Abundance and diversity of wild bees along gradients of heavy metal pollution

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Summary

1. Wild bees are one of the most important groups of pollinators in the temperate zone. Therefore, population declines have potentially negative impacts for both crop and wildflower pollination. Although heavy metal pollution is recognized to be a problem affecting large parts of the European Union, we currently lack insights into the effects of heavy metals on wild bees.

2. We investigated whether heavy metal pollution is a potential threat to wild bee communities by comparing (i) species number, (ii) diversity and (iii) abundance as well as (iv) natural mortality of emerging bees along two independent gradients of heavy metal pollution, one at Olkusz (OLK), Poland and the other at Avonmouth (AVO), UK. We used standardized nesting traps to measure species richness and abundance of wild bees, and we recorded the heavy metal concentration in pollen collected by the red mason bee Osmia rufa as a measure of pollution.

3. The concentration of cadmium, lead and zinc in pollen collected by bees ranged from a background level in unpolluted sites [OLK: 1.3, 43.4, 99.8 (mg kg⁻¹); AVO: 0.8, 42.0, 56.0 (mg kg⁻¹)], respectively] to a high level on sites in the vicinity of the OLK and AVO smelters [OLK: 677.0, 440.1 (mg kg⁻¹); AVO: 9.3, 356.2, 592.4 (mg kg⁻¹)], respectively.

4. We found that with increasing heavy metal concentration, there was a steady decrease in the number, diversity and abundance of solitary, wild bees. In the most polluted sites, traps were empty or contained single occupants, whereas in unpolluted sites, the nesting traps collected from 4 to 5 species represented by up to ten individuals. Moreover, the proportion of dead individuals of the solitary bee Megachile ligniseca increased along the heavy metal pollution gradient at OLK from 0.2 in uncontaminated sites to 0.5 in sites with a high concentration of pollution.

5. Synthesis and applications. Our findings highlight the negative relationship between heavy metal pollution and populations of wild bees and suggest that increasing wild bee richness in highly contaminated areas will require special conservation strategies. These may include creating suitable nesting sites and sowing a mixture of flowering plants as well as installing artificial nests with wild bee cocoons in polluted areas. Applying protection plans to wild pollinating bee communities in heavy metal-contaminated areas will contribute to integrated land rehabilitation to minimize the impact of pollution on the environment.

Key-words: Apoidea, biodiversity, cadmium, contamination, lead, pollen, pollinators, zinc

Introduction

Wild bees (hereafter bees) are a major group of pollinators in the temperate zone (Kevan 1999). Bees provide key ecosystem services essential to maintaining wild plant diversity (Ashman et al. 2004; Aguilar et al. 2006; Potts et al. 2010) and agricultural productivity (Klein et al. 2007; Gallai et al. 2009; Lenda, Skórka & Moron 2010). Many plant species that are directly dependent on insect pollination for fruit and seed production (Wilkaniec, Giejdasz & Prószyński 2004; Morandin & Winston 2005; Veltkuis & van Door 2006) might experience
pollination limitation when pollinator species are scarce (Ashman et al. 2004). Therefore, the declines of wild bee populations reported throughout Europe and North America (Stefan-Dewenter, Potts & Packer 2005; Biesmeijer et al. 2006; Potts et al. 2010) are alarming.

Many potential factors that negatively affect wild bee communities and are suspected of being responsible for pollinator decline have been identified. One of the major factors causing declines of bee diversity and abundance is habitat loss and fragmentation driven mostly by intensification of agriculture (Banaszak 1995; Stefan-Dewenter 2003; Le Fèon et al. 2010). Other factors include pesticide use (Alston et al. 2007; Brittain et al. 2010), the impact of non-native invasive species (Moroń et al. 2009), competition with managed populations of *Apis mellifera* (Walther-Hellwig et al. 2006) or *Bombus terrestris* (Kenta et al. 2007), pathogen spread (Colla et al. 2006) and genetic introgression (Kraus et al. 2011). Although heavy metal pollution is likely to be a problem affecting much of the European Union (Lado, Hengl & Reuter 2008), studies are urgently needed to provide insights into the effects on bees.

Heavy metal contamination can have negative effects on invertebrate diversity (Syrek et al. 2006; Beyrem et al. 2007; Pola & Johnston 2008) as a result of differences between species in susceptibility to stress (Kammenga & Riksen 1996). Taking into consideration the complicated interactions among organisms (e.g. competition and predation), elimination of one species group by heavy metal pollution could even increase the diversity and/or abundance of others more resistant to pollution (Russell & Alberti 1998; Nahmani & Lavelle 2002; Migliorini et al. 2004). Some studies show an impact of heavy metals on pollinators (Niemen, Nuorteva & Tulisalo 2001; Mulder et al. 2005). It has been demonstrated that metals (Cd, Cu, Fe, Mn and Zn) may play a direct role in the widespread decline of the butterfly *Parnassius apollo* in Finland (Niemen, Nuorteva & Tulisalo 2001; Mulder et al. 2005). It has been demonstrated that metals (Cd, Cu, Fe, Mn and Zn) may play a direct role in the widespread decline of the butterfly *Parnassius apollo* in Finland (Niemen, Nuorteva & Tulisalo 2001). On the other hand, Mulder et al. (2005) hypothesized that butterfly decline in the NE of the Netherlands is an indirect effect of pollutant stress (e.g. Cd, Cu and Zn) on plants. Very little evidence exists on how heavy metal pollution affects solitary, wild bee communities (Moroń et al. 2010). Moroń et al. (2010) detected a direct negative impact of Zn contamination on the survival of the solitary bee, *Osmia rufa*, whereas Szentgyörgyi et al. (2011) did not find a significant correlation between heavy metal pollution (Cd, Pb and Zn) and bumblebee diversity. Despite the small number of studies, in a questionnaire undertaken by Kosior et al. (2007), specialists considered heavy metal pollution to be one of the most important factors causing bumblebee decline in Europe (ranked 6th of 16 stressors).

The aim of our study was to investigate the relationship between heavy metal pollution and wild bee communities. To this end, we compared wild bee species richness and diversity as well as the natural mortality of emerging bees along two gradients of heavy metal pollution, one in Poland and the other in the UK, where the main pollutants were cadmium, lead and zinc (Zygmunt, Maryański & Laskowski 2006; Stefanowicz, Nikińska & Laskowski 2008). We used standardized nesting traps to measure the species richness and abundance of wild bees (Tschamntke, Gathmann & Steffan-Dewenter 1998; Westphal et al. 2008). We hypothesized that with increasing concentration of heavy metals in the environment, there would be a reduction in wild bee species richness, abundance and diversity.

The study was conducted within the framework of the EU Integrated Projects, ALARM and STEP, which assess large-scale risks to biodiversity as well as population trends within European pollinators (http://www.alarmproject.net, Settele et al. 2005; http://www.STEP-project.net).

**Materials and methods**

**FIELD SITES**

The study was carried out in the vicinity of two Zn/Pb smelters, one located in Olkusz (OLK), Poland (50°16′38″N, 19°28′17″E), and the second in Avonmouth (AVO), UK (51°30′28″N, 02°41′01″W). Both smelters produced a similar spectrum of heavy metal contamination, that is, cadmium (Cd), lead (Pb) and zinc (Zn); however, the smelter in OLK has operated since 1967, whereas the AVO smelter since 1923 (abandoned in 2003). Metal concentration in the soil layer in the OLK region exceeds 20 mg kg⁻¹ of cadmium, 800 mg kg⁻¹ of lead and 2200 mg kg⁻¹ of zinc and in the AVO region exceeds 350 mg kg⁻¹ of cadmium, 25 000 mg kg⁻¹ of lead and 12 000 mg kg⁻¹ of zinc (Stefanowicz, Nikińska & Laskowski 2008).

Seven meadow sites in OLK and five in AVO were selected along the pollution gradient (Table 1) based on the concentration of metals in the topsoil (Stefanowicz, Nikińska & Laskowski 2008) and representing the full range of pollution in the two regions. Mean annual temperature and precipitation in the OLK area are 8 °C and 650 mm and in AVO are 11 °C and 600 mm. Sites were more than 1 km apart and had similar soils (OLK: poor sandy soils; AVO: alluvial gley soils). Size (c. 20 ha) and landscape (OLK: mixture of meadows and Scots pine forests; AVO: agricultural fields and pastures). The distance from a site centre to the nearest permanent grassland was not correlated with site pollution index (for more information, see Statistical Analysis: OLK: *r*ᵣ = −0.07, *N* = 7, *P* = 0.91, AVO: *r*ᵣ = 0.6, *N* = 5, *P* = 0.35). Also, the distances to the nearest watercourse (OLK: *r*ᵣ = −0.39, *N* = 7, *P* = 0.40, AVO: *r*ᵣ = 0.50, *N* = 5, *P* = 0.45), nearest forest (OLK: *r*ᵣ = 0.14, *N* = 7, *P* = 0.78, AVO: *r*ᵣ = 0.20, *N* = 5, *P* = 0.78) and human settlements (OLK: *r*ᵣ = 0.04, *N* = 7, *P* = 0.96, AVO: *r*ᵣ = 0.72, *N* = 5, *P* = 0.17) were uncorrelated with the site pollution index. Study sites were selected to keep plant communities constant along the gradients (OLK: ChAll: *Koelerion glaucae*, ChCl: *Molinio-Arhenatheretum*, ChAss: *Epilobio-Salicetum capreae*, ChCl: *Nardo-Callunetea*, AVO: ChAss: *Arhenatheretum elatioris* (Stefanowicz, Nikińska & Laskowski 2009). In addition for five of the seven sites at the OLK gradient (OLK1, OLK4–7), we did not detect a correlation between site pollution index and plant species richness (OLK: *r*ᵣ = −0.10, *N* = 5, *P* = 0.95; AVO gradient plant data were not available at the time of bee sampling).

**TRAP NESTS AND EXPERIMENTAL SET-UP**

To evaluate the effects of heavy metal pollution on the diversity and abundance of bees, standardized nest sites for above-ground nesting bees (Tschamntke, Gathmann & Steffan-Dewenter 1998; Steffan-Dewenter 2002; Moroń et al. 2008; Westphal et al. 2008) were established in each site. Studies were conducted during 2004–2006 in OLK area.
Table 1. Heavy metal (Cd – cadmium, Pb – lead, Zn – zinc) concentration in dry pollen collected by red mason bee *Osmia rufa* on sites along pollution gradients near Olkus (OLK) and Avonmouth (AVO), distance of these sites to sources of pollution and number of collected trap nests.

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance (km)*</th>
<th>Metal concentration (mg kg⁻¹)</th>
<th>Number of traps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cd</td>
<td>Pb</td>
</tr>
<tr>
<td>OLK1</td>
<td>1.2</td>
<td>5.62</td>
<td>196.64</td>
</tr>
<tr>
<td>OLK2</td>
<td>1.4</td>
<td>2.59</td>
<td>126.30</td>
</tr>
<tr>
<td>OLK3</td>
<td>1.6</td>
<td>6.71</td>
<td>277.05</td>
</tr>
<tr>
<td>OLK4</td>
<td>3.6</td>
<td>4.13</td>
<td>197.13</td>
</tr>
<tr>
<td>OLK5</td>
<td>4.0</td>
<td>3.06</td>
<td>115.47</td>
</tr>
<tr>
<td>OLK6</td>
<td>8.3</td>
<td>1.73</td>
<td>57.26</td>
</tr>
<tr>
<td>OLK7</td>
<td>19.8</td>
<td>1.32</td>
<td>43.37</td>
</tr>
<tr>
<td>AVO1</td>
<td>0.7</td>
<td>9.31</td>
<td>356.16</td>
</tr>
<tr>
<td>AVO2</td>
<td>1.3</td>
<td>6.39</td>
<td>345.58</td>
</tr>
<tr>
<td>AVO3</td>
<td>2.8</td>
<td>3.58</td>
<td>238.99</td>
</tr>
<tr>
<td>AVO4</td>
<td>5.9</td>
<td>0.80</td>
<td>61.52</td>
</tr>
<tr>
<td>AVO5</td>
<td>10.4</td>
<td>0.76</td>
<td>42.05</td>
</tr>
</tbody>
</table>

*Distance from the smelter; this measure is not consistent with distances to spoil tips that are also pollution sources; thus, distance from the smelter is not strictly correlated with pollen contamination.

and in 2006 in AVO area. At each site, seven trees were randomly chosen separated by distances of >200 m, each fitted with one trap nest for bees at a height of c. 3 m. Each trap consisted of 110, 25-cm-long stems of common reed *Phragmites australis* (Cav.) Trin. ex Steud., with nodes in the middle. The mean reed stem diameter was 7.8 ± 1.9 mm (range 6–12 mm). A bundle of stems was tied with a string and covered with a plywood roof (OLK) or half a PVC pipe (AVO). Trap nests were protected from attack by birds with metal mesh. The traps were set up at the beginning of April and collected in October. Because of random events (e.g. storms and vandalism), the number of collected nests per site per year varied between 6 and 7 for OLK and between 2 and 6 for AVO gradient (Table 1). During winter, trap nests were stored in laboratory conditions at +4°C. In spring, all reed stems with brood chambers of bees were removed and placed at room temperature in plastic containers. For each nest, the species and the number of emerged individuals were identified.

To standardize our evaluation of pollution, we analysed heavy metal concentrations in pollen collected by bees. Four randomly selected trap nests in each site were populated with 75 cocoons of the solitary red mason bee *Osmia rufa* (Linnaeus, 1758). We artificially added *O. rufa* because the abundance of naturally occurring bees in trap nests was generally too low to provide an adequate analysis of heavy metals in collected pollen. The red mason bee is broadly distributed in Poland and the UK with no special associations with habitat type or food preferences (polylectic species) (Banaszak 2010). Pollen collected by female *O. rufa* and deposited in brood chambers as food for larvae was excavated and used to evaluate heavy metal pollution.

**CHEMICAL ANALYSES**

Five samples of pollen deposited by *O. rufa* in five different stems of common reed were randomly collected from each nest trap. We selected pollen from brood cells in which individuals died before feeding on the collected pollen, that is, development stopped at the egg stage. Before analysis, samples were homogenized and dried at 105°C. Samples were analysed for total concentrations of cadmium, lead and zinc with AAnalyst 800 Spectrometer (PerkinElmer®, Boston, MA, USA). Total fractions of cadmium and lead were analysed using graphite furnace atomic absorption spectrometry (GF-AAS), and concentrations of zinc were analysed by flame atomic absorption spectrometry (FAAS). Total metals were extracted with Suprapur HNO₃ (Merck, Darmstadt, Germany). Three blank samples were also analysed for background contamination, and analytical precision was assessed with three reference samples with known metal concentrations (lyophilized bovine liver CRM 185R, European Commission). Percentage recovery was 80%, 86% and 126% for cadmium, lead and zinc, respectively.

**STATISTICAL ANALYSIS**

Concentrations of the metals were highly correlated with the pollution gradients; therefore, we decided to describe the study sites with a single measure of pollution rather than analysing separate models for each metal separately or choosing one arbitrarily. We performed a principal component analysis using metal concentrations in the pollen and, in further analyses, we used a pollution index defined as the first principal component (PCI pollen) score of each site (Zygmunt, Maryaiński & Laskowski 2006).

To examine the relationship between soil and pollen contamination, we used heavy metal concentrations in soil of OLK1, OLK4–7 and AVO1–5 given by Stefanowicz, Nińklińska & Laskowski (2008). We calculated the first principal component score (PCI soil) for soil contamination as described for pollen. Then, we tested the correlation between PCI soil and PCI pollen for each gradient with Spearman rank correlation.

Spearman’s rank correlation was used to assess the relationship between pollution level and the community of trap nesting bees by comparing data on the number of individuals, the number of species and the species diversity with the pollution index. The hierarchical richness index (HRI) was used as a diversity measure (Sparks 2000). The HRI provides an assessment of both taxonomic diversity and abundance in a single measure (French 1994), and it ranks sites according to easily definable objective criteria (Fabricius, Burger & Hocket 2003). The relationship between contamination level and survival of wild bees was examined by assessing natural mortality against the pollution index with Spearman’s rank correlation. Natural mortality was calculated as the number of adults emerging from the trap nest divided by the number of brood cells. However, a sufficient sample size for statistical analysis was only available for *Megachile ligniseca* (Kirby, 1802) in the OLK gradient (sites OLK 1–3, 5–7).
Abundance, species richness, diversity and natural mortality were calculated as the mean per trap nest per site per year. The data sets for OLK and AVO gradients were analysed separately. Because O. rufa were introduced into the sites, this species was excluded from all analyses. All statistical analyses were performed using R v.2.11 software (R Development Core Team 2010).

Results

We recorded six bee species emerging from trap nests (Table 2). Two species comprised about 60% of the total number of bees: Hoplitis adunca (Panzer, 1798) (32%) and Megachile liginesca Alken, 1924 (24%) at OLK, and M. centuncularis (Linnaeus, 1758) (33%) and M. willughbiella (Kirby, 1802) (32%) at AVO.

Concentrations of cadmium, lead and zinc in pollen collected by O. rufa ranged from background levels at unpolluted sites [OLK: 1·3, 43·4, 99·8 (mg km⁻¹)]; AVO: 0·08, 42·0, 56·0 (mg km⁻¹), respectively] to a high level [OLK: 6·7, 277·0, 440·1 (mg km⁻¹); AVO: 9·3, 356·2, 592·4 (mg km⁻¹)] at sites in the vicinity of the smelters. Metal concentrations in pollen were significantly correlated (Table 3a,b). In the principal component analysis, PC1 explained 97·0% and 97·2% of the total variability in concentrations of metals at OLK and AVO, respectively. The heavy metal concentration in pollen (PC1p) was positively correlated with that in top soil (PC1s) (OLK: $r_s = +0·90, N = 5, P = 0·083$; AVO: $r_s = +1·00, N = 5, P = 0·017$; Fig. 1).

The mean number of bee species decreased with increasing metal concentration (PC1p) (OLK: $r_s = -0·89, N = 7, P = 0·012$; AVO: $r_s = -0·82, N = 5, P = 0·089$; Fig. 2a). In the most polluted sites, we found none or only a single bee species, whereas in unpolluted sites, we recorded 4–5 species. Wild bee diversity (HRI) was negatively correlated with the PC1p (OLK: $r_s = -0·86, N = 7, P = 0·024$; AVO: $r_s = -0·90, N = 5, P = 0·083$; Fig. 2b). The number of individual bees was significantly negatively correlated with PC1p (OLK: $r_s = -0·86, N = 7, P = 0·024$; AVO: $r_s = -1·00, N = 5, P = 0·017$; Fig. 2c). Up to ten individuals emerged per trap in unpolluted sites and one individual from the most polluted sites. The natural mortality of the solitary bee M. liginesca increased with increasing heavy metal concentration (PC1p) at the OLK gradient ($r_s = +0·94, N = 6, P = 0·017$; Fig. 3). The proportion of individuals that died before emerging varied from 0·2 in uncontaminated sites to 0·5 in sites with a high level of pollution.

Discussion

Studies on the effects of heavy metal pollution on solitary, wild bee communities are very rare (but see Moron et al. 2010); however, given the widely reported declines in pollinators in parts of the world (e.g. Biesmeijer et al. 2006; Natural Research Council 2006), it is critical to understand the underlying drivers of change if we mitigate against further losses and avoid the negative impacts on pollination services (Potts et al. 2010). Heavy metal pollution is thought to affect pollinator populations both negatively, for example, by harmful intoxication (Beyrem et al. 2007; Piola & Johnston 2008), and positively, for example, via a lower number of competitors (Nahmani & Lavelle 2002; Migliorini et al. 2004). Despite this, we only found a negative relationship between pollution and bee community size (Fig. 2a,c). Decreasing hierarchical richness index along the heavy metal gradients emphasizes the combined effects of diminishing abundance as well as species richness (Fig. 2b). Note that the same response to pollution was found in two geographically distinct areas. The strong,

![Table 2. Species and number of solitary bees (excluding Osmia rufa) collected from trap nests established along heavy metal pollution gradient in Olkusz (OLK) and Avonmouth (AVO). All species belong to superfamly Apoidea and family Megachilidae](image-url)

<table>
<thead>
<tr>
<th>Species</th>
<th>OLK</th>
<th>AVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoplitis adunca</td>
<td>190</td>
<td>0</td>
</tr>
<tr>
<td>Megachile alplicola</td>
<td>115</td>
<td>0</td>
</tr>
<tr>
<td>Megachile centuncularis</td>
<td>88</td>
<td>25</td>
</tr>
<tr>
<td>Megachile liginesca</td>
<td>141</td>
<td>11</td>
</tr>
<tr>
<td>Megachile willughbiella</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>Osmia caerulescens</td>
<td>65</td>
<td>16</td>
</tr>
</tbody>
</table>

![Table 3. Correlation matrix of metal concentrations in pollen at Olkusz (a) and Avonmouth (b)](image-url)

<table>
<thead>
<tr>
<th></th>
<th>Zn</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) OLK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>0.98***</td>
<td>1.00</td>
</tr>
<tr>
<td>Cd</td>
<td>0.91***</td>
<td>0.97***</td>
</tr>
<tr>
<td>(b) AVO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>0.95*</td>
<td>1.00</td>
</tr>
<tr>
<td>Cd</td>
<td>0.98*</td>
<td>0.95*</td>
</tr>
</tbody>
</table>

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

AVO, Avonmouth; OLK, Olkusz.
positive correlation between diversity of above-ground nesting bees (about 5% of all bee species; Tscharntke, Gathmann & Steffan-Dewenter 1998) and the diversity of all bee communities (Tscharntke, Gathmann & Steffan-Dewenter 1998; Westphal et al. 2008) supports the extrapolation of our findings to all wild bee species.

Then the negative correlation between metal pollution and wild bee communities may be the result of direct as well as indirect mechanisms. Chronic intoxication of individuals by heavy metals may lead directly to expenditure of additional energy on detoxification (Silby & Calow 1989; Janczur, Kozłowski & Laskowski 2000), which most frequently decreases fitness parameters (Mozdzer et al. 2003). Indirectly, the pollution affecting flowering plants (decreasing their diversity, abundance and/or pollen quality; Sawidis & Reiss 1995) may, as a result, reduce the availability of forage for bees. This study did not determine whether direct or indirect mechanisms were most important in the negative correlation between heavy metals and wild bee populations. However, a steady increase in mortality among emerging *M. ligniseca* along the gradient (Fig. 3) suggests that larvae feeding on contaminated pollen were more at risk. Similar results were obtained for the wild bee *O. rufa*, the larvae of which feed on pollen contaminated with Zn (Moroń et al. 2010). This suggests a direct impact of pollution on wild bee abundance, especially because plant communities were comparable along the gradients.

This study is the first focusing on the contamination of pollen collected by wild bees rather than honeybees. Bee larvae feed exclusively on pollen (Michener 2000); thus, in polluted sites, they consume food that is contaminated with heavy metals (Table 1). The main source of heavy metal pollution of pollen is soil deposited on flowers or on the pollen during transport to and placement in the bee's nest (Szczesna 2007; Fig. 1). This suggests that the soil type (e.g. granulation) and the type of flower can affect the deposition of heavy metals on pollen (Szczesna 2007). For bee species nesting in the ground, the impact of polluted soil is likely to be even greater because larvae are surrounded by highly contaminated material. Adults may be intoxicated by heavy metals during nest building (e.g. excavating of soil) and constructing mud walls between brood chambers. Different life strategies, for example, sociality and food specialization (Michener 2000), may influence the susceptibility of bee species to heavy metal pollution. Social species, for example, honeybees and bumblebees, can cover long distances during foraging (Ratnieks 2000) and may collect food outside the contaminated area, therefore avoiding the negative effects of pollution. Polylectic species may avoid collecting pollen from the plants that accumulate high levels of heavy metals, but oligolectic bees that are linked with a specific food source may be limited to foraging on more contaminated plants. Because the susceptibility of wild bees to competition varies with their biology, that is, whether they are social or solitary, oligolectic or polylectic species (Strickler 1979), pollution...
may additionally modify the interactions among species. This, however, requires further study.

Our findings demonstrate a negative correlation between heavy metal pollution and populations of wild bees. We suggest that increasing wild bee richness in highly contaminated areas will require special conservation strategies. Where there is a direct effect of pollution (e.g. intoxication), the creation of suitable sites for nesting may be most effective. We recommend placing artificial nests in the contaminated areas because they are simple to prepare and are low cost (Tscharntke, Gathmann & Stefan-Dewenter 1998; Wilkaniec & Giejdasz 2003a; Moroń et al. 2010). Additionally, wild bee abundance may be boosted locally by attaching bee cocoons to the nests. It is straightforward to produce cocoons of Anthophora plantipes (Pallas 1772), Chelostoma florissinome (Linnaeus, 1758), O. rufa and O. cornuta (Latreille, 1805) (Kručič & Stanisavljević 2006). There are many examples of successful management of wild bees in agriculture, especially in orchards (Bosch & Kemp 2002; Wilkaniec & Giejdasz 2003b). However, only native bee species should be introduced into contaminated habitats because natural communities could be negatively affected by non-native pollinators, for example, by competition (Kenta et al. 2007).

In situations where bees are indirectly affected by pollution (e.g. reduced plant species richness), it may be appropriate to sow seed mixtures of wild flowers (Haaaland, Naibist & Bersier 2011). This would attract a large number of bees and bumblebees as well as hoverflies and some butterflies (Carreck & Williams 1997, 2002). Seed mixtures are beneficial to pollinators and easy to establish, and by sowing in sequences from early spring to summer, a long flowering period is provided (Haaaland, Naibist & Bersier 2011). Implementation of conservation strategies to protect wild bees across a range of heavy metal pollution levels will contribute to integrated land rehabilitation. Plants used in land rehabilitation (phytoremediation) will benefit from increased numbers of pollinators because some are pollinated by insects (e.g. Thlaspi spp.) (Baker, Reeves & Hajar 1994; Brown et al. 1994).

High concentrations of heavy metals in soils are a widespread problem (Lado, Hengl and Reuter 2008), and pollen contamination is as detrimental to wild bees as habitat loss or fragmentation (Kosior et al. 2007). It is possible that some wild bee species will migrate from adjacent habitats to polluted ones. However, the mean flight distance for most wild bee species is <200 m (Gathmann & Tscharntke 2002) so the boosting of populations on contaminated sites by migrants does not seem very probable for most bee species. It is more likely that bees nesting in contaminated sites will forage further away. Szentgyörgyi et al. (2011) showed that bumblebee diversity did not correlate with heavy metals in the soil, which may be a consequence of their ability to fly long distances (1–2 km; Greenleaf et al. 2007). The inter-relationships between wild bees and plants are complex, and our study emphasizes the need to undertake further investigations on bee communities in polluted habitats to develop effective conservation strategies.

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References


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