Crop rotation and agri-environment schemes determine bumblebee communities via flower resources

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Abstract

1. In many parts of the world, farmland pollinators decreased significantly during the last half of the 20th Century mainly due to land use changes and agricultural intensification.

2. We studied the effect of different typical crop rotations and agri-environment schemes (AES) on bumblebee diversity in Estonia. We compared species abundances between four crop rotation types [cereal rollover (no change from one year to the next), cereal to mass flowering crops (hereafter MFC), MFC rollover, and MFC to cereal fields] where all counts were conducted in the second year, and in three farming types (conventional farming, organic farming and environmentally friendly management).

3. We surveyed bumblebees and flower cover along 401 field margins in five consecutive years, and recorded twenty species and more than 6000 individuals. Abundances of long-tongued and threatened bumblebee species were higher at the field margins of cereal rollover fields than for the other three crop rotation types. In addition, cereal rollover field margins had higher abundances of medium colony species, generalists, and forest scrub species than MFC rollover and MFC to cereal or cereal to MFC field margins. Bumblebee species richness was higher at the field margins of both AES types than those of conventional farming. However, in general the strongest driver of bumblebee presence was flower cover.

4. Higher bumblebee abundances in cereal rollover field margins were probably owing to a concentration effect there and/or a dilution effect into MFC fields. Both AES schemes supported increasing flower cover in field margins and thereby diversity of bumblebees, indicating positive AES impacts upon wild pollinators.

5. *Synthesis and applications*. Crop rotation and AES determine bumblebee richness and abundance via the availability of flower resources, but crop rotation constrains bumblebees differently based on their traits. Therefore, future agri-environmental policy should account

for these management options. Crop rotation could be a simple, but efficient solution to increase the biodiversity of agricultural landscapes.

Keywords: agri-environment schemes, biodiversity, bumblebee, concentration effect, crop rotation, dilution effect, functional traits, land use, organic management, pollinator

1. Introduction

Bumblebees, among other pollinating insects, contribute to wild plant and crop pollination, and therefore to plant biodiversity and food production (Kremen *et al.,* 2007). Pollination by bumblebees is known to increase the yields of almost 40 crops (Goulson, 2010). Thirty-five percent of global crop production depends, to a degree, on pollinators (Klein *et al*., 2007), and the global annual economic value of insect pollination is estimated to be between 215–529 billion dollars (IPBES, 2016). Therefore, conservation of farmland pollinators is one of the key challenges of global crop production (Potts *et al.,* 2016).

Industrial agriculture has caused remarkable declines in the diversity and abundance of native flowers and semi-natural habitats, which in turn has caused decreases of wild pollinators, particularly long-tongued bumblebees (Goulson, Lye & Darvill, 2008). Based on a recent IUCN report, 46% of bumblebee species populations in Europe have declined (Nieto *et al.,* 2014). Drivers of the decline in pollinators include landscape homogenization, land-use changes (e.g. the loss of semi-natural habitats and the increase in the area of cereal crops) and the increasing use of synthetic pesticides and fertilizers (Winfree *et al*., 2009; Potts *et al.,* 2010; Bommarco *et al.,* 2012; Goulson *et al.,* 2015). A reduction in the number of small-scale farms has resulted in a decline in crop diversity and the loss of field margins (Sutcliffe *et al.,* 2015). Agri-environment schemes (AES), such as set-aside semi-natural habitat, organic farming, and wildflower strips for pollinators, have been developed and introduced in the European Union since the late 1980s as a tool to address the negative environmental impacts, including declines in biodiversity, of large-scale agricultural intensification (Batáry *et al.,* 2015).

Across the EU, the effectiveness of AES in terms of species conservation has been questioned owing to goals remaining unachieved as a consequence of a lack of targeting (Hole *et al.,* 2005; Kleijn *et al.,* 2011). Nonetheless, there is evidence of a positive effect of many AES upon bumblebee abundances (recently e.g., Carvell *et al.,* 2015; Wood *et al.,* 2015). However, AES availability and utilisation might not be enough to halt and reverse declines in bumblebees and particularly threatened species. Therefore, agricultural intensity as well as landscape structure are also important factors with regard to conservation efforts (Tscharntke *et al.,* 2005, 2012).

Mass-flowering crops, such as clover species and oilseed rape, are significant food resources for bumblebees and at the same time benefit from being pollinated. E.g. in Northern Europe, sweet and red clover, which have deep corolla, benefit from being pollinated by long-tongued bumblebee species (Westphal, Steffan-Dewenter & Tscharntke, 2003; Wood, Holland & Goulson, 2015). In addition, resource continuity (Blüthgen & Klein, 2011) is important, because mass-flowering crops are not always available to bumblebees during their lifecycles. Therefore, the availability of wild flowers, especially those with deep corolla, is an important driver of bumblebee diversity and population development (Williams & Osborne, 2009; Williams *et al.,* 2015).

There is a knowledge gap regarding how temporal land-use change affects bumblebees. To the best of our knowledge, this is the first multi-year study to evaluate the effect of crop rotation on bumblebee communities. We investigated the impact of four different common crop rotation types on bumblebee species richness and abundance, including comparisons between species with different functional traits (tongue length, threat status, colony size, habitat preference), during 2010–2014. In Estonia, crops are usually rotated every second year, e.g. after being a cereal field for one or two years, there will be a rotation to mass flowering crops or grasslands and *vice versa*. Hence, the overarching question is how does the type of crop rotation determine the following year's bumblebee community (species richness, total abundance, and tongue-length/threat status/colony size/habitat preference group abundances)? We hypothesized that bumblebee species richness and abundance are higher in the field margins of mass-flowering crops than in the field margins of cereal crops, regardless of the previous year's crop in those fields (illustrative photos are shown in Fig. S1, Supporting Information). In addition, we hypothesized a positive effect upon bumblebees of organic and environmentally friendly management compared to conventional farming. We collected data to test whether crop rotation and/or AES benefit bumblebees, and to identify the possible drivers of bumblebee abundances (e.g., concentration or dilution effects depending on the crop rotation type).

2. Materials and methods

2.1. Monitoring areas

We sampled true bumblebees *Bombus* ssp. (hereafter bumblebees) as part of an ongoing evaluation of AES under the framework of the Estonian Rural Development Plan 2007–2013 (Agricultural Research Centre, 2015). Two regions of Estonia were studied: Põlva, Võru and Valga counties (hereafter referred to as Southern Estonia; centre coordinates 57°52´N, 26°57´E) and Lääne-Viru, Järva and Jõgeva counties (hereafter Northern Estonia; centre coordinates 59°4´N, 26°12´E; a map of the study areas is available in Fig. S2, Supporting Information). These regions were selected based on differences in agricultural yields, AES uptake, and landscape structure. Southern Estonia has a more diverse landscape and lower yields (average cereal yield over 2004–2013 was 2792 kg/ha). Northern Estonia is characterized by larger fields, a more open landscape, and high yields by Estonian standards (average cereal yield for 2004–2013 was 3011 kg/ha). Additional information about the regions, and selection of study farms, is available in Marja *et al*. (2014).

In each region 11 organic, 11 environmentally friendly managed (both had five-year AES obligations with the possibility to prolong the obligation to six years, started in 2009), and 11 conventionally managed farms (non-AES) were surveyed, i.e. 66 in total. One of the aims of environmentally friendly management scheme is to promote farmland biodiversity, with the major requirements of farmers being to allocate a minimum of 15% of arable land (including rotational grasslands) to legumes, use diversified crop rotation, take soil samples to determine optimal fertilizer requirements and create a fertilization plan, maintain/create permanent grassland field margins (2–5 m wide), not use black fallow (fallow land with bare soil, where the height of weeds does not exceed 5 cm), protect landscape elements, and limit glyphosate applications. Organic farmers followed the Organic Farming Act by not using any synthetic pesticides or GMOs, and restricting their use of most mineral fertilizers. Detailed information about AES requirements and conventional farming rules is provided in Table S1, Supporting Information.

2.2. Biodiversity survey and study design

Fieldwork for the evaluation of AES measures was carried out during the summers of 2010–2014. Every year, each transect was surveyed three times (once in June, July, and August). The first visit was made during the 23^{rd}–30^{th} of June, the second visit from the 15^{th}–28^{th} of July, and the third between the 12^{th}–23^{rd} of August. Bumblebees were surveyed by walking slowly along a 2 m wide and 500 m long transect, of which 400 m was permanent between years and located in field margins (usually permanent grassland strips between the field and a road/other field/ditch/forest etc., or if the margin was narrow, occasionally also on the edge of a cropped field), with the remaining 100 m located in a field with an insect-pollinated crop (e.g. clover) if present in the crop rotation, or if not, also in a field margin. Data from these 100 m section located in the field were not included in the analyses. Transects were divided into shorter sections differentiated by crop types. The sections were marked on a map (scale 1:5000). During each fieldwork session, flower cover was estimated on a scale of 0–3 per whole 2 m wide transect section where: 0 = no flowers suitable for bumblebees; 1 = >0 to 1/3 of the area with flowers suitable for bumblebees; 2 = 1/3 to 2/3 with suitable flowers, 3 = >2/3 covered with suitable flowers (Marja *et al.,* 2014). All flowering-plant species known to be used by bumblebees for foraging were classified as suitable (Table S2, Supporting Information).

The bumblebee counts were conducted between 11:00 and 16:00 under good weather conditions (temperature always above 15^{o}C, and no rain or strong wind). We mainly identified bumblebees on flowers to species in the field. If identification on flowers was impossible, individuals were caught, identified, and released in the field, or on very rare occasions were retained to identify later in the laboratory. Each year the number of each bumblebee species was summed per transect over the three counts.

To test our hypotheses we included only bumblebees, flower cover, and crop rotation data of such transect sections which were located in the two most common types of field margins, those alongside cereals and mass-flowering crops. Cereal fields included rye, oat, barley, triticale, and wheat (hereafter cereals). The mass-flowering crop fields contained legumes (pea, bean, clover, alfalfa, sweet clover spp.) and oilseed rape (hereafter MFC). Crop harvest time depends on the crop and weather conditions and varies from June to September. Legumes are typically harvested in June (first cut) and August (second cut), but sometimes cut only once in July. Winter oilseed-rape is harvested at the end of July or in August, spring oilseed-rape in September, cereals typically in August or at the beginning of September (depending also if it is sown in autumn or in spring). The overall sample to test our hypotheses comprised 401 transect sections, whose lengths varied between 40–500 m (mean 226 ±SEM 6 m). Sample size for each year (number of transect sections) were as follows: 2010: 80; 2011:78; 2012: 73, 2013: 84 and in 2014: 86 transect sections (401 in total). A cross table of sample size by crop rotation and management type is given in Table 1. All other crop rotation types, such as potato, short-term grassland, permanent grassland, and pasture were excluded from the analysis.

Part of the bumblebee dataset, the explanatory variables management type and flower cover (years 2010–2012), is already published in Marja *et al*. (2014). However, in this study we used a more comprehensive bumblebee dataset (2010–2014) that also included crop rotation types. We added management type and flower cover into the analyses, as these are important drivers of bumblebee abundances (Marja *et al.,* 2014). Moreover, the present study investigated different bumblebee variables: abundance of bumblebees sub-divided by functional groups (tongue-length, colony size, and habitat preference), and threat status.

2.3. Statistical analysis

We analysed flower cover and bumblebee variables using linear mixed-effects models in R (R Development Core Team, 2016). The 'lme4' (Bates *et al.,* 2016) package for R was used to conduct all analyses. Bumblebee response variables modelled were species richness, abundance of all bumblebee species, abundance of long-tongued species (three species: *Bombus distinguendus*, *B. hortorum*, and *B. subterraneus*), abundance of short- and medium-tongued species (all other species, hereafter short-tongued species), abundance of threatened species, and abundance of non-threatened species. We analysed long-tongued bumblebees separately due to their specific ecological niche, i.e. only these species can pollinate flowers with deep corollas, such as red clover and field bean. Species classified as vulnerable (hereafter threatened) in Europe under the recent IUCN list (Nieto *et al.,* 2014) were: *Bombus confusus*, *B. distinguendus*, *B. hypnorum*, and *B. muscorum*. We also modelled pooled bumblebee abundances based on species' colony size (large, medium, and small) and main habitat (open-land specialists, forest specialists, and generalists). We used these life-history traits, because a recent study indicated that bumblebees have trait-dependent vulnerability based on landscape heterogeneity (Persson *et al.,* 2015). We provide a list of the bumblebee species with classification according to tongue length, colony size, preferred habitat, and threat status in Table S3, Supporting Information.

Owing to the bumblebees being over-dispersed, we used mixed-effects models with a negative binomial distribution. The explanatory variables of main interest were crop rotation type [four factors: cereal rollover fields (rollover = no change from one year to the next); cereal to MFC fields; MFC rollover fields; MFC to cereal fields], (e.g. in cereal to MFC fields, surveying was done in MFC field margin), management type (three levels: conventional; environmentally friendly management; organic farming), and flower cover (average value over the three counts per transect). Note that bumblebee response variables were always taken during the second year of crop rotation. First, we tested flower cover as a dependent variable in relation to crop rotation and management. Second, we tested all bumblebee variables against crop rotation, management, and flower cover. Since we had multiple years and the study regions had different landscape structures (Northern Estonia has a simpler landscape structure than Southern Estonia), we treated year and region as crossed random factors in the model (R command: (1|year)+(1|region). As the length of transect sections ranged from 40 to 500 m, they were treated as an offset function [R command: offset=log(transect length)]. We also calculated the variance inflation factor between explanatory variables (R package "car", Fox & Weisberg, 2011), and identified no values exceeding 1.4 for any of the models, which suggests that no collinearity occurred.

3. Results

We observed a total of 6092 individuals of 20 bumblebee species during 2010–2014 (see Table S3, Supporting Information). We provide mean values and standard errors of investigated flower cover and bumblebee variables per transect sections length according to crop rotation and management type in Tables S4 and S5, Supporting Information.

Flower cover was higher in organic and environmentally friendly managed field margins, compared to the margins of conventional fields, but was not related with crop rotation types (Fig. 1). As an explanatory variable, flower cover was positively associated with all bumblebee groups (Fig. 2,3,4 and Fig. S3,S4).

Crop rotation type was not related to bumblebee species richness or abundance (Fig. S3, Supporting Information). Bumblebee species richness in the field margins of both AES management types were higher compared to the margins of conventional fields. Bumblebee abundance was significantly higher in environmentally friendly managed field margins compared to those of conventional fields; no significant difference in bumblebee abundance occurred between the field margins of organic and conventionally managed fields.

Abundances of non-threatened species did not differ between crop rotation types, but abundance of threatened species was highest in cereal rollover field margins, compared to the other three rotation types (Fig. 2). Bumblebee abundance of non-threatened species was significantly higher in environmentally friendly managed field margins compared to those of conventional field margins. Abundances of threatened species were higher in both AES management types field margins, compared to the margins of conventional fields.

Crop rotation type was associated with abundances of bumblebees of medium colony sizes (Fig. 3). Abundance of medium colony sized species was higher in cereal rollover field margins, compared to MFC rollover filed margins. Both AES management types had higher abundances of small-sized colony species.

Abundance of open land bumblebee species did not differ between crop rotation types. Abundance of generalist species was higher in cereal rollover field margins, compared to cereal to MFC and MFC rollover field margins (Fig. 4). Abundance of forest-scrub species was higher in cereal rollover field margins compared to MFC to cereal and MFC rollover field margins. Abundances of open land species and generalists did not differ between field margins under AES and conventional farming. Organic field margins hosted a higher abundance of forest-scrub species compared to the margins of conventional fields.

Abundances of short-tongued species were similar in all investigated crop rotation types (Fig. S4, Supporting Information). Abundance of long-tongued species was higher in cereal rollover field margins compared to the other three crop rotation types. Bumblebee abundance of short-tongued species was significantly higher in environmentally friendly managed field margins compared to those of conventional field margins. Abundances of long-tongued bumblebee species did not differ between management types.

4. Discussion

Our study shows that crop rotation has an important role in determining bumblebee community. We found that some bumblebee abundances (e.g. of long-tongued and threatened species) are higher at cereal rollover field margins than at the field margins of the other three crop rotation types. Furthermore, we found higher abundances of medium sized colony species, forest-scrub species, and habitat generalists in cereal rollover field margins than in MFC rollover and MFC to cereal or cereal to MFC field margins.

4.1. Concentration and dilution effects of bumblebees at field margins

Our study suggests that crop rotation type is an important management driver of bumblebee communities in field margins. Abundances of several bumblebee groups (e.g. long-tongued, threatened, and forest-scrub species) were higher at the field margins of cereal rollover compared to MFC rollover. This may not indicate that the *status quo* of fields remaining as cereals from one year to the next has a positive effect on bumblebee abundance, or that cereal margins are more important to bumblebees than MFC margins.

Our results can be interpreted in two ways. First, this might have been caused by a concentration effect in cereal field margins, similar to that found in Environmental Stewardship AES in England (Carvell *et al.,* 2007). More flower resources are available in the margins of cereal fields than inside the fields, owing to herbicide use controlling arable weeds within crops, thus reducing nectar sources (Brittain *et al.,* 2010). Second, a dilution effect in MFC fields (Holzschuh *et al.,* 2011) is likely as bumblebees may disperse into MFC fields, as they have more nectar resources than cereal fields. June and July, when 2/3 of our data were collected, is the main blooming time of legumes and oilseed rape in Estonia. Therefore, dilution of bumblebee individuals from certain trait based groups onto MFC fields was probably the main reason for the differences in bumblebee abundances between cereal and MFC rollover field margins. One limitation of our investigation was that it only accounted for bumblebees at field margins, not within fields. An important potential confounding factor that needs to be mentioned *vis-à-vie* the concentration–dilution hypothesis of bumblebees (and other pollinators) in cereal/MFC/other field margins, is the type of crop(s) being grown in adjacent fields. For example, is there a stronger concentration effect if cereal fields are on both sides of the field margin, than if the margin is between a cereal and MFC field? We suggest that future studies test the concentration–dilution hypothesis by: *i*) also running flower/pollinator transects from the edge to the centre of fields; *ii*) taking into account adjacent fields.

Our results suggest a negative temporal effect of cereal fields upon the food resources of bumblebees. Abundances of threatened, long-tongued, and forest-scrub species were lower in the field margins of MFC to cereal than cereal rollover fields. We offer the following explanation: if cereals are grown for two consecutive years, this may already negatively influence the flowering plant community of the field, reducing food resources for bumblebees within fields, thus making margins more attractive to bumblebees. In addition, as cereal rollover fields were mainly on conventional farms (Table 1), such field margins are less likely to: *i*) have MFC dispersal into the margin from the previous year; *ii*) be managed (including the sowing of seed mixes) for wildflowers. From a recent study (Magrach *et al.,* 2017) it is known that honeybees spillover from mass-flowering orange groves to flower-rich woodlands after orange bloom leading to a change in wild bee community composition and lower seed set of the most common plant species. Nevertheless, for the honeybee itself this might be a benefit. In a similar way, it is possible that for at least some bumblebee species, MFC can provide a benefit the following year, as suggested by our results (MFC>cereal compared to cereal rollover).

The importance of field margins is related to nectar and/or pollen continuity in agricultural landscapes (Schellhorn, Gagic & Bommarco, 2015). Owing to the seasonality and duration of nectar sources, legumes and oilseed rape fields are not fully available to bees throughout spring and summer in Northern Europe, thus bumblebees likely also use semi-natural habitats, such as field margins (Bäckman & Tiainen, 2002; Batáry *et al.,* 2015). Therefore, flowering field margins are of high importance during periods when legumes or oilseed rape resources are not available, thus creating a resource bottleneck (Persson *et al.,* 2015; Schellhorn, Gagic & Bommarco, 2015). In our study areas, a resource bottleneck might occur if MFC are not grown in certain years, do not flower until a certain date, or are harvested from a certain date onwards. Thus, it is highly likely that a combination of all three presented reasons affects the availability of food resources for bumblebees.

4.2. AES has a role in determining the bumblebee communities of field margins

We found that both organic farming and environmentally friendly management promoted bumblebee species richness in field margins. It might be possible that farming practice had a confounding effect on the results, e.g. conventional farms had a higher percentage of cereal rollover fields compared to organic and environmentally friendly management farms, but owing to the lack of collinearity, a significant bias seems to be unlikely. Nonetheless, future studies should aim to collect more balanced datasets. However, Marja *et al.* (2014), also demonstrated that Estonian AES promoted bumblebees, both within the fields and at their margins. Environmentally friendly management involves requirements to conserve or sow field margins with a flower mix of at least three species (including graminaceous); organic farming does not have such a requirement, but abundances of bumblebee threatened species, small-sized colony species, and forest-scrub species were still higher than per conventional farming. This was probably related to the strict management requirements (synthetic pesticides and most mineral fertilizers are forbidden) of organic farming. Our results indicate that threatened species are remarkably sensitive to agricultural management, and prefer more AES, farms; non-threatened species seemed to be less sensitive to management.

We found that the abundances of species with small colonies were related to AES management types, whereas abundances of species with medium and large colonies did not differ between management types. These results can be related to the mobility potential. Species with small colonies have more limited dispersal distances (Westphal, Steffan-Dewenter & Tscharntke, 2006). This adaptation makes them more sensitive to local environmental and agricultural conditions. It is also probable that there were more suitable habitat conditions in organic and environmentally friendly management field margins for bumblebee species with small colonies. Species with medium and large colonies are more mobile and search for resources at larger scales, and are therefore less influenced by local conditions.

4.3. Conservation of bumblebees

Both naturally-occurring plants and the sowing of seed mixes to provide nectar-rich plants (e.g. clover) at field margins can benefit bumblebees and other pollinators in Estonia as well as in Northern Europe in general (Scheper *et al.,* 2013). It is important when sowing nectar-rich plants mixes, to use only local flora to avoid introducing alien species. The conservation of non-cropped landscape elements, such as field margins and other flower resources, is essential to support the diversity of wild pollinators and their food plants. For instance, the latest results from Estonia showed that field margins need to be at least 3 m wide to support 'high nature value' plant species intolerant of modern farming practices (Aavik & Liira, 2010). For bumblebees, these plant species are potentially of higher value and provide more temporally stable food resources than agro-tolerant plant species. Thus, non-cropped field margins at least 3–5 m wide could be a key and simple solution to improve bumblebee diversity in cereal-dominated agricultural landscapes. Furthermore, permanent field margins are important for bumblebees in terms of the continuity of resources other than food, such as nesting and wintering habitat (Bäckman & Tiainen, 2002; Batáry *et al.,* 2015).

A recent study showed that almost 80% of crop pollination is performed by a limited number of bee species, and threatened bee species contribute little (Kleijn *et al.,* 2015). However, protecting the main, common pollinator species only is not a sustainable solution to the conservation of pollinator biodiversity. Senapathi *et al*. (2015) highlighted that maintaining whole pollinator species diversity, including widespread and rare species, is essential to provide ecosystem resilience and functioning in the future. Therefore, the conservation of different habitats and the whole pollinator species spectrum is crucial, because different pollinator species visit different parts of crops, or crops at different times of the day or year, and respond differently to environmental disturbances (Goulson *et al.,* 2015).

5. Conclusions

Our results indicate that cereal field margins can act as refugia to forest-scrub, long-tongued, and threatened bumblebee species, such as *B. hypnorum*, *B. distinguendus*, and *B. muscorum*, which are vulnerable in Europe (Nieto *et al.,* 2014). Semi-natural field margins, especially in intensively managed cropland, may be a viable option to support these species in Europe, because they represent permanent valuable landscape elements, offering places to nest and overwinter, as well as providing food resources. It is possible that the field margin requirement of Estonian AES is one of the reasons why Estonian bumblebee abundances were stable over a recent five year period (Agriculture Research Centre, 2015). Our study indicated a concentration–dilution effect of field margins upon bumblebee abundances, dependant on the type of crop being grown in the field (cereal = concentration at the margin; MFC = dilution into the field). To test the concentration–dilution hypothesis of field margins upon pollinators, future studies should account for within-field pollinator/flower abundances, and the influence of adjacent fields (or even landscape composition). Nonetheless, our results show that management of flower rich field margins, especially in cereal rollover fields, where few alternative nectar sources exist, is important and should form part of all AES targeting pollinators.

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Authors' Contributions

RM and PB conceived the study and designed the methodology; EV and MM coordinated data collection; RM analysed the data; RM led the writing of the manuscript. All authors (RM, EV, MM, JP, AMK, and PB) contributed critically to the manuscript and approved the submission.

Data accessibility

Data availability. The biodiversity and environmental data used in the analyses are archived at the research data repository Zenodo (https://zenodo.org/record/1161431).

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Table captions

Table 1 Cross-table of sample sizes by crop rotation and management types. Cereal (all rye, oat, barley, triticale, and wheat fields), MFC = mass-flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape).

Management type/ Crop rotation	Conventional farming	Environmentally friendly management	Organic farming	Crop rotation total
Cereal→cereal	86	22	9	117
Cereal→MFC	17	46	24	87
MFC→cereal	28	36	19	83
MFC→MFC	17	31	66	114
Management type total	148	135	118	401

Figure captions

Fig. 1. Comparison of flower cover in field margins between different crop rotation and management types. The figure shows results from linear mixed-effects models (p-value, lower and upper boundary of 95% CI). Indicated are effect sizes (y-axis) compared to the crop rotation type control group (cereal rollover field margins) and management type control group (conventional farming). The effect size is significantly different if the CIs do not overlap with zero. Asterisk symbols represent statistically significant p-values below 0.05, 0.01, and 0.001 (*, **, and ***, respectively). Cer = cereals (all rye, oat, barley, triticale, and wheat fields), MFC = mass flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape), Environmental = environmentally friendly management, Organic = organic farming.

Fig. 2. Comparison of bumblebee abundances in field margins between different crop rotation types, management types, and effect of flower cover for (a) non-threatened and (b) threatened bumblebee species. The figure shows results from linear mixed-effects models (p-value, lower and upper boundary of 95% CI). Indicated are effect sizes (y-axis) compared to the crop rotation type control group (cereal rollover field margins) and management type control group (conventional farming). The effect size is significantly different if the CIs do not overlap with zero. Asterisk symbols represent statistically significant p-values below 0.05, 0.01, and 0.001 (*, **, and ***, respectively). Cer = cereals (all rye, oat, barley, triticale, and wheat fields), MFC = mass flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape), Environmental = environmentally friendly management, Organic = organic farming, Flowers = flower cover.

Fig. 3. Comparison of bumblebee abundances in field margins between different crop rotation types, management types, and effect of flower cover for species based on their colony size, i.e. (a) large, (b) medium and (c) small colonies. The figure shows results from linear mixed-effects models (p-value, lower and upper boundary of 95% CI). Indicated are effect sizes (y-axis) compared to the crop rotation type control group (cereal rollover field margins) and management type control group (conventional farming). The effect size is significantly different if the CIs do not overlap with zero. Asterisk symbols represent statistically significant p-values below 0.05, 0.01, and 0.001 (*, ** and, ***, respectively). Cer = cereals (all rye, oat, barley, triticale, and wheat fields), MFC = mass flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape), Environmental = environmentally friendly management, Organic = organic farming, Flowers = flower cover.

Fig. 4. Comparison of bumblebee abundances in field margins between different crop rotation types, management types, and effect of flower cover for species based on their habitat preference, i.e. (a) open land, (b) generalists, and (c) forest-scrub. The figure shows results from linear mixed-effects models (p-value, lower and upper boundary of 95% CI). Indicated are effect sizes (y-axis) compared to the crop rotation type control group (cereal rollover field margins) and management type control group (conventional farming). The effect size is significantly different if the CIs do not overlap with zero. Asterisk symbols represent statistically significant p-values below 0.05, 0.01, and 0.001 (*, ** and, *** respectively). Cer = cereals (all rye, oat, barley, triticale, and wheat fields), MFC = mass flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape), Environmental = environmentally friendly management, Organic = organic farming, Flowers = flower cover.

Supporting Information

Table S1. Requirements of conventional farming and the two agri-environment schemes.

Table S2. Flowering plant species known to be used by bumblebees for foraging.

Table S3. Bumblebee species' traits based on tongue length, threat status, colony size and main habitat type.

Table S4. Investigated plant and bumblebee variables depending on crop rotation type (mean values and standard error of mean).

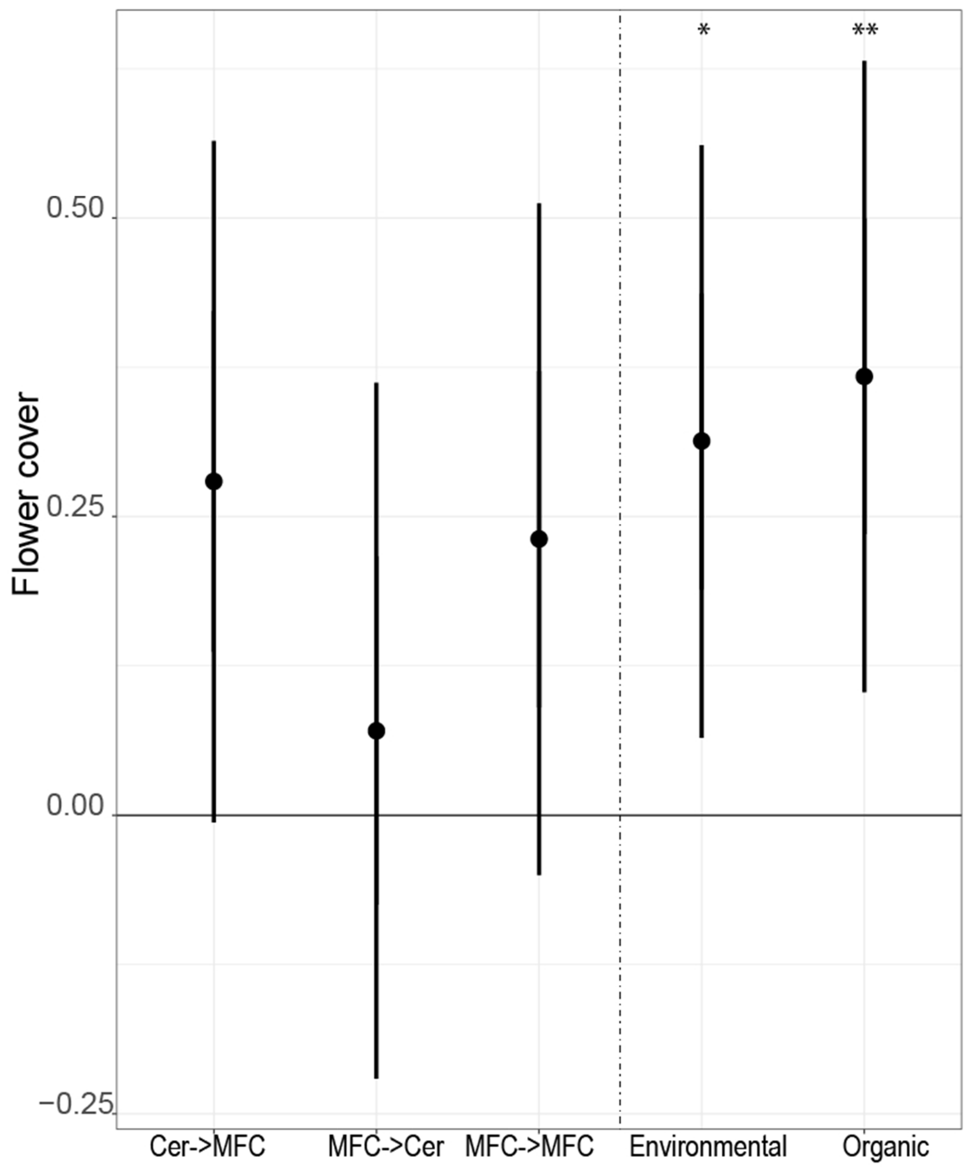
Table S5. Investigated plant and bumblebee variables depending on management type (mean values and standard error of mean).

Figure S1. Illustrative photos of field margins.

Figure S2. Study areas in the two regions of Northern and Southern Estonia.

Figure S3. Comparisons of bumblebee species richness and abundance in field margins between different crop rotation types, management types, and effect of flower cover.

Figure S4. Comparisons of bumblebee abundance of short- and long-tongued bumblebee species in field margins between different crop rotation types, management types, and effect of flower cover.



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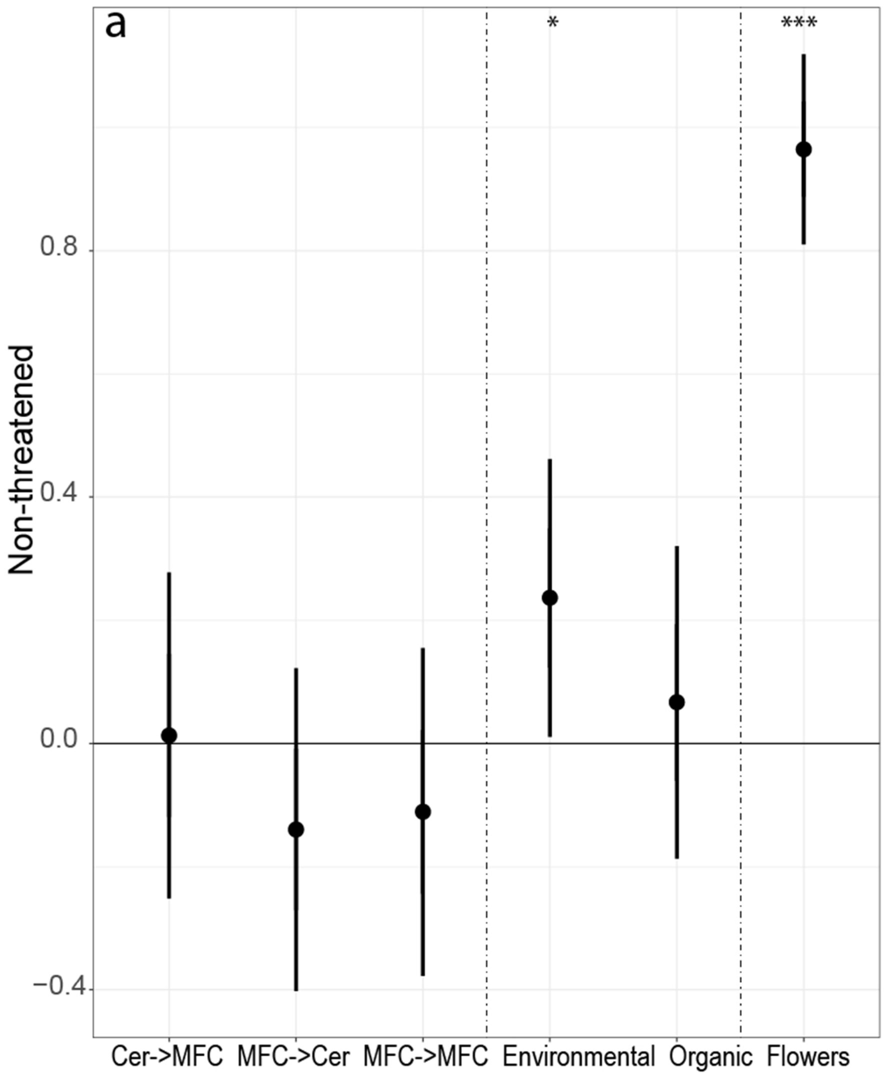

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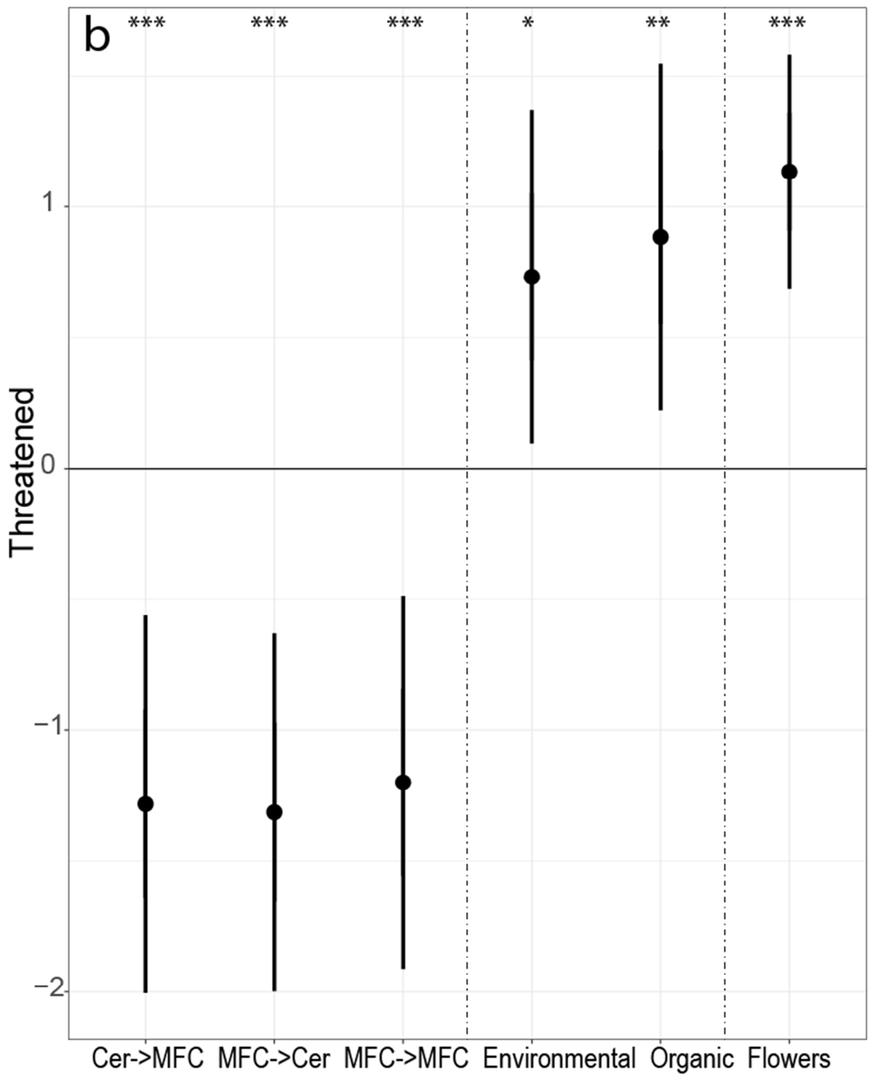

Figure 2 B

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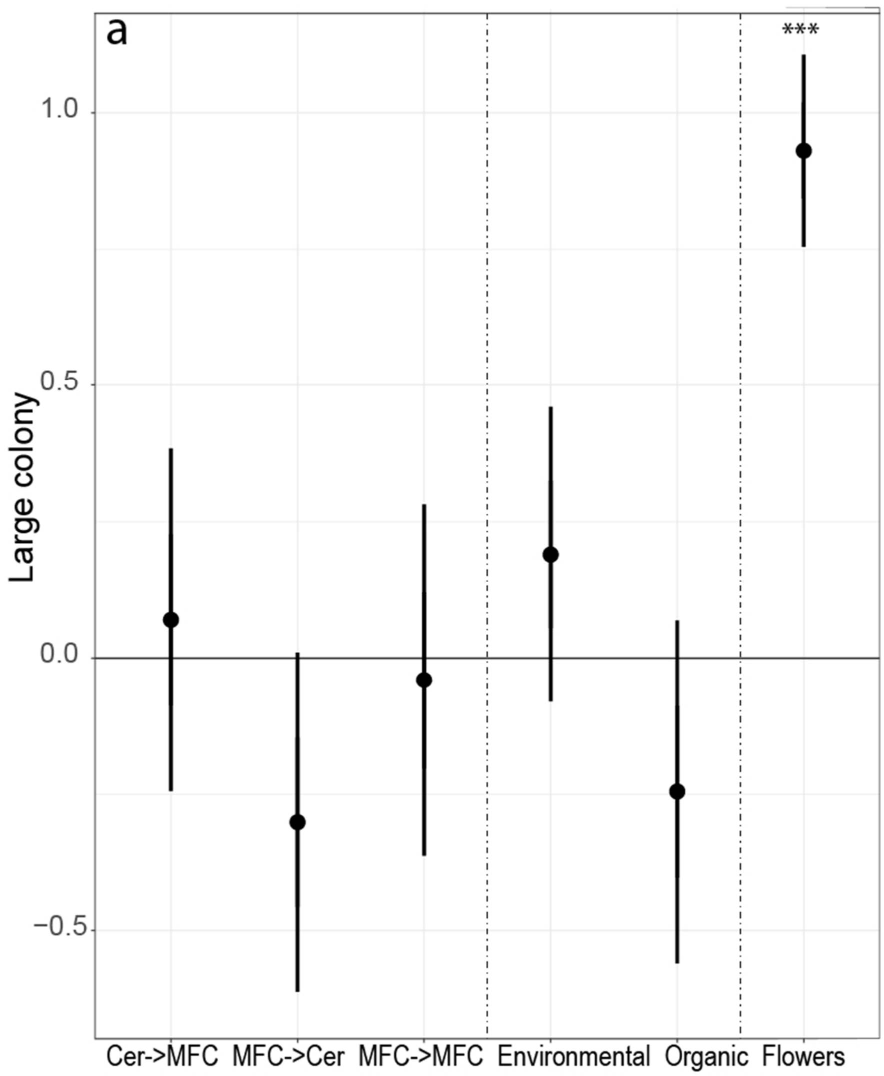

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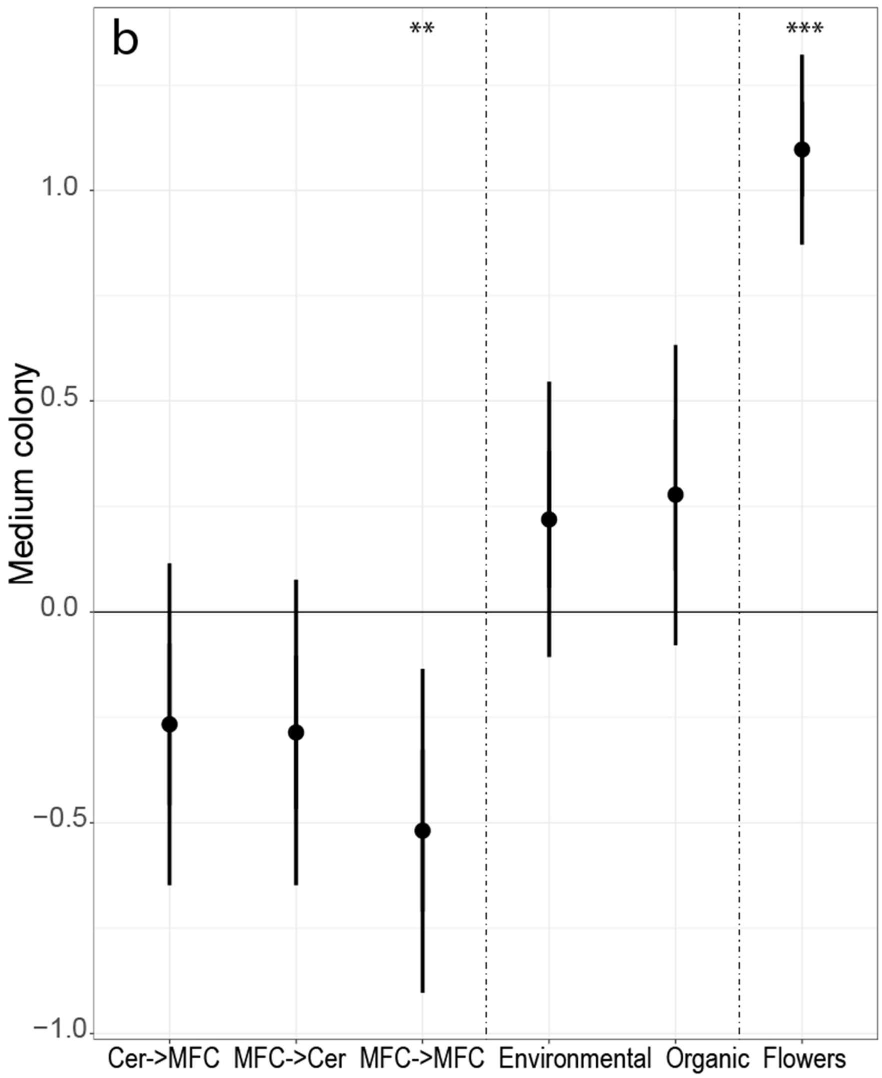

Figure 3 b

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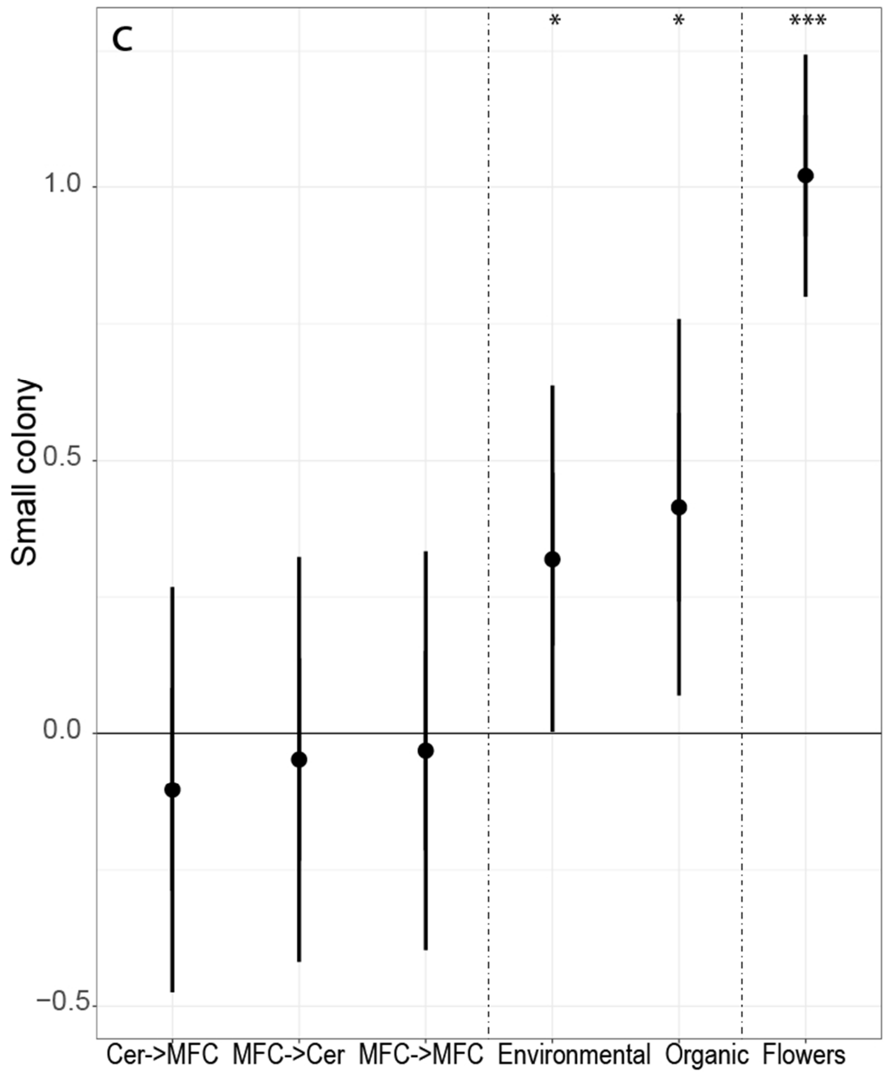

Figure 3 c

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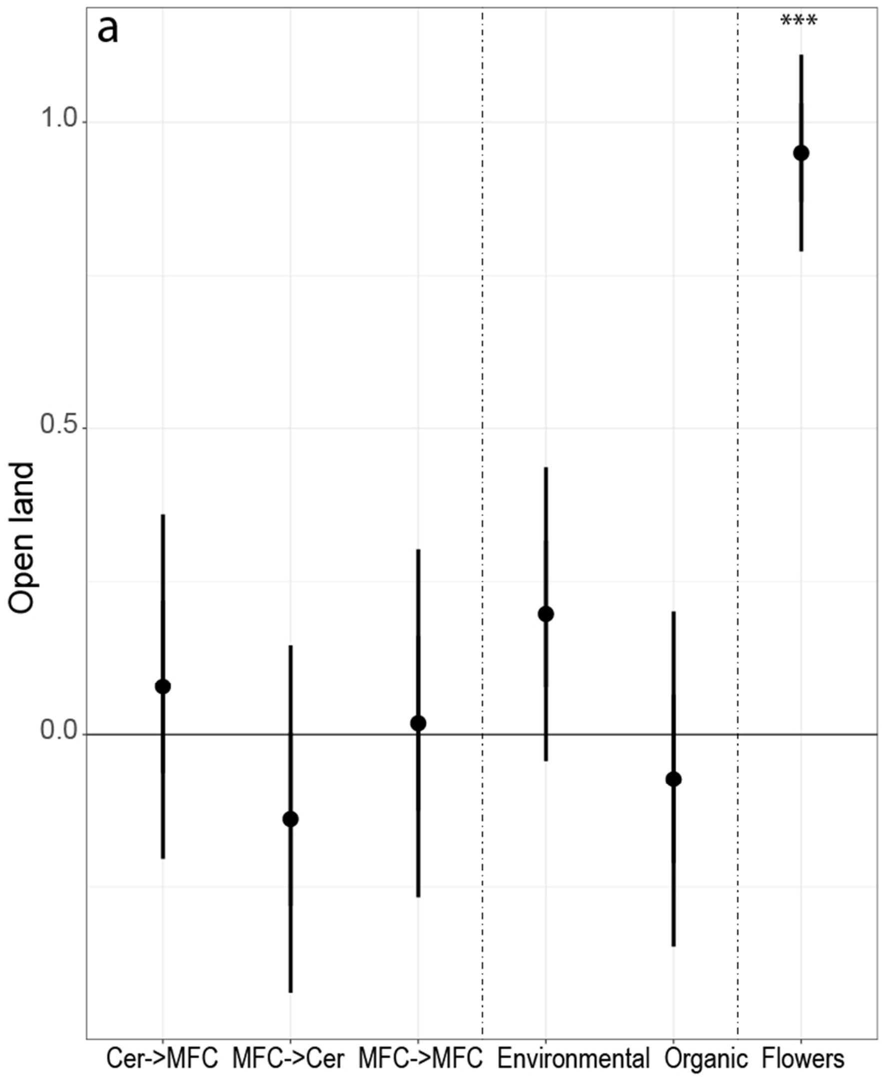

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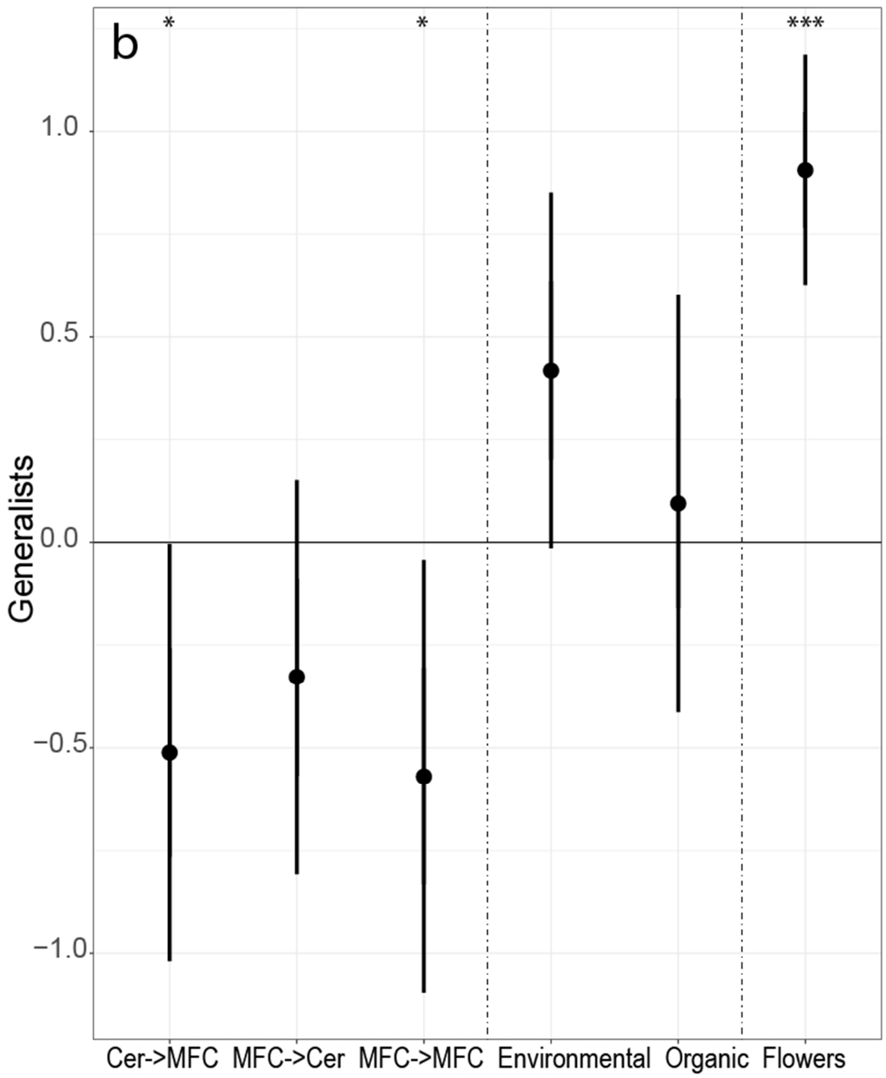

Figure 4 b

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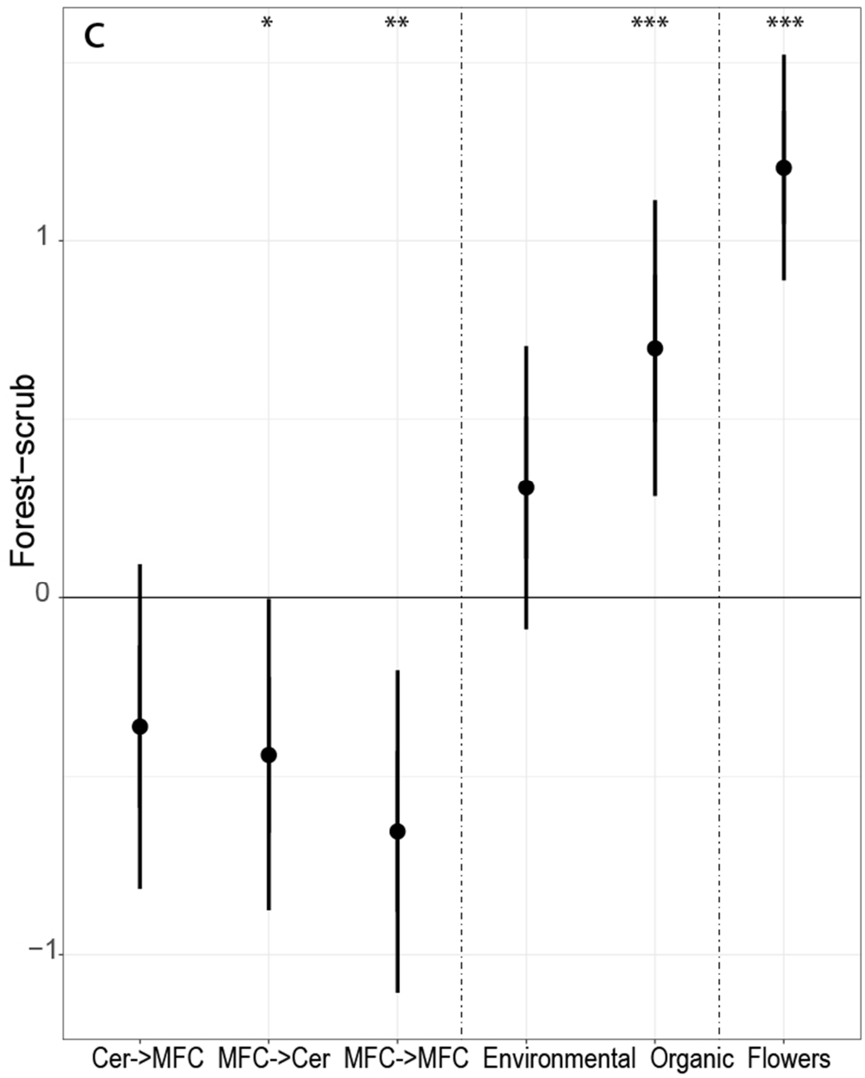

Figure 4 c

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Crop rotation and agri-environment schemes determine bumblebee communities via flower resources

Riho Marja, Eneli Viik, Marika Mänd, James Phillips, Alexandra-Maria Klein, Péter Batáry

SUPPORTING INFORMATION

Table S1. Requirements of conventional farming (single area payment scheme) and two agri-environment schemes (environmentally friendly management, and organic farming), of the Estonian Rural Development Plan 2007–2013 (Estonian Rural Development Plan 2007–2013, 2010).

Management type	**Pre-requisites of applying for support**	**Baseline requirements for obtaining agri-environment support**	**Additional requirements for obtaining agri-environment support, specific to each scheme**
Conventional farming	Cross-Compliance requirements. Minimum 1 ha of agricultural land entered into the register of agricultural support and agricultural parcels.		
Environmentally friendly management	Cross-Compliance requirements. Minimum requirements for the application of fertilizers and plant protection products. Self-employed person engaged in agriculture or a legal person. Minimum 1 ha of arable land entered into the register of agricultural support and agricultural parcels (permanent grassland is not eligible). 5-year obligation.	Keeping a field book. Compiling a cropping or crop rotation plan. Plant protection equipment have to pass a technical inspection after every three years. Agricultural crops are sown or planted by the 15th of June (spread of weeds avoided) or the agricultural land is kept as black fallow. In certain parishes, at least 30% of the agricultural land must remain under winter cover. Restrictions on using nitrogen. In certain cases, there have to be a grassland strip of at least 0.5 meters or another kind of landscape border element between the road and	**Basic scheme requirements:** Compiling a standard fertilization plan. Requirement of a cropping or crop rotation plan (e.g. 1st November to 31st March at least 30% under winter vegetation). At least 15% of agricultural crops sown with certified seed. Collection of soil samples once during the obligation period, and in the case of manure storage facilities, manure samples. To leave or establish a 2-5 m wide grassland strip with perennial vegetation or other kind of landscape element between the field and public road if the arable land area is larger than 20 ha (also some more detailed requirements). Cultural heritage sites and other valuable landscape elements

		field. Valuable landscape elements cannot be damaged or destroyed. Compulsory training (6+6 hours).	cannot be damaged or destroyed. **Basic + additional scheme requirements:** Basic scheme requirements. At least 15% of the eligible land is under leguminous crops. The application of glyphosates is prohibited from the time of the emergence of cultivated plants until harvesting. It is also prohibited on grasslands used as green manures. Plant growth regulators can only be used in case of growing winter cereals. Black fallow is prohibited. The amount of nitrogen fertilization is restricted.
Organic farming	Cross compliance requirements. Minimum requirements for the usage of fertilizers and plant protection products. Self-employed person engaged in agriculture or a legal person. Minimum 1 ha of agricultural land entered into the register of agricultural support and agricultural parcels. The enterprise must be approved according to the Organic Farming Act. To follow the Organic Farming Act. 5-year obligation.	Keeping a field book. Agricultural crops are sown or planted by 15th of June (spread of weeds avoided) or the agricultural land is kept as black fallow. Grasslands and orchards must be mowed once or grazed before 31st July and mowed grass removed or chopped. Destruction or spoiling of natural protected objects is prohibited. Damaging of semi-natural habitats is prohibited. Compulsory training (12+12 hours).	Requirements for organic plant production and for organic animal husbandry.

Estonian Rural Development Plan 2007–2013 (2010. URL: http://www.agri.ee/mak).

Table S2. Flowering plant species known to be used by bumblebees for foraging in Estonian agricultural landscapes based on our 2014 unpublished survey.

Plant species	Plant species	Plant species
Aegopodium podagraria	*Galopsis tetrahit*	*Symphytum officinale*
Anchusa arvensis	*Geranium pratense*	*Trifolium hybridum*
Anchusa officinalis	*Hieracium spp*	*Trifolium medium*
Arctium lappa	*Hypericum maculatum*	*Trifolium pratense*
Arctium minus	*Hypericum perforatum*	*Trifolium repens*
Arctium tomentosum	*Knautia arvensis*	*Veronica longifolia*
Bunias orientalis	*Lamium album*	*Vicia cracca*
Campanula cervicaria	*Lamium hybridum*	*Vicia sepium*
Campanula glomerata	*Lamium purpureum*	*Vicia villosa*
Campanula latifolia	*Lathyrus pratensis*	
Campanula medium	*Linaria vulgaris*	
Campanula persicifolia	*Lonicera xylosteum*	
Campanula rapunculoides	*Lotus corniculatus*	
Capsella bursa bastoris	*Lupinus polyphyllus*	
Carduus crispus	*Lythrum salicaria*	
Centaurea cyanus	*Medicago lupulina*	
Centaurea jacea	*Medicago sativa*	
Centaurea phrygia	*Medicago varia*	
Centaurea scabiosa	*Melampyrum nemorosum*	
Cirsium arvense	*Melilotus albus*	
Cirsium heterophyllum	*Mentha arvensis*	
Cirsium palustre	*Odontites serotina*	
Consolida regalis	*Odontites verna*	
Echium vulgare	*Origanum vulgare*	
Epilobium angustifolium	*Phacelia tanacetifolia*	
Fragaria vesca	*Rubus idaeus*	
Galega orientalis	*Silene alba*	
Galeopsis bifida	*Silene vulgaris*	
Galeopsis speciosa	*Sonchus oleraceus*	
Galeopsis tetrahit	*Stachys palustris*	
Galium album	*Symphytum asperum*	

Table S3. Bumblebee species' traits based on tongue length, threat status, colony size, and main habitat type, and their abundance in our sample. Colony size information is based on Benton (2006), Pawlikowski (2008), von Hagen & Aichhorn (2014), del Castillo *et al.* (2015), Weronika Banaszak-Cibicka (pers. comm.), and our unpublished data. Main habitat classification is based on Bäckman & Tiainen (2002), Diaz-Forero *et al.* (2011), and our own unpublished data. Threatened species at a European scale were classified as vulnerable under the recent IUCN list (Nieto *et al.*, 2014).

Bumblebee species	**Tongue length**	**Threat status**	**Colony size**	**Main habitat**	**Total number of individuals**
Bombus confusus	short- or medium-tongued	threatened	small	generalist	2
B. cryptarum	short- or medium-tongued	non-threatened	medium	generalist	11
B. distinguendus	long-tongued	threatened	small	forest-scrub	160
B. hortorum	long-tongued	non-threatened	medium	open	526
B. humilis	short- or medium-tongued	non-threatened	small	open	32
B. hypnorum	short- or medium-tongued	threatened	large	generalist	240
B. jonellus	short- or medium-tongued	non-threatened	small	forest-scrub	24
B. lapidarius	short- or medium-tongued	non-threatened	large	open	1006
B. lucorum	short- or medium-tongued	non-threatened	large	open	1150
B. muscorum	short- or medium-tongued	threatened	small	forest-scrub	61
B. pascuorum	short- or medium-tongued	non-threatened	medium	forest-scrub	785
B. pratorum	short- or medium-tongued	non-threatened	small	forest-scrub	165
B. ruderarius	short- or medium-tongued	non-threatened	small	open	486
B. schrencki	short- or medium-tongued	non-threatened	small	forest-scrub	50
B. semenoviellus	short- or medium-tongued	non-threatened	small	open	4
B. soroeensis	short- or medium-tongued	non-threatened	medium	generalist	405
B. subterraneus	long-tongued	non-threatened	small	open	46
B. sylvarum	short- or medium-tongued	non-threatened	small	open	419
B. terrestris	short- or medium-tongued	non-threatened	large	open	213
B. veteranus	short- or medium-tongued	non-threatened	small	open	307

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Table S4. Investigated plant and bumblebee variables depending on crop rotation type (mean values and standard error of mean per transect section) and transect sections length mean values and standard error of mean. Cereal (all rye, oat, barley, triticale, and wheat fields), MFC = mass-flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape). Scale of flower cover 0–3: 0 = no flowers suitable for bumblebees; 1 = >0 to 1/3 of the area with flowers suitable for bumblebees; 2 = 1/3 to 2/3 with suitable flowers, 3 = >2/3 covered with suitable flowers.

	Cereal→cereal	**Cereal→MFC**	**MFC→cereal**	**MFC→MFC**
Plants				
Flower cover	0.85 ± 0.05	1.32 ± 0.06	1.03 ± 0.06	1.36 ± 0.06
Bumblebees				
Species richness	3.92 ± 0.25	5.18 ± 0.33	4.31 ± 0.29	5.19 ± 0.32
Abundance	12.19 ± 1.16	18.64 ± 2.42	12.10 ± 1.36	17.89 ± 1.67
Short-tongued abundance	10.53 ± 1.03	16.69 ± 2.11	10.88 ± 1.22	15.55 ± 1.47
Long-tongued abundance	1.66 ± 0.24	1.95 ± 0.40	1.22 ± 0.22	2.34 ± 0.38
Non-threatened abundance	10.91 ± 1.04	17.53 ± 2.22	11.47 ± 1.31	16.46 ± 1.53
Threatened abundance	1.28 ± 0.21	1.11 ± 0.29	0.63 ± 0.14	1.44 ± 0.28
Large colony abundance	5.46 ± 0.64	8.45 ± 1.23	4.61 ± 0.60	7.47 ± 0.92
Medium colony abundance	3.68 ± 0.41	5.47 ± 0.96	3.61 ± 0.48	4.57 ± 0.53
Small colony abundance	3.05 ± 0.40	4.72 ± 0.78	3.87 ± 0.54	5.85 ± 0.67
Open land abundance	7.93 ± 0.82	12.91 ± 1.66	8.10 ± 0.97	12.86 ± 1.30
Generalists abundance	1.63 ± 0.23	1.87 ± 0.34	1.36 ± 0.26	1.68 ± 0.26
Forest-scrub abundance	2.62 ± 0.36	3.86 ± 0.92	2.64 ± 0.43	3.36 ± 0.46
Transect sections length	227.5 ± 11.7	208.7 ± 13.5	223.6 ± 13.7	224.0 ± 11.2

Table S5. Investigated plant and bumblebee variables depending on management type (mean values and standard error of mean per transect section) and transect sections length mean values and standard error of mean. Scale of flower cover 0–3: 0 = no flowers suitable for bumblebees; 1 = >0 to 1/3 of the area with flowers suitable for bumblebees; 2 = 1/3 to 2/3 with suitable flowers, 3 = >2/3 covered with suitable flowers.

	Conventional farming	**Environmentally friendly management**	**Organic farming**
Plants			
Flower cover	0.84 ± 0.04	1.23 ± 0.05	1.39 ± 0.06
Bumblebees			
Species richness	3.61 ± 0.21	5.19 ± 0.26	5.31 ± 0.30
Abundance	10.26 ± 0.88	18.88 ± 1.70	17.16 ± 1.69
Short-tongued abundance	9.01 ± 0.79	16.61 ± 1.48	15.13 ± 1.49
Long-tongued abundance	1.25 ± 0.18	2.27 ± 0.34	2.03 ± 0.31
Non-threatened abundance	9.47 ± 0.81	17.70 ± 1.59	15.58 ± 1.51
Threatened abundance	0.78 ± 0.15	1.19 ± 0.20	1.58 ± 0.29
Large colony abundance	4.69 ± 0.46	8.67 ± 0.97	6.31 ± 0.77
Medium colony abundance	3.02 ± 0.35	5.13 ± 0.53	4.98 ± 0.68
Small colony abundance	2.55 ± 0.34	5.09 ± 0.53	5.86 ± 0.69
Open land abundance	7.14 ± 0.66	13.34 ± 1.28	11.28 ± 1.15
Generalists abundance	1.26 ± 0.20	2.11 ± 0.27	1.58 ± 0.23
Forest-scrub abundance	1.86 ± 0.24	3.43 ± 0.43	4.30 ± 0.73
Transect sections length	236.0 ± 10.9	223.2 ± 11.0	201.8 ± 9.8

Fig. S1. Illustrative photos of studied field margins.

Fig. S2. Study sites (black dotes) in the two regions of Northern and Southern Estonia.

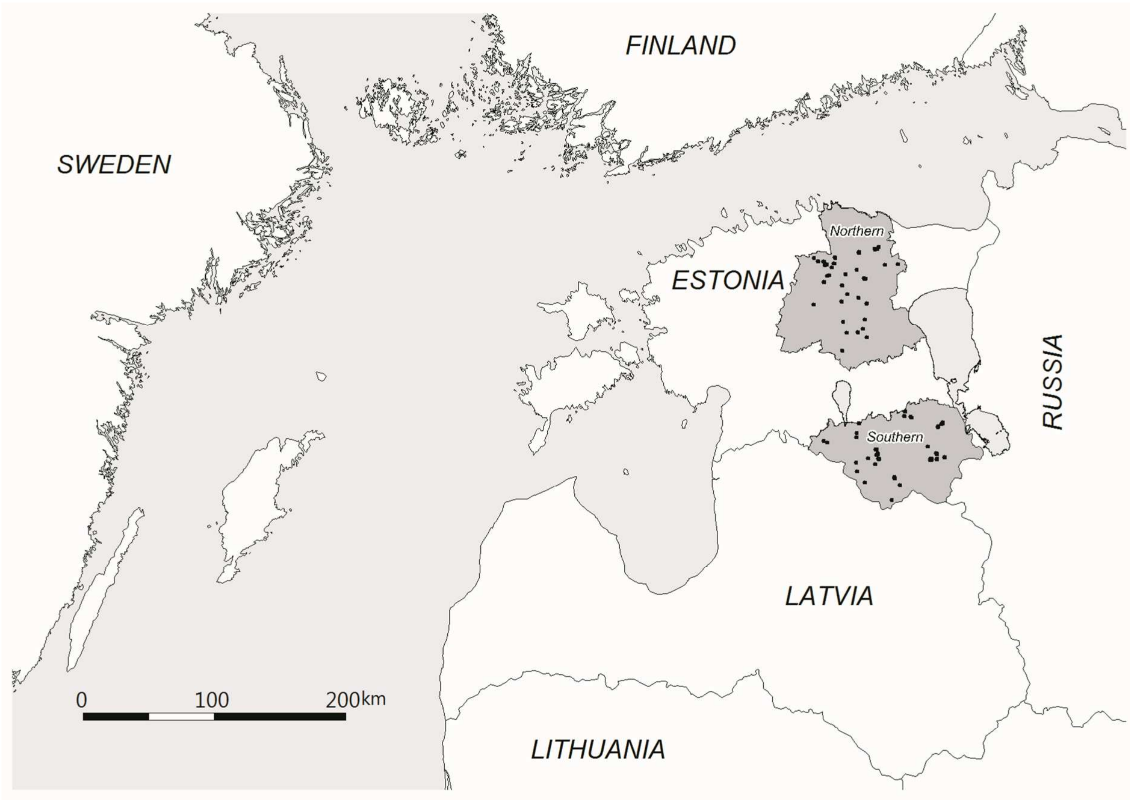

Fig. S3. Comparisons of bumblebee (a) species richness and (b) abundance in field margins between different crop rotation types, management types, and effect of flower cover. The figure shows results from linear mixed-effects models (p-value, lower and upper boundary of 95% CI). Indicated are effect sizes (y-axis) compared to the crop rotation type control group (cereal rollover field margins) and management type control group (conventional farming). The effect size is significantly different if the CIs do not overlap with zero. Asterisk symbols represent statistically significant p-values below 0.05, 0.01, and 0.001 (*, **, and ***, respectively). Cer = cereals (all rye, oat, barley, triticale, and wheat fields), MFC = mass-flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape). Environmental = environmentally friendly management, Organic = organic farming, Flowers = flower cover.

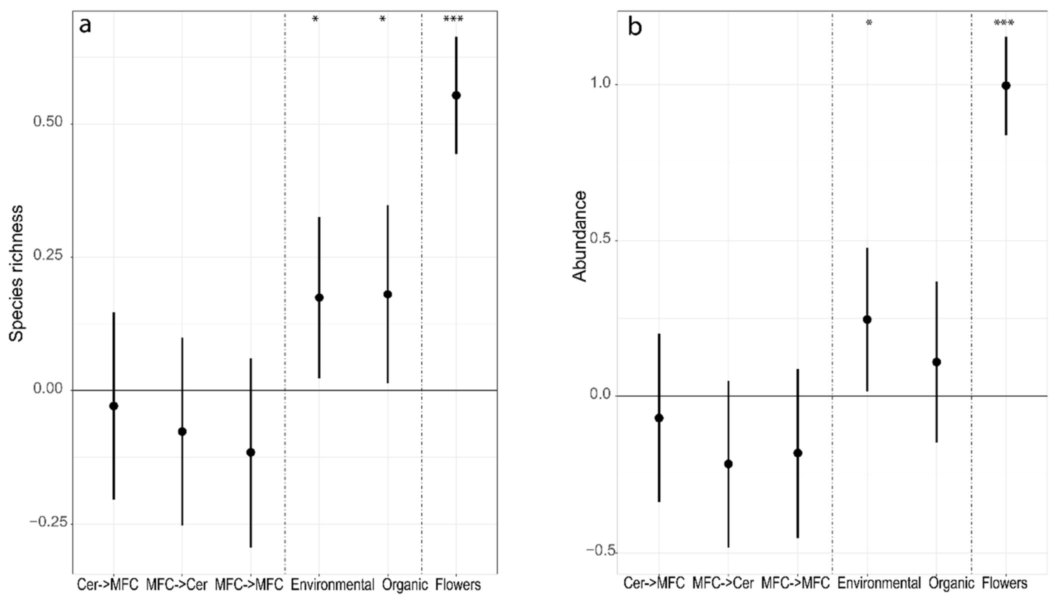

Fig. S4. Comparisons of bumblebee abundance in field margins between different crop rotation types, management types, and effect of flower cover for (a) short- and (b) long-tongued bumblebee species. The figure shows results from linear mixed-effects models (p-value, lower and upper boundary of 95% CI). Indicated are effect sizes (y-axis) compared to the crop rotation type control group (cereal rollover field margins) and management type control group (conventional farming). The effect size is significantly different if the CIs do not overlap with zero. Asterisk symbols represent statistically significant p-values below 0.05, 0.01, and 0.001 (*, **, and ***, respectively). Cer = cereals (all rye, oat, barley, triticale, and wheat fields), MFC = mass-flowering crops (pea, bean, clover, alfalfa, sweet clover species, and oilseed rape). Environmental = environmentally friendly management, Organic = organic farming, Flowers = flower cover.