Moderate pollination limitation in some entomophilous crops of Europe

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Abstract

Pollination services to crops may be worsening because of declines in farmland pollinators, but the consequences for yields have been uncertain. We therefore investigated pollination limitation in four entomophilous crops (oilseed rape, sunflower, pears and pumpkin) by quantifying the difference in harvestable mass between open-pollinated and saturation-pollinated (hand-pollinated) flowers. We also examined whether pollination limitation in the four crops was associated with the number of flower visits by insects. Across 105 commercial fields in six European countries, the average decrease in harvestable mass due to pollination limitation was 2.8% (SE = 1.15). Among crops, the highest decreases were in sunflowers (8%) and in one of three oilseed rape production regions (6%). We observed substantial variation among crops in the numbers of insect visits received by flowers, but it did not significantly correspond with the levels of pollination limitation. Our results suggest that yields in these crops were not severely pollination-limited in the regions studied and that other factors besides visitation by pollinators influenced the degree of pollination limitation.

Keywords: agroecology; pollinators; crop yield; landscape ecology; pollination; entomophilous crops

1. Introduction

Crops with entomophilous flowers such as oilseeds, squash and orchard fruits are important to food security and the farming economy (Losey and Vaughan, 2006). Entomophilous flowers typically have showy petals and offer nectar and/or pollen to visiting insects, which act as pollinators. Among insects, bees are a principal pollinator of many entomophilous crops and their declines in farmland of north western Europe and eastern North America are a cause of concern (Potts et al., 2016) because crop yields might become threatened by pollination limitation (IPBES 2016; Dainese et al. 2019). Pollination limitation is widespread among wildflowers (Wolowski et al., 2014), but its levels in many crops have been uncertain (Klein et al., 2007). We therefore conducted pollen supplementation experiments in commercial fields to quantify pollination limitation in some of the main entomophilous crops grown in Europe.

We conducted experiments on four entomophilous crops from three product classes (oilseeds, squash and orchard fruit) in regions of six countries (Estonia, Germany, Italy, the Netherlands, Switzerland, and the United Kingdom). Specifically, we measured pollination limitation and the number of insect visits received by flowers in: oilseed rape, *Brassica napus* L.; sunflower, *Helianthus annuus* L.; Hokkaido pumpkin, *Cucurbita maxima* Duch.; and Conference pear, *Pyrus communis* L. The objectives of our study were: (1) to determine the levels of pollination limitation in various crops and regions; and (2) to examine the association between the pollination limitation and the number of insect visits received by flowers in crop fields.

2. Methods

We studied crops of oilseed rape in Estonia, Switzerland and the United Kingdom, sunflower in Italy, pumpkin in Germany and pear in the Netherlands. In each of these six countries in

2014, we studied 18 fields in a single region with representative commercial practice, field sizes and that ranged from low to high levels of semi-natural habitat for the region (Appendix S1.1). The proportion of the main types of semi-natural habitat in a 1 km radius around each field were mapped (Table S1.1). In each field, we quantified pollination limitation by comparing the harvestable mass of pollen-saturated and open-pollinated flowers. Specifically, we estimated pollen limitation as the proportional decrease in harvestable mass observed in open-pollinated flowers relative to saturation-pollinated flowers:

$$\textit{pollen limitation} = 100 \times [1 - (M_{\text{open}} / M_{\text{supplemented}})]\ \% \qquad \text{eq 1}$$

Focal flowers were located on plants situated along a transect perpendicular to one of the field's edges and these experimental plants were located on the transect at four well-separated distances (Appendix S1). To minimize the influence of the other field boundaries on transects, the distance between the end of the transects and non-focal field boundaries had to be at least 1.25 times the length of the transect (Bartual et al., 2018).

In each field of sunflower and oilseed rape, outcross pollen was collected from at least five donor flowers, mixed and applied to receptive stigmas on different plants with a soft brush. In pear, a commercial pollen mix (Wellplus Co., Daejeon, Korea) was used to pollinate flowers. Flowers of oilseed rape and pear were hand-pollinated with a single dose whereas in sunflower the many receptive florets of each capitulum were hand-pollinated over three to five occasions at two-day or three-day intervals. In oilseed rape and sunflower, we quantified harvestable mass by the dry mass of mature seed produced per flower (oilseed rape) or capitulum (sunflower). In pears, we quantified the mass of the fruit produced by each experimental flower at the time appropriate to the commercial harvest. In Hokkaido pumpkin, we estimated harvestable mass by quantifying the pollen that had accumulated on stigmas of focal flowers and transforming to expected fruit mass using an experimentally established pollen-fruit mass relationship (Pfister *et al.*, 2017). Each pumpkin flower bloomed for only a few hours and we collected stigmas in the afternoon from senescent flowers which had opened that morning before counting the pollen in a microscope preparation (Pfister et al., 2017). Pollination limitation of each pumpkin flower was estimated by subtracting the estimated fruit mass from its maximum value, which was determined by saturating pollinations (Pfister et al. 2017). The numbers of replicate flowers (hand-pollinated, open-pollinated) in each of the 18 focal fields were: sunflower (8, 32); pear (5, 5); pumpkin (0, 32); oilseed rape: Estonia (16, 96), Switzerland (8, 8) and the United Kingdom (8, 8). To avoid pseudoreplication, we used the mean level of pollination limitation in each field for statistical analysis.

2.1 Estimating insect visits per flower

We quantified pollinator visitation by estimating the overall number of insect visits received by a receptive flower (Cresswell, 2008). In each field, we studied the insects visiting crop flowers, including bees, syrphids and other flies, and lepidopteran species during fine weather in 2014. In oilseed rape at each distance along the transect in each field, we recorded the total number of flowers probed by insects over 10-minute intervals in at least two 2 × 2 m quadrats and we also estimated the area density of flowers (i.e. flowers per m^2) for $10m^2$. We thereby calculated the expected number of insect visits per receptive flower for each field by assuming that flowers were receptive for 8 h d^{-1} × 2.7 d (Bell and Cresswell, 1998). Observations were made in 18 fields per country either once (United Kingdom: 14th-16th April) or twice (Estonia: 16th May, 6th June; Switzerland: 22nd-24th April, 5th-6th May). In sunflower (Italy), observations were made over 10 minutes in two replicate quadrats each containing four capitula. Observations were made in the 18 fields twice on separate days during peak bloom (capitula having >30% of florets open) between 24th June and 16th of July. Based on the observed visit rates, we estimated the expected number of insect visits per receptive flower by assuming that each floret in a capitulum was receptive for 8 h d^{-1} × 4 d (OECD, 2005). In pumpkin, we used video cameras (Sony HDR-CX115E, Sony Corporation, Tokyo, Japan) to record the activity of flower visitors. Each field was sampled at each one time period on three different days in July during the flowering period, once at 7:00, 8:30 and 10:00 am. On each occasion, four 15-minute-long videos, one at each 2, 10, 18 and 26 m transect, each surveying a different female pumpkin flower. We calculated mean visit rates for each field and calculated the expected number of visits received by a receptive flower by assuming that it was receptive for 4 h (Pfister et al., 2017). In pear, we observed clusters of approximately 500 flowers on a single branch and counted the number of insects that visited it during a 10-minute period. In each field (orchard) we conducted four replicate observations on one day between 2nd and 10th of April. The exact number of flowers visited by each insect was not recorded but it never exceeded 10, so we estimated per-flower visitation rates by assuming that insects visited either 10 flowers on the cluster or only a single flower. We thereby calculated the number of visits received by a receptive flower under each scenario (i.e. ‘probe-one flower’ or ‘probe-all flowers’ per cluster) by assuming that the duration of a flower’s receptivity was 8 h d^{-1} × 6.6 d.

3. Results

We found a moderate but significant level of pollination limitation across 105 commercial fields that produced data (mean = 2.8% of harvestable mass in supplemented flowers, SEM = 1.15; test H_0: $\mu = 0$ using standardized deviate on a normal distribution, $z = 2.3$, $P < 0.05$). Regionally, we detected pollination limitation in sunflower crops in Italy (c. 8%) and oilseed rape crops in Switzerland (c. 6%) (Fig. 2a). Western honey bees (*Apis mellifera* L.), thereafter honey bees, or flies were the dominant flower visitors in all regions (Appendix S2) and the number of insect visits received by flowers varied over ten thousand-fold among crops and regions (Fig. 2b). We estimate that sunflower capitula and pumpkin flowers each received more than 100 insect visits (principally bumblebees *Bombus* spp. and honey bees) during their receptive phase (Fig 2b). By contrast, in oilseed rape it appears that less than 10% of flowers received even a single insect visit (Fig. 2b). The variation in insect visitation did not correspond with the levels of pollination limitation (Fig. 2a).

4. Discussion

Our results show that the harvestable mass of individual flowers in crop fields was moderately depressed by pollen limitation (mean decrease = 2.8%). This finding is probably conservative because pollen supplementation overestimates pollination limitation if plants divert limited resources to well-pollinated flowers (Knight et al., 2006), but resource-limitation seems unlikely in well-fertilized crop fields. Therefore, our assays appear likely to have quantified pollination limitation among the flowers generally and hence indicate potential impacts on overall crop yields. If so, our findings suggest that the crop pollination systems that we studied were underperforming only slightly despite recent bee declines in some European countries (IPBES, 2016).

4.1 The influence of crop-specific factors on pollination

Among the focal crops, levels of pollination limitation were unrelated to the intensity of flower visitation by insects, which suggests the influence of crop-specific factors such as the pollination efficacy of the single pollinating species. We therefore discuss each crop separately below.

4.1.1 Sunflower

Sunflower fields were intensively visited by honey bees (a capitulum apparently received over 100 visits each day, on average), but the crop did not achieve full seed set. Commercial cultivars of sunflower often have a high level of pollinator-dependence (Bartual et al., 2018), but we speculate that pollination by honey bees was incomplete despite their high rate of flower visitation because either individual bees probed only a minority of receptive florets while visiting each inflorescence or their contacts with the sexual parts of the florets were not fully effective.

4.1.2 Oilseed rape

We found little pollination limitation in winter-sown oilseed rape despite low levels of insect visitation to flowers. Likewise, in field trials in the UK there was no effect on yield of pollinator exclusion (Garratt et al., 2018). In contrast, insect pollination in winter-sown oilseed rape in France contributed about 30% to crop yields, determined using pollinator exclusion, potentially because the area had a rich wild bee community (Perrot et al., 2018). Pollinators are normally scarce in the spring-flowering oilseed rape fields of northern Europe where they appear to pollinate no more than two thirds of the flowers, on average (Hoyle et al., 2007; Appendix S3), although was <10% in this study. Instead, pollination occurs through flower-to-flower collisions among windblown plants (Hayter and Cresswell, 2006). The regional differences in pollination limitation of oilseed rape may have originated from the differential efficacy of this wind-facilitated pollination, which could be due to variation among local plant varieties (stem flexibility) (Hudewenz et al., 2014), sowing regimes (plant density) or weather (wind speeds) that affected the intensity of wind-sway by plants in the crops. In spring-sown oilseed rape, which blooms in summer, rates of flower visitation by insects are substantially higher than in winter-sown fields (Hayter and Cresswell, 2006). Spring-sown crop varieties also show substantive levels of pollinator dependence (e.g. Lindström et al., 2016).

4.1.3 Pears

We found that Dutch pear orchards varied in the level of pollination limitation, but with no overall deficit in the region on average, perhaps because yields were buffered against low numbers of pollinator visits by the capacity of pear to produce fruit by spontaneous parthenocarpy (Quinet and Jacquemart, 2015).

4.1.4 Pumpkin

We found no evidence of pollination limitation in German pumpkin fields because the intense activities of honey bees and bumble bees saturated the pollen requirements of flowers (Pfister *et al.*, 2017, 2018).

4.2 Strategies for sustaining and enhancing pollination

The female pumpkin flowers in the fields that we studied were saturated by pollen deliveries made principally by honey bees and bumble bees, which are effective pollinators of pumpkin. Pollination services to these pumpkin fields can be sustained by assuring the future abundance of these bees. The sunflowers in the fields that we studied were visited intensively by honey bees, but nevertheless seed set was pollination-limited. The basis for the pollination limitation is unclear, but potentially it could be remedied either by encouraging the most effective wild insect pollinators (Blaauw and Isaacs 2014; Sutter et al., 2018) or by reducing the pollinator-dependence of the crop, which might involve using varieties with higher levels of autonomous self-pollination. In the pear orchards that we studied, insects apparently visited flowers at rather marginal rates and fruit mass was pollination-limited in some orchards, which suggests that some growers may benefit from boosting pollinator abundance. In the studied oilseed rape fields, insects appeared to visit flowers rather rarely and pollination limitation occurred in only one of three regions, which suggests that the crop has low pollinator-dependence in some instances. The earliness of flowering in relation to wild pollinator peak activity may limit improving winter oilseed rape pollination, however, there is evidence insect pollination was higher where there was a rich bee community, especially solitary bees (*Lasioglossum* spp.) (Perrot et al., 2018) and where flower-rich habitats were adjacent to oilseed rape fields and levels of greening measures were high (Sutter et al., 2018). In regions with low pollination potential growers may benefit from using crop varieties with lower pollinator-dependence or introduce honey bees for open-pollinated cultivars, as they were shown to increase yields by 11% (Lindström et al., 2015).

The proportion and types of semi-natural habitat in the landscape can influence the levels of pollinators and thereby pollination (Martins et al., 2014), although the proportion of crops can also be more important (Pfister et al., 2017). These studies were conducted in landscapes that encompassed a range of landscape compositions to provide a representative sample of what occurs. Further analyses to examine the role of landscape composition are planned.

Our findings indicate that pollination limitation in entomophilous crops is influenced by at least two factors besides the availability of pollinator visits. First, mechanisms of non-insect pollination can compensate for flower visitation by pollinators, as exemplified by the oilseed rape fields in Estonia and the United Kingdom. Second, plant traits can reduce the effectiveness of even high levels of pollinator activity, as exemplified by the sunflower fields in Italy. Taken together, our study suggests that strategies for reducing pollination limitation in crops require an integrated understanding of both pollinators and the plants that they pollinate. Such knowledge will help to better target ecological intensification efforts and other measures of integrated pollination management to minimize pollination limitation due to shortage in suitable insect pollinators.

5. Conclusions

Overall, our study supports two main conclusions: (1) pollination limitation existed at moderate although economically significant levels for some crops in Europe; and (2) the levels of pollination limitation in crops did not show a clear relation with levels of in-field insect activity, which suggests the importance of other factors such as the efficacy of the dominant pollinator species or level of autonomous self-pollination.

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Datasets

Data used in this study is available at the Open Research Exeter archive, *https://ore.exeter.ac.uk/repository/handle/####*

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SUPPLEMENTAL INFORMATION

APPENDIX S1: Locations and attributes of focal fields

Country	Latitude	Longitude	Crop	Variety	Production system (Conventional or organic)	Sowing date	Adjacent boundary type	Field size (ha)	% SNH in 1km radius	% Woody areal	% Woody linear	% Herbaceous areal	% Herbaceous linear	% Fallow
UK	-1.17090	51.10840	WOSR	Imagine	Conventional	28.08.13	HL	16.22	26.4	1.1	22.5	0.8	2.0	0.0
UK	-1.25210	51.12910	WOSR	Trinity	Conventional	26.08.13	WA	5.89	29.7	22.5	2.7	2.8	1.7	0.0
UK	-1.20580	51.11890	WOSR	Dk Cabernet	Conventional	22.08.13	WL	9.2	7.4	2.0	3.4	0.0	2.0	0.0
UK	-1.08160	51.07010	WOSR	Algria	Conventional	22.08.13	WL	6.92	14.2	9.9	2.5	0.3	1.6	0.0
UK	-1.54400	50.58260	WOSR	*	Conventional	*	HL	*	12.0	7.6	2.9	0.2	1.3	0.0
UK	-1.56170	50.56610	WOSR	Dk Camelot	Conventional	19.08.13	WA	14.82	21.1	18.7	2.0	0.1	0.4	0.0
UK	-01.09430	51.18830	WOSR	*	Conventional	*	HL	*	14.4	6.9	2.3	3.5	1.8	0.0
UK	-0.599410	51.06200	WOSR	Quartz	Conventional	27.07.13	WL	13.6	14.9	11.3	1.6	0.6	1.4	0.0
UK	-01.10590	51.02940	WOSR	PR46	Conventional	30.09.13	WA	6.61	16.4	12.7	2.3	0.0	1.4	0.0
UK	-02.00040	50.59410	WOSR	PR46W21	Conventional	28.08.13	WA	23.55	18.2	15.5	1.0	0.9	0.8	0.0
UK	-01.31840	51.09760	WOSR	*	Conventional	*	HL	*	8.3	5.6	0.9	0.7	1.1	0.0
UK	-01.51130	51.06390	WOSR	Expower	Conventional	08.09.13	HL	13.8	5.0	2.8	1.3	0.6	0.4	0.0
UK	-01.55430	51.05530	WOSR	*	Conventional	27.08.13	HL	16.1	4.9	2.5	1.2	0.6	0.7	0.0
UK	-01.10380	51.15870	WOSR	*	Conventional	*	WA	*	13.6	9.5	1.4	0.9	1.8	0.0
UK	-01.18010	51.17690	WOSR	Compass	Conventional	13.08.13	WL	16.65	12.9	8.9	1.7	0.8	1.6	0.0
UK	-01.48470	50.58250	WOSR	Marathon	Conventional	09.09.13	WA	20	17.0	13.8	2.1	0.0	1.1	0.0
UK	-02.01610	50.57500	WOSR	Charger	Conventional	28.08.13	WL	17.2	3.0	0.9	0.9	0.7	0.6	0.0
UK	-01.24590	51.11050	WOSR	Trinity	Conventional	27.08.13	WL	28.25	10.4	6.0	1.4	0.7	2.4	0.0
DE	N28897094405966	E41824635107227	Pumpkin	uchiki kuri	conventional	Sown 21/05/2014	CO	3	31.9	3.2	3.7	22.5	2.5	0.0
DE	N28880130949476	E4182932.8450030	Pumpkin	uchiki kuri	organic	Sown 30/04/2014	CO	4	5.0	0.0	2.8	0.6	1.6	0.0
DE	N28858438281958	E4186108.7754959	Pumpkin	uchiki kuri	organic	Sown 10/04/2014	HA	0.6	32.9	1.2	6.3	23.8	1.6	0.0
DE	N28876594677794	E4185213.0350074	Pumpkin	red kuri	organic	Sown 05/05/2014	WL	3.5	7.4	0.0	2.3	3.2	2.0	0.0
DE	N28896939315979	E4188046.0043662	Pumpkin	orange summer	organic	Planted 11/04/2014	HL	1.2	47.7	24.2	3.9	17.8	1.8	0.0
DE	N28887377049073	E4190082.5331985	Pumpkin	uchiki kuri	organic	Planted 04/04/2014	CO	6	22.0	10.0	3.6	6.6	1.8	0.0
DE	N28917768475927	E4196834.6145266	Pumpkin	uchiki kuri	conventional	Sown 14/04/2014	CO	3.1	27.1	9.3	4.0	11.2	2.6	0.0
DE	N28913634973089	E4190203.8455876	Pumpkin	uchiki kuri	conventional	Sown 15/05/2014	CO	2.6	21.0	16.0	0.5	3.3	1.2	0.0
DE	N28939676074367	E4192314.5232746	Pumpkin	uchiki kuri	conventional	Planted KW 20_15.05.2014	HL	2.7	34.0	19.8	4.7	7.1	2.5	0.0
DE	N28968210079054	E4189980.8058328	Pumpkin	orange summer	conventional	Planted KW 23_03.06.2014	WL	1.3	6.0	0.0	2.1	1.5	2.4	0.0
DE	N29087868484597	E4192359.9096982	Pumpkin	uchiki kuri	organic	Planted 07/04/2014	WL	1.3	31.7	2.8	4.3	23.2	1.4	0.0
DE	N29095789318034	E4197010.2627869	Pumpkin	uchiki kuri	conventional	Planted KW 15_07.04.2014	WA	1.2	49.8	38.4	2.3	7.7	1.4	0.0
DE	N29073828669745	E4203518.9593218	Pumpkin	uchiki kuri	organic	Sown KW 17_22.04.2014	CO	2	19.8	7.5	1.7	7.8	2.8	0.0
DE	N29179995806992	E4208906.1372457	Pumpkin	orange summer	organic	Planted KW 17_22.04.2014	WL	1.3	14.7	6.7	4.9	0.5	2.5	0.0
DE	N29256676766172	E4210620.3840509	Pumpkin	uchiki kuri	conventional	Sown 20/05/2014	HA	1.2	33.3	17.7	4.6	8.4	2.6	0.0
DE	N29219863419280	E4205039.2999303	Pumpkin	uchiki kuri	conventional	Planted 12/05/2014	WL	1.5	17.3	3.8	4.9	6.0	2.6	0.0
DE	N29277609514377	E4202216.4056308	Pumpkin	orange summer	organic	Planted 18/04/2014	HL	7.6	9.4	4.1	3.5	0.4	1.5	0.0
DE	N29255319906582	E4199506.0233252	Pumpkin	orange summer	conventional	Planted KW 19_08.05.2014	HL	9.4	8.1	0.0	3.6	2.8	1.7	0.0
IT	43.82100	10.34580	Sunflower	P64HE39-Pioneer	conventional	05/05/14	CO	5.29	85.6	85.3	0.0	0.3	0.0	0.0
IT	43.62250	10.51120	Sunflower	LG 56.56 HO-LG	conventional	10/04/14	CO	3.13	15.2	1.9	0.6	5.0	7.6	0.0
IT	43.62680	10.57220	Sunflower	PR64H42-Pioneer	conventional	09/04/14	HL	14.49	34.7	21.9	2.0	7.1	3.7	0.0
IT	43.51990	10.53540	Sunflower	LG 55.57 HO-LG	conventional	10/05/14	WL	2.94	27.7	24.7	1.1	1.9	0.0	0.0
IT	43.73790	10.41630	Sunflower	Klarika Cl-Caussade	conventional	17/05/14	WL	4.07	35.4	27.7	0.6	5.8	1.3	0.0
IT	43.80990	10.36920	Sunflower	PR64H42-Pioneer	conventional	07/04/14	WL	13.45	35.5	34.0	0.9	0.5	0.0	0.0
IT	43.67960	10.35200	Sunflower	P64HE39-Pioneer	conventional	14/04/14	HL	3.48	24.1	13.5	2.3	5.8	2.3	0.0
IT	43.60610	10.49130	Sunflower	PR64H41-Pioneer	conventional	14/04/14	HL	7.48	62.7	61.8	0.0	0.9	0.0	0.0
IT	43.61900	10.54420	Sunflower	Acteon-KWS	conventional	09/05/14	CO	5.32	29.0	25.2	0.5	3.4	0.0	0.0
IT	43.59940	10.66180	Sunflower	Sangria CS-Caussade	organic	06/05/14	CO	2.23	54.5	49.5	0.7	4.0	0.4	0.0
IT	43.78360	10.41510	Sunflower	P64HE39-Pioneer	conventional	05/05/14	WL	3.03	29.1	22.6	1.1	5.0	0.4	0.0
IT	43.67660	10.28770	Sunflower	Klarika Cl-Caussade	conventional	10/04/14	WL	1.73	16.5	3.2	1.8	8.4	3.1	0.0
IT	43.64630	10.36450	Sunflower	Imeria-Caussade	conventional	05/04/14	CO	11.30	67.6	55.4	1.8	8.7	1.7	0.0
IT	43.56190	10.53890	Sunflower	LG 55.57 HO-LG	conventional	15/04/14	WL	8.30	50.1	48.9	0.6	0.5	0.1	0.0
IT	43.60310	10.63820	Sunflower	Sangria CS-Caussade	organic	24/04/14	HL	9.10	58.6	55.5	0.1	3.0	0.0	0.0
IT	43.78160	10.32850	Sunflower	PR64H41-Pioneer	conventional	03/04/14	HL	7.02	57.9	53.6	0.5	3.8	0.0	0.0
IT	43.70950	10.59600	Sunflower	Mas 83.R-Maisadour	conventional	24/05/14	CO	2.42	29.0	21.4	1.0	6.6	0.0	0.0
NL	51.90620	5.71900	Pear	Conference	conventional	na	WL	2.38	1.6	0.0	49606.3	0.0	0.0	na
NL	51.90600	5.52000	Pear	Conference	conventional	na	WL	3.60	10.2	0.0	108612.5	67625.0	143356.3	na
NL	51.92500	5.58200	Pear	Conference	conventional	na	HL	1.14	9.1	0.0	30662.5	215956.3	40250.0	na
NL	51.92520	5.54650	Pear	Conference	conventional	na	HL	1.92	7.3	60981.3	47543.8	0.0	119550.0	na
NL	51.88800	5.87310	Pear	Conference	conventional	na	CO	1.80	6.3	39118.8	110643.8	49618.8	0.0	na
NL	51.92650	5.70210	Pear	Conference	conventional	na	CO	0.90	5.3	31237.5	123012.5	0.0	13168.8	na
NL	51.95600	5.50800	Pear	Conference	conventional	na	HL	1.26	3.6	25868.8	68512.5	0.0	19375.0	na
NL	51.96000	5.46800	Pear	Conference	conventional	na	WL	0.76	3.2	51793.8	37762.5	0.0	11593.8	na
NL	51.96890	5.43780	Pear	Conference	conventional	na	CO	0.98	5.2	0.0	76637.5	53837.5	33675.0	na
NL	51.88520	5.67700	Pear	Conference	conventional	na	WL	1.23	11.3	369462.5	83350.0	0.0	27075.0	na
NL	51.83030	5.29340	Pear	Conference	conventional	na	WL	1.00	8.6	149775.0	120818.8	80050.0	49368.8	na
NL	51.91320	5.32200	Pear	Conference	conventional	na	HL	0.90	13.3	156875.0	146125.0	86181.3	27531.3	na
NL	52.00930	5.27040	Pear	Conference	conventional	na	CO	1.99	13.4	203412.5	118237.5	39137.5	58993.8	na
NL	52.03220	4.97770	Pear	Conference	conventional	na	CO	2.80	1.5	0.0	36568.8	8443.8	987.5	na
NL	52.06190	5.23510	Pear	Conference	conventional	na	HL	3.84	22.8	382106.3	164362.5	61800.0	108693.8	na
NL	52.06700	5.18490	Pear	Conference	conventional	na	WL	0.90	12.8	173800.0	201137.5	19368.8	6981.3	na
NL	52.08440	5.19480	Pear	Conference	conventional	na	HL	0.75	21.0	403581.3	159762.5	66731.3	29493.8	na
NL	51.99330	5.33410	Pear	Conference	conventional	na	CO	1.15	19.2	473775.0	81731.3	37581.3	11425.0	na
Switzerland	41.985300	27.149700	Oilseed rape	V280OL	Conventional	22/08/2013	WL	1.4	47.1	40.3	1.6	3.5	1.7	0.0
Switzerland	42.05600	27.082300	Oilseed rape	V280OL	Conventional	30/08/2013	WL	0.93	12.6	8.7	2.0	0.4	1.4	0.0
Switzerland	41.995200	27.077100	Oilseed rape	V280OL	Conventional	05/09/2013	WL	3.7	49.6	45.5	1.1	2.8	0.2	0.0
Switzerland	42.104500	27.231500	Oilseed rape	V280OL	Conventional	03/09/2013	WL	0.82	11.6	5.4	0.9	5.0	0.4	0.0
Switzerland	42.083600	27.209200	Oilseed rape	V280OL	Conventional	03/09/2013	WL	5.36	34.1	27.2	1.9	3.6	1.4	0.0
Switzerland	41.949100	27.149800	Oilseed rape	V280OL	Conventional	03/09/2013	WL	1.95	38.6	25.7	2.5	8.8	1.6	0.0
Switzerland	42.0347400	27.108100	Oilseed rape	V280OL	Conventional	03/09/2013	HL	1.37	13.1	9.0	1.2	2.2	0.7	0.0
Switzerland	42.0990500	27.015700	Oilseed rape	Sensation	Conventional	31/08/2013	HL	2.99	21.0	19.9	0.2	0.5	0.5	0.0
Switzerland	42.062600	27.202700	Oilseed rape	V280OL	Conventional	05/09/2013	HL	3.08	29.6	21.0	1.0	6.3	1.2	0.0
Switzerland	42.129600	27.203000	Oilseed rape	Mendel	Conventional	28/08/2013	HL	1.01	35.4	24.2	1.8	8.6	0.8	0.0
Switzerland	41.991100	27.108500	Oilseed rape	V280OL	Conventional	05/09/2013	HL	1.32	12.1	3.8	3.2	3.9	1.3	0.0
Switzerland	41.905400	27.144200	Oilseed rape	Vispy	Conventional	08/09/2013	HL	1.24	40.4	35.8	0.4	3.4	0.8	0.0
Switzerland	42.096600	27.198800	Oilseed rape	V280OL	Conventional	03/09/2013	CO	1.67	39.1	29.2	1.5	5.2	3.1	0.0
Switzerland	42.069800	27.038700	Oilseed rape	V280OL	Conventional	03/09/2013	CO	1.24	27.2	12.9	4.6	8.8	0.9	0.0
Switzerland	42.100000	27.177500	Oilseed rape	V280OL	Conventional	31/08/2013	CO	1.5	41.7	24.9	1.4	14.1	1.2	0.0
Switzerland	41.956300	27.126900	Oilseed rape	V280OL	Conventional	03/09/2013	CO	1	16.2	10.0	2.7	2.6	0.9	0.0
Switzerland	41.974700	27.123600	Oilseed rape	V280OL	Conventional	30/08/2013	CO	1.58	18.5	13.8	1.0	2.2	1.5	0.0
Switzerland	42.009700	27.102400	Oilseed rape	V280OL	Conventional	30/08/2013	CO	2.71	14.4	10.4	1.2	1.9	1.0	0.0
Estonia	58.36700	26.62200	Oilseed rape	Abakus	Conventional	16/08/2013	Herbaceous linea	10.2	22.9	13.3	0.7	7.6	1.4	0.0
Estonia	58.21300	26.18400	Oilseed rape	Thorin	Conventional	21/08/2013	Control	38.49	43.0	34.9	0.1	2.1	0.8	5.1
Estonia	58.31500	26.49200	Oilseed rape	Rohan	Conventional	13/08/2013	Control	4.5	68.7	59.4	0.0	8.1	0.6	0.5
Estonia	58.31100	26.63000	Oilseed rape	Rohan	Conventional	13/08/2013	Control	3.4	26.1	18.3	0.3	6.0	0.3	1.3
Estonia	58.38600	26.54300	Oilseed rape	Visby	Conventional	16-17.08.2013	Herbaceous linea	27	33.7	20.2	0.3	12.0	1.3	0.0
Estonia	58.38600	26.58600	Oilseed rape	Visby	Conventional	16/08/2013	Woody linear	11.6	24.0	16.8	0.2	3.3	1.0	2.7
Estonia	58.43500	26.61000	Oilseed rape	Sherpa	Conventional	17/08/2013	Herbaceous linea	40.7	36.0	33.6	0.0	1.5	0.9	0.0
Estonia	58.36600	26.56200	Oilseed rape	Visby	Conventional	17/08/2013	Control	59.13	23.4	17.2	0.0	4.6	1.6	0.0
Estonia	58.40700	26.67300	Oilseed rape	Rohan	Conventional	16/08/2013	Woody linear	11.8	30.7	13.8	1.7	13.3	1.9	0.0
Estonia	58.31100	26.36000	Oilseed rape	Rohan	Conventional	10/08/2013	Woody linear	11.68	35.2	31.1	0.4	2.4	0.7	0.6
Estonia	58.24500	26.27900	Oilseed rape	Thorin	Conventional	21/08/2013	Herbaceous linea	6.18	34.2	27.6	0.8	3.1	0.8	1.9
Estonia	58.25800	26.31300	Oilseed rape	Thorin	Conventional	22/08/2013	Herbaceous linea	6.11	46.6	24.1	0.2	21.3	1.0	0.0
Estonia	58.28400	26.30100	Oilseed rape	Thorin	Conventional	21/08/2013	Herbaceous linea	30.8	37.1	29.5	0.1	6.7	0.8	0.0
Estonia	58.27200	26.27400	Oilseed rape	Rohan	Conventional	10/08/2013	Woody linear	73.82	39.3	22.8	0.9	8.6	0.5	6.5
Estonia	58.22000	26.30200	Oilseed rape	Rohan	Conventional	10/08/2013	Control	51.85	47.7	31.2	0.3	8.4	0.5	7.3
Estonia	58.29100	26.37800	Oilseed rape	Rohan	Conventional	10/08/2013	Woody linear	43.75	40.0	26.8	0.4	7.8	0.8	4.3
Estonia	58.22200	26.33400	Oilseed rape	Rohan	Conventional	10/08/2013	Woody linear	16.93	75.9	61.4	0.9	11.7	0.7	1.4
Estonia	58.22800	26.20900	Oilseed rape	Rohan	Conventional	10/08/2013	Control	13.87	20.9	16.5	0.1	3.1	0.7	0.4

Table S1.1. Locations of focal fields and crop management details of the four crops. There were 18 focal fields in each country. CH = Switzerland; DE = Germany; EE = Estonia; IT = Italy; NL = The Netherlands; UK = United Kingdom.

Crop (country)	Mean field area ha (SD)	mean % cover of SNH (SD)	Distance from boundary of sampling locations along transects (m)
oilseed rape (EE)	26 (21)	38 (15)	2, 25, 50, 75
oilseed rape (UK)	14 (6)	14 (7)	2, 25, 48, 71
oilseed rape (CH)	2 (0.7)	28 (13)	2, 9, 17, 25
sunflower (IT)	6 (4)	42 (19)	2, 16, 30, 44
pumpkin (DE)	3 (3)	23 (14)	2,10, 18, 26
pears (NL)	2 (1)	10 (6)	3, 11, 19, 27

Table S1.2. Sizes of focal fields of the four crops, mean proportion of semi-natural habitat (SNH) in surrounding landscapes (from 4 habitats in S1.1), which included a circular area of 1 km radius around each focal field and sampling locations along transects. There were 18 focal fields in each country. CH = Switzerland; DE = Germany; EE = Estonia; IT = Italy; NL = The Netherlands; UK = United Kingdom.

APPENDIX S2: Taxonomic breakdown of the insect faunas of focal entomophilous crops.

	Flower visits by taxon (% of total)								
Crop ↓	A.m.	*Bombus*	Solitary bees	Flies	Syrphids	Lepid.	Non-bee hymenopt.	Visits observed	hours
Sunflower IT	98.0	0.9	1.0	0.0	0.1	0.0		3428	85
Pumpkin DE	69.9	24.1	5.6	0.0	0.4			2254	54
Pear NL	75.7	6.7	0.0	1.0	16.3	0.3		387	11
OSR (CH)	95.5	1.0	1.0	1.5	0.9	0.0	0.1	36295	48
OSR (EE)	33.7	5.5	11.9	48.8				991	48
OSR (UK)	8.3	10.1	11.9	58.3	10.1	0.7	0.7	278	48

Table S2.1. Relative contributions (%) of insect taxa to the total number of flower visits recorded during observations of in-field quadrats in each crop and region.

OSR = oilseed rape.

CH = Switzerland; DE = Germany; EE = Estonia; IT = Italy; NL = The Netherlands; UK = United Kingdom.

A.m. = *Apis mellifera*; *Bombus* = *Bombus* spp.; Flies = all dipterans except syrphid flies; Lepid. = Lepidoptera; Non-bee hymenopt. = non-bee hymenoptera (principally wasps).

Visits = the total number of flower visits recorded (note: the magnitudes of these are not comparable across regions because of the different quadrat sizes and flower densities – see instead Fig. 1b).

Hours = the total number of hours of observation made in each region.

APPENDIX S3: Estimating the number of insect visits received by a receptive flower in a canola field in Northern Europe.

We can estimate the number of insect visits received by a receptive flower, V, by quantifying each of the parameters in the following relationship (Cresswell 2008):

$$V = \frac{B}{F} \cdot \frac{L}{H} \qquad \text{Eq. S5.1}$$

where B_i denotes the area density of flower-visiting insects in the field (insects m^{-2}), F denotes the area density of the crop's flowers in the field (flowers m^{-2}), L denotes the receptive lifetime of a flower (hours), and H (hours) denotes the elapsed time between successive flower visits by individual insects (i.e. duration of inter-flower travel + duration of handling time per probe).

Thus, L/H quantifies the number of visits that a flower could receive if a single insect concentrated on it exclusively and B/F quantifies the number of insects per flower, which is a cardinal indicator of pollinating intensity (Pleasants 1981).

Solution for spring-flowering canola

A survey of 60 sites across the United Kingdom (Hoyle et al. 2007) recorded one bee per 77 m^2 including both honey bees and bumble bees, i.e. $B = 0.013$.

Typical flower densities are *c*. 1000 flowers m^{-2} (Hayter & Cresswell, 2006), i.e. $F = 1000$

Foraging rates of honey bees and bumble bees are no more than 0.32 flowers visited sec^{-1} (Hayter & Cresswell 2006), i.e. $H = 9 \times 10^{-4}$ h.

Assume each flower is receptive for five days (8 h each day), i.e. $L = 40$ h.

Hence, $B/F = 1.3 \times 10^{-5}$ and $L/H = 46080$, i.e. $V = 0.6$.

Since $V < 1$, its value is the proportion of flowers that receive a single visit.

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