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Functional trait diversity maximizes ecosystem multifunctionality

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Supplementary Note 1. Mathematical demonstration of the skewness-kurtosis relationships and its implications

Mean, variance, skewness and kurtosis are the four first moments of a probability density function (p(x)) for a given stochastic variable (x). A moment of a probability density function is defined so that:

$$\mu_j = E\left[(x-\mu)^j\right] = \int_{-\infty}^{\infty} (x-\mu)^j p(x)dx \qquad \textit{equation (S1);}$$

where μ_j, represents the j^{th} moment of the probability density function. The general equations for any distribution might thus be read as:

$$Mean = \mu = E[X] = \int_{-\infty}^{\infty} xp(x)dx \qquad \textit{equation (S2);}$$

$$Variance = \sigma^2 = \mu_2 = E[(X-\mu)^2] = \int_{-\infty}^{\infty} (x-\mu)^2 p(x)dx \qquad \textit{equation (S3);}$$

$$Skewness = \gamma_1 = \frac{\mu_3}{\mu_2^{3/2}} = \frac{\mu_3}{\sigma^3} \qquad \textit{equation (S4);}$$

$$Kurtosis = \gamma_2 = \frac{\mu_4}{\mu_2^2} = \frac{\mu_4}{\sigma^4} \qquad \textit{equation (S5);}$$

being σ the standard deviation of the probability density function; skewness and kurtosis are divided by σ^3 and σ^4 to render them dimensionless.

Skewness and kurtosis are not independent because there are some relationships among moments that are based on far more general inequalities. One of them is that of Cauchy-Schwarz[65], which states that, for two real and integral functions f(x) and g(x), it holds that :

$$\left(\int_{-\infty}^{\infty} f(x)g(x)dx\right)^2 \leq \left(\int_{-\infty}^{\infty} f(x)^2 dx\right)\left(\int_{-\infty}^{\infty} g(x)^2 dx\right) \qquad \textit{equation (S6);}$$

Except for the case in which $f(x) = kg(x)$, being k a real constant. Then, for instance, with a probability density function, we can write:

$$f(x)g(x) = (x-\mu)^3 p(x) = \left[(x-\mu)^2\sqrt{p(x)}\right]\left[(x-\mu)\sqrt{p(x)}\right] \qquad \textit{equation (S7);}$$

Therefore,

$$\left(\int_{-\infty}^{\infty}(x-\mu)^3 p(x)dx\right)^2 \leq \left(\int_{-\infty}^{\infty}(x-\mu)^4 p(x)dx\right)\left(\int_{-\infty}^{\infty}(x-\mu)^2 p(x)dx\right) \quad \textit{equation (S8);}$$

From the equations (*S4*) and (*S5*), it follows that:

$$\mu_3^2 = \gamma_1^2\sigma^6 \leq \mu_4\sigma^2 = \gamma_2\sigma^6 \quad \textit{equation (S9);}$$

Therefore, it is always true that:

$$\gamma_2 \geq \gamma_1^2 \quad \textit{equation (S10);}$$

If we change the premise in (*S7*) such that:

$$f(x)g(x) = (x-\mu)^2 p(x) = \left[(x-\mu)^2\sqrt{p(x)}\right]\left[\sqrt{p(x)}\right] \quad \textit{equation (S11);}$$

Following the Cauchy-Schwarz inequalities (*S6*), we will get that:

$$\left(\int_{-\infty}^{\infty}(x-\mu)^2 p(x)dx\right)^2 \leq \left(\int_{-\infty}^{\infty}(x-\mu)^4 p(x)dx\right)\left(\int_{-\infty}^{\infty} p(x)dx\right) \xRightarrow{\textit{see eqn 3 and 5}} \gamma_2 \geq 1$$

equation (S12);

Thus, in principle kurtosis has a lower boundary which restricts its value to be greater than the maximum between 1 and skewness square:

$$\gamma_2 \geq max\{1, \gamma_1^2\} \quad \textit{equation (S13);}$$

To extract a better approximation of the lower bound, we can get it from:

$$E[(x-\mu+a)^2(x-\mu+b)^2] \geq 0 \quad \textit{equation (S14);}$$

Since the two terms in the parenthesis are non-negative for *a* and *b* real; by defining $u = a+b$ and $w=ab$ and expanding the product we get that:

$$\gamma_2 + \frac{1}{\sigma^2}(u^2+2w) + \frac{1}{\sigma}u + \frac{1}{\sigma^4}w^2 \geq 0 \quad \textit{equation (S15);}$$

Taking derivatives, the minimum happens for:

$$(u,w)_{min} = (-\gamma_2\sigma, -\sigma^2) \quad \textit{equation (S16);}$$

Therefore:

$$\gamma_2 \geq 1 + \gamma_1^2 \quad \textit{equation (S17);}$$

This inequality is always satisfied. There is neither absolute continuous nor discrete distribution that does not satisfy this inequality. The obvious conclusion of this mathematical demonstration is that the relationship between skewness and kurtosis will be found as part of the intrinsic properties of both moments in any probability density function. However, for a sample of a stochastic variable following a given distribution, we only know the lower boundary of this relationship. The actual relationship will vary depending on the type of distributions and the sample size under consideration. By taking into account these issues (equal sample size, and assuming equal distributions types of traits), we found in this study that the observed samples converged toward the lower boundary more often than expected by chance (see Main Text).

The SKR is a mathematical tool that is commonly used in various scientific fields, including economy, climatology, geomorphology, physics or astronomy[29,66,67] (See Fig. 2 Main text). The SKR is used in economy and finance to optimize budget portfolios[29,68], i.e., to maximize benefits and to minimize costs in multiple investments. In ecology, the SKR has important implications for the study of species coexistence and ecosystem functioning (see Main Text). The skewness and kurtosis complement the mean and the variance by describing the shape of the distribution, i.e. how species abundance is distributed within communities as a function of their trait values. The shape of the trait abundance distributions can be considered as the functional counterpart to the species abundance distribution[69]. In contrast to the mean and the variance, the skewness and the kurtosis are unitless. The mean and the variance characterize the functional identity of the community considered, e.g. (i) whether the community is dominated by tall or small plant species (mean); (ii) whether the range of trait values and the dispersion of their abundance is large or small (variance). By focusing on the shape of the distributions, the skewness and kurtosis describe the asymmetry, evenness and diversity of trait abundance distributions[25,31,32], independently from the type of community considered.

Our approach, based on a quantitative investigation of the shape of the trait-abundance distribution, has several advantages. First, the mathematical behaviour of the SKR is well described[37]. Second, the SKR has a lower boundary which defines the lowest value of kurtosis expected for any degree of skewness. It can thus be used in ecology to define the potential maxima of functional trait diversity expected for any degree of skewness. While species richness may bias functional diversity assessments using trait dispersion indices[70–72], the skewness and kurtosis are largely independent from species richness (Supplementary Table 2). This independence makes our analysis robust to the species pool used in our null model analyses (Table 1) and allows us to clearly disentangle the effect of species richness from the effect of functional trait diversity on multifunctionality (see Main Text). Finally, our approach also takes advantage of the mathematical relationship between skewness and kurtosis to fully isolate the effect of trait differences on the trait diversity observed within communities once controlling for the degree of skewness (see Main Text).

Supplementary Note 2. Additional results on community assembly

The empirical SKRs strongly differed from the predicted values obtained from the three null models (Table 1 Main Text, Supplementary Figure 2). The results were highly consistent for both specific leaf area and maximum plant height, and for the three null models considered. The use of log-transformed data improved the detection of non-random patterns (Table 1).

The conditional pseudo-P values for the Y-intercept α, P(α|β), were significant for all null models (Table 1a). These results indicated that the observed parameter α of the SKR was lower than expected by chance. We also observed significant conditional pseudo-P values for the slope β, P(β|α), indicating that β_{obs} was lower than expected by chance. Consequently, the probability of finding a model that minimize both α and β (P(β∩α) was highly significant (Table 1 and Supplementary Figure 2). Finally, the average distance to the lower boundary of the 124 observed kurtosis values (124 communities) was on average shorter than expected by chance (Table 1b) for any degree of skewness. This result indicated that the abundance within communities is generally more evenly distributed than expected by chance. Results were consistent for symmetric (Skewness ≈ 0) and asymmetric distributions (Skewness > 0), as well as among the different levels of constrains imposed on species and trait pools considered by the three null models.

Supplementary Note 3. Additional results on ecosystem multifunctionality

The averaged model for multifunctionality (based on all best models with ΔAICc < 2) showed a high explanatory power (*adj.* R^2 ~ 0.66; Fig. 4 and Supplementary Table 3). Aridity had a negative effect on multifunctionality (Fig. 4, see also refs.[5,28] for similar results). Soil pH had a quadratic effect centred on pH = 7, and the content of sand had significant negative effects on multifunctionality. In contrast, the slope and the geographical variables were never significant predictors of multifunctionality.

Species richness, the mean, variance, skewness and kurtosis of the trait-abundance distributions were all selected in the averaged model (model 4 in Supplementary Table 3, ΔAICc > 10 compared to all alternative models). These findings clearly showed that species richness and the mean and variance of trait-abundance distributions were critical to detect the effects of skewness and kurtosis on multifunctionality (Supplementary Table 3).

Altogether, species richness and the four moments of the trait-abundance distributions accounted for 58% of the explained variance found in multifunctionality (Fig. 4). Species richness alone accounted for 5% of the explained variance, and had a positive effect on multifunctionality. Our result on species richness is highly consistent with what was reported by Maestre et al.[5] when analysing the 224 sites comprising the full database we used (our analyses were restricted to a subset of 124 sites due to the availability of trait data). The four moments of trait-abundance distributions accounted for 52% of the explained variance, with a major effect of skewness and kurtosis (38%). The averaged model included the variance, the skewness, the kurtosis, as well as the square-kurtosis of SLA and height (Supplementary Table 3). Also, we noted that the mean was never selected for height, and was only selected in one third of the cases for SLA. The quadratic term of variance for SLA was the only low moment of the trait-abundance distributions studied that significantly affected multifunctionality (Fig. 4).

Multifunctionality decreased non-linearly as the variance of SLA increased, consistently with previous findings along a regional gradient in Spain[23]. Decreasing the skewness of height toward left-skewed distributions increased multifunctionality. This result is consistent with previous studies reporting that plant communities dominated by taller plants are generally associated with enhanced multifunctionality in drylands[73]. The skewness of SLA had a negligible impact on multifunctionality. Finally, the kurtosis of SLA, and kurtosis^2 of height significantly impacted multifunctionality.

Our null model analyses considering three independent null models and conducted at the ecosystem level showed that the observed relationship between the trait-abundance distributions and multifunctionality cannot be observed by chance (Fig. 4). Pseudo-P values for the Null model *Frequency* and *Richness* were < 0.001. In the most constrained null model *Independentswap* which randomized locally within each communities the trait values across co-occurring species (i.e. local species richness, species abundance distribution and the local trait pool were fixed), we found equivalent Null Model to our observed model (Fig. 4a) only in 5% of the cases (randomization based over 1000 simulations, Pseudo-Pvalue = 0.056, Fig. 4b). We can conclude that the observed relationship between the trait-abundance distributions and multifunctionality cannot be observed by chance and that this result is thus robust to the type of null model employed.

Including additional functions related to carbon, nitrogen and phosphorus stocks and cycling available from ref. 5 did not affect our results. Multifunctionality values calculated with all of the 22 functions available from that study were highly correlated with the *M* values calculated with the five variables selected in this study ($r^2 = 0.63$; Pvalue < 0.001). Results of model selections also showed a high consistency for the two multifunctionality indices calculated (Supplementary Figure 3). These supplementary results indicated that our analysis is robust to the number of functions used when evaluating multifunctionality.

Supplementary Note 4. Sensitivity analysis of the best select model of Multifunctionality

To illustrate the effect of the relationship between skewness and kurtosis on multifunctionality, we conducted a sensitivity analysis of the best selected model (model 4, Fig. 3). We predicted the additive effect of kurtosis and kurtosis^2 of SLA and maximum plant height on multifunctionality (Fig. 5). We predicted multifunctionality using averaged parameter estimates (a_i) of the best selected model (Model 4, see Fig. 4 for model estimates) for: (i) each of the 124 communities studied; (ii) the empirical SKRs for SLA and height, and (iii) the lower boundary. Multifunctionality (*M*) for SLA and height for each of the 124 communities studied was predicted according the following equations:

$$Predicted\ M_{SLA} = a_1\ log(K_{SLA}) + a_2\ log(K_{SLA})^2 \qquad equation\ (S18);$$

$$Predicted\ M_{H} = a_3\ log(K_{H}) + a_4\ log(K_{H})^2 \qquad equation\ (S19);$$

We then predicted multifunctionality for the two empirical SKRs (Fig. 3) by replacing *K* in equations (*S18*) and (*S19*) by their predicted value according to equations (*2*) and (3) (see Main Text, i.e. $K_{SLA}= 1.01\ S_{SLA}^2 + 1.96$; and $K_H = 1.06\ S_H^2 + 2.92$, respectively). We finally predicted multifunctionality at the lower boundary of the SKR by replacing *K* in equations (*S23*) and (*S24*) by $K = S^2 + 1$. We predicted multifunctionality for the averaged parameter estimates and for their 95 % confidence intervals (see Main Text).

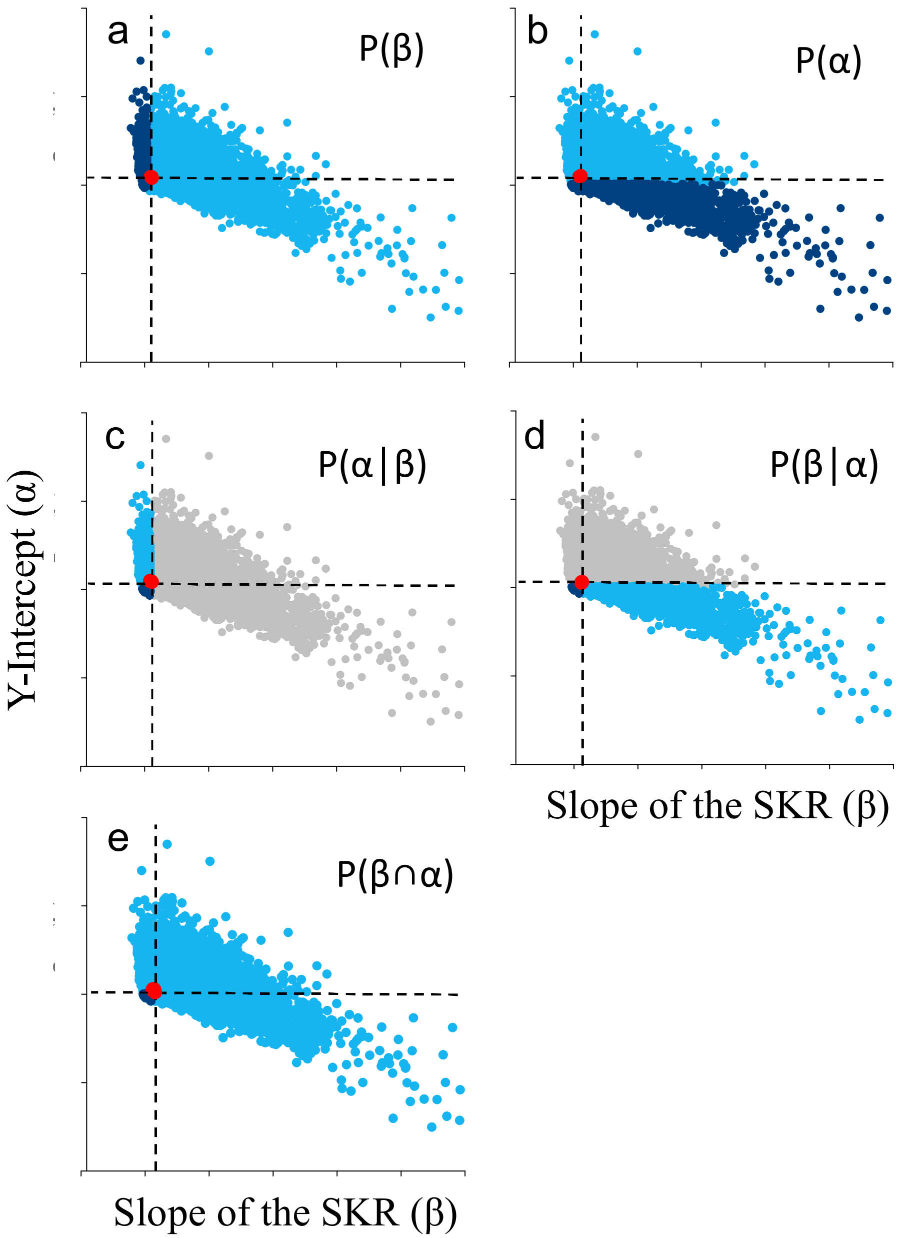
Empirical SKRs (green and red lines in Fig. 5a and 5b) predicted a peak of multifunctionality occurring at their Y-intercept α (when Skewness is set to 0) for a kurtosis value of *1.96* ± *se 0.217* for SLA (closed to the Uniform distribution) and *2.92* ± *se 0.23* for height (closed to the normal distribution). Each empirical SKR also defined a ridge of multifunctionality that minimized loss in ecosystem functions when skewness deviated from 0 (Fig. 5). Any deviation from the observed SKRs had strong detrimental effect on multifunctionality. The multifunctionality predicted at the lower boundary (grey shaded area in Fig. 5) was lower than the multifunctionality predicted by the empirical SKR for height (red line in Fig. 5) for skewness values between -2 and 2. This indicated that increasing trait diversity toward its highest potential value did not necessarily increased multifunctionality the most.

Supplementary Note 5. Details on Null models conducted at the ecosystem levels

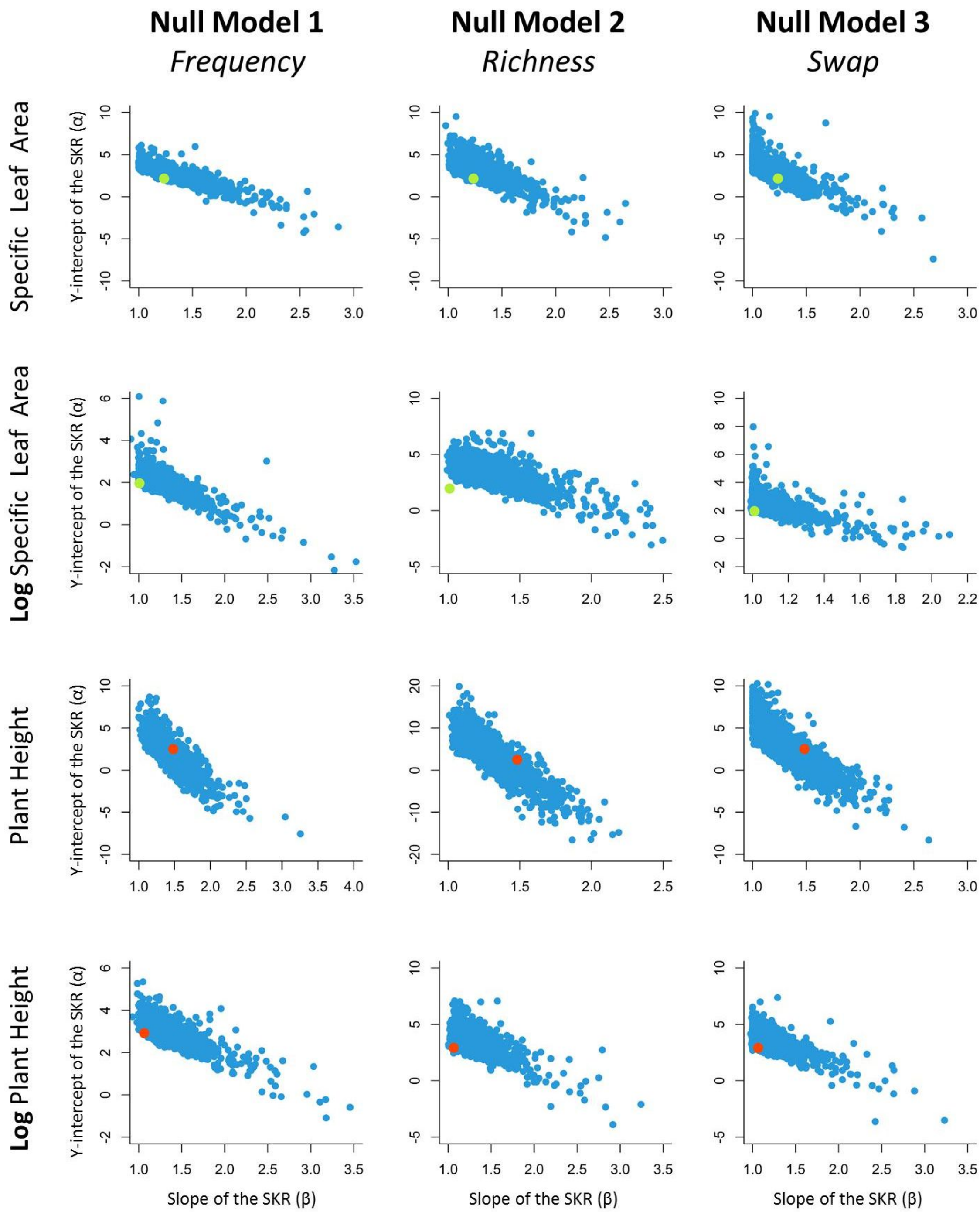
In a first step, we ran independently the three null models with an increased level of constraint on the species pool and the trait pool (i.e. the null models: *Frequency*, *Richness*, and *IndependentSwap*, see the community analysis above) to generate the Null-mean, -variance, -skewness and -kurtosis of random distributions of the 124 studied communities (1000 randomizations for each null model). In a second step, we estimated multifunctionality for each of the 1000 randomizations. Only the value of the four moments of the trait distributions changed for each randomization procedure (*i.e.,* the 1000 random distributions). All others model parameters were fixed to their observed value (i.e. geographic, abiotic variables and species richness, Fig. 4). For each of the 1000 randomizations, we used the same model selection procedure based on AICc described above (see ecosystem level analysis above; ΔAICc < 2 to select the best multifunctionality predictors). In a third step, we extracted the simulated *adj.* R^2 value of the best selected model for each randomization event (1000 simulated *adj.* R^2). We calculated the distribution of the 1000 simulated *adj.* R^2, and compared it to the observed *adj.* R^2 to calculate pseudo-P values.

Supplementary References (not listed in the main text)

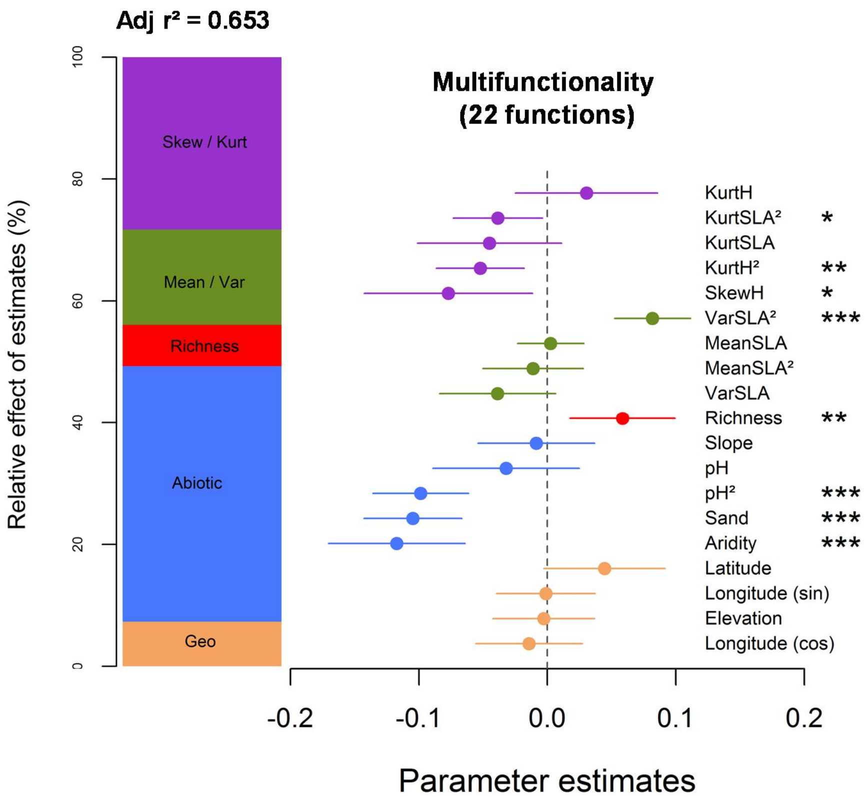
65. Schwarz, H. A. Gesammelte mathematische abhandlungen. 2, (American Mathematical Soc., 1890).
66. Bernardeau, F. Skewness and kurtosis in large-scale cosmic fields. ArXiv Prepr. Astro-Ph9312026 (1993).
67. Labit, B. et al. Universal statistical properties of drift-interchange turbulence in TORPEX plasmas. Phys. Rev. Lett. 98, 255002 (2007).
68. Favre, L. & Galeano, J.-A. Mean-modified value-at-risk optimization with hedge funds. J. Altern. Invest. 5, 21–25 (2002).
69. McGill, B. J. et al. Species abundance distributions: moving beyond single prediction theories to integration within an ecological framework. Ecol. Lett. 10, 995–1015 (2007).
70. Freschet, G. T. et al. Global to community scale differences in the prevalence of convergent over divergent leaf trait distributions in plant assemblages. Glob. Ecol. Biogeogr. 20, 755–765 (2011).
71. Taudiere, A. & Violle, C. cati: an R package using functional traits to detect and quantify multi-level community assembly processes. Ecography (2015).
72. Swenson, N. G. et al. Constancy in Functional Space across a Species Richness Anomaly. Am. Nat. 187, E83–E92 (2016).
73. Soliveres, S. et al. Plant diversity and ecosystem multifunctionality peak at intermediate levels of woody cover in global drylands. Glob. Ecol. Biogeogr. 23, 1408–1416 (2014).



Supplementary Figure 1 | Schematic representation of the calculation of pseudo- and conditional *P* values. Random parameters of the skewness-kurtosis relationship (SKR), the slope (β_{random}) and the Y-intercept (α_{random}), are represented in blue. The red dot represents the position of the observed parameter of the SKR. All probabilities are calculated as the number of simulated events within the dark blue area divided by the number of events within the light blue area. See the main text for details on the calculations.



Supplementary Figure 2 | Graphical representation of Null and observed SKRs parameters. Blue dots are random parameters of the SKR for the slope β, and the Y-intercept α (randomization n = 2000). We indicated the position of the observed parameters SLA and maximum plant height (green and red dots, respectively).



Supplementary Figure 3 | Effect of abiotic and biotic factors on multifunctionality assessed with 22 functions from Maestre et al.[5] We show averaged model predictors (standardized coefficients), associated 0.95 confident intervals, and their relative importance (see Supplementary Table 3 for AICc based model selections and model averaging). We also provide *adj.* R^2 for the two averaged models and the P-value of each predictor, *, $P < 0.05$; ** $P > 0.01$; *** $P < 0.001$ (see Supplementary Table 1 for more information on the selected functions).

Supplementary Table 1 | Correlations (Pearson coefficient) among the functions used, and between them and multifunctionality (M). a. 5 selected functions (M5); b, correlation among 22 functions including ecosystem stocks from ref.[5] (M22). Blue, green and orange denote functions related to carbon, nitrogen and phosphorus cycles respectively. Grey is our surrogate of productivity (I-NDVI). Abbreviations are: I-NDIV, average annual integral NDVI from 2000 to 2013; AVP (mg P ·Kg-1 soil), Available P; FOS (µmol PnP·g-1·h-1), Activity of phosphatase; P-HCL (mg P kg-1 soil), inorganic P; TON (%), Total N; AMO (mg N kg-1 soil), Ammonium; NIT (mg N kg-1 soil), Nitrate; DON (mg N kg-1 soil), Dissolved organic N; AMI (mg N kg-1 soil), Aminoacids; PRO (mg N kg-1 soil), proteins; AMP (mg N kg-1 soil day-1), Potential ammonification; NIP (mg N kg-1 soil day-1), Potential nitrification; DP (mg N kg-1 soil day-1), Potential depolymerization; MIN (mg N kg-1 soil day-1), Potential mineralization; NTR (mg N kg-1 soil day-1), Potential N transformation rate; BGL (µmol PnP·g-1·h-1), Activity of b-glucosidase; ORC (%), Organic C; PHE (mg C kg-1 soil), Phenols; ARO (mg C kg-1 soil), Aromatic compounds; HEX (mg C kg-1 soil), Hexose content; PEN (mg C kg-1 soil), Pentose content; CARB (mg C kg-1 soil), Carbohydrates (Sum of pentoses + hexoses).

a. Correlation among the 5 selected functions

	I-NDVI	FOS	AMP	NTR	BGL	M5
I-NDVI	1	0.32	-0.01	0.03	0.20	**0.54**
FOS		1	0.04	0.34	0.40	**0.76**
AMP			1	-0.03	-0.32	**0.26**
NTR				1	0.57	**0.67**
BGL					1	**0.65**
M5						**1.00**

b. Correlations among the 22 functions

	I-NDVI	AVP	FOS	P-HCL	TON	AMO	NIT	DON	AMI	PRO	AMP	NIP	DEP	MIN	NTR	BGL	ORC	PHE	ARO	HEX	PEN	CARB		M22	M5
I-NDV	1	-0.03	0.32	-0.34	0.28	0.30	0.12	0.26	0.21	0.03	-0.01	0.04	0.01	0.03	0.03	0.20	0.36	0.24	0.20	0.33	-0.05	0.24	I-NDVI	X	X
AVP		1	0.17	0.25	0.04	0.30	0.21	0.14	0.20	0.03	0.18	0.09	-0.09	0.18	0.09	0.23	-0.02	-0.03	-0.05	0.10	-0.12	0.02	AVP	X	
FOS			1	-0.24	0.49	0.54	0.12	0.14	0.44	-0.01	0.04	0.44	-0.06	0.48	0.34	0.40	0.48	0.07	0.05	0.40	-0.24	0.20	FOS	X	X
P-HCL				1	-0.36	-0.20	-0.16	0.04	-0.19	-0.16	0.16	-0.23	-0.24	-0.17	-0.26	-0.12	-0.38	-0.25	-0.25	-0.25	-0.04	-0.22	P-HCL	X	
TON					1	0.64	0.30	0.28	0.68	0.59	-0.36	0.67	0.38	0.53	0.62	**0.75**	**0.95**	0.61	0.68	0.64	0.13	0.58	TON	X	
AMO						1	0.42	0.29	**0.82**	0.46	-0.19	0.68	0.17	0.61	0.57	0.72	0.53	0.47	0.43	0.69	0.03	0.57	AMO	X	
NIT							1	-0.05	0.41	0.35	-0.26	0.35	0.38	0.24	0.39	0.34	0.27	0.26	0.30	0.15	0.14	0.19	NIT	X	
DON								1	0.34	0.15	-0.05	0.13	-0.46	0.11	-0.16	0.38	0.25	0.08	0.11	0.43	-0.05	0.32	DON	X	
AMI									1	0.37	-0.28	**0.72**	0.22	0.62	0.61	**0.73**	0.59	0.44	0.44	0.55	0.02	0.45	AMI	X	
PRO										1	-0.32	0.44	0.54	0.30	0.54	0.57	0.56	**0.80**	**0.84**	0.58	0.38	0.66	PRO	X	
AMP											1	-0.33	-0.29	0.15	-0.03	-0.32	-0.33	-0.25	-0.36	-0.25	-0.13	-0.26	AMP	X	X
NIP												1	0.24	**0.88**	**0.82**	0.68	0.59	0.36	0.38	0.51	0.13	0.47	NIP	X	
DEP													1	0.11	0.63	0.26	0.40	0.64	0.66	0.15	0.22	0.24	DEP	X	
MIN														1	**0.84**	0.55	0.45	0.25	0.23	0.41	0.07	0.37	MIN	X	
NTR															1	0.57	0.57	0.55	0.54	0.41	0.18	0.42	NTR	X	X
BGL																1	0.69	0.56	0.58	0.60	0.09	0.53	BGL	X	X
ORC																	1	0.66	**0.71**	0.59	0.19	0.57	ORC	X	
PHE																		1	**0.96**	0.59	0.33	0.64	PHE	X	
ARO																			1	0.56	0.32	0.61	ARO	X	
HEX																				1	0.12	**0.87**	HEX	X	
PEN																					1	0.60	PEN	X	
CARB																						1	CARB	X	

Supplementary Table 2 | Correlations (Pearson coefficient) among log-transformed explanatory variables of multifunctionality.

	Latitude	Longitude (sin)	Longitude (cos)	Slope	Aridity	Sand	pH	Richness	Mean H	Variance H	Skewness H	Kurtosis H	Mean SLA	Variance SLA	Skewness SLA	Kurtosis SLA
Elevation	0.29	0.08	0.24	0.1	-0.16	-0.11	0.14	-0.17	-0.43	-0.26	-0.09	0.15	0.41	-0.02	-0.16	-0.01
Latitude		0.08	-0.21	0.47	-0.11	-0.32	0.56	-0.04	-0.55	-0.45	-0.08	0.25	0.09	-0.09	0.04	-0.01
Longitude (sin)			-0.35	0.23	0.05	-0.1	0.1	-0.05	0.11	-0.14	-0.15	0.19	-0.12	-0.04	0.22	0.18
Longitude (cos)				-0.21	-0.03	0.07	-0.17	0.17	-0.09	0.2	0.09	-0.21	0.36	0.21	-0.41	-0.08
Slope					-0.31	-0.4	0.28	0.2	-0.2	-0.27	-0.02	0.17	0.05	0.08	0.02	-0.04
Aridity						0.18	0.4	-0.25	0.2	0.2	-0.06	-0.17	-0.27	-0.15	0.28	0.1
Sand							-0.24	-0.22	0.08	0.11	0.13	-0.21	-0.08	0.01	-0.04	-0.19
pH								-0.11	-0.16	-0.15	-0.17	0.26	-0.15	-0.03	0.14	0.13
Richness									0.24	0.45	0.14	-0.19	0.05	0.32	-0.08	-0.2
Mean H										0.5	-0.15	-0.08	-0.2	0.25	0.02	-0.14
Variance H											0.28	-0.54	-0.12	0.4	-0.17	-0.22
Skewness H												-0.68	0.28	0.11	-0.32	-0.35
KurtosisH													-0.22	-0.28	0.28	0.51
Mean SLA														0.08	-0.68	-0.33
Variance SLA															-0.38	-0.6
Skewness SLA																0.33

Supplementary Table 3 | Results of Model Selection. a. Akaike Information Criterion (AICc and ΔAICc) of the best selected models for multifunctionality (model with 5 functions). b. Results of multiple regression models of multifunctionality (model 4 for multifunctionality indices calculated with 5 and 22 functions, respectively). Model 1 included geographic, abiotic predictors and species richness. Model 2 included all selected variables in model 1 plus the mean and variance of trait distributions. Model 3 included all selected variables in model 1 plus the skewness and kurtosis of trait distributions. Model 4 included all selected variables in model 1 plus the mean, variance, skewness and kurtosis of trait distributions. We present the Model R^2, *adj.* R^2 and AICc for all selected models with a $\Delta AICc \leq 2$. Abbreviations for predictors are: Geo, geographic; Abio, abiotic; Rich, species richness; Var, variance; Skew, skewness; Kurt, kurtosis; SLA, Specific Leaf Area; H, maximum plant height. See Supplementary Table 1 for more information on the selected functions for each multifunctionality index.

a. Model Comparaison

Models	Model 1	Model 2	Model 3	Model 4
AICc	-38.56	-50.45	-39.88	-64.84
ΔAICc	26.33	14.44	25.01	0

b. Best Selected Models (ΔAICc < 2, model 4)

Multifunctionality		5 functions						22 functions	
Geo / Abio / Rich									
MeanSLA	x								
	x^2								
VarSLA	x								
	x^2								
MeanH	x								
	x^2								
VarH	x								
	x^2								
SkewSLA	x								
KurtSLA	x								
	x^2								
SkewH	x								
KurtH	x								
	x^2								
r^2		0.715	0.714	0.706	0.705	0.704	0.697	0.699	0.709
adj. r^2		0.659	0.658	0.652	0.651	0.65	0.645	0.65	0.655
AICc		-64.89	-64.49	-64	-63.83	-63.55	-63.32	-58.95	-57.43
ΔAICc		0	0.4	0.89	1.06	1.35	1.57	0	1.52
Weight		0.25	0.2	0.16	0.15	0.13	0.11	0.68	0.32