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Brownfield sites promote biodiversity at a landscape scale

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Abstract

Repurposing of brownfield sites is often promoted, because it is perceived that protecting the "green belt" limits damage to biodiversity; yet brownfield sites provide scarce habitats with limited disturbance, so conversely are also perceived to be ecologically valuable. Combining data from three national-scale UK biological monitoring schemes with location data on historical landfill sites, we show that species richness is positively associated with both the presence and increasing area of ex-landfill sites for birds, plants and several insect taxa. Assemblage rarity of birds is also positively associated with presence of ex-landfill sites. Species richness associated with ex-landfill sites declined over time for birds and insects but increased over time for plants. These findings suggest that development of brownfield sites may have unintended negative consequences for biodiversity, and imply that to minimise loss of biodiversity, brownfield site repurposing could be targeted towards smaller sites, or sites in areas with a high density of other brownfield sites.

Keywords

Abandoned land, contaminated land, Lepidoptera, Odonata, post-industrial sites, repurposing

1. Introduction

Brownfield sites (defined as abandoned land that has previously been developed) are often considered to be good locations for repurposing to a range of uses (e.g. Hard et al., 2019; Milbrandt et al., 2014). However, brownfield sites can, under some circumstances, have high ecological value (Beneš et al., 2003; Broughton et al., 2021; Eyre et al., 2003; Gardiner et al., 2013; Macadam and Bairner, 2012; Mathey et al., 2015; Small et al., 2002; Tropek et al., 2010; Woods, 2012). This value arises from features which can include low fertility and/or extreme soil characteristics (Ash et al., 1994) (providing niches for specialist species), early-successional habitats (Broughton et al., 2021), and low levels of disturbance from both humans and predators (Kamp et al., 2015), which may otherwise be rare in the landscape. As a consequence, there are concerns that repurposing of brownfields may have unintended consequences for biodiversity (Broughton et al., 2021; Fletcher et al., 2011; Meehan et al., 2010), and so the ecological value of such sites should be a consideration during planning. However, there is little direct evidence to suggest how ecological communities associated with brownfield sites compare directly to other land uses, or how brownfield sites contribute to biological richness at landscape scales.

Among brownfield sites, ex-landfill sites are globally relevant, since landfill is one of the most important forms of solid waste management in countries from all levels of socioeconomic development (Hoornweg and Bhada-Tata, 2012). In the UK, 24% of all waste was sent to landfill in 2018 (approx. 50 million tonnes in total), second only to recycling as a form of waste management (Department for Environment, Food & Rural Affairs, 2021). Ex-landfill sites are well-suited to landscape-scale studies of brownfield sites (and particularly their ecology) for both practical and scientific reasons: practically, they represent the only form of brownfield site for which a national-scale database has been collated (albeit covering only England, rather than the entire UK; and covering a range of waste types including municipal, commercial and industrial), whereas data on brownfield sites more generally is collated by local authorities in a wide and inconsistent range of formats. Scientifically, they may be particularly well suited to repurposing due to the combination of good access to critical infrastructure (e.g. roads) (Milbrandt et al., 2014) and limited physical structures from past use (most sites are restored to grassland post-closure (Simmons, 1999)), but restored grassland on ex-landfill sites can support ecological communities of similar richness to comparable natural and semi-natural habitat (Tarrant et al., 2013; Rahman et al., 2015).

In this study, we investigated whether landscapes (here, meaning 1 x 1 km grid squares surveyed as part of biodiversity recording schemes) containing ex-landfill sites differed from surrounding landscapes in terms of their biodiversity richness and assemblage rarity. To achieve this, we combined data on the locations of former landfill sites in England (Environment Agency, 2020) with landscape-scale citizen science data from three UK biodiversity recording schemes, covering multiple taxonomic groups: the Breeding Bird Survey (BBS; birds), the National Plant Monitoring Scheme (Pescott et al., 2015: NPMS; plants) and the Wider Countryside Butterfly Survey (Brereton et al., 2011a: WCBS; Lepidoptera (butterflies and moths) and Odonata (dragonflies and damselflies)).

Specifically, we tested the following questions for each taxon: (i) whether species richness and assemblage rarity differ between grid squares containing ex-landfill sites and those without; (ii) whether the area covered by ex-landfill sites within a grid square relates to its species richness and assemblage rarity; and (iii) whether the time since landfill site closure (i.e. site age) relates to its species richness and assemblage rarity. Because there is a perception that brownfield sites can have high ecological value due to the presence of early-successional habitats, we formed a general hypothesis that biodiversity richness and assemblage rarity would show a positive relationship with brownfield presence and size, but a negative relationship with brownfield age. However, we tested each taxon separately, because some taxa might respond differently to others as ecological succession proceeds on brownfield sites.

2. Material and methods

2.1. Datasets

We used data obtained by three recording schemes (with similar designs) to investigate the influence of brownfield sites on biodiversity at landscape-scales. Specifically, we used data from the Breeding Bird Survey (BBS) (Harris et al., 2020); the National Plant Monitoring Scheme (NPMS) (Pescott et al., 2015); and the Wider Countryside Butterfly Survey (WCBS) (Brereton et al., 2011a), in which recorders can optionally record moths (Lepidoptera), dragonflies (Odonata: Epiprocta) and damselflies (Odonata: Zygoptera) as well as the target taxon, butterflies (also Lepidoptera).

In each scheme, participants record target taxa within a 1 x 1 km grid square on at least two occasions per year. Grid squares are selected for recording using a stratified-random approach, ensuring that coverage of recorded squares is representative of the wider countryside rather than biased towards high-quality or protected habitats (c.f. the UK Butterfly Monitoring Scheme (Brereton et al., 2011b)). In both the BBS and the WCBS, participants record target taxa along two roughly parallel transects of 1km each across the survey square (Brereton et al., 2011a). In the NPMS, participants record at least five plots within the survey square (preferably from a shortlist of up to 25 plots distributed in a grid within the square), using a mixture of 5 x 5 m square plots and 1 x 25 m linear plots. Records are made to species level wherever possible, and abundance (as percentage cover, in the NPMS) recorded as appropriate. All three datasets were up-to-date to 2019 at the point of analysis, and recording in each scheme began in 1994 (BBS), 2006 (WCBS) and 2015 (NPMS) respectively.

Birds, plants and butterflies were the main target taxon of their respective recording schemes, so we assumed that all recorders made an attempt to record these groups and therefore included all squares in our initial dataset for these taxa. By contrast, recorders in the WCBS had the option to record any moths, dragonflies and damselflies encountered during their surveys, but were not obliged to do so. For these groups, we only included squares with non-zero species richness in our initial dataset, since it was impossible to know whether zero species richness indicated that no species were present, or that recorders had declined to record these optional taxa. We found that moths had been recorded in approximately half of WCBS squares in our final dataset (Supplementary Table 1), so we treated these separately from butterflies, even though the two groups form paraphyletic taxa within the order Lepidoptera. Similarly, we decided to treat dragonflies and damselflies separately even though they collectively form the order Odonata, because dragonflies are generally more familiar to the majority of recorders in the UK and therefore may have been recorded in some squares where damselflies were not (indeed, we found that dragonflies had been recorded in slightly more WCBS squares in our final dataset than damselflies).

We additionally made use of a well-established divide within British butterfly species between wider countryside (WC) generalists and habitat specialists (HS) (Asher et al., 2001) to examine whether the value of brownfield sites in the landscape varied according to species' ecological specialization. Like moths and odonates, habitat specialist butterflies were also only recorded in a proportion of all WCBS squares (Supplementary Table 1), but in this case, we decided that absence of records was more likely to indicate absence of species, since recorders were explicitly instructed to record all butterfly species observed (not just WC species). Therefore, we included all squares (including those with zero records of HS species) in our initial dataset for this taxon.

These schemes collectively provide high resolution species occupancy data for six taxonomic groups: birds, plants, butterflies (collectively, and split into generalists and specialists), moths, dragonflies, and damselflies. Across all three schemes, we assessed almost 10,000 1 x 1 km grid squares in our initial dataset (Supplementary Table 1).

To identify the location of historical landfill sites, we used the Environment Agency's Historic Landfill Sites database (Environment Agency, 2020). This provides the location of all sites for which there has previously been a Pollution Prevention and Control permit or waste management licence issued, but no permit or licence is currently in force, along with known landfill sites that existed before the current waste licensing regime commenced. The database contains information on a range of waste types including municipal, commercial and industrial; many commercial and industrial sites are classed as “inert” and are particularly well-suited to repurposing. Data were provided as vector-format shapefiles. This dataset covers England only, and therefore our study was restricted to England, even though our initial dataset for all three recording schemes included recorded squares in the other nations that comprise the UK.

To assess land use within recorded squares, we used raster data from the Land Cover Map 2015 (Rowland et al., 2017) to identify the dominant (modal) land use classification within each recorded square (i.e. that with the most 25 x 25 m pixels within the grid square).

2.2. Data curation and indicators

From our initial dataset, we used the Historic Landfill Sites data to quantify the area of historical landfill within each recorded square. From these, we identified all recorded squares with > 5 % landfill by area; these formed the focus of our study and were termed “target squares”. Among target squares, percentage cover by landfill ranged between 5.03–69.04 %, with the majority of squares falling between 5 and 20 % (Supplementary Fig. 1). Date of landfill site closure is documented in the Historic Landfill Sites database via two metrics, date of last input and date on which the relevant permit/licence was surrendered, with both variables available for some sites and neither for others. We used these metrics to estimate the date on which each landfill site was closed (giving preference to the date of last input for sites where both metrics had been recorded), and used this to calculate the time in years since each landfill site closed (Supplementary Fig. 2). Where a target square contained multiple ex-landfill sites, we used the minimum value of time since closure (i.e. the most recently-closed site) in analyses.

For each target square, we additionally identified the nearest recorded square with the same dominant habitat type (“matched land-use squares”), and the nearest three recorded squares with different dominant habitat types (“different land-use squares”), to provide comparison. In theory, this was intended to facilitate comparison between brownfield sites and other sites with both similar and different habitat types, since the biodiversity value of brownfield sites could be shaped by two non-mutually exclusive factors: first, the presence of early-successional habitats that often form on such sites as ecological succession proceeds post-abandonment or restoration (Tarrant et al., 2013) (but which do not *exclusively* form on brownfield sites), and second, characteristics unique to brownfield sites themselves (e.g. potentially polluted soils and low disturbance) (Ash et al., 1994). If the target square has similar biodiversity to its matched land-use square, but differs from the different land-use squares, then the effect is more likely to be driven by the dominant land use associated with squares containing ex-landfill sites, whereas effects associated with the ex-landfill sites themselves should present even in comparisons with matched land-use squares. However, it should be noted that the land use of the brownfield site itself may not be dominant within the target square (especially for target squares closer to the 5 % cover threshold for inclusion), and that other confounding factors might be present in target squares but not captured by this analysis. Similarly, within target squares, the intersection between ex-landfill sites and actual recording locations (where available) was often minimal or non-existent; therefore, data from these squares should not be considered to represent a census of the biodiversity of brownfield sites themselves, but rather of landscapes that contain brownfield sites (and likewise, data from matched land-use and different land-use squares represents censuses of the biodiversity of various landscapes that do not contain brownfield sites).

For all target, matched and neighbouring squares, we calculated four biodiversity indices: (i) observed species richness (simply the total number of species observed across all surveys of the square per taxon); (ii) estimated species richness, extrapolated using the Chao2 incidence-based estimator (Chao, 1987; we used Chao2 rather than the Chao1 abundance-based estimator because most squares had data from repeated visits across multiple years, and under such circumstances this approach is more robust than abundance-based estimation (Colwell and Coddington, 1994)); (iii) sampling completeness (a function of the relationship between observed and estimated species richness, allowing the consistency of sampling effort across sites in different treatments to be examined); and (iv) an index of species rarity which varied from 0 (when a square contained only species recorded in every single square nationally) to 1 (when a square contained only species recorded in no other square nationally). To calculate this index, we assigned each species a rarity weight according to the proportion of recorded squares in which it had been observed; e.g. among butterflies, Small Blue *Cupido minimus* (recorded in 32 squares; 1.5 %) and Meadow Brown *Maniola jurtina* (recorded in 1832 squares; 87.4 %) were assigned weights of 0.985 and 0.136 respectively. We calculated the square-level rarity index based on these species-level rarity weights, following the approach of Leroy *et al.* (2013; who used a different method to calculate species-level rarity weights).

2.3. Statistical analysis

We used two related approaches to assess the effect of historical landfill sites in the landscape on biodiversity richness and rarity.

First, we tested whether target squares (those containing ex-landfill sites) differed in their biodiversity richness and rarity from their corresponding matched land-use and different land-use squares. To this end, we fitted generalised linear mixed-effects models to data from all squares, with ‘square type’ (i.e. target, matched land-use, or different land-use) as the fixed effect and a grouping factor as a random effect (to allow the model to pair each target site with its own counterparts). Models were fitted with a Poisson error distribution for species richness (except in one case, estimated species richness of moths, where a Quasipoisson distribution was fitted to address under-dispersion), and a binomial error distribution for sampling completeness and rarity index. We tested significance of the full model using a Likelihood Ratio Test. We then refitted each model twice, to separately test for differences between target squares and matched land-use and different land-use counterparts respectively.

Second, we tested whether the area of ex-landfill within target squares, and the time since landfill site closure, were correlated with biodiversity richness and rarity. To this end, we fitted generalised linear models to data from target squares only, with either the logarithm of the percentage of the square's area which was ex-landfill (the logarithm was taken to normalize this variable's distribution) or the time in years since closure as the fixed effect. Error distributions and significance testing were as above.

For both sets of analyses (those comparing target squares to counterparts, and those assessing linear or log-linear effects within target squares), we conducted false discovery rate (FDR) correction using the Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995), because we effectively tested the same hypothesis (that biodiversity would be different in squares containing ex-landfill sites than other squares) multiple times, both by comparing separately within the same datasets to matched and different land-use squares, and by testing with data for multiple taxa.

All analyses were conducted in R version 4.0.3 (R Core Team, 2020), except initial assessment of the intersection between landfill sites and recorded grid squares, which was conducted in QGIS (QGIS Development Team, 2021). R scripts are archived on Zenodo (doi: 10.5281/zenodo.4580297).

3. Results

Overall, we found that estimated species richness was significantly higher in target squares than their counterparts in matched and different land-uses for birds, plants and moths (Fig. 1, Supplementary Table 2). Observed species richness was similarly higher in target squares for birds and moths, but significantly lower in target squares for plants (a clear discrepancy with the results for estimated species richness). However, analysis of sampling completeness revealed that it was highly variable between squares for all taxa, and in some cases showed evidence of systematic differences between squares in different categories (with a significant effect detected for butterflies (Supplementary Table 2), though not for other taxa recorded in the same WCBS surveys). Given this finding, we ascribe greater confidence to the results for estimated species richness, which indicate a consistent positive effect of brownfield sites across birds, plants and moths. A trend towards this same positive effect was also evident in both groups of Odonata, but was non-significant after Benjamini-Hochberg correction (Benjamini and Hochberg, 1995) for false discovery rate (FDR) in both instances (Supplementary Table 3). By contrast, no such effect was present among butterflies; indeed, among habitat specialist butterflies, observed and estimated species richness were lower in target squares than different land-use squares, with no difference to matched land-use squares (Supplementary Table 2). For birds only, assemblage rarity was also higher in target squares containing brownfield; this effect was absent in all other taxa after FDR correction (Fig. 1).

We found a consistent, positive relationship between the area of brownfield within a target square and estimated species richness across birds, plants, dragonflies and damselflies, but not any group of Lepidoptera (Fig. 2, Supplementary Table 4). However, only the effects on birds and dragonflies retained significance after FDR correction (Supplementary Table 5). The same outcomes were found for observed species richness across all groups except damselflies. In other words, target squares containing larger ex-landfill sites tended to have richer ecological communities. We found a consistent, negative relationship between the age of brownfield within a target square and estimated species richness across birds, moths, dragonflies and damselflies (Fig. 2, Supplementary Table 6; although the latter was not significant after FDR correction: Supplementary Table 7), with a converse significant positive relationship for plants and no relationship for butterflies. In other words, species richness of birds and insects in target squares containing ex-landfill sites tended to decline over time, whereas species richness of plants tended to increase over time. However, we found no effects of brownfield site area or age on assemblage rarity for any taxon.

4. Discussion

Overall, our results indicate a positive effect of ex-landfill sites on landscape-scale biodiversity. Grid squares containing historical landfill sites tend to have higher species richness across multiple taxa than other nearby squares, and may also support a rarer assemblage of birds. Among target grid squares, those containing larger ex-landfill sites again tend to have higher species richness across multiple taxa. However, it should be noted that despite statistical significance, effect sizes were extremely small. For example, our models predicted an estimated richness of 70.6 (± s.e. 1.1) bird species in target squares, compared to 66.4 (± s.e. 1.0) and 63.2 (± s.e. 0.9) species in matched land-use and different land-use squares respectively (Supplementary Fig. 3): an addition of only a few species to an already large assemblage. Similarly, predictions of estimated species richness of birds in target squares increased from 67.5 (± s.e. 1.0) species at 5 % coverage of landfill, to 78.3 (± s.e. 1.6) at 50 % coverage. Proportional effect sizes were similarly small for other taxa (Supplementary Figs. 4-9). Therefore, whilst presence of ex-landfill sites appears to be associated with an increase in landscape-scale biodiversity richness, it should not be concluded that the ex-landfill sites are the richest possible land-use for conservation purposes; indeed, it is possible that these brownfield sites have relatively low species richness themselves, but increase beta diversity within landscapes by increasing habitat heterogeneity and providing niches that are distinct from those already present in the surrounding area. If this were the case, one would predict that the positive effect of increasing area within target sites should level off or decline as area exceeds 50 % (because habitat heterogeneity would decline once brownfield became too dominant in a square). We were unable to assess this because few squares had >50 % coverage of ex-landfill in our dataset (Supplementary Fig. 1). One would also predict that the positive effect of ex-landfill sites might be more pronounced, and thus more detectable, in human-altered landscapes with low habitat heterogeneity (e.g. largely agricultural landscapes) compared to those with high habitat heterogeneity. Further field research is necessary to determine what proportion of full landscape-scale assemblages can be supported on brownfield sites themselves, which types of species are added to the assemblage by their occupation of brownfields, and which specific features of brownfield sites and their surrounding landscapes are responsible for driving the observed increase in landscape-scale assemblage richness. However, the contrasting effects of brownfield site age on plants and other taxa suggests the early-successional habitats associated with brownfield sites may be an important factor. Birds, moths and odonates are all relatively mobile taxa capable of rapidly colonising suitable early-successional habitat on recently-abandoned brownfield sites, but these sites may subsequently become less valuable as succession proceeds (e.g. Broughton et al., 2021). By contrast, plants are less mobile, and assemblages might colonise ex-landfill sites gradually over a period of years to decades post-closure.

Effects upon the index of rarity were only found for birds, not for other taxa. It is possible that this difference can be ascribed to statistical power, given that the BBS was by some margin the largest of the three in use (Supplementary Table 1). However, it is also conceivable that it represents a genuine ecological pattern relating to the way in which certain rare bird species respond to and/or make use of brownfield sites within the landscape (e.g. Broughton et al., 2021): by contrast to other taxa under study, birds are highly mobile, and also might respond more strongly to the reduced disturbance from humans and predators associated with brownfield sites (Kamp et al., 2015). As above, this point might be clarified by further research into species with particularly strong associations with brownfield sites.

Effects were mainly absent in butterflies across all analyses (after FDR correction), apart from a negative effect of brownfield sites on habitat specialist species. The absence of positive effects matching those in other taxa seems unlikely to be a consequence of low statistical power, given that such effects were variously detected in moths, dragonflies and damselflies, all of which were recorded incidentally by a subset of WCBS butterfly recorders (Supplementary Table 1) and therefore had lower power; nonetheless, the timing of the WCBS recording window (July-August) might potentially mask effects by precluding the possibility of recording early-flying species known occasionally to colonise brownfield sites (e.g. Grizzled Skipper *Pyrgus malvae* (Slater, 2007)). An alternative, but unconfirmed, explanation, is that interactions between the traits of butterflies and those of their larval host plants reduce the likelihood of butterflies (especially habitat specialists) colonising brownfield sites. Butterfly distributions are strongly tied to the presence of larval host plants, even at very local scales (Clausen et al., 2001). Under the C-S-R strategy model for plants(Grime, 1974), larval hostplants of the most widespread and abundant wider countryside generalist butterflies tend to have competitive or ruderal strategies (Dennis et al., 2004), occupying productive habitats (Hodgson, 1993), and therefore might not benefit from low-fertility or polluted soils (Hard et al., 2019) on ex-landfill sites. Many of the habitat specialist butterfly species resident in the UK are associated with host plants that are themselves habitat specialists of calcareous grassland (Asher et al., 2001), with requirements unsuited to colonising ex-landfill sites. Even in cases where host plants can occur on ex-landfill sites, the typical traits of habitat specialist butterflies (low mobility, closed population structure, and inherently limited geographic distribution) may make colonisation by the butterflies unlikely. Other major forms of brownfield sites (e.g. disused quarries) may provide favourable conditions for habitat specialist butterflies and their host plants (Beneš et al., 2003; Schmitt, 2003; Slater, 2007; Turner et al., 2009), as well as a range of other taxa (Tropek et al., 2010), and could therefore generate landscape-scale benefits similar to those from ex-landfill sites detected in this study for butterflies and other taxa.

4.1. Conclusions

Our findings warn that current policies of unrestricted, or even preferential, development upon brownfield sites (such as former landfills) could have unintended negative outcomes for biodiversity richness, by destroying the unique ecological communities that can develop on such sites. Further research is necessary to establish whether particular features of brownfield sites and their management can provide an indication of their likely biodiversity value, and therefore enable more considered decision-making about the individual merits of different brownfield sites at the planning stage. In the meantime, our results imply that to minimise loss of biodiversity, development upon brownfield sites could be targeted towards smaller sites (i.e. those with the least positive influence to lose), or sites in areas with a high density of other brownfield sites (therefore, likely to retain some regional benefit).

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Author contributions

This study was instigated and primarily designed by C.J.M., M.J.B., P.D. and W.M.M., in discussion with N.A.D.B. and D.B.R. The statistical analysis was conducted by C.J.M., who also prepared the first draft of the paper. All authors contributed substantially to revising the paper.

Competing interests

The authors declare no competing interests.

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Figure 1. Presence of brownfield (historical landfill) sites in the landscape promotes species richness in multiple taxa. For each combination of response variable and taxon, target squares (with > 5% landfill by area) were compared to matched and neighbouring squares (nearest neighbours with respectively the same, and different, modal land-use compared to the target square). Estimated species richness was significantly higher in target squares than matched and/or neighbouring squares for birds, plants, moths (with similar trends for dragonflies and damselflies), but not for wider countryside or habitat specialist butterflies. Effect sizes (ES) are from Poisson- or binomial-family models with log link functions, such that comparison square metrics = target square metrics x e^{ES} (therefore, a negative ES indicates that metrics are lower in comparison squares than target squares, and vice versa). No comparisons were made between sampling completeness of squares for habitat specialist butterflies due to severe under-dispersion of data (Supplementary Fig 6).

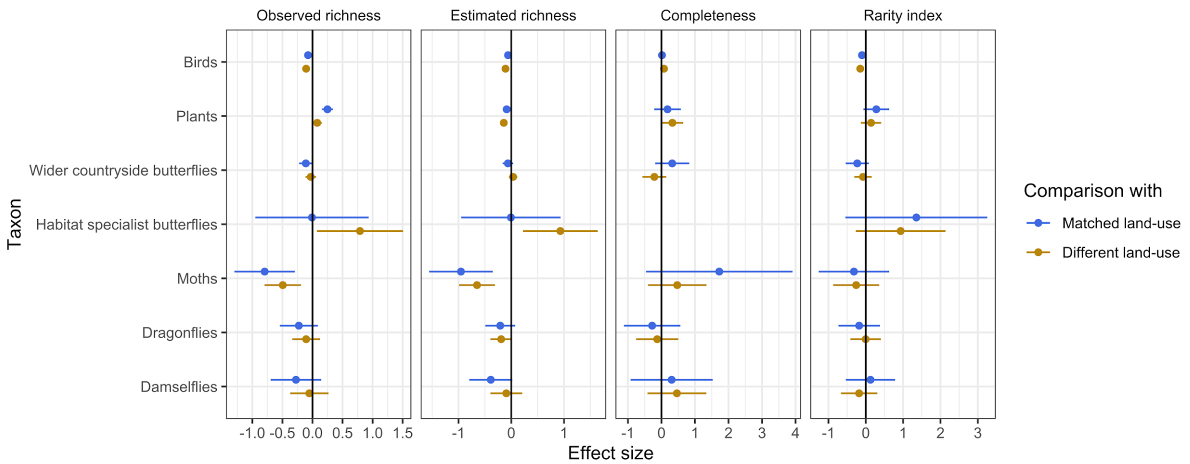

Figure 2. Area and age of brownfield sites affect species richness in multiple taxa. For each combination of response variable and taxon, the relationship between response variable and the explanatory variable (either percentage cover of brownfield sites or time since landfill site closure in years) was assessed, among all target squares (with > 5% landfill by area). Estimated species richness increased significantly with increasing area of brownfield for birds and dragonflies (with trends in the same direction for damselflies). For birds, moths and dragonflies, species richness decreased significantly with increasing time since landfill site closure (with trends in the same direction for damselflies), whereas for plants, species richness increased significantly with increasing time since landfill site closure. Effect sizes (ES) indicate slopes fitted by Poisson- or binomial-family models with log link functions (therefore, a negative ES indicates that metrics decrease as area or age of brownfield sites increase, and vice versa). Analyses of the effect of area of brownfield on habitat specialist butterflies are not plotted in order to preserve clarity for other taxa (due to extremely wide error bars), but are summarised in Supplementary Table 4.