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Supplementary Materials for

Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms

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Other Supplementary Materials for this manuscript include the following:
(available at www.sciencemag.org/content/351/6271/387/suppl/DC1)

Database S1

Materials and Methods

Experimental design

We sampled 344 fields of 33 crop systems in 12 countries (fig. S1 and table S1). Crop systems were defined as a given crop species, in a particular region and year, subject to similar management, except for flower-visitor density and richness (table S1). The crops considered include a wide array of annual and perennial fruit, seed, nut, and stimulant crops that are pollinator dependent to some degree. Crops pollinated primarily by wind or autonomous self-pollination were not studied. Crop systems were selected to represent the spectrum of management practices (traditional, intensive agriculture, organic agriculture), landscape settings (cleared, simple, complex landscapes), crop species, crop varieties (growth form, breeding system, pollinator dependence), abiotic and biotic variables, and we also included crops in their native and non-native (exotic crops) range. Some crops were sampled for one year, whereas others were sampled for up to three years, depending on the funding of each research partner (table S1). Fields were selected to encompass the environmental and management realities of the different producers within each crop system. Sampling plots were selected within each field following the same protocol *(18)* in all crop systems.

Variables

In multiple fields of each of the 33 animal-pollinated crop systems, we measured flower-visitor density, flower-visitor richness, and crop yield using the same protocol in landscapes dominated by small- or large-holdings *(18)*. All these variables were measured in the same plots (50 x 25 m), located in the center of small fields, and halfway between the center and border of large fields. Given that we measured crop yield in several entire plants or plots per field subjected to open pollination, our results properly represent average field conditions and are not biased by resource translocation within the plants to different flowers *(18)*. The same harvesting method was employed within each crop system. Our focus on crop yield at a relevant farmer level (kg ha^{-1}) prevents the use of hand pollination as a way to achieve maximum pollination because it is practically impossible for most crops to hand pollinate all the flowers of a plant. Furthermore, hand pollination typically is performed with pure pollen sources from a compatible individual, with pollen capable of successfully fertilizing the ovum of the female flower. Under natural conditions, however, pollinators deposit a mix of pollen from various sources, including the same individual or other individuals of the same variety *(30)*. Therefore, hand pollination may represent an unattainable goal under natural conditions, leading to estimates of pollen deficits that are not relevant for natural management or economic crop production. The pollination treatment to assess deficits was thus performed indirectly by manipulating the flower-visitor fauna.

Flower-visitor density was measured by scan sampling a fixed number of open floral units (hereafter "flowers") in each of four subplots in each field, on at least four dates during the main flowering period. By using the same protocol, we could express density directly as no. of visitors in 100 crop flowers, avoiding standardizations to integrate results from different crop systems. Flower-visitor species richness was measured by netting all visitors along six 25 m long and 2 m wide transects for herbaceous crops (or six pairs of adjacent trees for orchard crops) for 5 minutes per transect. This gives 30 minutes of active net sampling per field, with the clock stopped each time a captured insect is being handled, which implies at least two hours considering active sampling plus insect handling, further repeated on at least four dates during the main flowering period (i.e. 8 hours per field). Taking into account that the flowering period of most crops lasts only two or three weeks and that researchers need to sample several sites on the same date when weather is favorable, we consider this to be a high sampling effort. A few research partners sampled more than six transects per field. In these cases, we randomly sampled six transects to express the number of species per field in 30 minutes of net sampling and ensure that all sites were at a comparable level of sampling effort.

We also gathered information on several other potential predictor variables (table S1), including (a) the level of conventional intensification, a quantitative index ranging from -3 to 5, constructed as the balance between 5 variables of conventional intensification each adding 1 to the index (presence of monoculture, synthetic fertilizers, herbicides, pesticides, and fungicides) and 3 agroecological variables each adding -1 to the index (presence of polyculture, organic certification, and organic fertilizers); (b) isolation from semi-natural or natural habitats ($\log_{10}$ km; we classified natural habitats as in *(31)*); (c) crop pollinator dependence (%), based on *(32)*, which was updated with information from pollinator exclusion experiments on local varieties when available; (d) latitude (decimal degrees); (e) longitude (decimal degrees); (f) baseline level of flower-visitor density (10^{th} percentile: no. 100 flowers^{-1}); (g) yield gap ($10^{th}/90^{th}$ percentile); and (h) flower-visitor gap ($10^{th}/90^{th}$ percentile).

Statistical analyses

Crop yield ($\log_{10}$ kg ha^{-1}) was modeled through a general linear mixed-effects approach in R software (version 2.15.1, lme4 package, lmer function, Gaussian error distribution). Mixed-effects models produce similar results to Bayesian hierarchical models when uninformative priors are employed, especially with large samples, as in our case *(33–36)*. Fixed-effects included flower-visitor density (no. flower visitors in 100 flowers), flower-visitor richness (no. species in 30 minutes), field size ($\log_{10}$ ha), their two-way interactions, and their three-way interaction. When a two-way interaction is significant, it means that both predictor variables have an effect on the response variable. There is no need for a main effect to be significant. Indeed, as stated throughout statistical literature (e.g. see pages 718-720 in *(37)*), when interactions are present, interpreting main effects in isolation is misleading, as the effect of one predictor on the response variable depends on the level of the other predictor. Similarly, when a three-way interaction is present, such in our case (table S3), interpreting two-way interactions or main effects in isolation could be misleading. Finally, the hierarchical data structure (fields nested within crop systems) was accounted for by including crop system as a random-effect. In particular, our model estimated different intercepts and slopes of the influences of flower-visitor density and richness for each crop system.

Based on the corrected Akaike's Information Criterion (AICc), we selected the best model, after evaluating the models resulting from all possible combinations of the predicting variables (flower-visitor density, flower-visitor richness, and field size) and their interactions (MuMIn package, dredge function) *(38)*. We found no clear improvement (lower AICc) when considering curvilinear relations, and therefore we present only models with linear form. AICc values were obtained from maximum likelihood estimates of regression coefficients, whereas parameter estimates for final models were obtained using the restricted maximum likelihood method *(39)*. We also estimated R^2 based on the square of the Pearson's correlation coefficient between observed and predicted (considering both fixed- and random-effects) crop yields (table S3). To understand if observed responses in crop yield could be explained by environmental and management aspects that co-varied with flower-visitor density, flower-visitor richness, or field size (table S1), we added several co-variables to the previous mixed-effects model (see main text and Variables section above). We tested the Gaussian and homoscedasticity assumptions for the standardized residuals of the best model *(39)* and found that these assumptions were valid. Furthermore, we found no evidence of multicollinearity among predictor variables (table S3). We also performed the analyses with and without three potential outliers (i.e., the most extreme fields in terms of flower-visitor density) and our results remained the same.

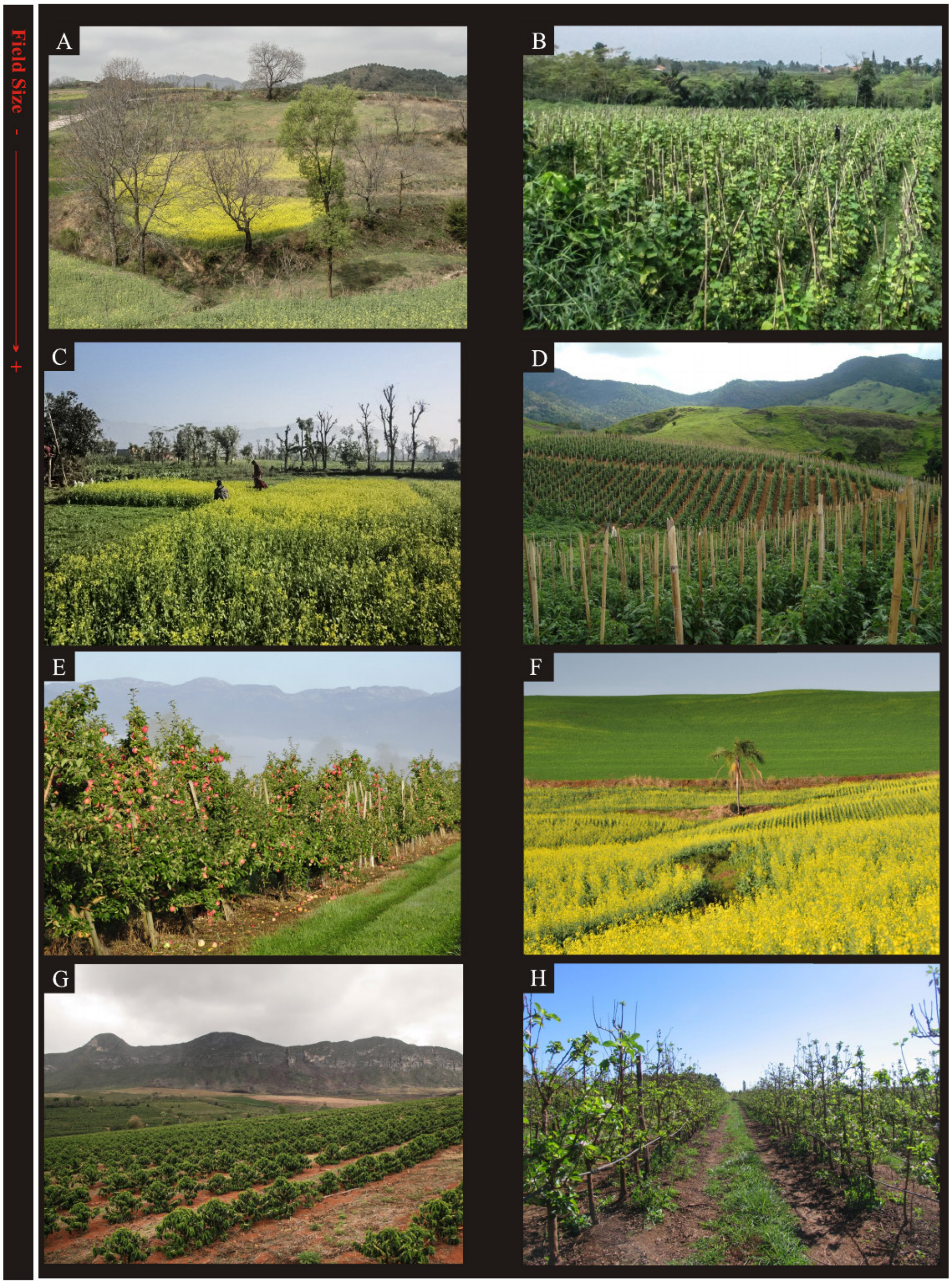

Fig. S1.

Examples of crop systems sampled in our study. (**A**) Turnip rape in China (0.12 ha), (**B**) Cucumber in Indonesia (0.16 ha), (**C**) Turnip rape and buckwheat in Nepal (0.30 ha), (**D**) Tomato in Brazil (1.05 ha), (**E**) Apple in Norway (2.58 ha), (**F**) Oil seed rape in Brazil (11 ha), (**G**) Coffee in Brazil (25 ha), (**H**) Apple in Brazil (43 ha).

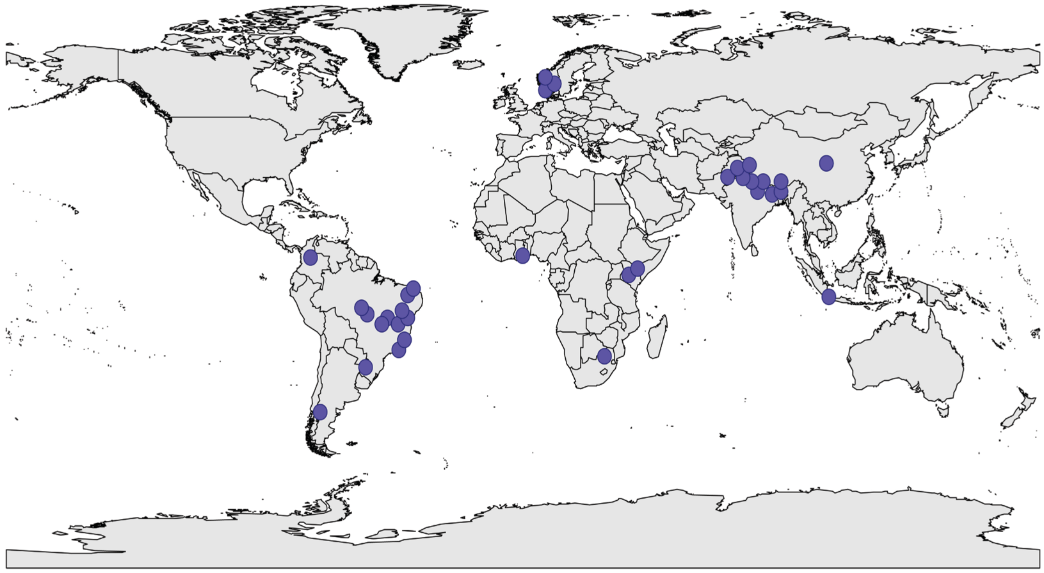

Fig. S2
Global distribution of the 33 crop systems.

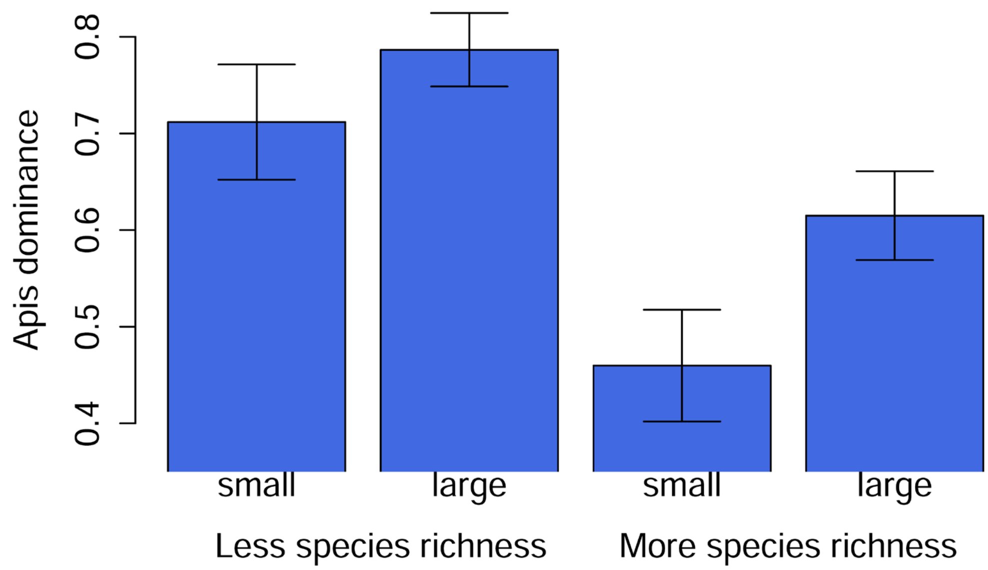

Fig. S3

Worldwide, larger holdings (≥ third quartile: 14 ha) have greater dominance of *Apis* spp. than smaller holdings (≤ first quartile: 0.5 ha), regardless of species richness. Small *vs*. large holdings, and low *vs*. high richness, are categories only for graphical purposes, while a mixed-effects model adjusted to the logit transformation of *Apis* dominance considered field size and species richness as quantitative variables. This model included fields nested within crop systems, and random intercept and slopes for crop systems. The inclusion of a two-way interaction between field size and species richness did not improve model fit (i.e. lower AICc).

Table S1.

Characteristics of the crop systems sampled. Average values are provided for all variables. Dependence = pollinator dependence. HB = honey bee.

Crop (variety)	Scientific name	Country	Year	Pollinator management contrast within crop systems	no. of fields	Field size	Latitude	Longitude	Intensification	Isolation	Dependence
						ha	Decimal degrees		Index	km	%
Turnip rape (Tianyou)	*Brassica rapa*	China	2013	Isolation from natural areas	10	0.12	34.42	106.00	-0.20	1.1	65
French bean (Julia)	*Phaseolus vulgaris*	Kenya	2012	Hedge plants and flower patches in the cropland	10	0.15	0.10	37.13	2.00	0.3	5
Cucumber (Alicia)	*Cucumis sativus*	Indonesia	2013	Isolation from natural areas	9	0.16	-6.55	106.74	0.33	1.4	65
French bean (Julia)	*Phaseolus vulgaris*	Kenya	2011	Hedge plants and flower patches in the cropland	10	0.21	0.01	37.13	2.00	0.5	5
Turnip rape (Sarson)	*Brassica rapa*	India	2012	Isolation from natural areas	3	0.22	29.71	79.61	-2.00	0.4	65
Turnip rape (Sarson)	*Brassica rapa*	India	2011	Isolation from natural areas	6	0.26	29.66	79.62	-2.00	0.4	65
Raspberry (Autumn bliss)	*Rubus idaeus*	Argentina	2014	Isolation from natural areas, density of HB hives, landscape heterogeneity	16	0.29	-42.04	-71.52	0.56	0.2	25
Turnip rape (Pragati)	*Brassica rapa*	Nepal	2012	Isolation from natural areas and density of HB hives	10	0.30	27.66	84.53	2.20	2.1	65

Buckwheat (Local)	*Fagopyrum esculentum*	Nepal	2012	Isolation from natural areas	4	0.38	27.58	84.26	0.00	3.1	65
Tomato (Dominador, Gault, Lumi, CLX, Future)	*Solanum lycopersicum*	Brazil	2011	Isolation from natural areas	18	1.05	-21.41	-41.97	5.00	0.5	5
Apple (Royal delicious)	*Malus domestica*	India	2012	Isolation from natural areas	20	1.05	32.09	77.18	0.30	1.9	65
Apple (Royal delicious)	*Malus domestica*	India	2011	Isolation from natural areas	18	1.08	32.09	77.18	0.33	1.8	65
Agraz (Wild)	*Vaccinium meridionale*	Colombia	2013	Density of HB hives	5	1.20	5.55	-73.72	-2.00	0.0	65
Tomato (Dominador, Gault, Lumi, CLX, Future)	*Solanum lycopersicum*	Brazil	2010	Isolation from natural areas	18	1.31	-21.41	-41.97	5.00	0.4	5
Apple (Aroma)	*Malus domestica*	Norway	2013	Isolation from natural areas, density of HB hives, landscape heterogeneity	13	2.58	59.53	8.85	3.08	0.1	65
Large cardamom (Ramsey)	*Amomum subulatum*	India	2010	Landscape heterogeneity and intensity of forest disturbance	3	3.33	27.20	88.39	-1.33	1.3	95
Large cardamom (Ramsey)	*Amomum subulatum*	India	2011	Landscape heterogeneity and intensity of forest disturbance	3	3.33	27.20	88.39	-1.33	1.3	95
Large cardamom (Ramsey)	*Amomum subulatum*	India	2012	Landscape heterogeneity and intensity of forest disturbance	3	3.33	27.20	88.39	-1.33	1.3	95
Coffee (Catuai)	*Coffea arabica*	Brazil	2013A	Isolation from natural areas	12	6.23	-13.33	-47.34	-0.33	0.2	34

Red clover seed (Lea)	*Trifolium pratense*	Norway	2013	Isolation from natural areas, landscape heterogeneity, and sowing of flower strips	10	6.81	59.46	10.41	2.40	0.2	65
Red clover seed (Lea)	*Trifolium pratense*	Norway	2014	Isolation from natural areas, landscape heterogeneity, and sowing of flower strips	20	7.92	59.49	10.42	2.15	0.1	65
Oil seed rape (Hyola 61)	*Brassica napus*	Brazil	2011	Isolation from natural areas	6	11.00	-28.20	-54.54	5.00	0.2	25
Mango (White chaunsa)	*Mangifera indica*	Pakistan	2012	Isolation from natural areas and density of HB hives	35	12.35	30.29	71.58	0.74	7.5	65
Mango (Keit)	*Mangifera indica*	Ghana	2010	Isolation from natural areas and landscape heterogeneity	6	18.21	6.02	0,01	5.00	1.1	65
Cashew (CCP 76)	*Anacardium occidentale*	Brazil	2011	Isolation from natural areas	10	29.50	-4.10	-38.41	0.00	1.3	65
Cashew (CCP 76)	*Anacardium occidentale*	Brazil	2012	Isolation from natural areas	10	29.50	-4.10	-38.41	0.00	1.5	65
Apple (Eva)	*Malus domestica*	Brazil	2010	Density of Melipona and HB hives	8	43.00	-13.27	-41.42	5.00	0.7	65
Apple (Eva)	*Malus domestica*	Brazil	2011	Density of Melipona and HB hives	6	43.00	-13.27	-41.42	5.00	0.7	65
Apple (Eva)	*Malus domestica*	Brazil	2012	Density of Melipona and HB hives	5	43.00	-13.27	-41.42	5.00	0.8	65
Coffee (Catuai)	*Coffea arabica*	Brazil	2013B	Isolation from natural areas	18	45.52	-13.20	-47.40	3.94	0.3	34
Cotton (FM 910)	*Gossypium hirsuntum*	Brazil	2011	Isolation from natural areas	5	292.92	-11.88	-55.60	5.00	0.2	25

Cotton (FM 910)	*Gossypium hirsuntum*	Brazil	2012	Isolation from natural areas	5	292.92	-11.88	-55.60	5.00	0.2	25
Sunflower (PAN 7355)	*Helianthus annuus*	South Africa	2011	Isolation from natural areas	10	327.25	-24.98	28.49	2.00	1.9	25

Table S2.

Crop yield and flower-visitor density gaps (defined as the difference between 90 and 10th percentiles) observed across fields. Pollinator deficit is defined as the degree of yield gap that can be reduced by increasing flower-visitor density from the 10th to the 90th percentile according to our best mixed-effects model with co-variables (see main text, Fig. 1, and table S3). The benefits from increasing flower-visitor density varies according to field size, flower-visitor richness, and isolation from natural areas (table S3). Average yields (2012 and 2013) at the world and national levels from FAOSTAT. Some national yields were obtained from other sources (indicated with asterisk) when FAO's data were not available. NA = data not available.

Crop – Country – Year	Field size	Flower-visitor richness	Crop yield					Flower-visitor density				Pollinator deficit	
			World – National average	90th percentile	10th percentile	gap	ratio	90th percentile	10th percentile	gap	ratio		
	ha	no. species 30 min^{-1}	kg ha^{-1}				10th / 90th	no. in 100 flowers			10th / 90th	kg ha^{-1}	% of yield gap
Turnip rape – China – 2013	0.12	6.3	NA – 2800*	4887	2717	2170	0.56	4.10	1.40	2.70	0.34	449	21
French bean – Kenya – 2012	0.15	2.5	13759 – 9277	8423	3323	5100	0.39	11.20	4.32	6.88	0.39	589	12
Cucumber – Indonesia – 2013	0.16	2.5	33113 – 10081	28095	16300	11795	0.58	10.06	4.78	5.29	0.47	11641	99
French bean – Kenya – 2011	0.21	1.6	13759 – 9277	2843	964	1879	0.34	10.22	4.10	6.12	0.40	830	44

Turnip rape – India – 2012	0.22	2.7	NA – NA	12	7	5	0.55	5.83	3.68	2.15	0.63	0,4	7
Turnip rape – India – 2011	0.26	5.0	NA – NA	298	186	111	0.63	5.64	3.29	2.35	0.58	16	14
Raspberry – Argentina – 2014	0.29	3.3	5784 – 4500*	6890	2801	4089	0.41	16.72	6.06	10.66	0.36	3209	78
Turnip rape – Nepal – 2012	0.30	2.7	NA – NA	881	476	405	0.54	10.13	5.92	4.21	0.58	229	57
Buckwheat – Nepal – 2012	0.38	2.8	975 – 955	599	409	190	0.68	5.36	3.28	2.08	0.61	86	45
Apple – India – 2012	1.05	3.9	15239 – 6491	49027	17285	31742	0.33	7.09	2.97	4.12	0.42	11581	36
Tomato – Brazil – 2011	1.05	4.6	33701 – 63734	63000	43500	19500	0.69	1.81	0.32	1.49	0.18	5085	26
Apple – India – 2011	1.08	3.6	15239 – 6491	45491	14284	31208	0.31	4.68	1.10	3.58	0.24	6694	21
Agraz – Colombia – 2013	1.20	3.9	Fruit collection from wild plants	0,70	0,18	0,52	0.26	7.41	4.52	2.90	0.61	-0,2	-37
Tomato – Brazil – 2010	1.31	3.2	33701 – 63734	74200	50000	24200	0.67	0.92	0.23	0.69	0.25	2725	11
Apple – Norway – 2013	2.58	2.4	15239 – 7427	50598	12915	37683	0.26	2.13	0.78	1.35	0.37	2073	6

Large cardamom – India – 2010	3.33	5.3	NA – 219*	487	243	244	0.50	5.99	4.54	1.45	0.76	46	19
Large cardamom – India - 2011	3.33	5.8	NA – 219*	509	244	265	0.48	7.95	4.00	3.95	0.50	115	43
Large cardamom – India - 2012	3.33	5.8	NA – 219*	384	219	165	0.57	3.75	2.65	1.10	0.71	30	18
Coffee – Brazil – 2013 A	6.23	0.1	896 – 1427	1910	799	1111	0.42	8.83	0.49	8.34	0.06	-130	-12
Red clover seed – Norway – 2013	6.81	4.4	NA – NA	795	485	310	0.61	1.74	0.74	1.00	0.43	10	3
Red clover seed – Norway – 2014	7.92	4.3	NA – NA	949	456	493	0.48	2.55	1.12	1.42	0.44	20	4
Oil seed rape – Brazil – 2011	11.00	1.8	1939 – 1426	6370	2745	3625	0.43	2.39	1.92	0.47	0.80	16	0
Mango – Pakistan – 2012	12.35	6.2	7870 – 9769	8920	6410	2510	0.72	0.14	0.06	0.08	0.44	112	4
Mango – Ghana – 2010	18.21	2.4	7870 – 12700	15548	1586	13961	0.10	15.42	8.36	7.06	0.54	2824	20
Cashew – Brazil – 2011	29.50	1.6	809 – 132	51	7	43	0.14	0.71	0.48	0.24	0.67	0	0

Cashew – Brazil – 2012	29.50	1.6	809 – 132	104	32	72	0.31	0.83	0.54	0.29	0.65	-1	-1
Apple – Brazil – 2010	43.00	1.8	15239 – 33398	15633	5903	9730	0.38	10.20	4.19	6.01	0.41	-2208	-23
Apple – Brazil – 2011	43.00	1.0	15239 – 33398	39537	21357	18180	0.54	7.69	4.33	3.36	0.56	-2312	-13
Apple – Brazil – 2012	43.00	1.2	15239 – 33398	40770	20124	20646	0.49	3.42	1.90	1.52	0.56	-257	-1
Coffee – Brazil – 2013 B	45.52	0.1	896 – 1427	1749	400	1349	0.23	2.43	0.43	2.01	0.17	-254	-19
Cotton – Brazil – 2011	292.92	0.7	783 – 1347*	5464	3042	2423	0.56	0.68	0.10	0.58	0.15	-380	-16
Cotton – Brazil – 2012	292.92	0.2	783 – 1347*	5560	4234	1326	0.76	0.08	0.00	0.08	0.00	-72	-5
Sunflower - South Africa – 2011	327.25	8.0	1623 – 1181	1541	763	778	0.50	2.40	0.67	1.73	0.28	942	121

*Alternative sources for national yield averages:
Turnip rape-China: *(40)*
Raspberry-Argentina: *(41)*
Cardamom-India: *(42)*
Cotton-Brazil: *(43)*; WORLD: *(44)*

† Kg per plant for Agraz because it is not cultivated as a crop but harvested as wild.

Table S3.

Akaike's Information Criterion (AIC), corrected AIC (AICc), and fixed effects (standard errors in parentheses) for mixed-effects models of the influences on crop yield (all effects tested are listed). The best models were derived from comparing AICc values of all possible combinations of predicting variables with or without co-variables (see methods). In bold, values for which the 95 % confidence interval do not overlap with zero. The table shows a significant Density x Richness x Field size interaction, which means that the three variables are relevant predictors of crop yield. It also implies that two-way interactions and main effects should be retained in the best model but cannot be interpreted in isolation. Fixed-effect values and their standard errors for Density, Richness, and Field size are very similar in models with and without co-variables showing their independent effects on crop yield. Highest Variance Inflation Factor (VIF_{max}) observed across all the variables of each model shows absence of multicollinearity. The magnitude of the fixed effects cannot be compared among predictor variables because they are expressed in different units.

	Best without co-variables	**Best with co-variables**
AIC	45	24
AICc	46	26
R^2	0.972	0.974
VIF_{max}	2.3	2.5
Intercept	**3.1 (0.21)**	**1.6 (0.52)**
Flower-visitor density (no. 100 flowers^{-1})	0.0089 (0.012)	0.019 (0.012)
Flower-visitor richness (no. species 30 min^{-1})	0.012 (0.015)	0.012 (0.017)
Field size (log_{10} ha)	**0.16 (0.055)**	**0.12 (0.056)**
Density x Richness	0.0014 (0.0032)	0.0018 (0.0032)
Density x Field size	**-0.039 (0.011)**	**-0.033 (0.011)**
Richness x Field size	**-0.026 (0.012)**	-0.018 (0.012)
Density x Richness x Field size	**0.0093 (0.0030)**	**0.0071 (0.0030)**
Co-variables		
Intensification (index)		**0.043 (0.014)**
Isolation (km)		**-0.087 (0.027)**
Pollinator dependence (%)		
Latitude (decimal degrees)		
Longitude (decimal degrees)		
Baseline level of flower-visitor density (10th percentile: no. 100 flowers^{-1})		
Yield gap (%)		
Flower-visitors gap (%)		**0.025 (0.0087)**
Density x Intensification		
Density x Isolation		**0.017 (0.0056)**
Density x Pollinator dependence		

Density x Latitude
Density x Longitude
Density x Baseline flower-visitor density
Density x Yield gap
Density x Flower-visitors gap

Additional Data table S1 (separate file)

Database_S1.txt: Data used in the analyses of this article.

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