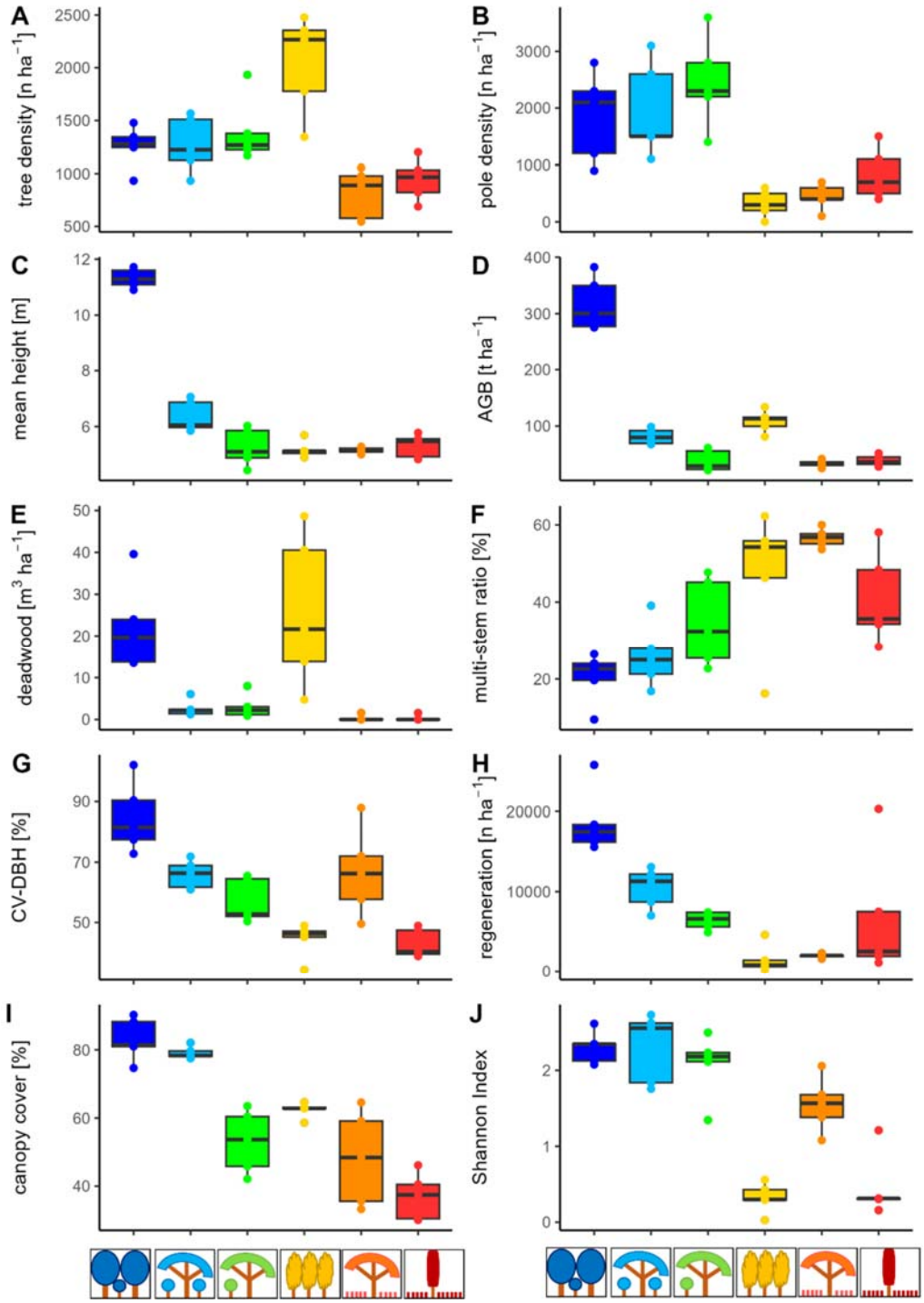

Figure S 6. Box plot of raw data per forest type presented in Table 1. Overview of forest inventory variables. From left to right: Mistbelt Forest, Mountain Woodland moist, Mountain Woodland dry, Ironwood Forest, Lowveld Woodland, Mopane Woodland

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