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Short communication

Is coal combustion the last chance for vanishing insects of inland drift sand dunes in Europe?

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ABSTRACT

Inland sand dunes rank highly in the most threatened environments throughout Europe, suffering accelerating losses of associated biodiversity. Although there is increasing evidence that vanishing species may find refuges at post-industrial barrens, insects specialised for the highly specific and extreme conditions of drift sands have not been known to colonise any surrogates. Because fly ash deposits share some substrate physical attributes with drift sands, we hypothesised that they could be colonised by drift sand communities. Here, we show that these relatively common landscape structures accompanying coal combustion indeed host insects of extraordinary conservation value. Surveying two fly ash deposits in Central Europe, we found an unusually high diversity of 227 species of bees and wasps, including 72 nationally endangered species (including four thought regionally extinct and 13 critically endangered), and 31 drift sand specialists. This conservation potential seems to diminish with successional overgrowing of the deposited ash. We also document that at the landscape level, the deposits are effectively supplementing the vanishing drift sands. Power-plants producing fly ash deposits, commonly viewed as biotic wastelands, thus paradoxically provide crucial refuges for vanishing biodiversity.

1. Introduction

The European energy industry still substantially depends upon coal combustion. Fly ash deposits, where the solid by-products of power production are stored, are found in nearly every European region, accompanying practically every power station, heating plant and many larger factories. These solid wastes are comprised mainly of fly ash, formed by very fine (average diameter <10 μm) glass-like particles of mineral residua which are carried out of the boiler in the flow of exhaust gases (Haynes, 2009). The other components (such as bottom ash, boiler slag and the flue gas desulphurisation materials) constitute about 25–30% (Haynes, 2009).

Much is known about the negative impacts of flying ash on human health and the environment (Borm, 1997; Adriano et al., 2002), and consequently, rapid reclamation of fly ash deposits is recommended and routinely practiced (Haynes, 2009). On the other hand, the evidence is accumulating that various post-industrial barrens, such as quarries, gravel pits, spoil heaps and brownfields, often harbour biotic communities of high conservation value, providing refuges for many species vanishing from human-affected landscapes (Benes et al., 2003; Lundholm and Richardson, 2010; Tropek et al., 2010; Heneberg et al., 2013; Lenda et al., 2012). From this point of view, the fly ash deposits, hitherto unexplored, may therefore deserve attention. The few published systematic surveys of biota colonising these sites have been restricted to plants (Ash et al., 1994; Kovar, 2004), lichens (Kovar, 2004) and fungi (Kubatova et al., 2002). These studies found minimum biodiversity with practically no species of conservation value, presumably due to hostile substrate chemistry. No study published so far has targeted insects, which represent the bulk of terrestrial biodiversity, and for which the physical and spatial microhabitats structure may be more decisive than the chemical composition of the substrate (e.g., Dennis et al., 2006).

Fly ash deposits share many important features with inland drift sand dunes, a highly endangered habitat in continental Europe. The shared features include finely grained and mechanically unstable substrate prone to desiccation (Andreotti et al., 2009; Haynes, 2009; Fanta and Siepel, 2010), and a resulting microclimate with wide fluctuations of daily and annual temperatures, as well as steep gradients of moisture and nutrients (Riksen et al., 2006; Exeler et al., 2009; Fanta and Siepel, 2010). Specialists of

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drift sands (psammophilous species herein) must withstand frequent disturbances and considerable stress. In many psammophilous species, the specialisation for large areas of the bare sands is so pronounced that they do not occur in any other natural habitat (Riksen et al., 2006; Exeler et al., 2009; Fanta and Siepel, 2010). Based on their shared features, we hypothesised that fly ash deposits should attract the specialised arthropods of drift sands.

Drift sands have suffered one of the highest rates of habitat loss among European environments (Hoekstra et al., 2005; Riksen et al., 2006; Fanta and Siepel, 2010). In the form of inland (continental) dunes, they had been widespread in many areas of Central Europe until the late 19th century. Abhorred as wastelands, they were often the first sites targeted for agricultural improvement, afforestation and building development (Fanta and Siepel, 2010; Riksen et al., 2006). Loss of these habitats accelerated with the decline of grazing, followed by succession, and with increased environmental eutrophication by atmospheric nitrogen deposition, the latter particularly harmful for specialists of low competition – high stress environments (Exeler et al., 2009; Benes et al., 2002). As a result, psammophilous insects are rapidly disappearing from much of Europe. For example, all the psammophilous butterflies of the Czech Republic died out in the late 20th century (Benes et al., 2002) and psammophilous species from other insect groups have been affected by similar losses across Europe (cf. Glowacinski and Nowacki, 2004; Farkac et al., 2005; Dicks et al., 2010).

Bees and wasps (Hymenoptera: Aculeata, except for ants) represent a conspicuous and species-rich insect group containing important pollinators, predators and parasitoids. They rank among the most severely declining insects (Dicks et al., 2010; New, 2012), with more than 30% of 1238 species recorded from the Czech Republic classified as regionally extinct or critically endangered (Straka, 2005a,b,c; Fig. 1). A large proportion of aculeate hymenopterans utilise sandy substrates for nest building (New, 2012). In the Czech Republic, a country that represents well the conditions in temperate Europe, 101 species are strict specialists of drift sands, restricted to this biotope (Macek et al., 2010), and from this number, 67% are regionally extinct or critically endangered (Fig. 1). The proportion is more than twice as high than the proportion of extinct and critically endangered species in the complete bee and wasp Czech fauna (32.7%), illustrating the high level of threat faced by inland drift sand specialists in Central Europe.

Here, we bring the survey of bees and wasps colonising two fly ash deposits aiming to answer the following questions: (1) Do ash deposits offer a surrogate habitat for vanishing psammophilous species? (2) Do the main microhabitat type within the deposits differ in their conservation potential for those species? (3) Do fly ash deposits have potential to supplement natural sand dunes in the studied region? Besides species richness, we evaluated the conservation potential of the studied habitats using specialisation and national red-list status of individual bee and wasp species (cf., Feest, 2006; Tropek et al., 2010) To the best of our knowledge, this paper represents a pioneering survey of any arthropod group in this so far neglected type of post-industrial barrens.

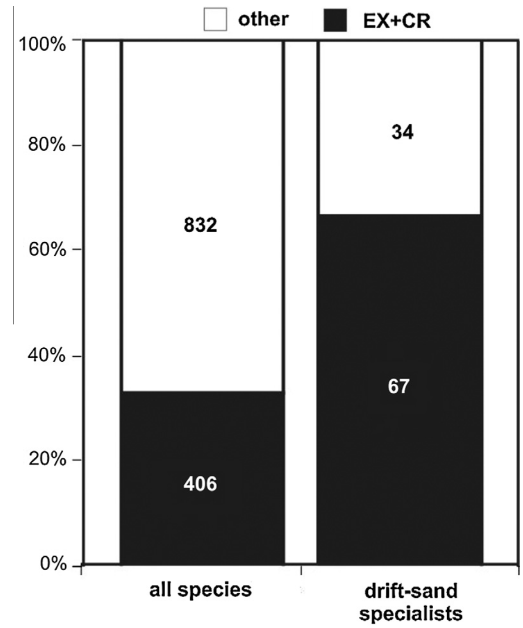

Fig. 1. The drift sand specialists are the most endangered guild of bees and wasps: proportions of regionally extinct (EX) and critically endangered (CR) species from complete fauna and from strict drift sand specialists in the Czech Republic.

2. Methods

We surveyed two localities of fly ash deposits in the Polabí region, Northern Czech Republic, Central Europe (Fig. 2). This lowland with a relatively mildly warm temperate climate (sensu Quitt, 1971; average temperature 8–9 °C, annual precipitation 550–700 mm) was the historical granary of the country. Continental drift sand habitats, once relatively common in this region, have disappeared almost entirely due to afforestation and/or succession during the last century. The Chvaletice ash deposit, (50°1′ N, 15°27′ E; 250 m alt.) had sedimented ash from the Chvaletice Power Station since the late 1970s, while the Bukovina ash deposit (50°7′ N, 15°50′ E; 250 m a.s.l.) had sedimented ash from the Opatovice nad Labem Power Station since the 1960s. At the beginning of 2000s, the establishment of desulphurisation in both power stations changed the ash deposition technology, terminating the sedimentation. Major parts of the ash sedimentation lagoons were drained and the exposed fly ash was left to spontaneous succession. At present, both localities are being technically reclaimed by covering with fertile topsoil and conversion to species-poor mesophilous grassland and/or forest plantation (cf. Tropek et al., 2012). In 2009, however, the unreclaimed ash surfaces still covered ca 20 ha in the Chvaletice ash deposit and 10 ha in the Bukovina ash deposit.

At both localities, insects were sampled in three spontaneously developed habitats: (i) plots with *barren dry* strongly desiccative and thus loose substrate (herbaceous cover <10%); (ii) plots in vicinity of water lagoons and/or in large depressions with *barren humid* and thus presumably more compact substrate (herbaceous cover <10%); and (iii) and plots *overgrown* by *Calamagrostis epigejos* and other grasses (herbaceous cover >80%). All the three habitat types and their transitions create the overwhelming majority of both studied deposits. We hypothesised that these distinct habitats were host to different bee and wasp species because of a totally different offer of microhabitats for their nesting. Three replicates of each habitat were selected within each locality to be as equally (in sense to avoid two neighbouring plots of the same habitat type) distributed as possible, with at least several tens of metres between any neighbouring plots. In each replicate, we established one 3 m × 3 m plot where 9 yellow pan traps (15 cm in diameter) filled by water with a small amount of detergent were exposed in a regular grid. Four exposure times (1–3 May, 13–15 June, 1–3 July, 30 July–1 August, all 2009), all under optimal weather (>25 °C, clear skies, not windy), covered the key emergence periods of the studied insect group. All collected bees and wasps (Hymenoptera: Aculeata, except for ants) were identified to species. Their threat status, distribution and life history, including their psammophilous specialisation, follow national red lists (Straka, 2005a,b,c) and catalogue (Macek et al., 2010).

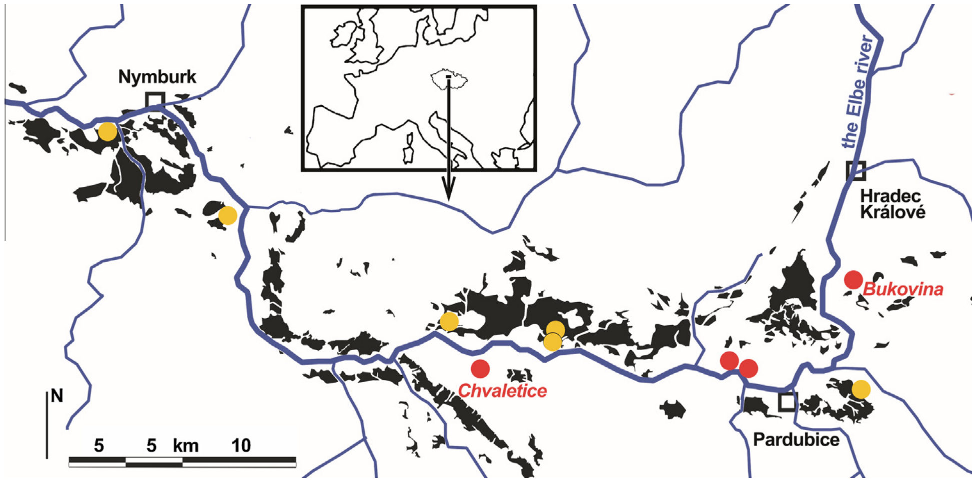

Fig. 2. A map of the original area of natural drift sands (black background) in the Western Polabí, Northern Czech Republic. Current drift sand dunes remnants (yellow circles) and fly ash deposits (red circles) are marked. Positions of the two studied fly ash deposits are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The importance of the particular habitats for *species richness* (i.e., number of all species per plot), *the richness of specialists* (i.e., number of species specialised for drift sand dunes), and the *conservation value* of communities (i.e., numbers of individuals of all species per plot weighted by their red-list status (EX – 4; CR – 3; EN – 2; VU – 1; LI – 0); see Tropek et al., 2010 for details) was compared by generalised linear mixed-effect models with quasi-Poisson distribution in R 2.14.1 (R Development Core Team, 2008), using *glmmPQL* function in MASS package (Venables and Ripley, 2002). The contents of all pan traps from the four sampling periods in each plot were pooled to avoid the pseudo-replicative design. The numbers of all and the sand-dune specialised species, and the community conservation values (see above) per plot were the response variables, habitat was the fixed-effect factor and locality the random factor. The post-hoc comparisons among the habitats were done by Tukey HSD test.

Additionally, we reviewed the extent of drift sand dunes remnants and non-reclaimed fly ash deposits in the Polabí region (Fig. 2). All such localities were surveyed in the field and the area of bare finely drained substrates (drift sand and fly ash) were estimated using ArcInfo 10.0 (Environmental Systems Research Institute, Inc., Redlands, USA). All available sites were pre-selected by aerial surveying (Geodis, 2012) and geological (Czech Geological Survey, 2012) maps and regional literature (Mertlik, 2011). Differences in the local extent of the bare substrate and sparse grasslands were compared by t-test in Statistica 9.0 (StatSoft Inc., Tulsa, USA).

3. Results

During the survey of the two fly ash deposits in the Czech Republic (Fig. 2), we recorded 3 479 bees and wasps belonging to 227 species (see Table A1). Nationally red-listed species were represented by four species so far considered as regionally extinct and hence rediscovered for the country; and 13 critically endangered species with only a handful of remaining localities, 22 endangered and 33 vulnerable species. Additionally, 31 of all recorded species were strict drift sand specialists, not occurring in other less-endangered fine-substrate biotopes, such as alluvial sands or loess faces.

The species richness of the particular habitats within the studied fly ash deposits did not differ ($F_{2,14} = 1.85$, $p = 0.19$). On the other hand, the habitats significantly differed in the numbers of drift sand specialists ($F_{2,14} = 20.23$, $p < 0.001$) and in their conservation value ($F_{2,14} = 6.29$, $p = 0.01$) so that successionally-overgrown plots were colonised by fewer specialists and had lower potential for harbouring of red-listed species than the two habitat types with bare substrate (Fig. 3).

In the whole region, six drift sand dunes and four fly ash deposits with bare substrate larger than 50 m^2 exist (Fig. 2). The total area of both bare substrate (dunes: 1.57 ha, deposits: 82.84 ha) and sparse grassland (dunes: 0.13 ha, deposits: 17.83 ha) is substantially higher in the fly ash deposits, and the same applies for average per site area of bare substrate (deposits: 2.07(±1.64) ha; drift sand dunes: 0.26(±0.31) ha; $p = 0.046$) and sparse grassland (fly ash deposits: 0.45(±1.64) ha; drift sand dunes: 0.02(±0.31) ha; $p = 0.053$).

4. Discussion

Our survey of bees and wasps colonising the hitherto unexplored biotope of coal combustion fly ash deposits returned a relatively high species number of drift sand dunes specialists and other regionally endangered species comparable with or even higher than open sand habitats in Central Europe (regionally summarised in Heneberg et al., 2013). The potential importance of these post-industrial barrens is further highlighted by rediscovery of four species thought to be nationally extinct (*Arachnospila westerlundi*, *Evagetes littoralis*, *Halictus smaragdulus*, and the Central European endemic *Nysson hrubanti*), and thirteen species classified as critically endangered in the Czech Republic. The finding of as many as a third of all nationally recorded drift sand specialists in merely two localities testifies to the tremendous importance of these hostile environments for psammophilous fauna. In addition, several of the high conservation priority species were recorded in high abundances (e.g. *Hedychridium krajniki*, *Mimumesa littoralis*, *Tachysphex helveticus*), indicating the existence of prospering populations.

Within the fly ash deposits, the drift sand specialists, most valuable from the conservation standpoint, occupied sparsely vegetated microhabitats with exposed drifting ash. The successionally-overgrown plots, although hosting similarly high species richness, contained much fewer drift sand specialists, presumably attracting species from other habitat types. This observation agrees with the knowledge of drift sand specialists' life histories, such as their requirements for relatively large stretches of finely grained sands for nest building (Macek et al., 2010; New, 2012). Other biodiversity surveys of post-industrial or urban sites also revealed that such biotopes are often highly heterogeneous internally,

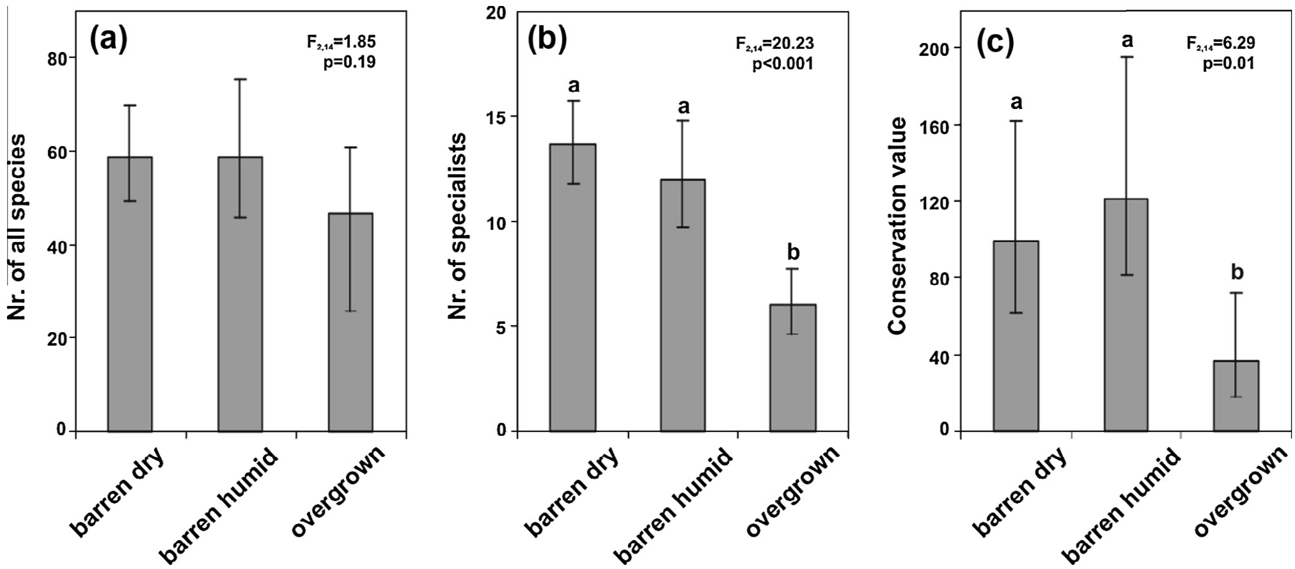

Fig. 3. Bee and wasp species richness (A), richness of drift sand specialists (B), and community conservation value (number of individuals weighted by their red-lis status) (C) of particular habitats within the two studied fly ash deposits (means and 95% confidential intervals are shown). Differing letters above the boxes indicate significant differences between individual habitats (post-hoc comparisons by Tukey HSD test). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

containing diverse abiotic conditions (Benes et al., 2003; Krauss et al., 2009; Heneberg et al., 2013). Within these sites, however, the most valuable species are frequently found at sparsely vegetated surfaces. This is attributable to the fact that human activities in cultural landscapes suppress both late and early successional stages while favouring mid-successional, and hence productive, vegetation formations (Thomas et al., 1994; Riksen et al., 2006). Consequently, species of both the very latest and the very earliest successional stages suffer a disproportional rate of habitat loss, unless – as in the case of post-industrial barrens – suitable habitat surrogates are provided as an unintentional effect of human activities (Tropek and Konvicka, 2008).

The conservation potential of the ash deposits is highlighted by the widespread existence of these structures across the world, almost wherever solid mineral fuels are combusted at industrial scale. In the Polabí region of the Czech Republic, as an example of a common European landscape, the deposits area is currently an order of magnitude larger than the remaining natural sand dunes, a widespread and spacious land cover type in the past (Fig. 2). Although no systematic survey of bees and wasps from the natural dune localities exists, their specialised fauna has been repeatedly inventoried (reviewed in Heneberg et al., 2013), without recording many of the species now surviving at the fly ash deposits. Most likely, much smaller open substrate areas at the remnant dunes disallow many of the rarest psammophilous specialists to maintain viable populations there. The fact that the fly ash deposits hosted several species absent in the wide environs, including species believed to be nationally extinct, is interpretable by past colonisations of the deposits that had occurred prior to losses of those species from remnant natural habitats.

As long as power production will depend on coal combustion, fly ash deposits will exist in human-dominated landscapes (Haynes, 2009). Without denying the high environmental and human health risks posed by fly ash (cf. Borm, 1997; Adriano et al., 2002), our findings indicate that these wastelands, unexpectedly, provide vital refuges for an unusually high representation of declining species. Broadly-devised restoration of natural and semi-natural habitats, the ultimate goal of global conservation efforts, will require pools of healthy populations of diverse species (Tropek and Konvicka, 2011). As we have discovered, for a sizeable number of bees and wasps, such populations found their refuges at environmentally controversial fly ash deposits, and these industrial barrens now represent their last chance to survive in human-altered regions such as Central Europe. Future research should establish whether other arthropod groups contain threatened specialists utilising fly ash deposits, and how to reconcile legitimate environmental concerns with long-term persistence of specialised rare species at these potentially hazardous sites.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2013.03.027.

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