

Increasing crop rotational diversity can enhance cereal yields

Supplementary Information

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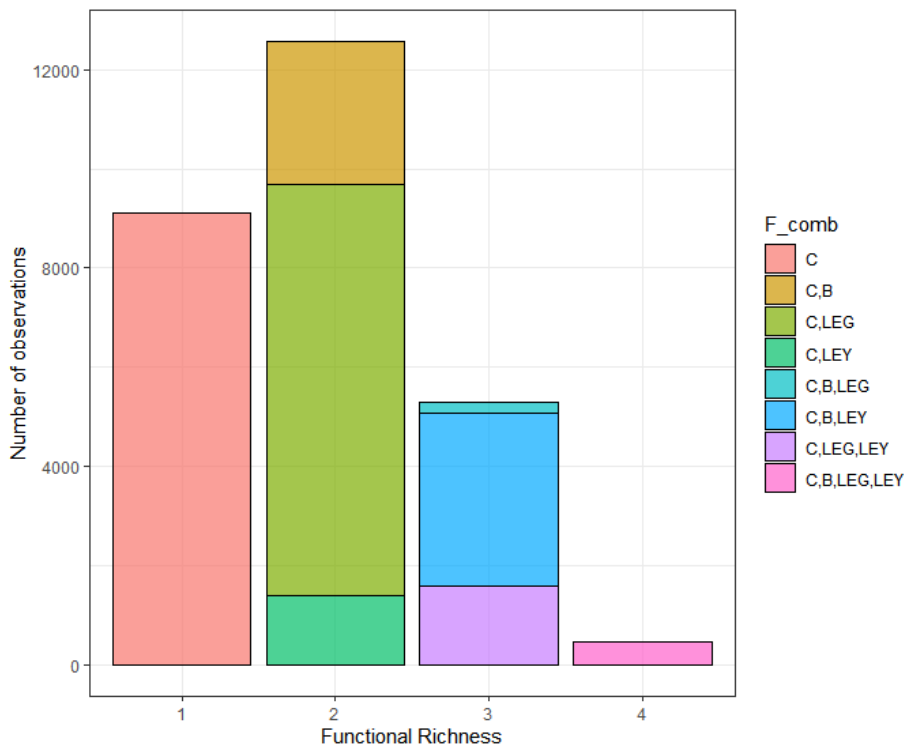
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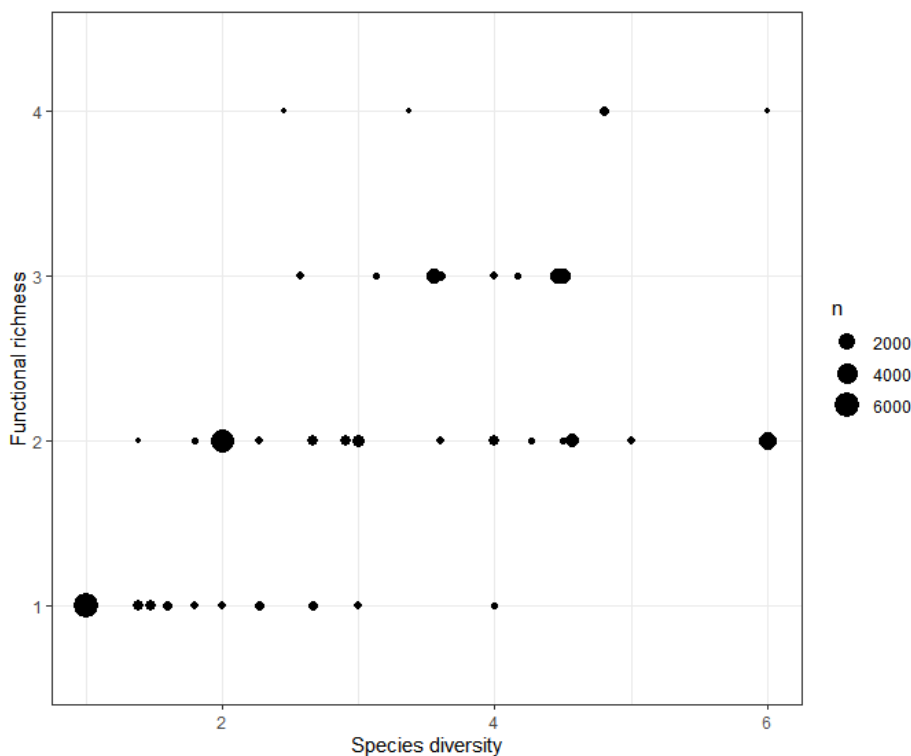
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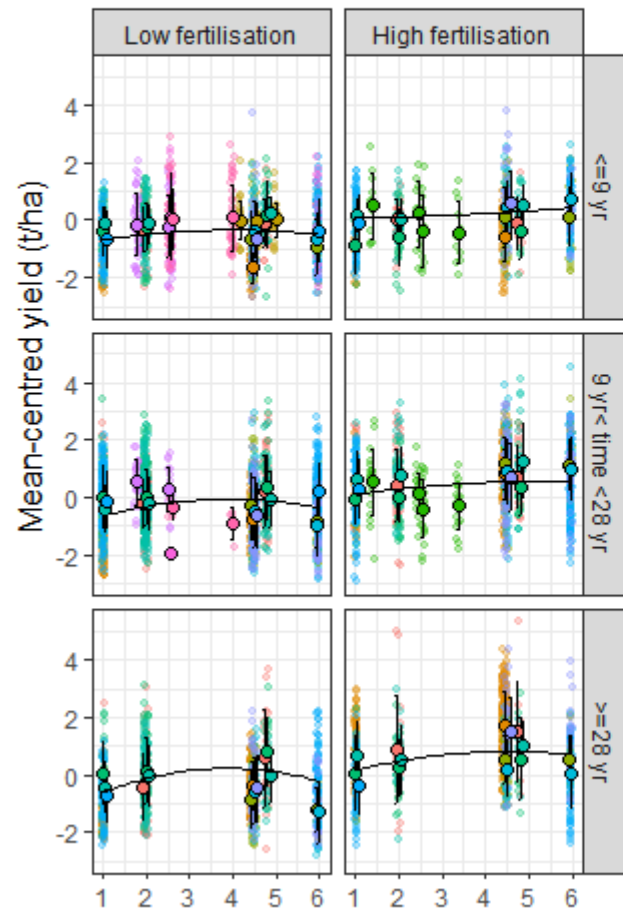
Supplementary Figure 1. Identity of functional richness levels. Distribution of crop functional groups (C=cereal, B=broadleaf, LEG=legume, LEY= biennial or perennial ley) within each level of functional richness, i.e., number of yield observations for each crop functional group included in the rotation, across the whole dataset.



Supplementary Figure 2. Relationship between species diversity (inverse Simpson's diversity index) and functional richness (number of crop functional groups included in the rotation) across all indicator crop datasets. The size of the circle is relative to the sample size (n) of yield observations for each species diversity x functional richness combination.

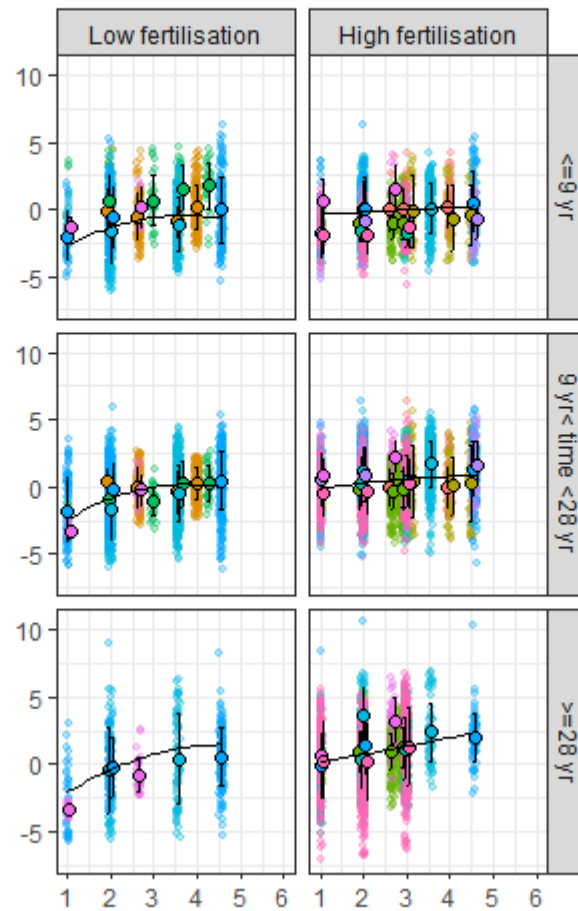
a) Spring small grain cereals

As LL Rb St WS
Brd LLTE SL TuE
GO Oj SLTE TuL



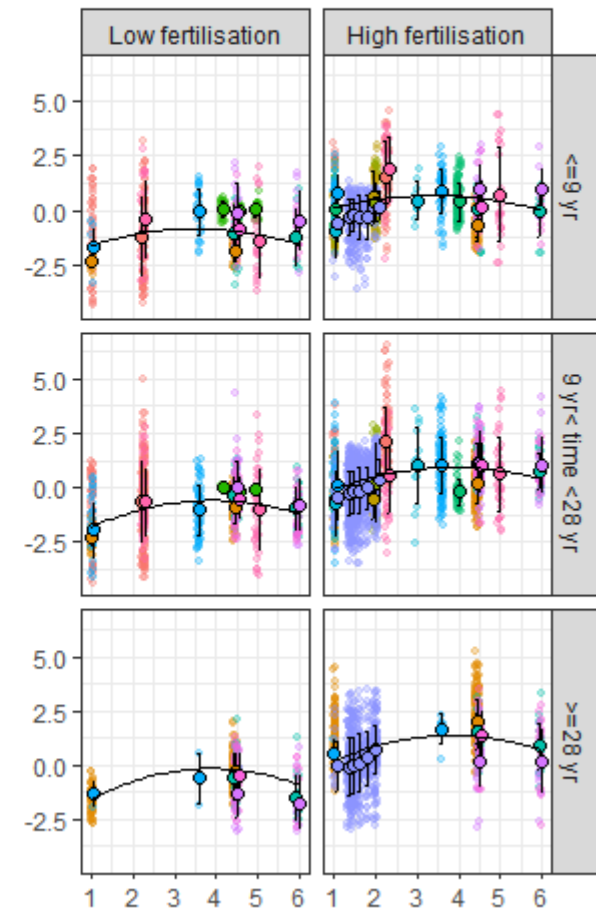
b) Maize

Ak EI La WoSI
Br HC Me Wst
Bv Hv RS



c) Winter small grain cereals

BB Fo LL Pe Wo
Brd GO Os SL
EE LCa Pa St



Species diversity

Supplementary Figure 3. Summary of the raw data used for our models. Distribution of mean-centred yields (calculated as the observed yield minus the long-term within-site average across all crop rotational diversity (CRD) treatments for an indicator crop species) for each indicator crop group (a-c). We modelled across CRD levels (species diversity based on the inverse Simpson's diversity index; x axis), sites (colours) at low (left panels) and high (right panels) external N fertilisation and grouped by three different time periods (rows) in years (yr) since the beginning of each experiment. Mean yields (also based on mean-centred yields per site, fertilisation, diversity and time periods) are represented by the black outlined circles coloured by site, and error bars represent standard deviations from the means. See Supplementary Table 1 for site codes. Black curves represent model predicted mean-centred yields for each indicator crop group after 5 (top), 20 (middle) and 35 (bottom) years since the beginning of the experiment (as in Fig. 2 but not compared to monocultures at year = 0).

Supplementary Table 1. Site information. Site location indicated as country and geographic coordinates. Fertilisation levels are relative to common practices, where high = at or above local recommendations, low = below local recommendations. Fertilisation type indicates whether inorganic, organic or both fertilisations were used for the specified fertilisation level. Application rates of fertilisers and crop protection chemicals were either the same between diversity treatments or variable based on need. Tillage regimes were always the same for comparisons between diversity levels and included: CT = Conventional Tillage, NT = No Tillage, RT = Reduced Tillage. Years indicates the difference between the last and first year of sampling per site +1. Seasonal mean temperature and total precipitation refer to the long-term average growing season temperature and mean of the total growing season precipitation to which yield data refer (sources of daily meteorological data: EObs ¹; Livneh *et al.* ² for North America). The LTEs growing seasons were determined as the average period from sowing to harvest dates for spring-sown crops (S), and the average period from the end of winter dormancy to harvest for winter-sown crops (W). We set the end of winter dormancy as the day when the growing degree days corrected by photoperiod (calculated as in Olesen *et al.* ³) began to increase steeply, i.e., increased of at least 4 °C with respect to the previous day. Annual mean temperature and precipitation are reported within parenthesis.

Site (code)	Country (state/province for North America)	Lat., °	Lon., °	Study design (replication)	Fertilisation level and type	Application rates between CRD comparisons		Till	Years	Seasonal	Seasonal	Source
						Fertiliser	Crop protection			mean T, °C	total P, cm	
Akron (Ak)	US (CO)	40.2	-103.1	Randomised block (3)	High Inorganic	Same	Variable	NT	23	S=19.6 (10.7)	S=27.7 (40.1)	4; 5
Beltsville (Bv)	US (MD)	39	-76.9	Split plot (4)	High Organic	Variable	Same (nill)	CT	20	S=22.4 (13.6)	S=52.3 (111.6)	6; 7
Broadbalk (BB)	England	51.82	-0.35	Split-split plot (1)	High Organic & Inorganic; Low Organic & Inorganic;	Same	Same	CT	21	W=12.3 (10.3)	W=40 (67.7)	8
Brody (Brd)	Poland	52.43	16.3	Split plot (4)	High Organic & Inorganic; Low Inorganic	Same	Same	CT	63	S=16.6 W=14 (8.6)	S=24.4 W=29.2 (53.9)	9
Brookings (Br)	US (SD)	44.4	-96.8	Randomised block (4)	Low Inorganic	Variable	Same	NT	16	S=18.1 (6.5)	S=43.4 (65.8)	10
El Encin (EE)	Spain	40.48	-3.37	Split-split plot (4)	High Inorganic	Variable	Variable	CT; NT; RT	14	W=13.3 (14.7)	W=16.9 (30.8)	11; 12; 13
Elora (El)	Canada (ON)	43.6	-80.4	Split plot (4)	High Inorganic	Same	Same	CT; NT;	36	S=13.7 (7.1)	S=59.3 (91.5)	14; 15

								RT				
Foggia (Fo)	Italy	41.45	15.6	Strip-strip plot (3)	High Inorganic	Same	Same	CT; RT	17	W=14.7 (17.6)	W=33.6 (65.2)	16; 17; 18
Grabow (GO)	Poland	51.35	21.66	Randomised block (4)	Low Organic	Same	NA	CT	10	S=13 W=15 (8.9)	S=29.7 W=27.5 (56.6)	19
Hickory Corners (HC)	US (MI)	42.4	-85.4	Randomised block (4)	Low Inorganic	Same (nill)	Same (nill)	CT	16	S=18.2 (10.1)	S=61.7 (101.9)	20; 21
Hoytville (Hv)	US (OH)	41.2	-83.8	Split plot (3)	High Inorganic	Same	NA	CT; NT; RT	51	S=19.5 (9.8)	S=43 (86.5)	22
La Canaleja (LC)	Spain	40.53	-3.33	Split plot (1)	High Inorganic	Variable	Variable	CT; NT	14	W=13 (14.6)	W=18.9 (37.7)	23
Lamberton (La)	US (MN)	44.2	-95.3	Split plot (3)	High Organic & Inorganic; Low Inorganic	Same	Variable	CT; RT	27	S=18.7 (7.2)	S=45.3 (70.6)	24; 25
Lanna Ley (LL)	Sweden	58.33	13.12	Split plot (1)	High or Low Organic	Same	Variable	CT	46	S=13.9 W=13.5 (6.6)	S=24.1 W=24.8 (57.1)	26
Lännäs LTE (LLTE)	Sweden	58.33	13.12	Split plot (1)	High Organic	Variable and Same	Variable	CT	33	S=14.24 (7.2)	S=26.83 (58.5)	26
Mead (Me)	US (NE)	41.1	-96.5	Split plot (5)	High or Low Inorganic	Same	Same	CT; NT	31	S=20.7 (10.1)	S=47.3 (74.4)	27; 28
Ojebyn (Oj)	Sweden	65.35	21.38	Split plot (1)	High Organic & Inorganic; Low Inorganic	Variable and Same	Variable	CT	43	S=12 (2.4)	S=22.5 (54.9)	26
Osiny (Os)	Poland	51.46	22.05	Block design (1)	High Inorganic	Variable	Variable	CT	24	W=14.9 (8.7)	W=25 (56)	29
Padova (Pa)	Italy	45.35	11.97	Split plot (3)	High Organic & Inorganic; Low Inorganic	Variable	Variable	CT	30	W=14.8 (14.2)	W=29.9 (80.6)	30
Perugia (Pe)	Italy	42.96	12.38	Split plot (3)	High Inorganic	Same	Variable	CT	40	W=12.8	W=30.6	31

										(14.4)	(73.2)	
Robacksdale n (Ro)	Sweden	63.82	20.28	Split plot (1)	High Organic & Inorganic; Low Inorganic	Variable and Same	Variable	CT	42	S=11.8 (3)	S=23.6 (63.6)	26
Rock Springs (RS)	US (PA)	40.7	-78	Split plot (4)	High Organic & Inorganic	Variable	NA	CT	17	S=17.3 (9.9)	S=49.4 (109.5)	32
Stenstugu Ley (St)	Sweden	57.6	18.43	Split plot (1)	High or Low Organic	Same	Variable	CT	45	S=13.8 W=14 (7.2)	S=18.9 W=18.3 (54.7)	26
Säby Ley (SL)	Sweden	59.82	17.7	Split plot (1)	High or Low Organic	Same	Variable	CT	42	S=14 W=14.1 (6.1)	S=23.5 W=23.3 (55.4)	26
Säby LTE (SLTE)	Sweden	59.82	17.7	Split plot (2)	High or Low Organic	Variable	Variable	CT	45	S=14.1 (6.1)	S=23.5 (55.6)	26
Tulloch Early (TuE)	Scotland	57.18	-2.25	Randomised block (2)	Low Organic	Variable	Same (nill)	CT	16	S=11.4 (8.2)	S=33.7 (82.3)	33
Tulloch Late (TuL)	Scotland	57.18	-2.25	Randomised block (2)	Low Organic	Variable	Same (nill)	CT	12	S=11.7 (8.5)	S=38.6 (83.8)	33
Woburn (Wo)	England	52.02	0.58	Split-split plot (1)	High or Low Inorganic	Same	Same	CT	21	W=12.5 (10.5)	W=36.7 (60.4)	8
Woodside (WS)	Scotland	57.63	-3.4	Randomised block (2)	Low Organic	Variable	Same (nill)	CT	12	S=11.8 (8.5)	S=31.6 (71.1)	33
Woodslee (WoSl)	Canada (ON)	42.21	-82.75	Split plot (1)	High or Low Inorganic	Same	Variable	CT	58	S=19.2 (9.4)	S=41.7 (86)	34; 35; 36
Wooster (Wst)	US (OH)	40.8	-81.9	Split plot (3)	High Inorganic	Same	NA	CT; NT; RT	52	S=18.8 (9.6)	S=48.2 (95.2)	22
Ås (As)	Sweden	63.25	14.57	Split plot (1)	High Organic & Inorganic; Low Inorganic	Variable and same	Variable	CT	44	S=11.1 (2.9)	S=25.0 (51.7)	26

Supplementary Table 2. Crop rotation information. Cropping sequence of all crop rotations per site (see Supplementary Table 1 for site name and information) whereby '-' indicates a shift in time (usually a year) when the next crop is grown, '+' indicates multiple crop species grown together in the same field and '/' indicates that the two crops either side are grown in alternate years. Mean yield and standard errors refer to the long-term raw yield mean of each indicator crop per rotation and per external N input level for the period to which the yield data refer (see Supplementary Table 1 data years). Yields are based on 100 % dry weight. Mean yields were calculated regardless of management (except N input), therefore could include yields from different tillage. The number of observations relates to yield observations in our dataset for each indicator crop per rotation and per external N input level. Note that some rotations will have observations for more than one indicator crop. Also listed are the CRD metrics, species diversity (SD; based on the inverse Simpson's diversity index) and functional richness (FR; the number of functional groups included in the rotation) and a list of the specific functional groups present in the rotation (whereby, C = cereal, B = broadleaf, Ley = ley and LEG = legume). Crop abbreviations are as follows: A = alfalfa, Be = beans, B = barley (phenology not known), C = canola, CP = chickpea, F= fallow, FB = fava bean, L = ley, Lg = legume (specific species changed over the years), M = maize, Mi = millet, O = oats, OSR = oilseed rape, Pe = pea, Po = potato, R = rye, RC = red clover, S = soy, Saff = safflower, SB = spring barley, SF = sunflower, Sg = sorghum, SuB = sugarbeet, SW = spring wheat, Swe = swede, Ti = timothy, US = the following crop was undersown with the previous crop, V = vetch, W = wheat (phenology not known), WB = winter barley, WR = winter rye, WT = winter triticale, WW = winter wheat.

Site code	Cropping sequence	Indicator crop	Mean yield $\pm$ SE, t ha ⁻¹ (observations)		SD	FR	Functional groups present
			Low N input	High N input			
Ak	M-F-WW	M	-	2.40 $\pm$ 0.15 (124)	3	1	C
	M-Mi-WW	M	-	1.91 $\pm$ 0.16 (63)	3	1	C
	M-Mi-F-WW	M	-	2.50 $\pm$ 0.19 (66)	4	1	C
	M-Mi-WW-WW	M	-	2.26 $\pm$ 0.20 (53)	2.67	1	C
	M-Saff-F-WW	M	-	2.07 $\pm$ 0.17 (64)	4	2	C, B
	M-Mi-Pe-WW	M	-	2.35 $\pm$ 0.21 (63)	4	2	C, LEG
Bv	M+R-S+V	M	-	3.78 $\pm$ 0.27 (74)	4	2	C, LEG
	M+R-S-WW+V	M	-	3.98 $\pm$ 0.30 (76)	4.5	2	C, LEG
	M+R-S-WW-A-A-A	M	-	4.22 $\pm$ 0.31 (72)	3.13	3	C, LEG, LEY
BB	WW	WW	3.26 $\pm$ 0.11 (210)	5.7 $\pm$ 0.1 (126)	1	1	C
	O-M-WW-WW-WW	WW	3.64 $\pm$ 0.11 (270)	6.42 $\pm$ 0.12 (162)	2.27	1	C
Brd	SB	SB	1.24 $\pm$ 0.04 (252)	3.23 $\pm$ 0.05 (504)	1	1	C
	WR	WR	1.82 $\pm$ 0.04 (252)	4.07 $\pm$ 0.06 (504)	1	1	C
	Po-SB-WT-A-A-WW-WR	SB	2.22 $\pm$ 0.05 (252)	3.95 $\pm$ 0.06 (504)	4.45	3	C, B, LEY
	Po-SB-WT-A-A-WW-WR	WR	3.05 $\pm$ 0.06 (252)	4.83 $\pm$ 0.06 (504)	4.45	3	C, B, LEY

Br	M-S	M	5.16 ± 0.17 (64)	-	2	2	C, LEG
	M-SF-SW-S	M	5.48 ± 0.16 (64)	-	4	3	C, B, LEG
	M-S-SW+RC	M	4.42 ± 0.17 (64)	-	3.6	2	C, LEG
	M-O-WW-S	M	5.33 ± 0.16 (64)	-	4	2	C, LEG
	M-S-SW-Pe	M	5.69 ± 0.21 (64)	-	4	2	C, LEG
	M-M-S-SW	M	4.40 ± 0.14 (128)	-	2.67	2	C, LEG
	M-S-SW-SF	M	5.02 ± 0.17 (64)	-	4	3	C, B, LEG
	M-C-WW-S	M	5.09 ± 0.16 (64)	-	4	3	C, B, LEG
	M-Pe-WW-S	M	5.13 ± 0.17 (64)	-	4	2	C, LEG
	M-S-SW-S	M	5.45 ± 0.18 (64)	-	2.67	2	C, LEG
EE	WW	WW	-	1.58 ± 0.12 (84)	1	1	C
	Pe/V-WW	WW	-	2.06 ± 0.13 (84)	2	2	C, LEG
EI	M	M	-	7.16 ± 0.08 (296)	1	1	C
	M-M-A-A	M	-	7.78 ± 0.10 (296)	2	2	C, LEY
	M-M-S-S	M	-	7.25 ± 0.09 (296)	2	2	C, LEG
	M-M-S-WW	M	-	7.48 ± 0.09 (288)	2.67	2	C, LEG
	M-M-O-SB	M	-	7.47 ± 0.09 (295)	2.67	1	C
	M-M-S-WW+RC	M	-	7.56 ± 0.09 (294)	2.91	2	C, LEG
	M-M-O+RC-SB+RC	M	-	7.76 ± 0.10 (287)	2.91	2	C, LEG
Fo	WW	WW	-	3.51 ± 0.17 (54)	1	1	C
	Lg-WW	WW	-	4.11 ± 0.19 (54)	2	2	C, LEG
GO	M-O+B+W+Pe-L-L-SW/WW	SW	1.68 ± 0.12 (28)	-	4.17	3	C, LEG, LEY
	M-O+B+W+Pe-L-L-SW/WW	WT	4.35 ± 0.06 (12)	-	4.17	3	C, LEG, LEY
	M-O+B+W+Pe-L-L-SW/WW	WW	2.38 ± 0.09 (20)	-	4.17	3	C, LEG, LEY
	M-SB-O+B+W+Pe-Pe-SW/WW	SW	1.70 ± 0.11 (28)	-	5	2	C, LEG
	M-SB-O+B+W+Pe-Pe-SW/WW	WT	4.14 ± 0.05 (12)	-	5	2	C, LEG
	M-SB-O+B+W+Pe-Pe-SW/WW	WW	2.43 ± 0.08 (20)	-	5	2	C, LEG
	M-O+B+W+Pe-SW-RC-SW/WW	SW	1.68 ± 0.11 (28)	-	4.55	2	C, LEG
	M-O+B+W+Pe-SW-RC-SW/WW	WT	3.90 ± 0.05 (12)	-	4.55	2	C, LEG
	M-O+B+W+Pe-SW-RC-SW/WW	WW	2.40 ± 0.07 (20)	-	4.55	2	C, LEG
HC	M	M	2.64 ± 0.19 (64)	-	1	1	C

	M+RC	M	3.38 ± 0.23 (63)	-	2	2	C, LEG
	M-S	M	4.05 ± 0.21 (63)	-	2	2	C, LEG
	M-S-WW	M	3.70 ± 0.22 (64)	-	3	2	C, LEG
	M+RC-S-WW+RC	M	4.78 ± 0.23 (64)	-	3.6	2	C, LEG
	M+RC+R-S-WW+RC+R	M	4.93 ± 0.21 (63)	-	4.26	2	C, LEG
Hv	M	M	-	6.93 ± 0.10 (453)	1	1	C
	M-S	M	-	7.45 ± 0.09 (454)	2	2	C, LEG
	M-O-L	M	-	7.92 ± 0.11 (452)	3	2	C, LEG
LCa	WW	WW	-	0.95 ± 0.05 (170)	1	1	C
	F-WW-Lg-WB	WW	-	1.29 ± 0.06 (170)	4	2	C, LEG
La	M-S	M	4.72 ± 0.09 (720)	7.25 ± 0.08 (681)	2	2	C, LEG
	M-S-O+A-A	M	5.71 ± 0.08 (731)	7.59 ± 0.07 (725)	3.56	3	C, LEG, LEY
LL	SW-F-OSR-WW-O-SB	O	2.05 ± 0.1 (91)	3.63 ± 0.09 (92)	6	2	C, B
	SW-F-OSR-WW-O-SB	SB	2.01 ± 0.1 (90)	3.77 ± 0.12 (90)	6	2	C, B
	SW-F-OSR-WW-O-SB	WW	2.81 ± 0.11 (88)	4.65 ± 0.11 (88)	6	2	C, B
	L-L-OSR-WW-O-SB	O	2.49 ± 0.1 (92)	3.91 ± 0.1 (92)	4.5	3	C, B, LEY
	L-L-OSR-WW-O-SB	SB	2.4 ± 0.13 (89)	3.58 ± 0.12 (90)	4.5	3	C, B, LEY
	L-L-OSR-WW-O-SB	WW	3.43 ± 0.11 (88)	5.07 ± 0.12 (88)	4.5	3	C, B, LEY
LLTE	SB-L-L-L-L-L	SB	-	3.07 ± 0.20 (31)	1.38	2	C, LEY
	SB-L-L-L-SB-SB+OSR+Lg	SB	-	2.74 ± 0.15 (32)	2.45	4	C, B, LEG, LEY
	SB-L-L-SB-Po-SB+OSR+Lg	SB	-	2.21 ± 0.16 (31)	3.38	4	C, B, LEG, LEY
	SB-L-SB-Po-SB-Po	SB	-	2.17 ± 0.20 (30)	2.57	3	C, B, LEG
Me	M	M	4.63 ± 0.13 (310)	6.93 ± 0.17 (155)	1	1	C
	M-S	M	6.45 ± 0.12 (310)	7.51 ± 0.17 (155)	2	2	C, LEG
	M-O+RC-Sg-S	M	7.43 ± 0.11 (310)	8.24 ± 0.16 (155)	4.57	2	C, LEG
	M-S-Sg-O+RC	M	6.73 ± 0.14 (310)	7.69 ± 0.18 (155)	4.57	2	C, LEG
Oj	SB	SB	2.67 ± 0.08 (168)	2.51 ± 0.17 (42)	1	1	C
	SB-SB-Lg+O	SB	2.84 ± 0.08 (162)	2.57 ± 0.18 (41)	2	2	C, LEG
	SB-SB-L-L	SB	2.65 ± 0.07 (164)	2.79 ± 0.14 (45)	2	2	C, LEY
	SB-L-L-Pe+O-Po-R	SB	3.17 ± 0.12 (84)	2.97 ± 0.17 (40)	4.8	4	C, B, LEG, LEY

Os	WW	WW	-	4.90 ± 0.29 (23)	1	1	C
	OSR-WW-SW	WW	-	6.54 ± 0.31 (23)	3	2	C, B
Pa	WW	WW	2.46 ± 0.11 (90)	4.6 ± 0.11 (180)	1	1	C
	M-SuB-M-WW-A-A	WW	3.58 ± 0.13 (90)	5.3 ± 0.09 (180)	3.6	3	C, B, LEY
Pe	WW	WW	-	4.19 ± 0.09 (120)	1	1	C
	WW-Sg	WW	-	5.14 ± 0.10 (93)	2	1	C
	WW-FB	WW	-	5.22 ± 0.10 (93)	2	2	C, LEG
	WW-M	WW	-	4.94 ± 0.09 (120)	2	1	C
	WW-WW-M	WW	-	4.58 ± 0.07 (240)	1.8	1	C
	WW-WW-WW-M	WW	-	4.45 ± 0.06 (357)	1.6	1	C
	WW-WW-WW-WW-M	WW	-	4.42 ± 0.05 (471)	1.47	1	C
	WW-WW-WW-WW-WW-M	WW	-	4.36 ± 0.04 (582)	1.38	1	C
	WW-OSR/SuB	WW	-	5.02 ± 0.10 (93)	2	2	C, B
	WW-SF	WW	-	5.09 ± 0.10 (93)	2	2	C, B
	WW-Pe/CP	WW	-	5.13 ± 0.10 (93)	2	2	C, B
Rb	SB	SB	2.02 ± 0.06 (168)	2.88 ± 0.15 (42)	1	1	C
	SB-SB-Lg+O	SB	2.34 ± 0.07 (167)	2.94 ± 0.18 (42)	2	2	C, LEG
	SB-SB-L-L	SB	2.09 ± 0.07 (167)	2.83 ± 0.14 (41)	2	2	C, LEY
	SB-L-L-Pe+O-Po-R	SB	2.38 ± 0.1 (84)	3.41 ± 0.17 (42)	4.8	4	C, B, LEG, LEY
RS	M	M	-	8.09 ± 0.19 (136)	1	1	C
	M-S	M	-	8.66 ± 0.17 (136)	2	2	C, LEG
	M-O+WW-RC+Ti-RC+Ti	M	-	9.13 ± 0.17 (136)	4.57	2	C, LEY
St	SW-F-OSR-WW-O-SB	O	2.1 ± 0.11 (88)	4.1 ± 0.12 (88)	6	2	C, B
	SW-F-OSR-WW-O-SB	SB	1.83 ± 0.11 (86)	2.89 ± 0.12 (84)	6	2	C, B
	SW-F-OSR-WW-O-SB	WW	3.03 ± 0.11 (86)	4.82 ± 0.12 (86)	6	2	C, B
	L-L-OSR-WW-O-SB	O	2.64 ± 0.11 (88)	3.50 ± 0.11 (88)	4.5	3	C, B, LEY
	L-L-OSR-WW-O-SB	SB	2.37 ± 0.14 (85)	2.96 ± 0.10 (84)	4.5	3	C, B, LEY
	L-L-OSR-WW-O-SB	WW	3.57 ± 0.11 (86)	4.34 ± 0.10 (86)	4.5	3	C, B, LEY
SL	SW-F-OSR-WW-O-SB	O	2.32 ± 0.12 (82)	4.01 ± 0.13 (82)	6	2	C, B
	SW-F-OSR-WW-O-SB	SB	2.35 ± 0.11 (82)	4.1 ± 0.12 (82)	6	2	C, B

	SW-F-OSR-WW-O-SB	WW	3.17 ± 0.15 (78)	4.96 ± 0.15 (78)	6	2	C, B
	L-L-OSR-WW-O-SB	O	2.85 ± 0.12 (80)	4.08 ± 0.13 (80)	4.5	3	C, B, LEY
	L-L-OSR-WW-O-SB	SB	2.78 ± 0.14 (79)	3.83 ± 0.12 (80)	4.5	3	C, B, LEY
	L-L-OSR-WW-O-SB	WW	3.76 ± 0.15 (78)	5.03 ± 0.15 (78)	4.5	3	C, B, LEY
SLTE	O	O	3.4 ± 0.09 (176)	3.56 ± 0.09 (176)	1	1	C
	SB	SB	3.21 ± 0.07 (174)	3.76 ± 0.07 (176)	1	1	C
	SW	SW	2.97 ± 0.07 (174)	3.55 ± 0.07 (174)	1	1	C
	F-OSR-WW-O-SB-SW	O	3.54 ± 0.09 (180)	3.9 ± 0.09 (178)	6	2	C, B
	F-OSR-WW-O-SB-SW	SB	3.57 ± 0.07 (180)	4.1 ± 0.08 (179)	6	2	C, B
	F-OSR-WW-O-SB-SW	SW	3.46 ± 0.07 (186)	4.04 ± 0.08 (185)	6	2	C, B
TuE	L-L-L-O-Swe-US O	O	5.03 ± 0.19 (32)	-	2.57	3	C, B, LEY
	L-L-L-O-Swe-US O	U/S O	3.27 ± 0.18 (32)	-	2.57	3	C, B, LEY
	L-L-L-L-O-US O	O	5.08 ± 0.19 (32)	-	1.8	2	C, LEY
	L-L-L-L-O-US O	U/S O	3.46 ± 0.19 (31)	-	1.8	2	C, LEY
TuL	L-L-L-O-Swe-US O	U/S O	2.71 ± 0.32 (24)	-	2.57	3	C, B, LEY
	US W-US Be-US B-US O-L-Po	U/S O	2.78 ± 0.32 (20)	-	6	3	C, B, LEG
	Po-US Be-US B-US O-L-US W	U/S O	2.87 ± 0.31 (21)	-	6	3	C, B, LEG
Wo	R-M-B-WW-R	WW	3.18 ± 0.23 (62)	5.02 ± 0.23 (64)	5	2	C, LEG
	L-L-L-WW-R	WW	3.78 ± 0.2 (66)	5.37 ± 0.22 (66)	2.27	2	C, LEY
WS	L-L-L-O-Po-US O	O	3.35 ± 0.22 (23)	-	2.57	3	C, B, LEY
	L-L-L-O-Po-US O	U/S O	2.64 ± 0.21 (23)	-	2.57	3	C, B, LEY
	L-L-O-Po-US O-L-Swe-US O	O	3.07 ± 0.24 (23)	-	4	3	C, B, LEY
	L-L-O-Po-US O-L-Swe-US O	U/S O	2.91 ± 0.24 (22)	-	4	3	C, B, LEY
WoSl	M	M	1.22 ± 0.12 (55)	5.05 ± 0.19 (58)	1	1	C
	M-O+A-A-A	M	3.81 ± 0.17 (58)	7 ± 0.23 (58)	2.67	2	C, LEY
Wst	M	M	-	7.19 ± 0.12 (443)	1	1	C
	M-S	M	-	7.17 ± 0.12 (450)	2	2	C, LEG
	M-O-ley	M	-	8.07 ± 0.13 (436)	3	2	C, LEG
As	SB	SB	2.73 ± 0.08 (161)	3.39 ± 0.19 (42)	1	1	C
	SB-SB-Lg+O	SB	2.57 ± 0.07 (157)	3.19 ± 0.21 (40)	2	2	C, LEG

SB-SB-L-L	SB	2.56 ± 0.07 (162)	3.3 ± 0.22 (41)	2	2	C, LEY
SB-L-L-Pe+O-Po-R	SB	3.05 ± 0.14 (82)	3.51 ± 0.21 (41)	4.8	4	C, B, LEG, LEY

Supplementary Table 3. Summary of statistics for Species Diversity (SD; based on the inverse Simpson's diversity index) and its interaction with fertilisation as explanatory factor. Model estimates, their standard errors (SE) and significance (p) from the linear mixed effect model 4 for a) spring small grain cereals, b) maize, and c) winter small grain cereals. The marginal and conditional R^2 show the variation explained by the fixed factors alone and by the entire model including fixed and random factors, respectively ³⁶.

Indicator crops	<i>a) Spring small grain cereals</i>			<i>b) Maize</i>			<i>c) Winter small grain cereals</i>		
Predictor	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p
Intercept (t ha ⁻¹)	-8.98×10 ⁻¹	1.24×10 ⁻¹	<0.001***	-4.43	3.45×10 ⁻¹	<0.001***	-2.09	1.90×10 ⁻¹	<0.001***
SD (t ha ⁻¹)	2.23×10 ⁻¹	5.06×10 ⁻²	<0.001***	1.97	1.70×10 ⁻¹	<0.001***	7.42×10 ⁻¹	6.77×10 ⁻²	<0.001***
SD ² (t ha ⁻¹)	-1.11×10 ⁻²	3.45×10 ⁻³	0.001**	-3.97×10 ⁻²	2.74×10 ⁻²	0.147	-6.09×10 ⁻²	1.23×10 ⁻²	<0.001***
Year (t ha ⁻¹ yr ⁻¹)	-2.71×10 ⁻²	7.42×10 ⁻³	<0.001***	-2.51×10 ⁻¹	3.04×10 ⁻²	<0.001***	-1.14×10 ⁻¹	1.09×10 ⁻²	<0.001***
Year ² (t ha ⁻¹ yr ⁻²)	NA	NA	NA	1.22×10 ⁻³	5.60×10 ⁻⁴	0.029*	1.26×10 ⁻³	2.28×10 ⁻⁴	<0.001***
High Fertilisation (t ha ⁻¹)	1.02	1.01×10 ⁻¹	<0.001***	4.05	2.90×10 ⁻¹	<0.001***	1.94	1.75×10 ⁻¹	<0.001***
SD × Year (t ha ⁻¹ yr ⁻¹)	1.59×10 ⁻²	1.66×10 ⁻³	<0.001***	5.78×10 ⁻²	1.47×10 ⁻²	<0.001***	2.43×10 ⁻²	2.97×10 ⁻³	<0.001***
SD ² × Year (t ha ⁻¹ yr ⁻¹)	-2.08×10 ⁻³	2.52×10 ⁻⁴	<0.001***	-1.12×10 ⁻²	2.87×10 ⁻³	<0.001***	-1.50×10 ⁻³	4.04×10 ⁻⁴	<0.001***
SD × Year ² (t ha ⁻¹ yr ⁻²)	NA	NA	NA	-1.22×10 ⁻³	3.43×10 ⁻⁴	<0.001***	-2.40×10 ⁻⁴	2.81×10 ⁻⁵	<0.001***

$SD^2 \times Year^2$ (t ha ⁻¹ yr ⁻²)	NA	NA	NA	3.07×10^{-4}	7.37×10^{-5}	<0.001***	NA	NA	NA
$SD \times High$ Fertilisation (t ha ⁻¹)	-2.99×10^{-1}	5.02×10^{-2}	<0.001***	-2.05	1.44×10^{-1}	<0.001***	-2.02×10^{-1}	6.18×10^{-2}	0.001**
$SD^2 \times High$ Fertilisation (t ha ⁻¹)	4.71×10^{-2}	7.37×10^{-3}	<0.001***	2.97×10^{-1}	2.55×10^{-2}	<0.001***	2.40×10^{-2}	1.03×10^{-2}	0.020*
<i>No. of observations</i>	8492			11833			7198		
<i>Marginal R²</i>	0.154			0.128			0.295		
<i>Conditional R²</i>	0.719			0.771			0.775		

Supplementary Table 4. Summary of statistics with Functional Richness (FR; number of crop functional groups included in the rotation) and its interaction with fertilisation as explanatory factor. Model estimates, their standard errors (SE) and significance (*p*) from the linear mixed effect model 5 for a) spring small grain cereals, b) maize, and c) winter small grain cereals based on mean-centred observations, i.e., the difference from to the long-term within-site average across all CRD treatments. The marginal and conditional R² show the variation explained by the fixed factors alone and by the entire model including fixed and random factors, respectively ³⁶.

Indicator crops	<i>a) Spring small grain cereals</i>			<i>b) Maize</i>			<i>c) Winter small grain cereals</i>		
Predictor	Estimate	SE	<i>p</i>	Estimate	SE	<i>p</i>	Estimate	SE	<i>p</i>
Intercept (t ha ⁻¹)	-7.46×10 ⁻¹	1.10×10 ⁻¹	<0.001***	-2.98	2.88×10 ⁻¹	<0.001***	-1.66	1.75×10 ⁻¹	<0.001***
FR2 (t ha ⁻¹)	1.35×10 ⁻¹	3.93×10 ⁻²	0.001**	1.97	8.48×10 ⁻²	<0.001***	6.00×10 ⁻¹	1.05×10 ⁻¹	<0.001***
FR3 (t ha ⁻¹)	3.28×10 ⁻¹	4.87×10 ⁻²	<0.001***	1.90	1.34×10 ⁻¹	<0.001***	7.64×10 ⁻¹	8.50×10 ⁻²	<0.001***
FR4 (t ha ⁻¹)	2.10×10 ⁻¹	7.45×10 ⁻²	0.005**	NA	NA	NA	NA	NA	NA
Year (t ha ⁻¹ yr ⁻¹)	4.20×10 ⁻³	2.94×10 ⁻³	0.154	1.64×10 ⁻²	2.23×10 ⁻²	0.463	-2.06×10 ⁻²	1.13×10 ⁻²	0.069
Year ² (t ha ⁻¹ yr ⁻²)	NA	NA	NA	1.26×10 ⁻⁴	4.43×10 ⁻⁴	0.776	7.59×10 ⁻⁴	2.16×10 ⁻⁴	0.001**
High Fertilisation (t ha ⁻¹)	7.92×10 ⁻¹	8.02×10 ⁻²	<0.001***	2.61	2.44×10 ⁻¹	<0.001***	1.82	1.66×10 ⁻¹	<0.001***
FR2 × Year (t ha ⁻¹ yr ⁻¹)	3.53×10 ⁻³	1.41×10 ⁻³	0.012*	7.22×10 ⁻³	6.83×10 ⁻³	0.291	1.55×10 ⁻²	8.59×10 ⁻³	0.071
FR3 × Year (t ha ⁻¹ yr ⁻¹)	1.62×10 ⁻²	1.42×10 ⁻³	<0.001***	1.66×10 ⁻¹	1.94×10 ⁻²	<0.001***	3.95×10 ⁻²	5.77×10 ⁻³	<0.001***
FR4 × Year (t ha ⁻¹ yr ⁻¹)	1.42×10 ⁻²	2.90×10 ⁻³	<0.001***	NA	NA	NA	NA	NA	NA
FR2 × Year ² (t ha ⁻¹ yr ⁻²)	NA	NA	NA	2.07×10 ⁻⁴	1.43×10 ⁻⁴	0.148	-3.52×10 ⁻⁴	2.01×10 ⁻⁴	0.079

FR3 × Year ² (t ha ⁻¹ yr ⁻²)	NA	NA	NA	-5.20×10 ⁻³	7.11×10 ⁻⁴	<0.001***	-5.95×10 ⁻⁴	9.65×10 ⁻⁵	<0.001***
FR4 × Year ² (t ha ⁻¹ yr ⁻²)	NA	NA	NA	NA	NA	NA	NA	NA	NA
FR2 × High Fertilisation (t ha ⁻¹)	1.93×10 ⁻¹	3.85×10 ⁻²	<0.001***	-1.74	6.98×10 ⁻²	<0.001***	-1.72×10 ⁻¹	8.62×10 ⁻²	0.046*
FR3 × High Fertilisation (t ha ⁻¹)	-2.23×10 ⁻¹	4.78×10 ⁻²	<0.001***	-2.18	1.01×10 ⁻¹	<0.001***	-4.64×10 ⁻¹	6.45×10 ⁻²	<0.001***
FR4 × High Fertilisation (t ha ⁻¹)	4.54×10 ⁻²	7.68×10 ⁻²	0.554	NA	NA	NA	NA	NA	NA
<i>No. of observations</i>	8429			11833			7198		
<i>Marginal R²</i>	0.173			0.125			0.303		
<i>Conditional R²</i>	0.730			0.766			0.776		

Supplementary Table 5. Summary of statistics for inclusion of annual legumes, annual broadleaves, and biennial or perennial ley in the rotation as dependent variable. With linear mixed effect model estimates, their standard errors (SE) and significance (*p*) for spring small grain cereals, maize, and winter small grain cereals. Mean-centred observations, i.e., the difference from to the long-term within-site average across all CRD treatments were used. The marginal and conditional R^2 show the variation explained by the fixed factors alone and by the entire model including fixed and random factors, respectively ³⁶.

Indicator crops	<i>a) Spring small grain cereals</i>			<i>b) Maize</i>			<i>c) Winter small grain cereals</i>		
Predictor	Estimate	SE	<i>p</i>	Estimate	SE	<i>p</i>	Estimate	SE	<i>p</i>
Intercept (t ha ⁻¹)	-4.32×10 ⁻¹	1.28×10 ⁻¹	0.001**	-1.05	1.98×10 ⁻¹	0.001**	-7.20×10 ⁻¹	1.39×10 ⁻¹	0.001**
Ley (t ha ⁻¹)	3.02×10 ⁻³	4.46×10 ⁻²	0.946	5.52×10 ⁻¹	4.62×10 ⁻²	0.001**	5.48×10 ⁻²	6.27×10 ⁻²	0.382
Legumes (t ha ⁻¹)	2.06×10 ⁻¹	4.46×10 ⁻²	<0.001***	7.35×10 ⁻¹	4.24×10 ⁻²	0.001**	4.16×10 ⁻¹	5.01×10 ⁻²	0.001**
Broadleaves (t ha ⁻¹)	3.40×10 ⁻¹	2.84×10 ⁻²	<0.001***	9.93×10 ⁻²	1.20×10 ⁻¹	0.409	4.51×10 ⁻¹	5.10×10 ⁻²	0.001**
<i>No. of observations</i>	<i>8429</i>			<i>11833</i>			<i>7198</i>		
<i>Marginal R²</i>	<i>0.0267</i>			<i>0.0329</i>			<i>0.0547</i>		
<i>Conditional R²</i>	<i>0.528</i>			<i>0.481</i>			<i>0.597</i>		

Supplementary Table 6. Stepwise model selection for yield responses of the three indicator crop groups to Species Diversity (SD; based on the inverse Simpson's diversity index) over time (Years since experiments begun) and with high or low fertilisation. Polynomials of Year and SD and interaction terms were explored as part of the model selection process and only models that were based on hypotheses were included. Values of Akaike Information Criteria (AIC) and p refer to models that exclude the predictor shown on the leftmost column. For each step, single predictors with non-significant contribution to the model were removed based on the lowest AIC, and the process was repeated until all predictors showed statistical significance ($p < 0.05$). Asterisks on AIC and p values indicate predictors that were removed from the final model at a given step.

Full model: Yield ~ SD + SD ² + Year + Year ² + Fertilisation + SD : Year + SD ² : Year + SD : Year ² + SD ² : Year ² + Fertilisation : SD + Fertilisation : SD ² + (1 Site:M.group) + (1 Site:C.year)		<i>a) Spring small grain cereals</i>		<i>b) Maize</i>		<i>c) Winter small grain cereals</i>	
Predictors dropped from model	Step	AIC	p	AIC	p	AIC	p
None	1	18249	-	37196	-	16987	-
SD : Year	1	18253	0.014	37210	<0.001	16993	0.005
SD ² : Year	1	18250	0.066	37210	<0.001	16986	0.337
SD : Year ²	1	18247	0.695*	37207	<0.001	16986	0.220
SD ² : Year ²	1	18247	0.562	37212	<0.001	16985	0.967*
Fertilisation : SD	1	18282	<0.001	37395	<0.001	16996	0.001
Fertilisation : SD ²	1	18287	<0.001	37330	<0.001	16990	0.020
None	2	18247	-	NA	NA	16985	-
SD : Year	2	18301	<0.001	NA	NA	17049	<0.001
SD ² : Year	2	18309	<0.001	NA	NA	16997	<0.001

SD : Year ²	2	18246	0.292*	NA	NA	17055	<0.001
Fertilisation : SD	2	18280	<0.001	NA	NA	16994	0.001
Fertilisation : SD ²	2	18286	<0.001	NA	NA	16988	0.020
None	3	18246	-	NA	NA	NA	NA
Year ²	3	18245	0.817*	NA	NA	NA	NA
SD : Year	3	18336	<0.001	NA	NA	NA	NA
SD ² : Year	3	18312	<0.001	NA	NA	NA	NA
Fertilisation : SD	3	18280	<0.001	NA	NA	NA	NA
Fertilisation : SD ²	3	18285	<0.001	NA	NA	NA	NA
None	4	18245	-	NA	NA	NA	NA
SD : Year	4	18334	<0.001	NA	NA	NA	NA
SD ² : Year	4	18310	<0.001	NA	NA	NA	NA
Fertilisation : SD	4	18278	<0.001	NA	NA	NA	NA
Fertilisation : SD ²	4	18283	<0.001	NA	NA	NA	NA

Supplementary Table 7. Stepwise model selection for yield responses of the three indicator crop groups to Functional Richness (FR) over time (Years since experiments begun) and with high or low fertilisation. Polynomials of Year and interaction terms were explored as part of the model selection process and only models that were based on hypotheses were included. Values of Akaike Information Criteria (AIC) and p refer to models that exclude the predictor shown on the leftmost column. For each step, single predictors with non-significant contribution to the model were removed based on the lowest AIC, and the process was repeated until all predictors showed statistical significance ($p < 0.05$). Asterisks on AIC and p values indicate predictors that were removed from the final model at a given step.

Full model: Yield ~ FR + Year + Year ² + Fertilisation + FR : Year + FR : Year ² + FR : Fertilisation + (1 Site:M.group) + (1 Site:C.year)		<i>a) Spring small grain cereals</i>		<i>b) Maize</i>		<i>c) Winter small grain cereals</i>	
Predictors dropped from model	Step	AIC	p	AIC	p	AIC	p
None	1	18200	-	37524	-	17136	-
FR : Year	1	18220	<0.001	37597	<0.001	17179	<0.001
FR : Year ²	1	18199	0.199*	37582	<0.001	17171	<0.001
Fertilisation : FR	1	18284	<0.001	38161	<0.001	17190	<0.001
None	2	18199	-	NA	NA	NA	NA
Year ²	2	18197	0.977*	NA	NA	NA	NA
FR: Year	2	18341	<0.001	NA	NA	NA	NA
Fertilisation : FR	2	18282	<0.001	NA	NA	NA	NA
None	3	18197	-	NA	NA	NA	NA
FR : Year	3	18339	<0.001	NA	NA	NA	NA

Fertilisation : FR	3	18280	<0.001	NA	NA	NA	NA
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Supplementary References

1. Cornes, R. C., Schrier, G. van der, Besselaar, E. J. M. van den & Jones, P. D. An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *J. Geophys. Res. Atmos.* **123**, 9391–9409 (2018).
2. Livneh, B., Bohn T. J., Pierce, D. W., Munoz-Arriola, F., Vose, R., Cayan, D. R., Brekke, L., A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and Southern Canada 1950–2013. *Sci Data*. **2**, 150042 (2015).
3. Olesen, J. E. *et al.* Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. *Food Addit. Contam. - Part A Chem. Anal. Control. Expo. Risk Assess.* **29**, 1527–1542 (2012).
4. Mikha, M. M., Benjamin, J. G., Vigil, M. F. & Nielson, D. C. Cropping intensity impacts on soil aggregation and carbon sequestration in the Central Great Plains. *Soil Sci. Soc. Am. J.* **74**, 1712–1719 (2010).
5. Nielsen, D. C., Halvorson, A. D. & Vigil, M. F. Critical precipitation period for dryland maize production. *F. Crop. Res.* **118**, 259–263 (2010).
6. Cavigelli, M. A., Teasdale, J. R. & Conklin, A. E. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. *Agron. J.* **100**, 785–794 (2008).
7. Spargo, J. T., Cavigelli, M. A., Mirsky, S. B., Maul, J. E. & Meisinger, J. J. Mineralizable soil nitrogen and labile soil organic matter in diverse long-term cropping systems. *Nutr. Cycl. Agroecosystems* **90**, 253–266 (2011).
8. Macdonald, A. *et al.* Rothamsted Long-Term Experiments. *Rothamsted Research* **58** http://www.era.rothamsted.ac.uk/home/Web_LTE_Guidebook_2019.pdf (2019).
9. Blecharczyk, A., Sawinska, Z., Małecka, I., Sparks, T. H. & Tryjanowski, P. The phenology of winter rye in Poland: an analysis of long-term experimental data. *Int. J. Biometeorol.* **60**, 1341–1346 (2016).
10. Lehman, R. M., Osborne, S. L. & Duke, S. E. Diversified no-till crop rotation reduces nitrous oxide emissions, increases soybean yields, and promotes soil carbon accrual. *Soil Sci. Soc. Am. J.* **81**, 76–83 (2017).
11. Gonzalez-Andujar, J. L., Aguilera, M. J., Davis, A. S. & Navarrete, L. Disentangling weed diversity and weather impacts on long-term crop productivity in a wheat-legume rotation. *F. Crop. Res.* **232**, 24–29 (2019).
12. Hernández Plaza, E., Navarrete, L. & González-Andújar, J. L. Intensity of soil disturbance shapes response trait diversity of weed communities: The long-term effects of different tillage systems. *Agric. Ecosyst. Environ.* **207**, 101–108 (2015).
13. Hernanz, J. L., Sánchez-Girón, V., Navarrete, L. & Sánchez, M. J. Long-term (1983–2012) assessment of three tillage systems on the energy use efficiency, crop production and seeding emergence in a rain fed cereal monoculture in semiarid conditions in central Spain. *F. Crop. Res.* **166**, 26–37 (2014).
14. Gaudin, A. C. M. *et al.* Increasing crop diversity mitigates weather variations and improves yield

- stability. *PLoS One* **10**, 1–20 (2015).
15. Munkholm, L. J., Heck, R. J. & Deen, B. Long-term rotation and tillage effects on soil structure and crop yield. *Soil Tillage Res.* **127**, 85–91 (2013).
 16. Montemurro, F. Cropping systems: the role of continuous cropping, crop rotation, leguminous crops, and catch crop in Mediterranean conditions. in *Crop Rotation* (ed. Berklian, Y. U.) 141–171 (Nova Science Publishers, Inc., 2008).
 17. Montemurro, F. & Maiorana, M. Agronomic practices at low environmental impact for durum wheat in Mediterranean conditions. *J. Plant Nutr.* **38**, 624–638 (2014).
 18. Montemurro, F. & Maiorana, M. Cropping systems, tillage and fertilization strategies for durum wheat performance and soil properties. *Int. J. Plant Prod.* **8**, 52–75 (2014).
 19. Jończyk, K. & Martyniuk, S. Productivity of crop rotations and selected indicators of soil fertility in different types of ecological farms. *J. Res. Appl. Agric. Eng.* **62**, 153–157 (2017).
 20. Smith, R. G., Gross, K. L. & Robertson, G. P. Effects of crop diversity on agroecosystem function: Crop yield response. *Ecosystems* **11**, 355–366 (2008).
 21. Tiemann, L. K., Grandy, A. S., Atkinson, E. E., Marin-Spiotta, E. & Mcdaniel, M. D. Crop rotational diversity enhances belowground communities and functions in an agroecosystem. *Ecol. Lett.* **18**, 761–771 (2015).
 22. Kumar, S., Kadono, A., Lal, R. & Dick, W. Long-Term No-Till Impacts on Organic Carbon and Properties of Two Contrasting Soils and Corn Yields in Ohio. *Soil Sci. Soc. Am. J.* **76**, 1798–1809 (2012).
 23. Martinez, S., Gabriel, J. L., Alvarez, S., Capuano, A. & Mar Delgado, M. Del. Integral assessment of organic fertilization on a camelina sativa rotation under mediterranean conditions. *Agric.* **11**, 1–18 (2021).
 24. Coulter, J. A. *et al.* Agronomic performance of cropping systems with contrasting crop rotations and external inputs. *Agron. J.* **103**, 182–192 (2011).
 25. Porter, P. M., Huggins, D. R., Perillo, C. A., Quiring, S. R. & Crookston, R. K. Organic and other management strategies with two- and four-year crop rotations in Minnesota. *Agron. J.* **95**, 233–244 (2003).
 26. Bergkvist, G. & Öborn, I. Long-term field experiments in Sweden - what are they designed to study and what could they be used for? *Asp. Appl. Biol.* **113**, (2011).
 27. Sindelar, A. J., Schmer, M. R., Jin, V. L., Wienhold, B. J. & Varvel, G. E. Crop rotation affects corn, grain sorghum, and Soybean yields and nitrogen recovery. *Agron. J.* **108**, 1592–1602 (2016).
 28. Wienhold, B. J. *et al.* Cropping system effects on soil quality in the Great Plains: synthesis from a regional project. *Renew. Agric. Food Syst.* **21**, 49–59 (2006).
 29. Martyniuk, S., Gajda, A. & Kuś, J. Microbiological and biochemical properties of soils under cereals grown in the ecological, conventional and integrated system. *Acta Agrophysica* **52**, 185–192 (2001).

30. Morari, F., Lugato, E., Berti, A. & Giardini, L. Long-term effects of recommended management practices on soil carbon changes and sequestration in north-eastern Italy. *Soil Use and Management* **22**, 71–81 (2006).
31. Bonciarelli, U., Onofri, A., Benincasa, P., Farneselli, M., Guiducci, M., Pannacci, E., Tosti, G., Tei, F. Long-term evaluation of productivity, stability and sustainability for cropping systems in Mediterranean rainfed conditions. *Eur J Agron* **77**, 146–155 (2016).
32. Grover, K. K., Karsten, H. D. & Roth, G. W. Corn grain yields and yield stability in four long-term cropping systems. *Agron. J.* **101**, 940–946 (2009).
33. Watson, C. A. *et al.* Influence of ley duration on the yield and quality of the subsequent cereal crop (spring oats) in an organically managed long-term crop rotation experiment. *Org. Agric.* **1**, 147–159 (2011).
34. Drury, C. F. & Tan, C. S. Long-term (35 years) effects of fertilization, rotation and weather on corn yields. *Can. J. Plant Sci.* **75**, 355–362 (1995).
35. Gregorich, E. G., Drury, C. F. & Baldock, J. A. Changes in soil carbon under long-term maize in monoculture and legume-based rotation. *Can. J. Soil Sci.* **81**, 21–31 (2001).
36. Woodley, A. L. *et al.* Long-term Cropping Effects on Partitioning of Water Flow and Nitrate Loss between Surface Runoff and Tile Drainage. *J. Environ. Qual.* **47**, 820–829 (2018).
37. Barton, K. MuMIn: Multi-Model Inference. (2020).