

The potential of electricity transmission corridors in forested areas as bumble bee habitat

Running head: Bumble bees and powerlines

Bruce Hill¹ and Ignasi Bartomeus^{2*}

¹ Greater Wellington Regional Council, Shed 39, 2 Fryatt Quay, Pipitea, Wellington 6011, New Zealand.

² Estación Biológica de Doñana (EBD-CSIC), Avda. Américo Vespucio s/n, Isla de la Cartuja, E-41092 Sevilla, Spain.

*corresponding author: nacho.bartomeus@gmail.com

Abstract

Declines in pollinator abundance and diversity are not only a conservation issue but also a threat to crop pollination. Maintained infrastructure corridors, such as those containing electricity transmission lines, are potentially important wild pollinator habitat. However, there is a lack of evidence comparing the abundance and diversity of wild pollinators in transmission corridors with other important pollinator habitats. We compared the diversity of a key pollinator group, bumble bees (*Bombus spp.*), between transmission corridors and the surrounding semi-natural and managed habitat types at ten sites across Sweden's Uppland region. Our results show that transmission corridors have no impact on bumble bee diversity in the surrounding area. However, transmission corridors and other maintained habitats have a level of bumble bees abundance and diversity comparable to semi-natural grasslands and host species that are important for conservation and ecosystem service provision. Under the current management regime, transmission corridors already provide valuable bumble bee habitat, but given that host plant density is the main determinant of bumble bee abundance, these areas could potentially be enhanced by establishing and maintaining key host plants. We show that in northern temperate regions the maintenance of transmission corridors has the potential to contribute to bumble bee conservation and the ecosystem services they provide.

Keywords

Bombus, ecosystem service, conservation, pollination, maintained electricity transmission corridor, Sweden.

Introduction

Pollinators provide an essential ecosystem function, with 80% of plants being dependent on animal pollination for their reproduction [1]. Pollinators also provide an equally important regulating ecosystem service wherein 35% of total global crop production is reliant on animal pollination [2]. The discrepancy between supply and demand for honey bees provision of this regulating service has resulted in wild pollinators contribution to pollination gaining more recognition [3]. This is because pollination services provided by wild pollinators are often equal, complementary or superior to that provided by honey bees [4, 5]. A minority of bee species, including both managed and wild bumble bee species (*Bombus spp.*), pollinate most crops [6]. As bumble bees forage more effectively in colder temperatures than other bee species, their importance increases with latitude [7].

Pollinators are threatened by human induced environmental modification, including habitat loss, climate change and pesticides use [8, 9, 10]. Bumble bees are more sensitive to these changes than other bee species [11, 12]. Although some bumble bee species can use human modified habitats and are thriving, others are declining or near-extinct [11, 13]. For example, of the 68 bumble bee species recorded in Europe 31 species are in decline and an additional 16 species are threatened with extinction [14]. Habitat destruction [15] and a corresponding decrease of preferred host plant species [16] is one factor driving declines in bumble bee populations. For example, Europe's semi-natural grasslands, which are a significant bumble bee nesting and foraging habitat [17, 18], have decrease by 12.8% between 1990 and 2003 [19].

In response to pollinator decline, many government and international organisations are recognising the importance of maintaining pollination services [20, 21, 22, 23]. The

economic benefit provided by pollinators globally and within the EU level is estimated at €153 and €15 billion respectively [24] and therefore, maintaining and enhancing pollination is a significant area of policy. One policy response is the use of incentives. These include payments available in US through the Farm Bill 2014 [25] and in the EU through the EU Common Agricultural Policy (CAP) Agri-environmental schemes (AES). Using AES for ecological enhancement has been shown to boost bumble bee nesting and foraging habitat [26, 27, 28]. However, the potential of human-modified areas outside of agricultural land has so far received little attention from policy makers.

There is growing recognition that the routine utilitarian maintenance and disturbance of infrastructure corridors (electricity transmission corridors [29, 30, 31, 32]), roadsides [33, 34] and railway embankments [35] provides the valuable early successional landscapes required by many pollinators [36]. For example, roadside mowing has increased bee and butterfly abundance in the Netherlands [37]. Bee fauna in unmown electricity transmission corridors (hereafter transmission corridors) was richer than in adjoining annually mown grassy fields in Maryland, USA [29]. In Sweden, butterflies were more abundant in transmission corridors than in semi-natural grasslands [31, 32]. In the USA, integrated vegetation management in transmission corridors has improved the habitats of the threatened Frosted Elfin (*Callophrys irus* (Godast, 1824) and Karner Blue (*Lycaeides Melissa samuelis* (Nabokov, 1944) butterflies [38, 39].

In extensively forested parts of Europe [40, 41] and North America [38] transmission corridors can be valuable as they provide an environment suitable for herbaceous vegetation in otherwise largely forested landscapes [41]. Moreover, transmission corridors have the potential to connect discrete parts of the similar habitats [42]. However, there is limited

knowledge about pollinator abundance and diversity within transmission corridors. For example, little is known about how transmission corridors compare to other pollinator habitat types and the relationship between maintenance costs of different types of infrastructure corridors and their respective pollinator abundance and diversity [36].

With the many threats to pollinators, the recognition of small-grained landscape features such as transmission corridors as valuable habitat is timely. Here, we examine the importance of transmission corridors as habitat for bumble bees, which are a key pollinator group in Sweden's Uppland region. We compared bumble bee diversity and abundance in seven habitat types within ten spatially discrete sites - five bisected and five not bisected by transmission corridors. We predicted that transmission corridors would connect discrete patches of similar habitat and allow greater dispersal of bumble bees, consequently lowering overall beta diversity at the landscape level. However, among habitats we predicted that semi-natural grasslands would contain higher diversity compared with human-modified habitats such as transmission corridors, especially for threatened species. Finally, we reviewed the cost of maintaining and/or enhancing semi-natural grasslands and transmission corridors.

Method and materials

Site selection

The Swedish national transmission corridor grid (the system of 220-400 kV lines) occupies approximately 40,000 hectares, with 36,000 hectares passing through forest and consequently, requires regular maintenance. This network is owned, maintained and operated by Svenska kraftnät (SK), a state-owned public utility. SK's transmission corridors are subject to an easement that allows them the perpetual right to construct, keep and maintain

the transmission corridor grid irrespective of the underlying land tenure. In the Uppland region, transmission corridors are maintained on an eight year cycle. In year zero, transmission corridors are cleared of tall vegetation; in year three, trees threatening transmission lines are removed; in year four, transmission corridor access roads are cleared and in year seven, fast growing trees are felled. SK's maintenance is conducted by mechanical means (J Bjermkvist, 2014 pers. comm, 3 December SK).

To investigate the influence of transmission corridors on the surrounding area, we selected ten sites of four km² (2 x 2 km squares) in Sweden's Uppland region (Supplementary Material, Figure S1). In order to minimise landscape composition confounding our results, we ensured that 1) all sites had at least 45% forest cover (range 45-70%); 2) that the second most common land use was agriculture, and 3) that all target habitats were represented (see Table 1 for habitat description). Sites were between 3.2 and 6.4 km apart. There can be a wide variation in foraging distances between bumble bee species, with radio-tracked *B. terrestris* (L, 1758) and *B. ruderatus* (Fabricius, 1775) workers foraging up to 2.5 km and 1.9 km respectively from their nests [43], while *B. muscorum* (L, 1758) has a much smaller foraging range of between 100-500 m [44]. Therefore, the distances between our sites minimised the chance that bumble bees recorded in one site were also recorded in another. Five sites were bisected by a transmission corridor section (widths ranging between 50-70 m), of which between 1.2-1.5 km was bordered by closed canopy forest. At the time of surveying, four sites were in year three of their maintenance schedule (all the tall vegetation was removed in 2011) and the remainder was in year six (all tall vegetation was removed in 2008). All corridors ran from north/northeast to south/southwest. The other five sites were at least 3 km from any other transmission corridors.

In order to capture the variability among the surveyed habitat, we conducted multiple transects per site in each habitat (mean of 2.25 transects per habitat and site). Some sites had no representation of particular habitat types. Overall we surveyed 158 transects spread across seven habitat types (Table 1, see photos in Supplementary Material Figure S2). These habitat types were transmission corridors, semi-natural grasslands, maintained roadsides (roadsides), forest/ semi-natural grasslands boundaries, cereal crop edges, maintained drains and forests. All these habitats, except forests, have been identified as valuable bumble bee habitat in the Uppland region [17].

To our knowledge none of the surveyed transects were in areas that had been ecologically enhanced. The surveyed roadsides (all quiet tertiary or quaternary roads) are mown once annually (M. Lindqvist 2014, pers. comm, 20 May Trafikverket) whilst drains are maintained on an as-needed basis. The semi-natural grasslands surveyed met the EU's definition of permanent pasture and grassland [45].

Each transect included an area 50 m long and up to 3m wide. All transects contained a representative density of flowering plants. Within each transect we surveyed bumble bee abundance and diversity by slowly walking along the transect for 15 minutes (a method recommended in [46]). Transects were walked twice (back and forth) but always keeping the area surveyed and the survey time fixed.

Where possible, bumble bees were identified while foraging, but most individuals could not be readily identified on the wing and therefore, were caught by net, identified and released if possible. Caught specimens that were not identified in the field were killed then identified later. Due to the difficulty distinguishing *B. terrestris* and *B. lucorum* (L. 1761) workers, all

specimens were combined as *B. terrestris* [26]. Both species are common, extremely difficult to distinguish and are often grouped as they are ecologically similar. Hence, this grouping does not affect our distinction between ecosystem service providers and species of conservation concern. Collection handling time was not included in the 15 minute survey time.

When possible, the host plant of each foraging bumble bee was identified to species level during the survey, otherwise plant specimens were identified later. To correspond with peak bumble bee activity in the Uppland region [17] each site was surveyed twice between 9th July 2014 and 25th August 2014, with at least 2 weeks between surveys. Each survey took one day, was undertaken between 9 am and 5.30 pm and only during dry periods in temperatures above 15°C. Transects in transmission corridors were always in un-shaded areas. Before beginning each survey within the respective transect, flower density was estimated as the total percentage of the transect area covered by flowers. The categories used were “<1%”, “1-5%”, “6-10%”, “11-20%”, “21-40%”, “41-60%” and “>61%” coverage. Because all surveying were conducted by one person, this semi-quantitative measure enabled a quick yet consistent assessment of the flower density in all transects.

Statistical analysis

To compare species abundance and richness (alpha diversity) across sites and habitats we built a generalised linear model (GLM) with species richness or abundance per transect as a function of site type (transmission corridors/no transmission corridor) and habitat type. Flower density was also included as a covariable. To account for the hierarchical structure of the data, transect nested within site was included as a random factor. Residuals were investigated to ensure they fulfilled the model assumptions and to meet the postulation of

homoscedasticity we used a constant variance function. All models (see also below) were constructed using package nlme [47] in R [48]. The statistical power of the models to detect a 20% difference was calculated using package *Simr* [49].

Beta diversity was analysed on two scales. Firstly, we investigated if sites containing a transmission corridor had lower turnover rates among the different habitats. Secondly, we investigated beta diversity among different sites of the same habitat. To determine species turnover, we used additive partitioning of species richness [50, 51, 52, 53]. Alpha diversity was defined as the mean number of species per transect (i.e. species richness). The beta diversity among sites with and without transmission corridors was calculated as the total number of species found within a transmission corridor site (gamma diversity) minus the mean number of species per transect on that transmission corridor site (alpha). Beta diversity among habitats was calculated as the rarefied number of species found across all transects of a given habitat type (gamma) minus the mean number of species per transect surveyed for that habitat type (alpha). Rarefaction in gamma diversity was undertaken to 90 individuals to avoid difference in sampling intensity across habitats using the package *vegan* [54] (Supplementary Material Figure S3).

From the recorded set of bumble bee species, we determined which habitats were utilised by bumble bees listed as threatened in Europe by the IUCN [14] (*B. muscorum*) and species listed as declining by Scheper et al. [16]. These included *B. humilis* (Illiger, 1806), *B. sylvarum* (L, 1761) and *B. soroeensis* (Fabricius, 1777) and are hereafter termed “threatened species”. We also recorded which habitats were used by the species that are the main providers of crop-pollination in Europe: *B. terrestris*, *B. lapidarius*, *B. pascuorum* (Scopoli, 1763), *B. hypnorum* (L, 1758), *B. pratorum* (L, 1761) and *B. hortorum* (L, 1758) [6], and are

hereafter termed “provider species”. We constructed a GLM with abundance of both threatened species and provider species per transect as a function of habitat and flower density. Transect nested within site was also included as random factor. To meet the model assumptions of homoscedasticity we used a constant variance function.

Finally, to assess the importance of each host plant species for every recorded bumble bee species in the surveyed habitats, we calculated the plant species’ strengths [55] for the pool of transects of transmission corridor habitats, semi-natural grassland habitats and all habitats combined. For each plant, strength is defined as the sum of all pollinators’ dependencies on that given plant. Pollinator dependence is the fraction of all pollinator recorded visits performed on that given plant species. Therefore, a plant species could have high strength values if it attracted many pollinator species that had low dependency on it, or if it attracted few pollinators which were highly reliant on it. Note that this metric measures plant species use, not preference; a plant species could be visited by a given pollinator simply because it was the most abundant, not because it was preferred.

Cost of managing and/or enhancing roadsides, semi-natural grasslands and transmission corridors

These managing costs were gathered from EU member material [56, 57, 58], peer-reviewed literature [26, 27, 59] and from conversations with Svenska kraftnät and Trafikverket (the Swedish Transport Administration) staff. There is large variation in the years that the management and/or enhancement costs for roadsides, semi-natural grasslands and transmission corridors were published or sourced and the initial currency in which these costs were originally stated. Therefore, no attempt was made to adjust these costs to inflation or currency fluctuations. Consequently, to enable an approximate comparison of these costs, all

are expressed in Euros per hectare per annum, with the conversion of the original currency to Euros being carried out in June 2015.

Results

In total, we recorded 1016 bumble bee specimens, comprising 20 species. These were recorded foraging on 24 plant species. Transmission corridor bisecting a site did not change bumble bee abundance (Table 2, Fig 1A) or species richness (Table 2, Fig 1B). Similarly, we found no differences among habitats in terms of total bumble bee abundance or species richness (Table 2, Fig 2A and B). As we predicted, flower density was the strongest predictor of bumble bee abundance and richness (Table 2). While the power to detect a 20% difference among sites that were bisected and not bisected by a transmission corridor is low (power ranges from 19% for abundance model to 31% for richness model), our power to detect a 20% difference between semi-natural grasslands and transmission corridors is higher (67% for the abundance model; 89% for the richness model).

Patterns of species beta diversity reveal that sites bisected by a transmission corridor did not have more homogenous species composition compared with sites not bisected by a transmission corridor (test for differences in beta diversity: $n = 10$, $F_{1,8} = 0.03$, $P = 0.85$, Fig 1B). We also found that species turnover among transects of the same habitat was similar, with all habitats having between 11 and 15 rarefied species (i.e. gamma diversity; Fig 2B).

We found that provider species were present in most habitats. *B. pascuorum* and *B. terrestris* were present in all habitats and were also the most abundant, while *B. lapidarius* was found in all habitats except forest. Overall, the abundance of provider species was not different across habitats (Fig 3A, Table 3). Interestingly, threatened species were not limited only to

semi-natural grasslands (*B. sylvarum* and *soroensis*), but were also found in roadsides (*B. humilis*, *soroensis* and *sylvarum*) and transmission corridors (*B. muscorum* and *humilis*). However, threatened species were rarely found in the other habitat types (Fig 3B, Table 3). Flower density did not explain threatened species abundance (Table 3).

Throughout all the sites *Carduus crispus* (L., 1753), *Trifolium pratense* (L., 1753) and *Centaurea jacea* (L., 1753) were the most important host plants for sustaining both threatened and provider species (Table 4, Fig 4). However, the importance of plant species measured as its strength varied between transmission corridors and semi-natural grasslands. For example, due to their abundance, species in the genus *Trifolium* were more important in semi-natural grasslands than in transmission corridors. Overall, important plant species sustained both bumble bee species that were not overly reliant on them and threatened species (e.g. *B. sylvarum*, *B. humilis*: Fig 4).

There was a large range in the costs of maintaining and/or ecologically enhancing transmission corridors, roadsides and semi-natural grasslands. The current maintenance of transmission corridors in Uppland costs approximately €60/ha per year (J Bjermkvist, 2014 pers comm., 3 December). Mowing Uppland roadsides similar to those surveyed costs between €500-1000/ha per year (M. Lindqvist, 2015 pers comm., 20 May). In comparison, the EU funding of Swedish AES for semi-natural grassland maintenance and enhancement, depending on inputs ranges between €121-506/ha per year [59]. Where funding is awarded, implementation of the AES is only required for 5 years [59]. This style of active management has achieved little in maintaining a diversity of grassland flora [59].

Discussion

We found that SK's current maintenance regime resulted in transmission corridors having
bumble bee abundance and diversity equivalent to that in semi-natural grasslands. This
supports the increasing recognition that transmission corridors are valuable wild pollinator
habitat as in Sweden [17, 60]. In order to prevent tall vegetation damaging overhead lines,
operative transmission corridors within forested areas should continue being maintained.
Continuation of SK's current management regime should result in transmission corridors
providing bumble bee habitat equivalent to that supplied by semi-natural grasslands.

The fact that both transmission corridors and roadsides can sustain similar numbers of
bumble bees is remarkable, especially given that the area of semi-natural grasslands in
Sweden is estimated to be <10% of what it was one century ago [61]. This is particularly true
for threatened species as 18 of the 41 bumble bee species in Sweden are in decline and seven
more are threatened with extinction [14]. Hence, areas of transmission corridors in forested
areas could provide some mitigation to the loss of semi-natural grasslands.

Roadsides also provided valuable habitat for threatened and provider species, with numbers
of individuals per transect in both groups ranking higher than semi-natural grassland and
forest/grassland boundaries. Roadsides tended to have high flower cover (30% density on
average) which is similar to that of semi-natural grasslands. Maintained drains and cereal
crop edges also had flower coverage similar to transmission corridors (13-20%), but
sustained fewer bumble bee individuals, particularly those of threatened species. Dense grass
swards were observed in many of the maintained drains. These swards possibly limited the
habitat available for the favoured host species such as *T. pratense*, which are light demanding
and low growing [62]. Overall, cereal crop edges were the narrowest habitat, with some being
≤1m wide, and hence provided the least suitable area for host plants. As forested areas of tall

evergreen trees (predominantly *Pinus sylvestris* (L., 1753) and *Picea abies* (L. 1753)) had little flower cover (average of 5% density), it is not surprising that this habitat type hosted few bumble bees.

In comparison, transmission corridors and roads bisecting those forest patches were flower rich and may have an aggregation effect, concentrating pollinators into these resource rich areas [26]. However, it is important to note that flower density did not explain threatened species abundance, which suggests other factors, such as nesting sites, may be more limiting for these species [26]. It is not known what the effects of electrical and magnetic field radiation from high voltage powerlines have on bees [36] and quiet roads potentially represent a minor threat to bumble bees [33]. It is possible that these risks are countered in transmission corridors by providing suitable habitat for rodents, thereby potentially increasing nesting availability for bumble bees using abandoned rodent cavities as nesting sites [63]. Similarly, roadsides often contain areas of withered grass and tussocks that are crucial for nesting sites [17].

Overall, our results do not indicate that transmission corridors enhance bumble bee abundance or species richness by increasing connectivity of non-forested habitats or by having a spill-over effect into surrounding habitats. However, with only 10 sites the power to detect such landscape effects in our dataset is limited. The intrinsic variability in bumble bee populations between years [64] suggests that long term data in different boreal countries are needed to confirm our results.

Within transmission corridors the main host plants for bumble bees are mostly limited to small areas that are not dominated by shading shrubby vegetation (B. Hill 2015 pers. obs, 12

November). Floral density is an important predictor of bumble bee diversity and abundance. The large areas of herbaceous vegetation and shrubs within transmission corridors could provide considerable potential to enhance bumble bee habitat. Such actions could also assist in providing the ~2% of flower-rich habitat within farmland that is required to maintain provider bumble bee species colonies [65].

Maintaining and enhancing the abundance of early flowering *Salix* species such as *Salix caprea* (L. 1753) is a way of potentially improving the quality of bumble habitat in transmission corridors. Early flowering *Salix* species provide critical forage for early emerging bumble bee queens and subsequently, successful colony establishment. It has been shown that >1000m³ crown volume/ha positively influenced bumble bee abundance [17]. Flower abundance later in the season is also critical for late emerging species because many of these are threatened [16]. In Sweden, bumble bees are mostly active up to early September, after which the new queens hibernate underground [17]. As we surveyed almost to this period, we assume that we captured the peak phenology of most bumble bee species, including the threatened species.

For most bumble bee species, legumes and other nectar rich flowers are a significant resource [62] and our results support this observation. Although we did not separate nectar and pollen foraging trips, it is likely that different plant species are important for different reasons. For example, while *T. pratense* is a rich source of nectar and pollen, most thistle species may be used only for nectar [62]. However, in comparison to semi-natural grasslands, the transmission corridors we surveyed had a lower abundance of key plants such as *T. pratense*. The sowing of nectar rich flower seeds is a proven way of enhancing bumble bee abundance and diversity [28]. This is a possible means of enhancing bumble bee habitat in transmission

corridors and would cost approximately €42/ha/yr [58]. Suitable open areas include access roads as these are not dominated by shading shrubby vegetation, and the additional areas of bare earth exposed during their maintenance.

Increasing the amount of open habitat within transmission corridors is another potential way of increasing host plant habitat and consequently, bumble bee diversity and abundance [29, 37, 65]. Removal of existing shrubs on transmission corridors would cost approximately €14/ha/yr [66]. Host plants might then naturally colonise these areas or seeds of suitable species could be sown.

Funding the enhancement of bumble bee habitat within transmission corridors could be an effective way to both benefit bumble bee conservation and increase the pollination services they provide. It might also augment the ecological value of these areas. Depending on the location, enhancing the ecological value of transmission corridors could be conducted in tandem with the protection of ecological focus areas as prescribed by the EU [45]. The opportunity cost of producing an ecological focus area via converting productive agricultural land to unproductive biodiversity rich areas can be considerable. For example, winter wheat which is a major crop in Uppland region, can provide gross returns of between €565/ha-€1505/ha [67, 68]. The establishment and maintenance of biodiversity rich areas within transmission corridors, like those studied here, would avoid any such opportunity cost. The permanence of transmission corridors in the landscape also means that any enhancement within these is likely to provide long-term benefits. Such actions might well aid in meeting the EU's *Biodiversity Strategy to 2020* Target 2, as well as the 2020 headline target [20]. However, areas of transmission corridors do not meet the EU's CAP, enabling definitions of

either “eligible hectare” or “ecological focus area”. Therefore, funding via EU AES for the ecological enhancement of such areas is not currently possible [45].

Pollinator habitat within transmission corridors is spatially limited to certain areas. Moreover, we only tested for the effect of transmission corridors in forested landscapes. The ability of transmission corridors to sustain pollinators in non-forested landscapes is still unexplored. Consequently, transmission corridors cannot substitute AES, but can complement it. In other situations it has been shown that tailoring inputs for specific results is possible. Application of AES is simple - resource poor landscapes e.g. croplands had the greatest benefit to provider species, whilst applying AES in more complex landscapes provided more benefit to threatened species [69]. The widespread geographic extent of transmission corridors through many northern hemisphere landscapes provides valuable but yet to be fully exploited opportunities for bumble bee conservation. However the benefit of transmission corridors for biodiversity other than bumble bees has not yet been explored.

Conclusions

Bumble bee abundance and diversity is threatened by many factors. Given both the intrinsic value of bumble bees and the ecosystem service they provide, actions are being taken to counter these threats. Studies, including ours have shown that the maintenance of transmission and other infrastructure corridors may unintentionally create valuable habitat for pollinators. Our study also shows that SK's current transmission corridor maintenance regime is a cost effective way of producing such habitat when compared to other maintenance regimes. The permanence and extent of transmission corridors means that any wild pollinator habitat created due to their maintenance is likely to be present long-term. There are simple,

proven management practices to enhance bumble bee richness and abundance but further research is needed to evaluate and optimise conservation approaches. Funding is needed for such work. Any future reviews of the Europe 2020 Strategy, CAP, or similar policy may provide opportunities to promote incentives to enhance the valuable pollinator habitat provided by maintaining infrastructure corridors.

Data, code and materials: All data and code to reproduce this analysis are deposited in www.github.com/ibartomeus/powerlines. Data available from the Dryad Digital Repository: <http://dx.doi.org/10.5061/dryad.v32df>

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Author contributions: BH and IB conceived the study; BH collected field data, participated in the design of the study and drafted the manuscript; IB designed the study, carried out the statistical analyses, coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

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References:

1. Ollerton J, Winfree R, Tarrant S. 2011 How many flowering plants are pollinated by animals? *Oikos*, **120**, 321-326.
2. Klein AM, Vaissiere BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T. 2007 Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society of London B: Biological Sciences*, **274**, 303-313.
3. Breeze TD, Bailey AP, Balcombe KG, Potts SG. 2011 Pollination services in the UK: How important are honeybees? *Agriculture, Ecosystems , Environment*, **142**, 137-143.
4. Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, Kremen C, Carvalheiro LG, Harder LD, Afik O, Bartomeus I, *et al.* 2013 Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*, **339**, 1608-1611.
5. Rader R, Bartomeus I, Garibaldi LA, Garratt MP, Howlett BG, Winfree R, Cunningham SA, Mayfield MM, Arthur AD, Andersson GK, Bommarco R. *et al.* 2016 Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences*, **113**(1):146-51.

474 **6.** Kleijn D, Winfree R, Bartomeus I, Carvalheiro LG, Henry M, Isaacs R, Klein AM,
475 Kremen C, M'Gonigle LK, Rader R, Ricketts TH *et al.* 2015 Delivery of crop pollination
476 services is an insufficient argument for wild pollinator conservation. *Nature communications*,
477 **6**, 7414.

478

479 **7.** Corbet SA, Williams IH, Osborne JL. 1991 Bees and the pollination of crops and wild
480 flowers in the European Community. *Bee world*, **72**, 47-59.

481

482 **8.** Winfree R, Bartomeus I, Cariveau DP. 2011 Native pollinators in anthropogenic habitats.
483 *Annual Review of Ecology, Evolution, and Systematics*, **42**, 1-24.

484

485 **9.** González-Varo JP, Biesmeijer JC, Bommarco R, Potts SG, Schweiger O, Smith HG,
486 Steffan-Dewenter I, Szentgyörgyi H, Woyniecowski M, Vilà M. 2013 Combined effects of
487 global change pressures on animal-mediated pollination. *Trends in Ecology, Evolution*, **28**,
488 524-530.

489

490 **10.** Kerr JT, Pindar A, Galpern P, Packer L, Potts SG, Roberts SM, Rasmont P, Schweiger O,
491 Colla SR, Richardson LL, Wagner DL. *et al.* 2015 Climate change impacts on bumblebees
492 converge across continents. *Science*, **349**, 177-180.

493

494 **11.** Bartomeus I, Ascher JS, Gibbs J, Danforth BN, Wagner DL, Hedtke SM, Winfree R.
495 2013. Historical changes in northeastern US bee pollinators related to shared ecological traits.
496 *Proceedings of the National Academy of Sciences*, **110**, 4656-4660.

497

- 498 **12.** Packer L, Owen R. 2001 Population genetic aspects of pollinator decline. *Conservation*
499 *Ecology*, **5**(1), 4.
500
- 501 **13.** Cameron SA, Lozier JD, Strange JP, Koch JB, Cordes N, Solter LF, Griswold TL. 2011
502 Patterns of widespread decline in North American bumble bees. *Proceedings of the National*
503 *Academy of Sciences*, **108**, 662-667.
504
- 505 **14.** Nieto A, Roberts SPM, Kemp J, Rasmont P, Kuhlmann M, García Criado M, Biesmeijer
506 JC, Bogusch P, Dathe HH, De la Rúa P, De Meulemeester T, Dehon M, Dewulf A, Ortiz-
507 Sánchez FJ, Lhomme P, Pauly A, Potts SG, Praz C, Quaranta M, Radchenko VG, Scheuchl
508 E, Smit J, Straka J, Terzo M, Tomozii B, Window J, Michez D. 2014 European red list of
509 bees. *IUCN, European Commission, Luxembourg*.
510
- 511 **15.** Vanbergen AJ, Baude M, Biesmeijer JC, Britton NF, Brown MJ, Brown M, Bryden J,
512 Budge GE, Bull JC, Carvell C, Challinor AJ. 2013 Threats to an ecosystem service: pressures
513 on pollinators. *Frontiers in Ecology and the Environment*, **11**, 251-259.
514
- 515 **16.** Scheper J, Reemer M, van Kats R, Ozinga WA, van der Linden GT, Schaminée JH,
516 Siepel H, Kleijn D. 2014 Museum specimens reveal loss of pollen host plants as key factor
517 driving wild bee decline in The Netherlands. *Proceedings of the National Academy of*
518 *Sciences*, **111**, 17552-17557.
519
- 520 **17.** Svensson B. 2002 Foraging and nesting ecology of bumblebees in agricultural landscapes
521 in Sweden. Doctoral Thesis. Swedish University of Agricultural Sciences, Uppsala, Sweden
522

18. ICUN. 2014 Bad news for Europe's bumblebees. <<http://www.iucn.org/?14612/Bad-news-for-Europes-bumblebees>> 6th June 2015.

19. FAO (Food and Agricultural Organisation of the United Nations) 2006: FAO Statistical Yearbook. – FAOSTAT

20. EU 2011- Our life insurance, our natural capital: An EU biodiversity strategy to 2020. Brussels. 3.5.2011 COM (2011) 244 Final. Targets mentioned in text: “Target 2: By 2020, ecosystems and their services are maintained and enhanced by establishing green infrastructure and restoring at least 15% of degraded ecosystems”; “Headline Target: Halting the loss of biodiversity and the degradation of ecosystem services in the EU by 2020 and restoring them in so far as feasible, while stepping up the EU contribution to averting global biodiversity loss”.

21. Whitehouse. 2015 National Strategy to promote the health of honey bees and other pollinators. Pollinator Health Task Force. May 19th 2015.

22. Potts SG, Biesmeijer JC, Bommarco R, Felicioli A, Fischer M, Jokinen P, Kleijn D, Klein AM, Kunin WE, Neumann P, Penev LD. 2011 Developing European conservation and mitigation tools for pollination services: approaches of the STEP (Status and Trends of European Pollinators) project. *Journal of Apicultural Research*, **50**(2), pp.152-164.

23. Defra. 2014a The National Pollinator Strategy: for bees and other pollinators in England. Department for Environment, Food and Rural Affairs, London, UK.

- 548 **24.** Gallai N, Salles JM, Settele J, Vaissière BE. 2009 Economic valuation of the
549 vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics*,
550 **68**, 810-821.
551
- 552 **25.** Vaughan M, Skinner M. 2015. Using 2014 Farm Bill Programs for Pollinator
553 Conservation. *USDA Biology Technical Note*, **78**, 2nd Ed.
554
- 555 **26.** Lye G, Park K, Osborne J, Holland J, Goulson D. 2009 Assessing the value of Rural
556 Stewardship schemes for providing foraging resources and nesting habitat for bumblebee
557 queens (Hymenoptera: Apidae). *Biological Conservation*, **142**, 2023-2032.
558
- 559 **27.** Carvell C, Meek WR, Pywell RF, Nowakowski M. 2004 The response of foraging
560 bumblebees to successional change in newly created arable field margins. *Biological*
561 *Conservation*, **118**, 327-339.
562
- 563 **28.** Carvell C, Meek WR, Pywell RF, Goulson D, Nowakowski M. 2007 Comparing the
564 efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on
565 arable field margins. *Journal of Applied Ecology*, **44**, 29-40.
566
- 567 **29.** Russell KN, Ikerd H, Droege S. 2005 The potential conservation value of unmowed
568 powerline strips for native bees. *Biological Conservation*, **124**, 133-148.
569
- 570 **30.** Wagner DL, Metzler KJ, Leicht-Young SA, Motzkin G. 2014 Vegetation composition
571 along a New England transmission line corridor and its implications for other trophic levels.
572 *Forest Ecology and Management*, **327**, 231-239.

573

574 **31.** Berg Å, Ahrné K, Öckinger E, Svensson R, Söderström B. 2011 Butterfly distribution and
575 abundance is affected by variation in the Swedish forest-farmland landscape. *Biological*
576 *conservation*, **144**, 2819-2831.

577

578 **32.** Berg Å, Ahrné K, Öckinger E, Svensson R, Wissman J. 2013 Butterflies in semi-natural
579 pastures and powerline corridors—effects of flower richness, management, and structural
580 vegetation characteristics. *Insect conservation and diversity*, **6**, 639-657.

581

582 **33.** Hopwood J, Winkler L, Deal B, Chivvis M. 2010 Use of roadside prairie plantings by
583 native bees. *Living Roadway Trust Fund* < [http://www. iowalivingroadway.](http://www.iowalivingroadway.com/ResearchProjects/90-00-LRTF-011.pdf)
584 *com/ResearchProjects/90-00-LRTF-011. pdf*> 1st November 2011.

585

586 **34.** Hanley ME, Wilkins JP. 2015 On the verge? Preferential use of road-facing hedgerow
587 margins by bumblebees in agro-ecosystems. *Journal of Insect Conservation*, **19**, 67-74.

588

589 **35.** Morón D, Skórka P, Lenda M, Rozej-Pabijan E, Wantuch M, Kajzer-Bonk J, Celary W,
590 Mielczarek ŁE, Tryjanowski P. 2014 Railway embankments as new habitat for pollinators in
591 an agricultural landscape. *PloS one*, **9**, p.e101297.

592

593 **36.** Wojcik VA, Buchmann S. 2012 Pollinator conservation and management on electrical
594 transmission and roadside rights-of-way: A review. *Journal of Pollination Ecology*, **7**.

595

596 **37.** Noordijk J, Delille K, Schaffers AP, Sýkora KV. 2009 Optimizing grassland management
597 for flower-visiting insects in roadside verges. *Biological Conservation*, **142**, 2097-2103.

598

599 **38.** Conniff R. 2014 Electric Power Rights of Way: A New Frontier for Conservation.

600 Environment 360 [Online]. <

601 http://e360.yale.edu/feature/electric_power_rights_of_way_a_new_frontier

602 [_for_conservation/2816/](http://e360.yale.edu/feature/electric_power_rights_of_way_a_new_frontier_for_conservation/2816/)> 28th April 2015.

603

604 **39.** Forrester JA, Leopold DJ, Hafner SD. 2005 Maintaining critical habitat in a heavily
605 managed landscape: effects of power line corridor management on Karner blue butterfly
606 (*Lycaeides melissa samuelis*) habitat. *Restoration Ecology*, **13**, 488-498.

607

608 **40.** Sydenham MAK, Eldegard K, Totland Ø. 2014 Spatio-temporal variation in species
609 assemblages in field edges: seasonally distinct responses of solitary bees to local habitat
610 characteristics and landscape conditions. *Biological Conservation*, **23**, 2393.

611

612 **41.** Eldegard K, Totland Ø, Moe SR. 2015 Edge effects on plant communities along power
613 line clearings. *Journal of Applied Ecology*, **52**, 871-880.

614

615 **42.** Haddad NM. 1999 Corridor and distance effects on interpatch movements: a landscape
616 experiment with butterflies. *Ecological Applications*, **9**, 612-622.

617

618 **43.** Walther-Hellwig K, Frankl R. 2000 Foraging habitats and foraging distances of
619 bumblebees, *Bombus* spp.(Hym., Apidae), in an agricultural landscape. *Journal of Applied*
620 *Entomology*, **124**, 299-306.

621

44. Hagen M, Wikelski M, Kissling WD. 2011 Space use of bumblebees (*Bombus* spp.) revealed by radio-tracking. *PloS one*, **6**, p.e19997.
45. EU 2013- Official Journal of the European Union L347, 17 December 2013 1-63
46. Westphal C, Bommarco R, Carré G, Lamborn E, Morison N, Petanidou T, Potts SG, Roberts SP, Szentgyörgyi H, Tscheulin T, Vaissière BE. 2008 Measuring bee diversity in different European habitats and biogeographical regions. *Ecological Monographs*, **78**, 653-671.
47. Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team, 2015. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-122, <http://CRAN.R-project.org/package=nlme>.
48. R Core Team. 2013 R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org/>.
49. Green, P. and MacLeod, C. J. (2016), SIMR: an R package for power analysis of generalized linear mixed models by simulation. *Methods Ecol Evol*, **7**: 493–498.
doi:10.1111/2041-210X.12504
50. Tylianakis JM, Klein AM, Tscharntke T. 2005 Spatiotemporal variation in the diversity of Hymenoptera across a tropical habitat gradient. *Ecology*, **86**, 3296-3302.

51. Lande R. 1996 Statistics and partitioning of species diversity, and similarity among multiple communities. *Oikos*, **76**, 5-13.
52. Veech JA, Summerville KS, Crist TO, Gering JC. 2002 The additive partitioning of species diversity: recent revival of an old idea. *Oikos*, **99**, 3-9.
53. Crist TO, Veech JA, Gering JC, Summerville KS. 2003 Partitioning species diversity across landscapes and regions: a hierarchical analysis of α , β , and γ diversity. *The American Naturalist*, **162**, 734-743.
54. Oksanen J, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Henry M, Stevens H, Wagner H. 2013. vegan: Community Ecology Package. R package version 2.0-10. <http://CRAN.R-project.org/package=vegan>
55. Bascompte J, Jordano P, Olesen, JM. 2006. Asymmetric coevolutionary networks facilitate biodiversity maintenance. *Science*, **312**, 431-433.
56. Defra. 2014b Introducing Countryside Stewardship. Department for Environment, Food and Rural Affairs, London, UK.
57. Scottish Government. 2009 < <http://www.gov.scot/Topics/farmingrural/Agriculture/Environment/Agrienvironment/Rural/Steward> > 29th August, 2015.
58. Defra 2013 Entry Level Stewardship: Environmental Stewardship Handbook, Fourth Edition. Department for Environment, Food and Rural Affairs, London, UK.

672

673 **59.** Dahlström A, Luga A, Lennartsson T. 2013 Managing biodiversity rich hay meadows in
674 the EU: a comparison of Swedish and Romanian grasslands. *Environmental Conservation*,
675 **40**, 194-205.

676

677 **60.** Sandell J. 2007 Bumblebee distribution in space and time in three landscapes in south
678 eastern Sweden. M.Sc Thesis, Linköping University, Sweden

679

680 **61.** Palmgren E. 2010 Distribution of Semi-Natural Pastures in Sweden: A Comparison of
681 Coverage Estimation Using Random Sampling and Total Registration Data Sets. M.Sc.
682 Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden

683

684 **62.** Kleijn D, Raemakers I. 2008 A retrospective analysis of pollen host plant use by stable
685 and declining bumble bee species. *Ecology*, **89**, 1811-1823.

686

687 **63.** Clarke DJ, White JG. 2008 Recolonisation of powerline corridor vegetation by small
688 mammals: timing and the influence of vegetation management. *Landscape and urban*
689 *planning*, **87**, 108-116.

690

691 **64.** Crone EE. 2013 Responses of social and solitary bees to pulsed floral resources. *The*
692 *American Naturalist*, **182**, 465-473.

693

694 **65.** Dicks LV, Baude M, Roberts SP, Phillips J, Green M, Carvell C. 2015 How much flower-
695 rich habitat is enough for wild pollinators? Answering a key policy question with incomplete
696 knowledge. *Ecological Entomology*, **40**, 22-35.

697
698
699
700
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721

66. Ekvall H. 2014 Cost-effectiveness of Measures to Improve Biodiversity in Swedish Forests. Doctoral Thesis. Swedish University of Agricultural Sciences, Umeå. Sweden

67. Production of cereals, dried pulses and oilseeds in 2014. <http://www.scb.se/en_/Finding-statistics/Statistics-by-subject-area/Agriculture-forestry-and-fishery/Agricultural-production/Production-of-cereals-dried-pulses-and-oil-seed/Aktuell-Pong/9431/Behallare-for-Press/379926/> 29th August 2015.

68. Wheat Daily Price. < <http://www.indexmundi.com/commodities/?commodity=wheat>> 29th August 2015.

69. Scheper J, Holzschuh A, Kuussaari M, Potts SG, Rundlöf M, Smith HG, Kleijn D. 2013. Environmental factors driving the effectiveness of European agri-environmental measures in mitigating pollinator loss; a meta-analysis. *Ecology letters*, **16**, 912-920.

722 **Tables and figures:**

723 **Table 1:** Types of habitats and number of transects completed in each of these.

Transmission corridors	Maintained roadsides	Forest	Forest / semi- natural grassland boundaries	Semi- natural grasslands	Cereal crop edges	Maintained drains
32	18	18	19	20	29	22

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Table 2: Flower density is the main predictor explaining bumble bee abundances and richness. Having a transmission corridor bisecting the landscape does not increase abundance or richness. The table shows bumble bee abundance and richness models.

Bumble bee abundance	Degrees of freedom	F-value	p-value
Flower density	1,73	13.25	<.001
Habitat	6,73	1.67	0.14
Transmission corridor	1,8	1.16	0.31
Bumble bee richness			
Flower density	1,73	11.73	0.001
Habitat	6,73	1.33	0.25
Transmission corridor	1,8	2.96	0.12

Table 3: Abundance differences across habitats for ecosystem service providers and threatened species. While provider species mirror the general abundance pattern, for threatened species we found habitat differences, but flower cover is not longer significant.

Provider species abundance	Degrees of freedom	F-value	p-value
Flower density	1, 134	11.01	0.001
Habitat	6, 134	1.52	0.18
Threatened species abundance			
Flower density	1, 62	0.02	0.89
Habitat	6, 62	2.72	0.02

Table 4: Plant species strengths (the sum of pollinator dependencies) across all interactions observed in transmission corridors, semi-natural grasslands and over all habitats combined. Rankings are in parenthesis' because raw numbers can not be compared among habitats. Plant species with high strengths are the most important in supporting a combination of provider and threatened species. Strength values can be high because plant species support several bumble bee species with low dependence on it, or because it supports bumble bee species that are dependent on the plant species for foraging.

Plant Species	Strength (all habitats)	Strength (corridors)	Strength (grasslands)
<i>Centaurea jacea</i>	3.49 (1)	4.71 (2)	1.00 (6)
<i>Trifolium pratense</i>	2.85 (2)	0.36 (8)	2.82 (2)
<i>Carduus crispus</i>	2.28 (3)	6.43 (1)	0.63 (7)
<i>Cirsium arvense</i>	1.80 (4)	0.85 (6)	3.09 (1)
<i>Calluna vulgaris</i>	1.31 (5)	2.42 (3)	-
<i>Lythraceae salcaria</i>	1.12 (6)	1.35 (4)	-
<i>Trifolium hybridum</i>	0.75 (7)	0.27 (9)	1.14 (5)
<i>Satureja vulgaris</i>	0.71 (8)	0.02 (12)	1.35 (4)
<i>Centaurea scabiosa</i>	0.70 (9)	-	-
<i>Succisa pratensis</i>	0.67 (10)	0.96 (5)	-
<i>Trifolium repens</i>	0.54 (11)	-	-
<i>Lathyrus pratensis</i>	0.44 (12)	0.05 (11)	0.56 (8)
<i>Leontodon autumnalis</i>	0.43 (13)	-	1.81 (3)
<i>Campanulaceae rapunculoides</i>	0.32 (14)	-	-
<i>Filipendula ulmaria</i>	0.24 (15)	0.44 (7)	0.08 (10)
<i>Melampyrum pratense</i>	0.17 (16)	-	0.43 (9)
<i>Centaurea cyanus</i>	0.16 (17)	-	-
<i>Carduus helenioides</i>	0.14 (18)	-	-
<i>Arctium tomentosum</i>	0.12 (19)	-	-
<i>Malva spp</i>	0.11 (20)	-	-
<i>Campanulaceae rotundifolia</i>	0.11 (21)	-	-
<i>Crepis tectorum</i>	0.10 (22)	-	-
<i>Prunella vulgaris</i>	0.07 (23)	-	-
<i>Epilobium adenocaulon</i>	0.06 (24)	-	-
<i>Vicia cracca</i>	0.06 (25)	-	0.05 (11)
<i>Lamium maculatum</i>	0.06 (26)	-	-
<i>Trifolium medium</i>	0.05 (27)	-	-
<i>Galeopsis terrahit</i>	0.04 (28)	-	-
<i>Carduus arvense</i>	0.03 (29)	0.12 (10)	-
<i>Solidago virgaurea</i>	0.03 (30)	-	-
<i>Lamium galeobdolon</i>	0.02 (31)	-	-
<i>Hypericum maculatum</i>	0.01 (32)	-	-
<i>Taraxacum spp</i>	0.01 (33)	-	-

742	<i>Sonchus glabrescens</i>	0.01 (34)	-	-
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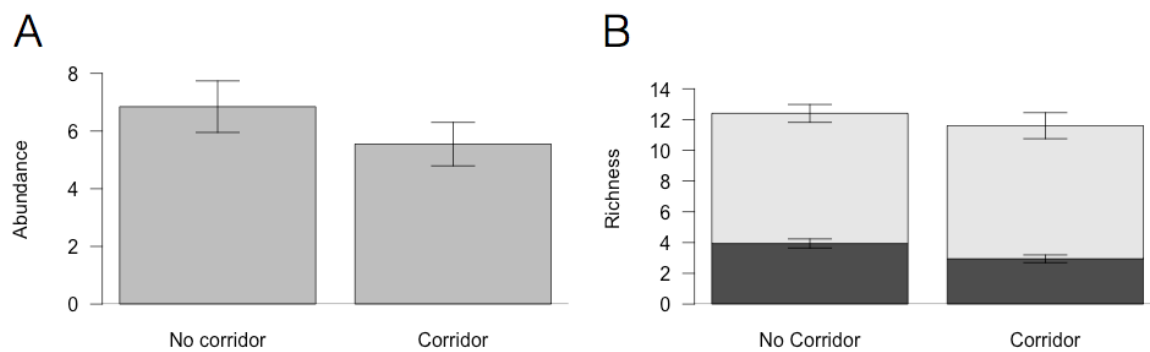
Figure 1: Species abundance and richness are not different in sites bisected or not bisected by a transmission corridor. A) Mean number of individuals and standard error collected per transect in transmission corridor and non transmission corridor sites. B) Mean species richness and standard error per transect in transmission corridor and non transmission corridor sites (black bars) and species beta diversity (grey bars) across habitats in sites bisected and not bisected by a transmission corridor (grey bars). The sum of both bars represents the gamma diversity of each site (n = 10 sites).

Figure 2: Species abundance and richness is not different across habitats. A) Mean number and standard error of individuals collected per transect in each habitat. B) Mean species richness and standard error per habitat (black bars) and species beta diversity (grey bars) between different transects of the same habitat. The sum of both bars can be seen as the gamma diversity of each habitat.

Figure 3: Species abundance of A) provider species is not different across habitats while for B) threatened species, transmission corridors, roadsides, semi-natural grasslands and forest-semi-natural grassland boundaries have higher abundances than the other habitats. The bars represent the mean number of individuals collected per transect in each habitat and its standard error.

Figure 4: Relationship between bumble bees species and the plant species they visit. Black boxes are proportional to their total abundance. The width of the grey links between bumble bees species and the plant species they visit are proportional to the visitation frequency.

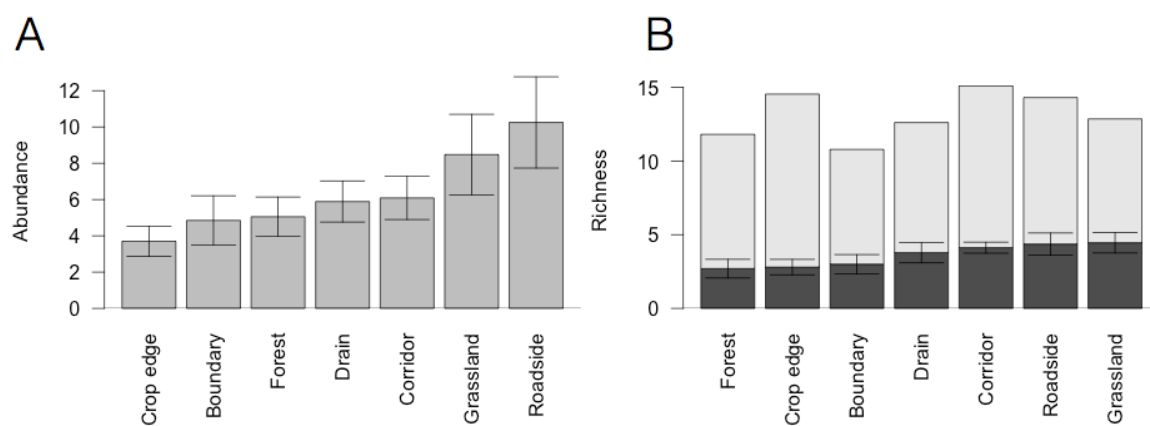
764 Figure 16*80/100:



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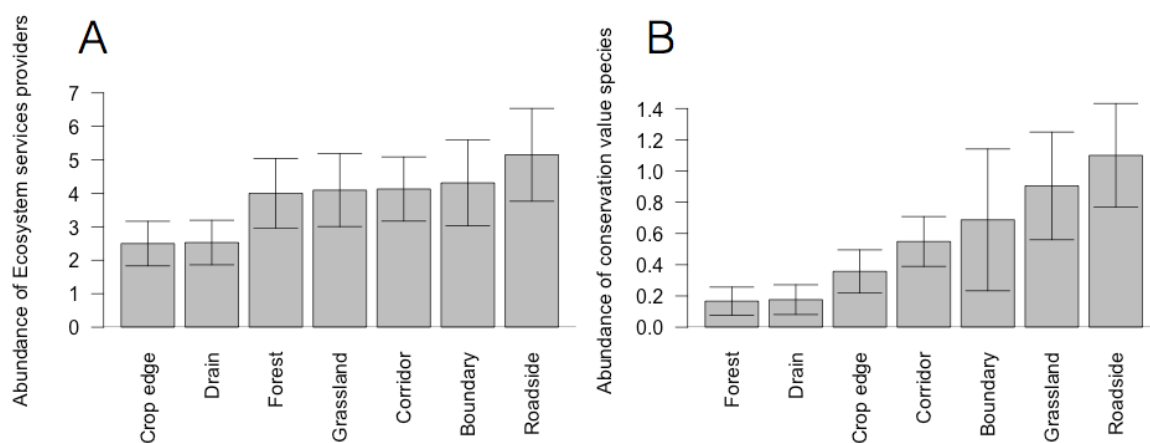
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