Major shifts in species' relative abundance in grassland mixtures alongside positive effects of species diversity in yield

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Appendix S1. Additional details on the statistical analysis.

NOTE 1

Equation (1) in the main text is:

$$RGR_{GF12} = \log(y_{2GF} / y_{1GF}) = \mu_j + \alpha M + \gamma_1 y^c_{1GF} + \gamma_2 y^c_{1GP} + \gamma_3 y^c_{1LF} + \gamma_4 y^c_{1LP} + \varepsilon \quad (1)$$

Each coefficient was assumed to vary randomly from site to site around their mean value using a random coefficients model (Littell *et al.* 2006), where a single common variance was assumed for each μ_j, a unique variance for α and for each of the γ coefficients, and covariances among random terms were assumed zero. The residual error term was assume to be normally distributed with constant variance.

NOTE 2

Equation 2 in the main text is:

$$y = \sum_i \beta_i P_i + \alpha M + \delta E + \varepsilon \quad (2)$$

The value of the diversity effect coefficient, δ, reflects the additional yield that is achieved by the net interaction effects, and is added to the average of the monoculture yields to give the expected yield of the equi-proportional mixture (E=1). For mixtures other than the equi-proportional ($E \neq 1$), δE is added to the weighted monoculture yields ($\sum_i \beta_i P_i$) to give the overall expected yield. We summarised across sites the presence or not of diversity effects (i.e. significant or non-significant δ coefficient) by year (1, 2, 3) and average legume percentage category within year (low (0-15%), medium (15-30%) and high (>30%)). Further

exploration and interpretation of diversity effects in yield for these data is in Finn *et al*. (2013).

NOTE 3

We fitted a repeated measures regression model to the scaled estimated diversity effect coefficients in years 2 and 3, with the average legume percentage in the preceding year as the predictor. This regression model was estimated by maximum likelihood with a weight $(1/(\text{legume abundance})^2)$ included to allow for non-constant variance, and differences in slopes and intercepts between the two years were tested with likelihood ratio tests.

References

Finn, J.A., Kirwan, L., Connolly, J., Sebastià, M.T., Helgadóttir, A., Baadshaug, O.H., Bélanger, G., Black, A., Brophy, C., Collins, R.P., Čop, J., Dalmannsdóttir, S., Delgado, I., Elgersma, A., Fothergill, M., Frankow-Lindberg, B.E., Ghesquiere, A., Golinska, B., Golinski, P., Grieu, P., Gustavsson, A.M., Höglind, M., Huguenin-Elie, O., Jørgensen, M., Kadziuliene, Z., Kurki, P., Llurba, R., Lunnan, T., Porqueddu, C., Suter, M., Thumm, U. & Lüscher, A. (2013) Ecosystem function enhanced by combining four functional types of plant species in intensively managed grassland mixtures: a 3-year continental-scale field experiment. *Journal of Applied Ecology,* **50,** 365–375.

Littell, R.C., Milliken, G.A., Stroup, W.R., Wolfinger, R.D. & Schabenberger, O. (2006) *SAS for mixed models,* 2nd edn. SAS Press.

Table S1. Information on the 31 experimental sites.

Species group	Site #	Country	Site	Latitude	Longitude	Altitude (m.a.s.l.)	Nitrogen fertiliser (kg N ha^{-1} per annum) (year 1, 2, 3)	Harvests per annum (year 1,2,3)	Size of plots (m^2)	Size of subplots sampled (m^2)	Annual rainfall (mm)	Air temperature (ºC)			# years
												Min	Mean	Max	
ME	10	Germany_a	Renningen	48º46'N	9º11'E	460	150	4,5,5	18	8.75	634	-13	9	31	3
ME	11	Germany_b	St. Johann	48º28'N	9º18E	700	150	4	18	8.75	1046	-16	7	30	2
ME	15	Ireland_a	Wexford	52º16'N	6º30'W	54	150	5	16	6	952	-1	11	23	3
ME	18	Lithuania_a	Dotnuva	55º24'N	23º50'E	71	120	3	47.5	18.75	480	-18	7	29	3
ME	19	Lithuania_b	Dotnuva	55º24'N	23º50'E	71	120	3,2,2	6.5	6	482	-18	7	29	3
ME	20	Lithuania_c	Dotnuva	55º24'N	23º50'E	71	120	3,3,2	24	12.5	482	-18	7	29	3
ME	21	Netherlands	Wageningen	51º58'N	5º40'E	7	0,108,108	5	6	6	794	-7	11	31	3
ME	22	Norway_a	Saerheim	58º46'N	5º39'E	90	0	3	12	8	1440	-6	8	24	3
ME	24	Norway_c	Ås	59º40'N	10º51'E	95	135	3	12	9.75	760	-16	7	27	3
ME	26	Poland_a	Brody	52º26'N	16º18'E	94.2	120	4,4,3	9	6.25	600	-14	9	32	3

Species group	Site #	Country	Site	Latitude	Longitude	Altitude (m.a.s.l.)	Nitrogen fertiliser (kg N ha^{-1} per annum) (year 1, 2, 3)	Harvests per annum (year 1,2,3)	Size of plots (m^2)	Size of subplots sampled (m^2)	Annual rainfall (mm)	Air temperature (°C)			# years
												Min	Mean	Max	
ME	27	Poland_b	Brody	52°26'N	16°18'E	91.4	90	4,3	9	6.25	607	-15	9	32	2
ME	30	Spain_b	Gosol	42°13'N	1°39'E	1410	0	2	8.25	4.32	574	-7	9	28	1
ME	31	Sweden_a	Svalöv	55°55'N	13°07'E	55	0	3	8.8	8.8	574	-11	8	27	3
ME	32	Sweden_b	Svalöv	55°55'N	13°07'E	55	0	3	8.8	8.8	677	-11	8	28	3
ME	34	Switzerland	Zurich-Reckenholz	47°26'N	8°32'E	491	150	5	18	9	883	-11	10	32	3
ME	35	Wales_a	Aberystwyth	52°26'N	4°01'W	30	90	4	6	1	924	-5	11	26	3
ME	36	Wales_b	Bronydd Mawr	51°57'N	3°37'W	323	93	4,3,4	6	1	1505	-5	10	25	3
ME	40	Slovenia	Ljubljana	46°3'N	14°28'E	300	120	4	8.6	4.3	1147	-9	11	35	2
NE	13	Iceland_a	Korpa	64°09'N	21°45'W	35	40	2	6	0.4	1090	-13	5	21	3
NE	14	Iceland_b	Korpa	64°09'N	21°45'W	35	80	2	10	10	1067	-13	5	21	3
NE	23	Norway_b	Tromsø	69°40'N	18°56'E	15	60	2	21	8	1100	-10	4	23	3

Species group	Site #	Country	Site	Latitude	Longitude	Altitude (m.a.s.l.)	Nitrogen fertiliser (kg N ha^{-1} per annum) (year 1, 2, 3)	Harvests per annum (year 1,2,3)	Size of plots (m^2)	Size of subplots sampled (m^2)	Annual rainfall (mm)	Air temperature (°C)			# years
												Min	Mean	Max	
NE	25	Norway_d	Løken	61°07'N	9°04'E	435	80	2	10.5	8.25	554	-21	3	25	3
NE	33	Sweden_c	Öjebyn (Piteå)	65°19'N	21°24'E	5	60	2,3,2	19	19	631	-25	3	26	3
NE	52	Canada	Lévis	46°46'N	71°12'W	43	60	2	12	3.68	1174	-25	5	30	3
MM	9	France	Auzeville Tolosane	43°05'N	1°43'E	162	120	3,2,3	6	1	548	-5	14	35	3
DM	16	Italy	Ottava	40°44'N	8°32'E	80	31, 57, 61	4,5,5	9	1	660	1	16	37	3
DM	28	Spain_a	Zaragoza	41°44'N	2°53'E	225	61	2,3,1	9	4	249	-6	14	37	3
WE	43	Ireland_b	Athenry	53°17'N	8°44’W	40	75	7	10	6.4	885	-4	10	25	2
WE	44	Ireland_c	Moorepark	52°8'N	8°16'W	48	100	7	10	6.4	761	-4	10	24	2
O1	1	Belgium	Merelbeke	50°59'N	3°49E	11	150	4,3,4	8.4	8.3	709	-6	11	31	3
O2	7	Finland	Mikkeli	61°40'N	27°13'E	107	60	3	16	15	677	-24	4	27	2

The plots in Switzerland (site 34) were weeded for the first two harvests in the establishment year and the plots at Spain-Zaragoza (site 28) were weeded only in year 1 of harvesting. In Finland (site 7), barley was used on all plots as a nurse crop at establishment and harvested in the establishment year, as per conventional practice at this site. Daily precipitation values were summed and daily mean temperature values were averaged within each year for each site. The average of the lowest ten daily minimum temperature values and average of the highest ten daily maximum temperature values within each year was also computed for each site. The values averaged across the experimental years for each site are presented here.

Table S2. The average relative abundance (%) of each species at each site and year.

Species			Year 1				Year 2				Year 3			
group	Site	Country	G_F	G_P	L_F	L_P	G_F	G_P	L_F	L_P	G_F	G_P	L_F	L_P
ME	10	Germany_a	51	20	25	4	52	40	6	1.4	38	61	0.6	0.3
	11	Germany_b	51	14	29	7	34	36	27	3	-	-	-	-
	15	Ireland_a	28	55	11	7	6	94	0.1	0.1	5	95	0.0	0.2
	18	Lithuania_a	41	14	34	11	31	52	14	3	18	71	8	4
	19	Lithuania_b	27	58	13	2	6	91	3	0.2	0.3	99	0.3	0.0
	20	Lithuania_c	40	42	17	1	6	92	2	0.1	0.0	100	0.0	0.0
	21	Netherlands	57	18	14	10	36	47	10	7	17	75	4	4
	22	Norway_a	12	11	60	17	5	32	48	15	6	58	13	23
	24	Norway_c	46	17	28	8	38	53	5	4	13	86	0.3	0.5
	26	Poland_a	78	7	10	5	46	48	4	2	15	85	0.0	0.0
	27	Poland_b	52	40	7	2	24	76	0.3	0.1	-	-	-	-
	30	Spain_b	21	7	56	16	-	-	-	-	-	-	-	-
	31	Sweden_a	34	30	23	12	6	63	17	13	4	76	5	15
	32	Sweden_b	20	39	28	14	4	55	25	17	3	86	2	8
	34	Switzerland	47	14	28	10	32	23	32	13	21	67	10	2
	35	Wales_a	17	9	56	18	11	40	33	16	1.0	87	8	3
	36	Wales_b	36	25	20	18	20	61	4	15	4	79	1.1	16
	40	Slovenia	42	4	46	8	42	24	31	3	-	-	-	-
NE	13	Iceland_a	55	26	13	6	46	35	8	11	32	45	3	21
	14	Iceland_b	46	28	0.3	25	40	43	0.1	17	25	46	0.7	29
	23	Norway_b	57	9	28	6	41	33	14	12	22	56	13	9
	25	Norway_d	64	10	12	13	46	33	6	15	33	49	7	10
	33	Sweden_c	39	8	47	6	26	27	43	3	5	50	42	2
	52	Canada	52	7	38	2	55	31	14	0.5	48	52	0.2	0.0
MM	9	France	39	5	20	36	37	8	20	34	39	5	20	36
DM	16	Italy	43	8	29	20	27	37	5	31	5	52	1.3	41
	28	Spain_a	92	4	0.0	4	34	54	0.0	12	15	66	0.0	20
WE	43	Ireland_b	22	30	47	0.3	28	46	26	0.1	-	-	-	-
	44	Ireland_c	21	53	26	0.2	25	59	15	0.2	-	-	-	-
O1	1	Belgium	24	23	43	9	19	25	54	3	9	70	19	2
O2	7	Finland	47	32	14	7	28	35	25	12	-	-	-	-

Table S3. The estimated relative growth rate model coefficients for all species and periods of comparison. This expanded version of Table 2 (main text) includes the intercepts from the species groups MM (1 site), DM (2 sites), WE (2 sites), O1 (1 site) and O2 (1 site). The square root of all variance component estimates are also shown. Intraspecific density dependence coefficients are highlighted in grey.

	Year 1 to year 2								Year 2 to year 3							
	G_F		G_P		L_F		L_P		G_F		G_P		L_F		L_P	
Intercepts																
ME	**-0.90**	a	**0.97**	b	**-1.37**	a	**-1.22**	a	**-1.60**	a	**0.22**	b	**-3.09**	c	**-1.71**	a
NE	**-0.87**	a	0.22	b	**-1.46**	a	-0.69	ab	-0.92	a	0.05	a	-1.22	a	-1.06	a
MM	-0.50	a	0.45	a	0.54	a	-0.25	a	0.02	a	**-0.80**	a	-0.25	a	0.04	a
DM	**-3.18**	a	**-4.46**	b	-1.36	ab	-2.04	ab	-1.74	ab	0.21	ab	-1.44	a	0.91	b
WE	0.08	a	0.56	a	-0.34	a	-1.93	a								
O1	0.56	a	1.00	a	1.40	a	0.05	a	-1.07	ab	0.58	ab	-2.13	a	-0.18	b
O2	-0.41	a	0.32	a	0.54	a	0.81	a								
Seed abundance	0.03	a	0.01	a	**0.13**	a	0.02	a	-0.02	a	-0.01	a	-0.11	a	-0.09	a
Initial biomass (density dependence)																
y^c_{1GF}	**-0.16**	a	**-0.08**	b	-0.06	b	-0.06	ab	y_{2GF} -0.08	a	**0.06**	bc	0.10	b	0.04	ac
y^c_{1GP}	**-0.30**	ab	**-0.58**	a	**-0.19**	b	**-0.19**	ab	y_{2GP} -0.07	a	**-0.09**	a	0.01	a	-0.06	a
y^c_{1LF}	-0.06	a	**-0.05**	a	**-0.13**	b	-0.10	ab	y_{2LF} 0.03	ab	**0.05**	ab	0.08	a	-0.05	b
Y^c_{1LP}	0.00	a	-0.05	a	**-0.24**	b	**-0.55**	b	Y_{2LP} 0.02	a	**0.09**	a	-0.05	ac	**-0.46**	bc

Square root of variance component estimates								
Intercept	0.92	0.39	1.54	1.98	1.30	0.24	1.81	1.99
Seed abundance	0.06	0.00	0.25	0.00	0.00	0.00	0.00	0.20
y^{c}_{1GF}	0.10	0.05	0.05	0.08	0.02	0.00	0.00	0.02
y^{c}_{1GP}	0.21	0.73	0.02	0.10	0.22	0.05	0.23	0.09
y^{c}_{1LF}	0.10	0.07	0.00	0.16	0.23	0.00	0.00	0.00
Y^{c}_{1LP}	0.16	0.05	0.03	0.30	0.00	0.00	0.06	0.39
Residual	0.54	0.44	1.05	1.44	0.89	0.36	1.54	1.37

Bold indicates significantly different from 0 at α=0.05. Within each row and each period of comparison, coefficients that share a letter are not significantly different from one another. It follows, that letters on coefficients are only comparable within but not across rows.

Table S4. For each site and year (a) the average percentage of legumes in mixture and (b) the estimated diversity effect coefficient (δ) for yield (total plus weed). Diversity effects were estimated using sown proportions (eqn 2, main text). In (a) the shading gets lighter as values get closer to 0, in (b) shaded values indicate significance.

		(a) Average % of legumes			(b) Estimated diversity effect (t ha^{-1})		
Species group	Site	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
ME	10	28.9	7.4	1.0	4.84	3.61	3.04
	11	35.4	30.2		1.80	1.63	
	15	17.4	0.1	0.2	3.75	1.51	1.71
	18	45.1	17.3	11.9	0.34	1.84	1.81
	19	15.3	2.9	0.3	2.44	1.71	0.92
	20	18.1	2.1	0.0	2.17	1.87	0.86
	21	24.4	16.5	7.8	3.70	5.44	3.82
	22	77.4	63.4	36.0	6.85	4.08	3.97
	24	36.6	9.2	0.8	2.13	3.44	1.42
	26	15.1	6.7	0.0	1.77	2.66	0.77
	27	8.1	0.4		3.75	0.39	
	30	71.7			1.41		
	31	35.1	30.2	19.8	2.85	5.75	5.96
	32	41.5	41.2	10.7	3.67	5.29	3.46
	34	38.6	45.1	12.3	5.64	7.50	5.43
	35	74.2	49.1	11.6	4.37	2.21	-0.16
	36	38.8	18.8	17.0	4.68	4.12	2.80
	40	53.3	33.8		5.20	2.91	
NE	13	18.3	19.1	23.3	1.13	0.49	0.54
	14	25.7	16.9	29.7	1.16	1.25	1.37
	23	34.2	25.9	22.0	4.87	2.43	2.11
	25	25.8	21.6	17.6	2.40	2.04	0.90
	33	53.0	46.2	44.2	2.38	2.97	1.50
	52	40.5	14.2	0.2	2.22	0.24	-0.18
MM	9	55.9	54.5	55.5	1.71	1.98	2.34
DM	16	48.6	35.4	42.6	1.62	1.00	0.28
	28	4.0	12.1	19.9	3.57	0.05	0.15
WE	43	47.7	26.6		3.52	2.19	
	44	25.8	15.6		2.73	2.18	
O1	1	52.2	56.5	21.5	5.18	9.14	6.56
O2	7	21.3	37.1		2.65	3.40	

Table S5. Estimates and standard errors (from restricted maximum likelihood estimation), and likelihood ratio tests (LRT, from maximum likelihood estimation) for climatic variables in the models of relative growth rate responses. Bold indicates significantly different from 0 at α=0.05. Note that the coefficient estimates are given here as a guide to effect sizes but need to be interpreted relative to each other and alongside other model coefficients. The net effects of the minimum temperature coefficients are shown in Fig. 5, main text, for the ME and NE species groups.

		Precipitation			Minimum temp		
Species	Period	Est	SE	LRT *P*-value	Est	SE	LRT *P*-value
G_F	1-2	0.0010	0.00057	0.107	0.044	0.0364	0.168
G_F	2-3	0.0012	0.00079	0.121	0.076	0.0473	0.074
G_P	1-2	-0.0001	0.00029	0.752	0.023	0.0175	0.147
G_P	2-3	**0.0004**	**0.00014**	**0.005**	**0.021**	**0.0089**	**0.010**
L_F	1-2	0.0007	0.00095	0.439	0.017	0.0597	0.752
L_F	2-3	0.0006	0.00112	0.584	**0.151**	**0.0599**	**0.008**
L_P	1-2	**0.0027**	**0.00118**	**0.030**	**0.173**	**0.0697**	**0.007**
L_P	2-3	**0.0025**	**0.00112**	**0.032**	**0.177**	**0.0601**	**0.002**

		Mean temp			Maximum temp		
Species	Period	Est	SE	LRT *P*-value	Est	SE	LRT *P*-value
G_F	1-2	**0.303**	**0.1426**	**0.018**	0.078	0.0606	0.138
G_F	2-3	0.223	0.2474	0.317	-0.047	0.0984	0.584
G_P	1-2	0.031	0.0736	0.655	-0.011	0.0300	0.655
G_P	2-3	0.050	0.0497	0.254	-0.025	0.0188	0.121
L_F	1-2	-0.196	0.2484	0.343	-0.002	0.0988	1.000
L_F	2-3	0.054	0.3463	1.000	**-0.371**	**0.1051**	**<.001**
L_P	1-2	0.089	0.3298	0.752	-0.212	0.1246	0.061
L_P	2-3	0.114	0.3701	0.655	**-0.444**	**0.0991**	**<.001**

Fig. S1. The relative abundance of yield for each species (G_F, G_P, L_F and L_P) and each year averaged over (a) all 31 sites, (b) the 18 Mid-European (ME) sites, and (c) the six North European (NE) sites.

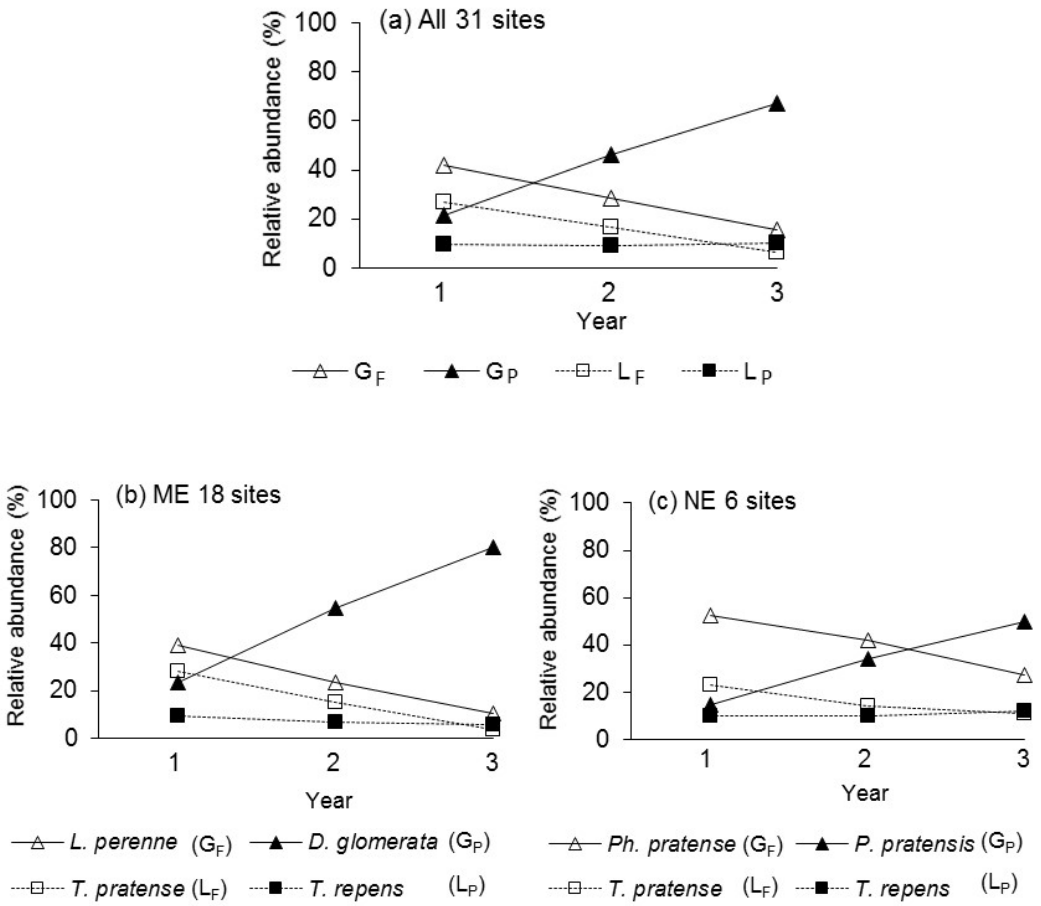

Fig. S2. Predicted relative abundances for the North European (NE) sites in years 2 and 3 as affected by the relative abundance of each species in years 1 and 2, respectively. The total biomass in the initial year is kept constant at the NE average of 7.8 (year 1) and 6.9 (year 2); likewise, the relative abundances of the three species other than the target species (on the x-axis) are kept equal. Predictions are made at average seed abundance and respect the ranges of the predictor variables in the observed data. *P. pratensis* predictions in grey are ignoring density dependence.

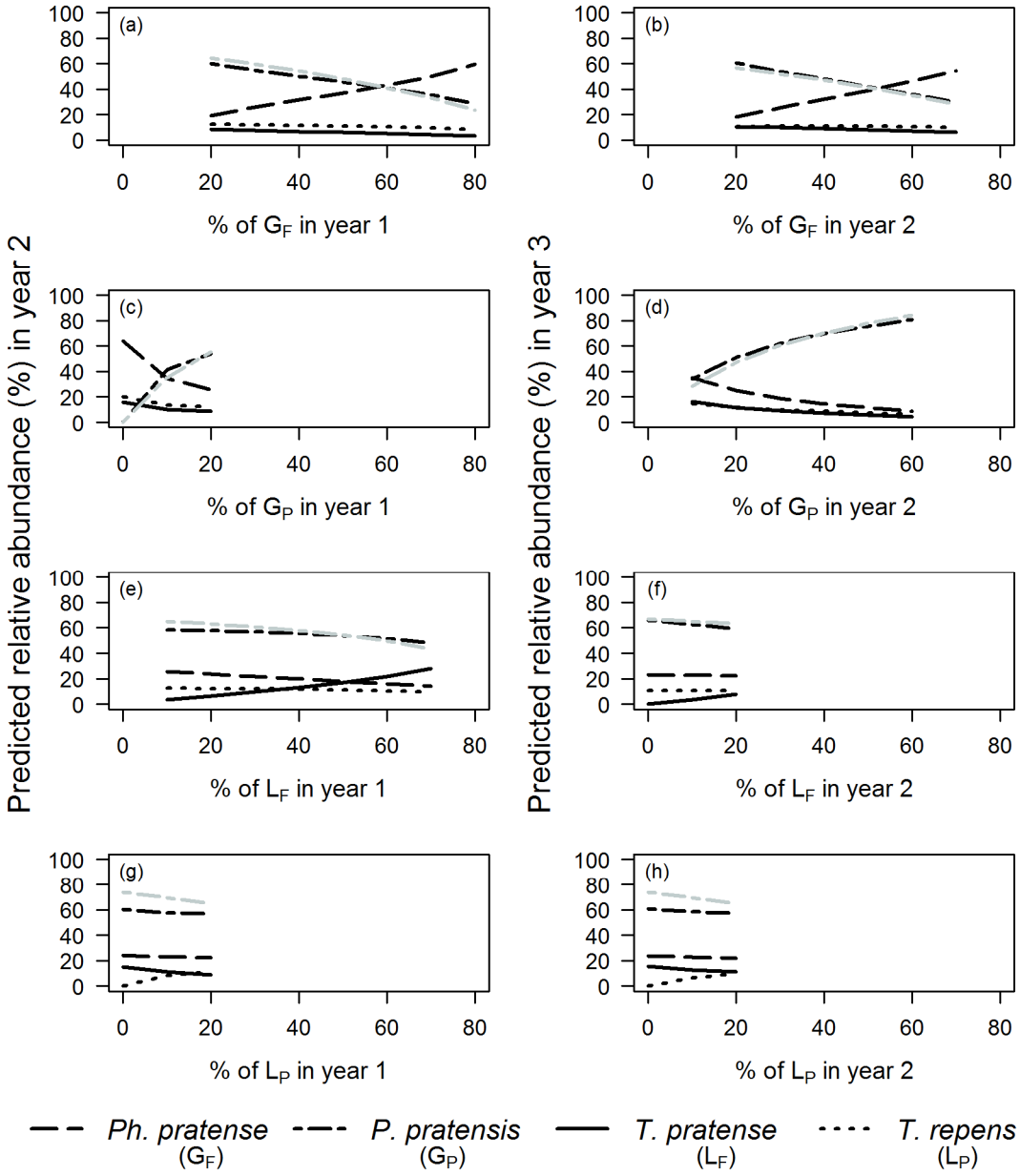

Fig. S3. Average legume percentage vs. minimum temperature for each site and year. Correlations are computed and trend lines fitted excluding outliers (denoted by ◇) in years 2 and 3.

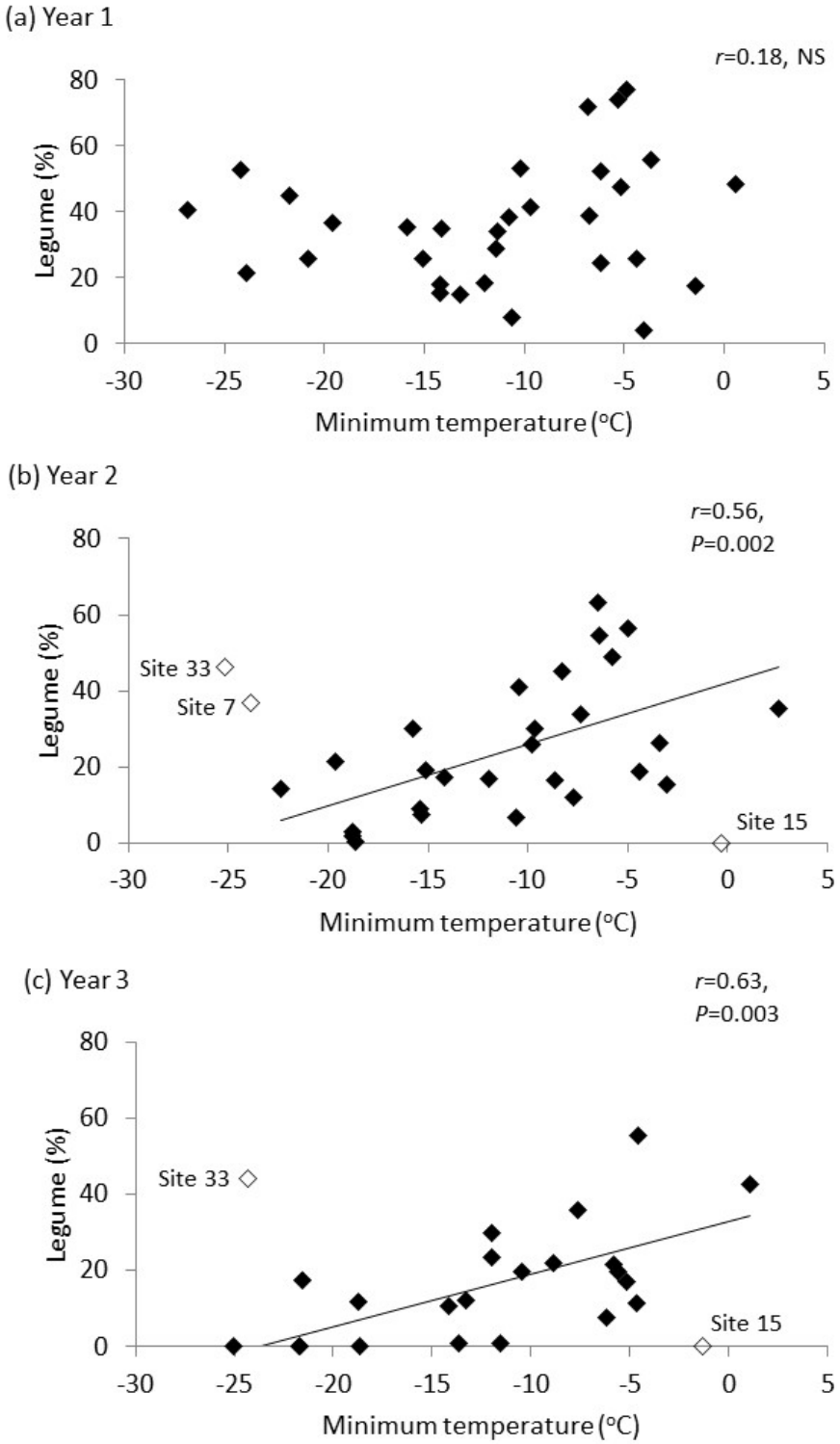

Fig. S4. The percentage of sites with average legume abundance in each of the categories low (0-15%), medium (15-30%), and high (30-100%), for each year. The white portion of the bar represents those sites that had a significant diversity effect coefficient and the grey those with a non-significant diversity effect (DE). Since the total number of sites changed over years, the number of sites with a significant diversity effect coefficient is provided in each bar. Diversity effect coefficients (δ) were estimated at each site using sown proportions (eqn 2 in main text).

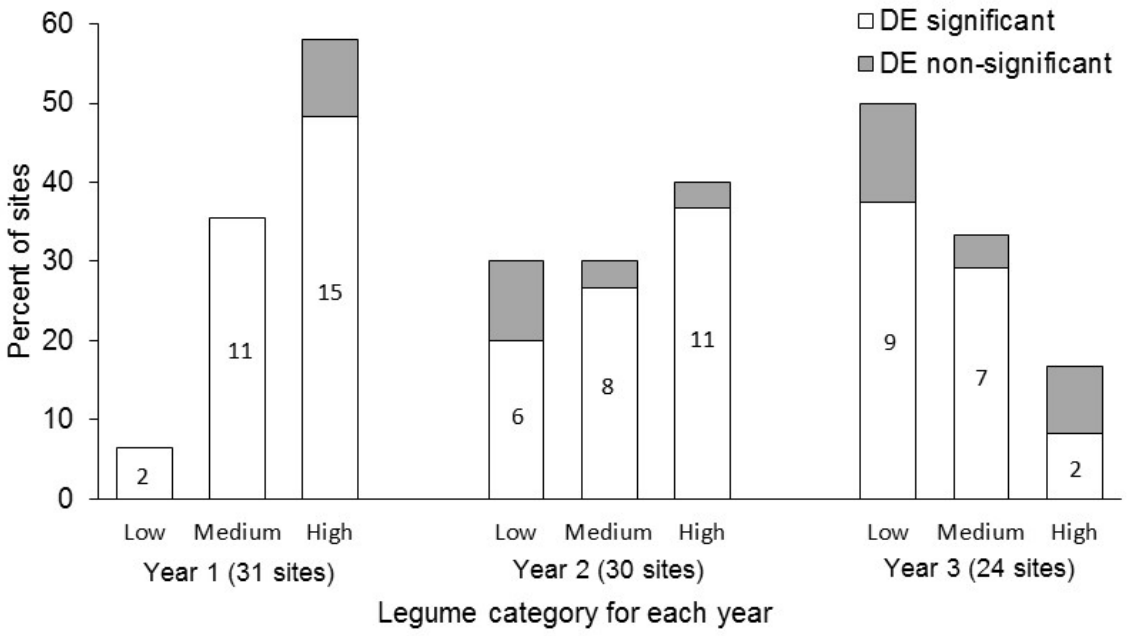

Fig. S5. Average relative abundance in each year for the twelve sites that had medium (15%-30%) or high (> 30%) legume abundance (L_F+L_P) in year 3. Species group is indicated below site number.