Received: 11 November 2022 | Accepted: 18 April 2023

DOI: 10.1002/2688-8319.12243

Ecological Solutions and Evidence

BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Urban wildflower meadow planting for biodiversity, climate and society: An evaluation at King's College, Cambridge

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Funding information
Biotechnology and Biological Sciences Research Council, Grant/Award Number: BB/N021908/1, BB/R011311/1 and BB/S006397/1; Gatsby Charitable Foundation; King's College Cambridge, University of Cambridge

Handling Editor: Harriet Downey

Abstract

1. The biodiversity and climate crises are critical challenges of this century. Wildflower meadows in urban areas could provide important nature-based solutions, addressing the biodiversity and climate crises jointly and benefitting society in the process. King's College Cambridge (England, UK) established a wildflower meadow over a portion of its iconic Back Lawn in 2019, replacing a fine lawn first laid in 1772.
2. We used biodiversity surveys, Wilcoxon signed rank and ANOVA models to compare species richness, abundance and composition of plants, spiders, bugs, bats and nematodes supported by the meadow, and remaining lawn, over 3 years. We estimated the climate change impact of meadow vs lawn from maintenance emissions, soil carbon sequestration and reflectance effect. We surveyed members of the university to quantify the societal benefits of, and attitudes towards, increased meadow planting on the collegiate university estate.
3. In spite of its small size (0.36 ha), the meadow supported approximately three times more plant species, three times more spider and bug species and individuals, and bats were recorded three times more often over the meadow than the remaining lawn. Terrestrial invertebrate biomass was 25 times higher in the meadow compared with the lawn. Fourteen species with conservation designations were recorded on the meadow (six for lawn), alongside meadow specialist species.
4. Reduced maintenance and fertilising associated with meadow reduced emissions by an estimated 1.36 Mg CO_2-e per hectare per year compared with lawn. Relative reflectance increased by 25%–34% for meadow relative to lawn. Soil carbon stocks did not differ between meadow and lawn.

5. Respondents thought meadows provided greater aesthetic, educational and mental wellbeing services than lawns. In open responses, lawns were associated with undesirable elitism and social exclusion (most colleges in Cambridge restrict lawn access to senior members of college), and respondents proved overwhelmingly in favour of meadow planting in place of lawn on the collegiate university estate.
6. This study demonstrates the substantial benefits of small urban meadows for local biodiversity, cultural ecosystem services and climate change mitigation, supplied at lower cost than maintaining conventional lawn.

KEYWORDS
biodiversity, climate change, lawn, nature recovery, nature-based solutions, restoration, urban ecology, wildflower meadow

1 | INTRODUCTION

The climate and biodiversity crises are critical challenges of this century. Urban areas have been cited as an important part of both the climate and biodiversity problem (Aronson et al., 2014) and solution (Beninde et al., 2015; Cadotte et al., 2021). Wildflower meadows are often encouraged as part of offsetting schemes, nature recovery plans and city greening initiatives (Bretzel et al., 2016; Her Majesty's Government, 2019; Klaus, 2013). Wildflower meadows in urban areas could provide important nature-based solutions, addressing the climate and biodiversity crises jointly, and benefitting society in the process (Stafford et al., 2021).

Although 40% of land cover in the United Kingdom is grassland (Carey et al., 2008), just 2% of this comprises biodiverse and carbon-rich semi-natural grassland (Bullock, 2011; Norton et al., 2021). Semi-natural grasslands declined by 97% between 1930 and 1970 due to ploughing, drainage and fertilisation (Fuller, 1987), with the result that more conservation priority species are associated with grasslands in the United Kingdom than with any other habitat type (The Grasslands Trust, 2011). Wildflower meadows are semi-natural grassland habitats, rich in native forbs, managed by taking a regular hay crop with or without aftermath grazing (Rothero et al., 2016). Not only do meadows have high biodiversity value, under the right circumstances they can contribute to climate change mitigation and adaptation, and improved human wellbeing (Norton et al., 2021). As anthropogenic semi-natural habitats, meadowlands are central in our cultural and social history (Lewis-Stemple, 2015; Rackham, 2000). The preservation and restoration of wild flower meadows is now of strategic national interest (Her Majesty's Government, 2019).

In the United Kingdom, 84% of people live in urban areas (World Bank, 2022). An estimated 25% of the UK's urban area is grassland, of which 64% is found in patches smaller than <2500 m^2, and about half of which is found in gardens (Evans et al., 2009). Most urban grassland comprises lawn: short mown, species poor, *Lolium perenne* (perennial rye grass) sports turfs, or *Agrostis-Festuca* fine turfs (Hubbard, 1992). Lawns have been the dominant form of urban grassland since the 20th century and are now a social norm, attributed with easy establishment, maintenance, recreational and aesthetic benefits (Hoyle et al., 2017; Ignatieva et al., 2017; Norton et al., 2019). By converting urban lawns to urban meadows, urban grasslands could present a significant opportunity to integrate grassland conservation efforts within human-dominated landscapes for the benefit of both people and wildlife (Chollet et al., 2018; Norton et al., 2019). The opportunity is significant thanks to the low baseline biodiversity value of lawn, and the extent of amenity lawns across the UK's cities.

Although both lawns and meadows are semi-natural habitats created and maintained by people, they differ in the intensity of management regime, with lawns being more frequently mown, fertilised, watered and applied with pesticides (Rorison & Hunt, 1980). These important differences in management between lawns and meadows have consequences for biodiversity both above-ground and below-ground, carbon sequestration, aesthetics and amenity value. Above-ground, restored or experimental meadow plots have been associated with high dicot: monocot ratios and high overall plant species richness (Chollet et al., 2018; Scotton & Rossetti, 2021). This in turn promotes significant richness and abundance of pollinating insect species (Hutchinson et al., 2020), with positive consequences for higher trophic feeding levels (Scherber et al., 2010). Below-ground, changes to the soil microbial community of bacteria and fungi were observed in recently established urban meadow plots (Norton et al., 2019), while plant diversity and composition altered soil nematode communities in manipulated grasslands (Viketoft et al., 2009). Meadows' potential role in climate change mitigation includes increased rates of carbon sequestration compared with amenity grasslands: species-rich grasslands restored from species-poor swards showed increased rates of carbon sequestration compared with species poor swards (Yang et al., 2019), and increased plant species richness in manipulated meadow plots (Norton et al., 2019). For people, biodiverse perennial meadows were found to increase residents' perceptions of site quality in urban greenspace (Southon et al., 2017), and were considered the most attractive of a range of grassland planting schemes to respondents in China (Jiang & Yuan, 2017). While natural and semi-natural grasslands are well studied, urban grasslands have received relatively less attention from the restoration ecological community (Klaus, 2013).

The lawn probably first appeared in medieval times in Europe (Ignatieva et al., 2017). Lawn became more widely established with the development of the picturesque and gardenesque landscape architectural styles in the 18th and 19th centuries in Europe, the United States, Australia and New Zealand and has been used on a very wide scale in all green areas, public and private, since the 20th century (Ignatieva et al., 2017). The city centre of Cambridge, in southern England (UK), is aesthetically and culturally dominated by buildings associated with the departments and colleges of the University of Cambridge, many of which were established during the medieval period and stand today more or less as they were first designed. King's College occupies a very central position in the City, on King's Parade. The much-photographed King's Chapel, Gibbs building and Back Lawn together comprise the iconic and most often-used image of Cambridge (Figure 1, aerial view). The land Henry VI acquired for King's College through the 1440s was already in the centre of Cambridge. This densely populated area accommodated hostels, gardens, a convent, some common ground and a churchyard with burial ground, the remains of which all lie under the college buildings today (Willis & Clark, 1886).

Although it is tempting to think of the landscape of collegiate Cambridge as unchanging, in 1574, the college and city lands west of the river now known as 'the Backs' was a simple landscape of unimproved marshy pasture, which by 1592 had been formalised with avenues of trees, an artificial pond, and a duck house. In place of the King's Back Lawn were an orchard, a bowling green and a fellows' garden, which were replaced in 1688 with a grass sward divided by paths and avenues of trees. The Gibbs building was constructed from 1724. Not until 1772 did the idea to improve the land between Gibbs and the river take shape; the tree lined avenues were removed and the whole area was laid out as lawn to form the 'Great Square' of grass, known today as the Back Lawn. Where the fashion in landscapes and gardens had once been about the demonstration of wealth via productivity, by the 1770s, good taste now dictated the opposite, that wealth be demonstrated by how much land one could afford to keep out of productivity, which was very much the statement made by the Back Lawn (Willis & Clark, 1886).

In autumn 2019, King's College Cambridge sowed a wildflower meadow in place of a portion of the Back Lawn. In designing the planting, the aim of the college governing body was to improve the wildlife value and reduce greenhouse gas emissions, while providing greater benefits to the college and wider Cambridge community. Here, we evaluate the performance of the King's meadow using 3 years of data, in each of three areas: (1) wildlife value, (2) climate change mitigation and (3) societal benefits. We consider the desirability and feasibility of increased meadow planting across collegiate Cambridge and beyond.

2 | MATERIALS AND METHODS

2.1 | Study site

2.1.1 | Meadow establishment

The meadow area covers about 40% of the original extent of the King's College Back Lawn, which was first laid in 1772 (Figure 1). The dimensions are 96 × 66 m lawn (0.63 ha) and 96 × 37 m meadow (0.36 ha). A soil study commissioned before sowing showed both the topsoil (of 30 cm depth) and subsoil were strongly alkaline (pH 8.4) sandy loams. The topsoil had intermediate fertility (20–27 mg/L extractable phosphorus, 131–167 mg/L extractable potassium, 0.50%–0.52% total nitrogen using Dumas method), while the subsoil had moderately high fertility (35–54 mg/L extractable phosphorus, 69–129 mg/L extractable potassium, 0.24%–0.39% total nitrogen). Thus, topsoil removal was not necessary, and seed was sown into glyphosate treated scarified topsoil at 6 g/m^2 in October 2019. Three different seeds mixes sourced by Emorsgate were sown: the Great Lawn meadow mix, a perennial meadow species mix intended as the long-term flora of the meadow; a Cornfield Annual mix intended to provide first year colour; and a Supplementary Mix composed of species with lower establishment probability from seed, but high conservation value (Table S3).

2.1.2 | Meadow management

The meadow is managed as an East Anglian hay meadow following traditional Lammas practices as far as possible. Hay is cut once a year around August 1st (Lammas day) to a height of c. 350 mm, with one subsequent cut at 350 mm in December, in place of the historical light grazing. Hand weeding was performed through the visitor seasons to remove the occasional individual of undesirable species (mainly *Sonchus oleraceus* and *Cirsium vulgare*). No other management or intervention has been practised. Management of the remaining 60% of lawn continues as before; the lawn is a fine lawn mix with *Agrostis stolonifera* and *Festuca rubra* dominant. It is maintained with twice-weekly cuts from March to September, weekly cuts from October to December, dropping to biweekly cuts in January and February. NPK fertiliser is applied at c. 30 g/m^2 in spring (8% N, 7% P, 8% K) and winter (3% N, 8% P, 8% K). A selective herbicide (Praxys) is applied to the remaining lawn at the minimum dosage once to twice per year. Insect pesticides are no longer applied, and watering is avoided as far as possible. Fertiliser and herbicide is applied in a directional fashion by ride-on vehicle during suitable weather conditions only to minimise run-off.

2.2 | Biodiversity

2.2.1 | Plants

Botanical surveys were carried out in July for each flowering summer (2020, 2021) and in September for the pre-sowing baseline (2019). Five quadrats 50 × 50 cm were placed every 15 m perpendicular to the edge in both the meadow and the lawn (KBME01-KBME05, KBSO01-KBSO05, Figure 1). The origin of the meadow transect is 15 m from the northern lawn edge, and 5 m from the eastern lawn edge, at latitude 52.204691°N, longitude 0.115580°E. The origin of the lawn transect is 15 m from the southern lawn edge, and 5 m from the eastern lawn edge, at latitude 52.204045°N, longitude 0.115737°E. Abundance was measured by counting presence in each of 25 equal subdivisions of the quadrat. Mean plant height was recorded. In addition, running checklists of all species present in the lawn and meadow separately were collected over the course of each year, with 2–3 principle recording visits made each year in March, April and July. Plants were identified as sown or non-sown using the stated seed mix (Table S3). Plant attribute data (distribution, scarcity) were sourced from PLANTATT (Hill et al., 2004). Designated species follow JNCC (2022).

2.2.2 | Invertebrates

Above-ground invertebrates were sampled by sweep net (July 2020, July 2021, pre-mowing) and pitfall trap (September 2019, 2020, 2021, post-mowing) at five points in both the meadow and lawn (Figure 1). Sweep net transects were 20 paces each, centred on the plant quadrat locations. Sweep net specimens were identified to species level for all taxa in 2020, using morphospecies names as necessary, and to species for Hemiptera (bugs) and Araneae (spiders) only in 2021. 2020 data were restricted to Hemiptera and Araneae for analysis. Pitfall traps were sited at the centre of the plant quadrat locations. Pitfall trap specimens were weighed in 2021 only. Pitfall specimens were identified to species for all taxa present in 2019 and to species for Hemiptera, Araneae and Orthoptera only in 2020 and 2021. Spider attribute data (hectad occurrence, habitat preferences) were sourced from British Spiders (2022). Hemiptera habitats were sourced from British Bugs (2022), with hectad distribution data from National Biodiversity Network (2022). Arthropod body size data were compiled from NatureSpot, British Bugs, BugGuide and Bugwoodwiki (2022); male and female maximum body lengths were averaged. Designated species follow JNCC (2022).

2.2.3 | Bats

Bats were surveyed via two unattended ultrasonic recorders (Wildlife Acoustics Song Meter SM4BAT FS Ultrasonic Recorder) placed adjacent to the meadow, and the lawn (Figure 1). Recorders were left for five or six nights each over four recording periods in May, June, July and October in 2021 only. Audio files were auto-identified to species using Kaleidoscope version 5.4.6 before being checked manually. All records of *Barbastella barbastellus* were accepted, one record of *Myotis bechsteinii* was assigned to *Myotis daubentonii; Plecotus austriacus* records were assigned to *Plecotus auritus* or *Eptesicus serotinus*, one *Rhinolophus ferrumequinum* record was assigned to *Pipistrellus pipistrellus. Myotis* species are generally considered indistinguishable by audio recording only. The only *Myotis* species recorded in our dataset was auto-identified as *Myotis daubentonii*, which was also seen foraging at the river, and so the identity has been retained for analysis. The total number of echolocations recorded over the year in each habitat is used as a proxy for abundance (several passes by the same bat would not be distinguished). Designated species follow JNCC (2022).

2.2.4 | Soil nematodes

Soils were sampled contemporaneously with the pitfall traps in September 2019, 2020 and 2021, and were co-located (Figure 1). Approximately 7 cm width by 10 cm depth of soil was dug and mixed. Nematodes were extracted by wetting 180–200 g of soil on top of a paper towel with RO water. The wetted soil was left overnight in a tray covered with an autoclave bag to prevent evaporation. The flowthrough was collected in 1 L glass media bottles (Fisherbrand), and left to settle at a 45° angle for 24 h. The sediment was pipetted into a 50 mL conical centrifuge tube (Corning) using a soda lime glass pipette (Fisherbrand) and centrifuged at 300× RCF for 15 min. The pellet was transferred to a 1.5 mL microcentrifuge tube (Eppendorf) and centrifuged at 20,000 RCF for 1 min and snap frozen in liquid nitrogen. The frozen tissue was lysed at 30 Hz in a tissue lyser (Qiagen) for 2 min with one 5-mm and two 2-mm glass beads (Qiagen). From the samples, DNA was extracted using a ChargeSwitch™ gDNA Micro Tissue Kit mini protocol. Using the well-established 18S RNA primers, NemFopt and 18Sr2bRopt (Waeyenberge et al., 2019) DNA was amplified (Q5® High-Fidelity DNA Polymerase) via PCR and cleaned using the Monarch® PCR & DNA Cleanup Kit 5 μg. The amplified DNA was sent to the GENEWIZ Takely Laboratory (UK) for next-generation sequencing.

2.2.5 | Analysis

Mean richness and abundance of plants, spiders and bugs (pitfalls, sweeps), nematodes and bats recorded in the meadow in 2021 were compared with the pre-sowing meadow baseline (2019) and lawn control (2021) using Wilcoxon signed-rank tests, paired for bats only as observations are paired across nights, with bat activity each night highly variable (Table 1; Figure 2). p values are reported at $p < 0.001$, $p < 0.01$ and $p < 0.05$, with $p < 0.05$ taken as significant, that is, the Bonferroni correction is not applied. In this case all tests are of a priori hypotheses; while the Bonferroni correction reduces the chance of type I errors, the likelihood of type II errors increases substantially with this stringent correction. Vague names were excluded from analyses and checklist totals, unless unambiguously assignable to a unique species, for example, *Zelotes* sp. where no other *Zelotes* species was recorded. Missing pitfall trap values were replaced with the group mean for model testing.

The study has a before-after-control-impact (BACI) design, with sampling initiated before the meadow was established. BACI designs are an effective method to evaluate perturbations when treatment sites cannot be randomly allocated or blocked, as in the current context (Conner et al., 2015). A significant interaction between location (control/impact) and year (before/after) allows any change in response variables to be attributed unequivocally to the meadow planting rather than temporal or spatial heterogeneity. BACI hypothesis testing was carried out using ANOVA, with response variables transformed after visual inspection of the residuals showed this was necessary; transformations used are reported alongside the Results (Table 2). Contrasts were calculated post-hoc using Tukey Honest Significant Difference; significant contrasts are presented in Table S1.

Non-metric multidimensional scaling (NMDS) ordination was carried out in R package VEGAN 2.5.5 (Oksanen et al., 2019) using a Bray–Curtis dissimilarity matrix calculated from the plants, sweeps, nematodes and bats datasets from the five meadow and five lawn sample sites across all 3 years ($n = 30$) (Figure 3). Two axes were specified (three for bats); convergence was reached within 20 runs with stress <0.2 for all analyses. A chi-squared test of association between bat species and location was performed (Figure 5). All analyses were carried out in R version 3.6.0 (R Core Team, 2020) unless otherwise stated.

2.3 | Climate change

2.3.1 | Emissions reductions

Greenhouse gas emissions (CO_2e) associated with the maintenance regimes (mowing and fertilising) of the lawn and meadow were estimated using literature values (Table 3). The total area of greenspace across Cambridge College sites was estimated using computer vision on high-resolution image exports from the University Map website (https://map.cam.ac.uk). The scale bar in the interactive viewport (e.g. 50 pixels = 500 m) was noted for each image and used to convert area measurements from pixels to metres squared. The method was checked for consistency against staff estimates and a measurement from Google Earth. Map exports were produced at several scales to check for scaling errors. The commented code and resources are hosted at https://github.com/DOD14/map_area_calculator.

2.3.2 | Carbon sequestration

Soil organic matter (SOM) was measured as a proxy for soil carbon sequestration. Soils were sampled contemporaneously with the pitfall traps in September 2019 and 2021 and were co-located (Figure 1). 7 cm width by 10 cm depth of soil was dug and mixed. For SOM, 100 g of soil from each sample was dried at 70°C for 2 days, homogenised and sieved (2 mm), then weighed into three pseudoreplicates of 5.00 g each per sample location. SOM was estimated using the loss on ignition method: samples were subjected to 8 h in a muffle furnace at 450°C and reweighed once cool (Pribyl, 2010). SOM for the meadow and lawn samples were normally distributed and were compared using a *t*-test. We used a conversion factor of 2 (Pribyl, 2010) to convert from SOM to soil carbon, that is, SOM is 50% carbon, and a literature value for soil density of 1440 kg/m^3 for sandy loam (Yu et al., 1993). Above-ground dry biomass was estimated for the meadow by counting the hay harvest in bales, weighing a bale, calculating the proportion of water in a bale by oven drying a sample and multiplying up. These values are not included in the carbon sequestration figures as the pool is short lived; nevertheless, the productivity of the meadow is noted here.

2.3.3 | Relative reflectance

Albedo is calculated from the ratio of reflected light to down-coming light on a vertical surface. Here, we measure relative reflectance without vertical surface images or down-coming light estimation, as a proxy for albedo. Relative reflectance values were calculated for meadow and lawn from images at three times of year: a March 2020 satellite image retrieved from zoom.earth, an aerial view of the meadow in early flower 26 May 2020, and a phone camera photograph taken on the ground (October 20). Analysis was performed in Image J (Gilchrist, 2011).

2.4 | Society

A survey was designed to assess respondents' opinions of the cultural services provided by meadow and lawn, and respondents' preferences for meadow and lawn (Appendix S1). Ethics oversight for the survey design and administration was provided by the Cambridge Hub. The survey was administered once in 2021 with responses recorded between 6 February and 26 March. At this time, the meadow had had one flowering season and was in a winter dormant period. Given the timing and method of recruitment respondents are likely to have seen the meadow for themselves, although we did not insist on this. A total of 278 respondents were recruited via mailing lists of the University faculties, colleges, societies and University-affiliated organisations. Respondents were informed of the purpose, methods and end use of the research and gave their informed consent to their data being collected and used for the purposes described in a privacy notice. An opt-out of having answers quoted was provided. No risks to participants were identified and participants were free to withdraw at any time. A small financial incentive was offered to respondents in the form of an Amazon gift voucher awarded to two randomly chosen respondents. Participants remained anonymous, unless they opted into being contacted for the randomly selected reward. All identifying information was deleted after disbursement of the rewards. Questions were always asked in the same order. The question of preference for lawn, meadow or a mixture was repeated after the provision of information on the benefits of lawns and meadows. This information consisted of a written summary of the provisioning, regulating, cultural and supporting ecosystem services derived from wildflower meadows and lawns and was written by the survey administrator from published peer-reviewed literature. References to the primary sources were provided to participants. Responses were analysed using Wilcoxon signed-rank tests and chi-squared tests of association. Open responses were analysed by identifying and exploring common themes qualitatively.

3 | RESULTS

3.1 | Biodiversity

3.1.1 | Species richness, abundance and biomass

Plant species richness was 3.6 times higher in the meadow compared with its lawn control in 2021 (means 15.8 vs. 4.4 species; $t=8.497$, $df=4.773$, $p<0.001$) (Table 1). The combined spider and bug species richness recorded during sweep netting was 3.7 times higher in the meadow than the lawn (2021, average 6.6 vs. 1.8 species $t=-4.382$, $df=5.039$, $p=0.007$), while the number of spider and bug individuals caught in pitfall traps was 3.8 times higher in the meadow than the lawn (2021, 7.6 vs. 2 individuals, respectively; $t=3.572$, $df=6.23$, $p=0.011$) (Table 1). At the top of the food chain, insectivorous bats were recorded 3.1 times more often over the meadow than over the lawn (100 vs. 32 times, respectively; paired $t=5.249$, $df=21$, $p<0.001$), and on average more bat species were recorded on the meadow each night (4.31) compared with the lawn (3.45) (paired $t=2.425$, $df=21$, $p=0.024$) (Table 1). Total invertebrate biomass was 25 times higher in the meadow than in the lawn (2021, $t=-6.7757$, $df=4.2247$, $p=0.002$). The mean body length of lawn arthropod species was 4.79 mm, cf. mean body length of 8.75 mm for meadow arthropods ($t=-3.78$, $df=41.5$, $p=0.0005$). Below-ground, there was no difference in nematode species richness nor abundance in the meadow cf. lawn in 2021, nor in the meadow in 2021 compared with its lawn baseline in 2019. Meadow biomass was estimated from bale production; 142 bales came off the meadow in 2020 versus 322 bales in 2021, giving an estimated productivity of 2.12 and 5.07 Mg/ha/year, respectively.

During BACI hypothesis testing (Table 2), a significant interaction term was found for plant species richness, with the meadow plant richness significantly higher than its original baseline and the lawn control in all years (Figure 2; Table 2; Table S1 for contrasts). For bats, abundance increased over the growing season more sharply over the meadow than over the lawn; by October the meadow had been mown, and there was no difference in bat activity at this time point. For nematodes, abundance was significantly increased in 2020 in both the meadow and lawn relative to both 2019 and 2021 and was significantly higher in the meadow than the lawn in 2020 only. Thus, the greater abundance in 2020 was not sustained into 2021, and being an intermediate year, it does not feature in the (non-significant) comparisons tested in Table 1. Nematode richness was significantly higher in 2021 for both meadow and lawn compared with 2020 and 2019, that is, although there were more nematode genera in total in 2021, there was no difference between our meadow and lawn treatment of interest (as is tested in Table 1).

A total of 84 plant species, 16 bug and spider species, 149 nematode genera and 8 bat species were recorded during sampling. Of the 84 plant species recorded in 2021, only 33 were sown species (24 from the perennial meadow species seed mix, 6 persisting from the cornfield annual mix and 4 of the supplementary mix: *Odontites vernus*, *Onobrychis viciifolia*, *Ononis spinosa* and *Iberis amara*, a nationally scarce species). Additionally, nine species of parasitic microfungi (such as powdery mildews and rusts) were recorded by C. Preston on three visits in June, July and August 2022, including a new county record of the fungal plant pathogen *Cercospora zebrina* on *Medicago arabica*.

3.1.2 | Species of conservation priority

The meadow supports 14 species with conservation designations, compared with 6 species with conservation designations in the lawn. All the designated species recorded in the lawn were also recorded from the meadow (*Lygus pratensis*, *Barbastellus barbastellus*,

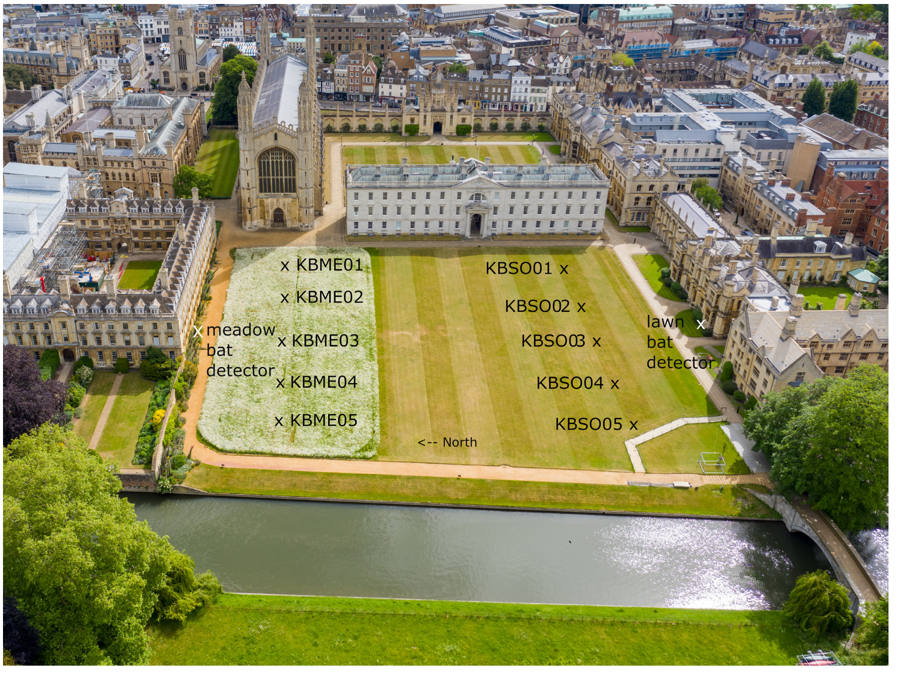

FIGURE 1 King's Back Lawn and meadow (photo 10 June 2020, ©Geoff Robinson/BAV Media). The 10 sampling locations for plants and invertebrates, and two sites of static bat detectors, are marked. The land to the west of the river is Scholars' Piece. The white building facing the lawn is the Gibbs building. The Chapel stands to the north of the Gibbs building.

TABLE 1 Mean richness and abundance of plants, spiders and bugs (pitfalls, sweeps), nematodes and bats recorded in the meadow in 2021, compared with the presowing meadow baseline (2019) and lawn control (2021). Significance tests are Wilcoxon signed-rank tests, paired for bats only. The change in each response variable is reported first. Significant changes are shown in bold, ***$p<0.001$, **$p<0.01$, $p<0.05$*. Checklist totals are included at the end of the table.

Response variable	Meadow 2021	Presowing baseline (meadow 2019)	Change ratio cf baseline	Lawn 2021	Change ratio cf control
Plant mean richness	15.8	4.2	3.76** $W=25$, $p=0.0097$	4.4	**3.59*** $W=25$, $p=0.011$
Plant mean abundance	91	77.8	1.17 $W=18$, $p=0.31$	62.6	1.45 $W=21$, $p=0.095$
Pitfall mean richness	3	3.2	0.94 $W=14.5$, $p=0.32$	1.75	1.71 $W=11.5$, $p=0.91$
Pitfall mean abundance	7.6	5	1.52 $W=18$, $p=0.29$	2	**3.8*** $W=19$, $p=0.032$
Sweep mean richness	6.6	N/A	N/A	1.8	**3.67*** $W=25$, $p=0.011$
Mean invertebrate biomass (pitfalls) (g)	5.60	N/A	N/A	0.225	**24.89*** $W=20$, $p=0.016$
Nematode generic mean richness	48.2	31.4	1.54 $W=13.5$, $p=0.92$	49.2	0.98 $W=20$, $p=0.15$
Nematode mean abundance	1169.4	2805.8	0.42 $W=4$, $p=0.095$	970.4	1.21 $W=15$, $p=0.69$
Bat mean richness	4.31	N/A	N/A	3.45	**1.25*** $V=134.5$, $p=0.032$
Bat mean abundance	100.32	N/A	N/A	32.36	**3.10***** $V=224$, $p=0.00017$
Totals: plants	84	22	3.82	28	3.00
Totals: pitfalls	7	10	0.70	7	1.00
Totals: sweeps	16	N/A	N/A	9	1.78
Totals: nematode genera	90	54	1.66	89	1.01
Totals: bats	8	N/A	N/A	7	1.14

Eptysicus serotinus, *Nyctalus leisleri*, *Pipistrellus pipstrellus*), apart from *Pipistrellus nathusii*, which was not recorded over the meadow. The full list of meadow species with conservation designations has nine plants (*Agrostemma githago*, *Glebionis segetum*, *Bupleurum rotundifolium*, *Euphrasia confusa*, *Iberis amara*, *Knautia arvensis*, *Ononis spinosa*, *Briza media*, *Onobrychis viciifolia*), four bats (*Barbastellus barbastellus*, *Eptysicus serotinus*, *Nyctalus leisleri*, *Pipistrellus pipstrellus*) and one bug (*Lygus pratensis*). *Euphrasia confusa* (det. J. Shanklin 2020) had not previously been recorded in Cambridgeshire.

In 2021, the meadow supported approximately four times as many declining plant species (those with negative change indices) compared with the remaining lawn (44 cf. 11) and the original lawn baseline (44 cf. 10). Meadow plant species were on average rarer than lawn species, with meadow species found in 1982 hectads (10 km × 10 km) across GB, cf. 2463 hectads for the lawn species. Meadow spiders had a non-significantly slightly wider distribution than lawn species (means 1255, 1219, $n=17$, 14), and have shown a greater increase in records post-1992 (+99% cf +73%). Rarer bugs included *Dufouriellus ater* (28 hectads, meadow) and *Lygus pratensis* (92 hectads, meadow and lawn). No data on nematode species' conservation status or range have been published to our knowledge.

3.1.3 | Species composition and habitat associations

Samples are ordinated in Figure 3. For plants (Figure 3a), axis 1 distinguishes clearly the two meadow habitats (meadow 2020, meadow 2021) from the lawn habitats in all years, indicating different species composition between the habitats. The three lawn years and the pre-sowing meadow baseline 2019 (=lawn habitat) are not distinguishable from each other. Axis 2 distinguishes the meadow in 2020 from the meadow in 2021, as floral composition shifts year on year. For spiders and bugs from the sweep samples (Figure 3b), axis 1 also separates meadow habitat from lawn habitat very clearly, while axis 2 separates both habitats by year, showing that species composition is influenced by both habitat type and annual variation. For nematodes (Figure 3c), samples are grouped by year, rather than habitat type, suggesting that interannual variability in samples is the most significant influence on species composition. Axis 1 separates 2021, while axis 2 separates 2019 from 2020. Habitat types are barely distinguishable within years. For bats (Figure 3d), axis 2 separates samples clearly by habitat, indicating different species composition between the habitats. Axis 1 separates three samples from the rest, nights on which a lot of bat activity was recorded.

TABLE 2 Before-after-control-impact (BACI) hypothesis testing with ANOVA. Contrasts are calculated post-hoc using Tukey HSD (Table S1).

	df	*F*	*p*	Direction of significant contrasts
Plant richness, ln transformed				
Location (lawn, meadow)	1,24	128.13	<0.0001	Meadow > lawn
Year (2019, 2020, 2021)	2,24	39.92	<0.0001	2021 = 2020 > 2019
Location × year	2,24	19.24	<0.0001	Meadow:2020 > lawn:2019 Meadow:2021 > lawn:2019 Meadow:2020 > meadow:2019 Meadow:2021 > meadow:2019 Meadow:2020 > lawn:2020 Meadow:2021 > lawn:2020 Lawn:2021 < meadow:2020 Meadow:2021 > lawn:2021
Plant abundance, untransformed				
Location (lawn, meadow)	1,24	8.705	0.00663	Meadow > lawn
Year (2019, 2020, 2021)	2,24	1.724	0.20066	N/A
Location × year	2,24	0.049	0.82700	N/A
Pitfalls richness, untransformed				
Location (lawn, meadow)	1,22	2.357	0.139	N/A
Year (2019, 2020, 2021)	2,22	0.645	0.535	N/A
Location × year	2,22	0.226	0.800	N/A
Pitfalls abundance, untransformed				
Location (lawn, meadow)	1,22	10.541	0.0037	Meadow > lawn
Year (2019, 2020, 2021)	2,22	1.054	0.3654	N/A
Location × year	2,22	1.818	0.1859	N/A
Sweep richness, ln transformed				
Location (lawn, meadow)	1,16	54.418	<0.0001	Meadow > lawn
Year (2020, 2021)	1,16	5.199	0.35800	
Nematode richness, ln transformed				
Location (lawn, meadow)	1,24	0.270	0.60791	N/A
Year (2019, 2020, 2021)	2,24	8.922	0.00127	2021 > 2020 = 2019
Location × year	2,24	0.111	0.89498	N/A
Nematode abun, sqrt transformed				
Location (lawn, meadow)	1,24	5.172	0.03219	Meadow > lawn
Year (2019, 2020, 2021)	2,24	77.386	<0.0005	2020 > 2019 > 2021
Location × year	2,24	8.250	0.00188	Meadow:2020 > lawn:2019 Meadow:2020 > meadow:2019 Lawn:2021 < meadow:2020 meadow:2021 < meadow:2020 Lawn:2021 < lawn:2020 Meadow:2021 < lawn:2020 Meadow:2020 > lawn:2020 Lawn:2020 > meadow:2019 Lawn:2020 > lawn:2019
Bat richness, untransformed				
Location (lawn, meadow)	1,39	3.804	0.05834.	Meadow > lawn
Month	3,39	6.509	0.00112	May = June < July < October
Bat abundance, sqrt transformed				
Location (lawn, meadow)	1,36	24.534	<0.0001	Meadow > lawn
Month	3,39	8.422	0.000227	May = June < July < October

TABLE 2 (Continued)

	df	*F*	*p*	Direction of significant contrasts
Location × month	3,36	2.929	0.046653	Meadow:June > lawn:May Meadow:July > lawn:May Lawn:October < meadow:May Meadow:June > lawn:June Meadow:July > lawn:June Lawn:October < meadow:June Meadow:October < meadow:June Meadow:July > lawn:July Lawn:October < meadow:July Meadow:October < meadow:July

TABLE 3 Emissions and costs associated with the mowing and fertilising regimes of meadow and lawn plantings, the two most carbon intensive management activities, for King's Back Lawn, and Cambridge College green space in total. See Table S2 for constituent values and references.

	Lawn		Meadow	
	GHG emissions (Mg CO_2-e/ha/year)	Cost (GBP/ha/year)	GHG emissions (Mg CO_2-e/ha/year)	Cost (GBP/ha/year)
Mowing	0.891	659.62	0.0122	9.04
Fertiliser	0.484	532.80	0	0
Mowing + Fertilising	1.375	1192.42	0.0122	9.04
Total for King's Back Lawn (0.99 ha)	1.361	1180.49	0.0120	8.95
Total lawn across all Cambridge colleges (43.7 ha)	60.08	52108.64	0.53	394.87

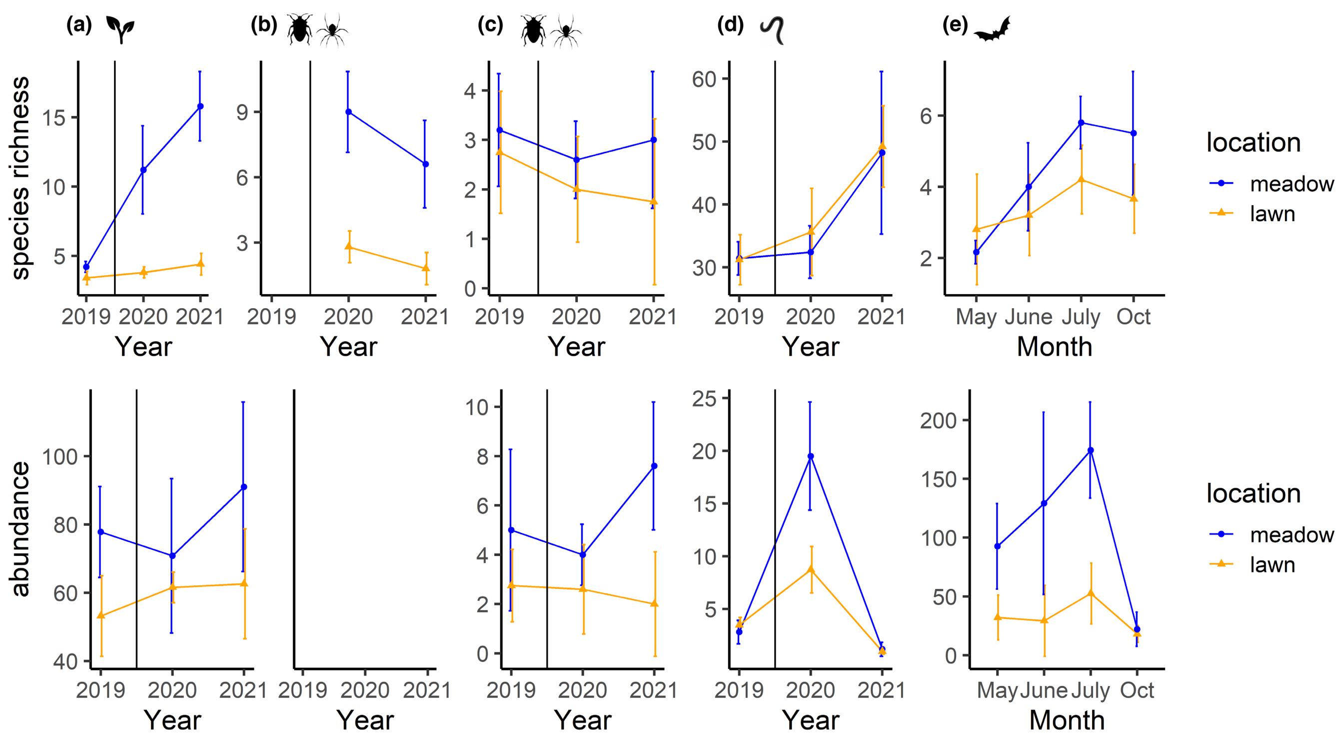

FIGURE 2 Species richness and abundance for a = plants, b = sweeps (spiders and bugs), c = pitfalls (spiders and bugs), d = nematodes, e = bats. Confidence intervals are mean ± (1.96 × SE). Abundance data were not collected during sweep netting (panel b). Abundance values are × 1000 *y* axis values in panel (d). Vertical blue line between 2019 and 2020 denotes meadow establishment.

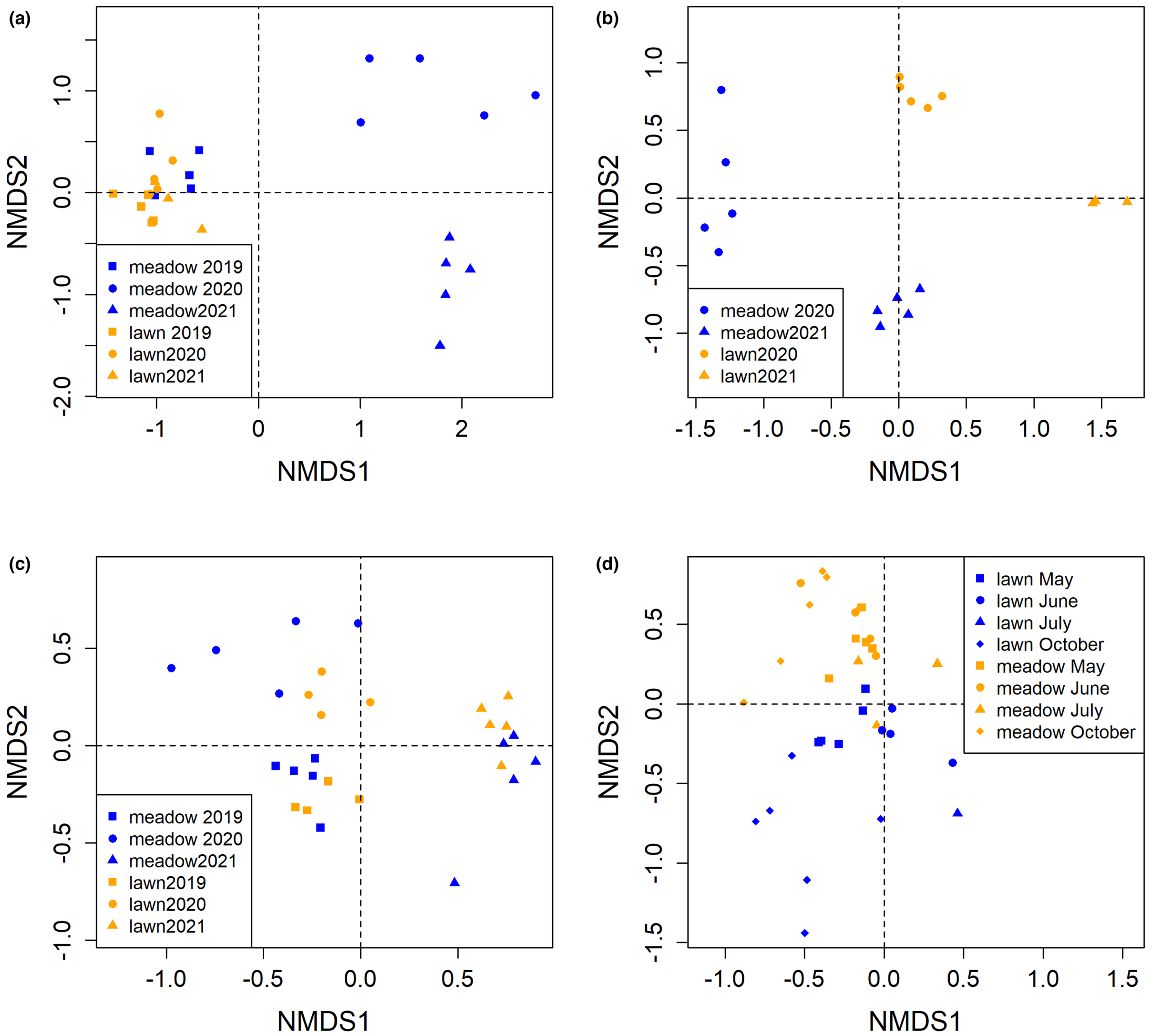

FIGURE 3 NMDS ordinations of Bray–Curtis dissimilarity matrices for samples, two axes were specified with each ordination (three axes for bats) and all ordinations converged with stress <0.2. a: plants, b: sweeps (spiders and bugs), c: nematodes, d: bats. Pitfall data were too few for valid ordination.

For plants in 2021, no association between broad habitat preferences and location was found overall ($X^2=12.706$, df=12, $p=0.3908$). Most strongly overrepresented are improved grassland species in the lawn (broad habitat 5, standardised residual=1.74) and calcareous grassland species in the meadow (broad habitat 7, standardised residual=2.54). The spiders found in our survey are habitat generalists, especially of grasslands and gardens, with a few of the meadow species characteristic of warm, sunny & exposed situations (*Enoplognatha latimana*, *Xysticus kochi*, *Ozyptila sanctuaria*), which are also the scarcer of the species being generally restricted to the south. All seven bug species of the lawn were also found in the meadow except *Scolopostethus thomsoni*, a generalist species feeding on nettles. Bug species of the meadow are grassland species or generalists, with most notable species including *Lygus pratensis*, a meadow specialist mirid bug with a southern but expanding distribution and *Orthops kalmii* and *O. campestris*, both umbel-feeding mirid bugs abundant in July, when the carrots *Daucus carota* were the dominant meadow plant.

Nematode functional guilds are defined as the combination of nematode feeding habit and coloniser-persister (cp) classification. The Enrichment Index and the Structure Index, both derived from the weighted relative numbers of each of the functional guilds in a sample, are descriptors of food web condition reflecting nutrient status and maturity of habitat, respectively (Ferris et al., 2001). Most samples fall within quadrant B, typical of managed grassland and agricultural systems (Berkelmans et al., 2003) (Figure 4). These have a high structure index value indicative of low disturbance or undisturbed soils and a high enrichment index value symptomatic of N-enrichment. The single exception is the meadow habitat in 2020:

with a lower enrichment index (lower fertility), it just falls within quadrant C, typical of natural grassland systems. However, this result is not recovered in 2021 (with the meadow back to quadrant B), so this is not likely to be significant. Nematode functional composition is similar across lawn and meadow.

For bats, there is a very significant association between species and location overall ($X^2=128.21$, df = 8, $p<0.001$; Figure 5). Most species were associated strongly with the meadow (serotine *Eptesicus serotinus*, common pipistrelle *Pipistrellus pipistrellus*, brown long-eared *Plecotus auritus*) or lawn (leisler's *Nyctalus leisleri*, noctule *Nyctalus noctula*, nathusius' pipistrelle *Pipistrellus nathusii*), while barbastelle *Barbastella barbastellus*, daubenton's *Myotis daubentonii* and soprano pipistrelle *Pipistrellus pygmaeus* were associated with each habitat equally.

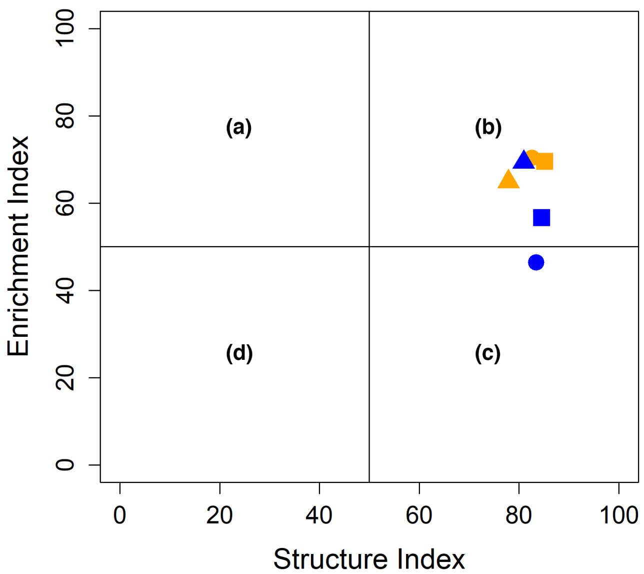

FIGURE 4 Functional ecology of the nematode communities derived from the weighted relative numbers of each functional guild in the samples. Enrichment index is a descriptor of food web condition reflecting nutrient status with higher scores having higher nitrogen availability. Structure index describes maturity of the habitat, with higher scores being less disturbed. Orange = lawn, blue = meadow; squares = 2019, circles = 2020, triangles 2021.

3.2 | Climate change

3.2.1 | Emissions reductions and cost savings

Using literature values and the maintenance regime at King's, we estimate that greenhouse gas emissions (CO_2-e/ha/year) are 112 times higher from lawn than meadow, while the maintenance regime is 132 times costlier for lawn than meadow (Table 3). Across all Cambridge colleges, converting all the current lawn area of 43.7 ha to meadow planting would reduce annual greenhouse gas emissions by 59.55 Mg CO_2-e each year, and cost £51,713 less each year to maintain. Overall, we estimate emissions of 1.375 Mg CO_2-e/ha/year from lawn (of which 65% came from mowing and 35% from fertilising) versus 0.0122 Mg CO_2-e/ha/year from the meadow for a single mow, giving a saving of 1.36 Mg CO_2-e/ha/year. King's has made available to other colleges and the City Council hay bales for green haying, eliminating the cost of seed, although there would still be site preparation costs like scarifying to consider. The area of greenspace managed by each college is estimated in Figure S3.

3.2.2 | Carbon sequestration

In 2020, with 10 samples (mean of three nested pseudoreplicates), we found no statistically significant difference in the mean SOM (SOM%) of the formal lawn (16%) and wildflower meadow at King's (17.3%) ($t=-1.44$, df = 5.69, $p=0.2$). Soil carbon was estimated at 124.56 Mg/ha in the top 0–10 cm. The carbon pool stored by the plant below-ground, for example, in roots was not measured.

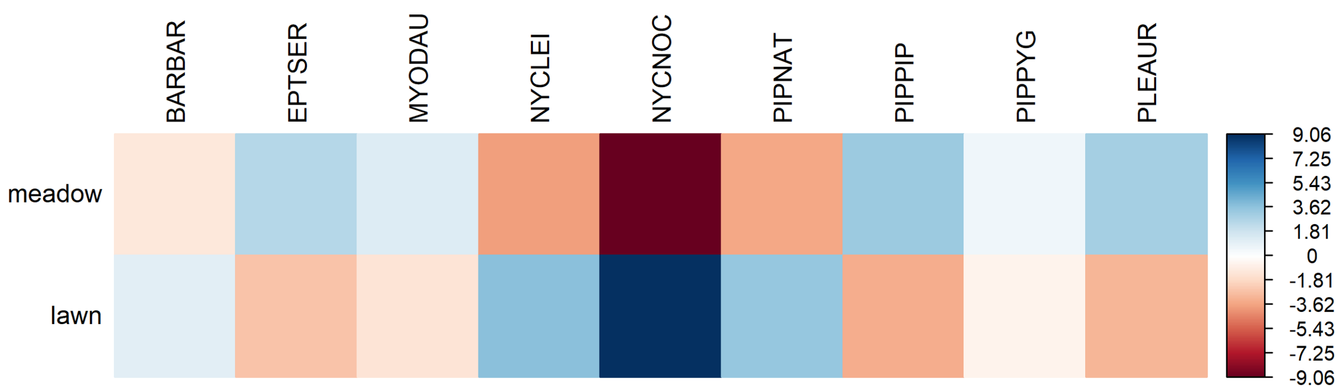

FIGURE 5 Bat species habitat associations. Colours and index refer to the standardised residuals of a chi-squared test, $X^2=128.21$, df = 8, $p<0.001$. BARBAR = barbastelle *Barbastella barbastellus*, EPTSER = serotine *Eptesicus serotinus*, MYODAU = daubenton's *Myotis daubentonii*, NYCLEI = leisler's *Nyctalus leisleri*, NYCNOC = noctule *Nyctalus noctula*, PIPNAT = nathusius' pipistrelle *Pipistrellus nathusii*, PIPPIP = common pipistrelle *Pipistrellus pipistrellus*, PIPPYG = soprano pipistrelle *Pipistrellus pygmaeus*, PLEAUR = brown long eared *Plecotus auritus*.

3.2.3 | Relative reflectance

Analysis of a series of photographs including both the meadow and lawn, taken throughout the year, showed the meadow reflectance to be 25%–34% higher than that of the adjacent lawn (Figure S2; Table S4).

3.3 | Society

Our attitudes survey attracted 278 respondents, a mixture of undergraduate students (50%), postgraduate students (23%), non-academic staff (13%), academic staff (10%), alumni (2%) and those with no affiliation (2%). 83% of respondents had a college affiliation, with 31 colleges represented. Survey questions can be found in Appendix S1.

The response to meadows was overwhelmingly positive. Respondents considered meadow more aesthetically pleasing than lawn (mean score 9.22 cf. 6.53, Wilcoxon $W = 10{,}661$, p-value < 0.0001) and more environmentally friendly than lawn (mean score 8.90 cf. 3.77, Wilcoxon $W = 2068$, p-value < 0.0001). 68% of respondents said they would prefer a mixture of lawn and meadow on campus/in their area, 30% said they would prefer entirely meadow to lawn, and just 1.4% (4 respondents) preferred entirely lawn. Significantly more respondents (83.5%) reported that meadows supported their mental well-being ('Meadows are great, they heal my soul'; 'Meadows would dramatically improve my well-being'), compared with lawns (45%) (X^2 (275,278) $= 89.6$, $p < 0.001$). 38.1% of respondents thought meadows had educational value, compared with just 4% for lawns. However, more respondents thought lawn provided recreational services (76%) than thought meadow provided recreational services (56%). After being presented with written information about the benefits of both lawn and meadow, 52% said they preferred a mixture of lawn and meadow, and 47% said they preferred entirely meadow to lawn (and 1% still preferred lawn), that is, respondents tended to move from a position of 'mixture' to 'entirely meadow'. There was no interaction between affiliation and habitat preference ($X^2 = 9.49$, df $= 10$, $p = 0.49$), nor college and habitat preference ($X^2 = 55.7$, df $= 62$, $p = 0.70$). The four King's respondents preferred meadow (2) or a mixture of lawn and meadow (2).

In Cambridge, most colleges restrict access to their lawns to senior members of the college only, that is, access is denied to students and visitors. This reduces the amenity value of lawn in collegiate Cambridge, while also increasing the perceived status of those lawns. Respondents were then divided as to whether that makes lawns a problematic emblem of classism and misdirected authority, or a heritage aesthetic that ought to be retained. For example, 'Lawns are a symbol of elitism and exclusion at Cambridge'. 'I find the overly tended lawns of the Cambridge colleges sterile and uninviting (not helped by the fact that one is often told not to walk on them)'. 'I find the lawns at Cambridge to be, in general, quite stuffy, classist, off-putting and generally self-defeating. (What is the point of grass you can't walk or sit on?)'. 'Lawns just seem really pretentious to me'. 'Particularly in Cambridge, lawns are forbidden territory'. 'I really like meadows and I understand that they are better environmentally (diversity of species etc), but I also really like to be able to sit on grass, picnic with friends, kick a football with children (obviously I'm not talking about the posh Cambridge lawns that you're not allowed to walk on!)'. 'I think that some of the grass courts in Cambridge are sort of iconic, so it'd be a shame to lose them all. That said, I'd definitely prefer the majority of green space in my college to be meadow'. 'I would only want a lawn over a meadow if I was allowed to use the lawn for recreational purposes. This is not allowed in most Cambridge colleges so I see no benefit to a lawn over a meadow'. 'I don't think the characteristic square/rectangular lawns of Cambridge colleges would look good as meadows'.

When respondents were asked if they had any objections to the conversion of lawn to meadow, 66% of 175 respondents had none at all. Recorded objections were that lawn area for recreation should be maintained e.g. for sports and sitting (22 respondents), aesthetic concerns (12 respondents), concern over increased hayfever, insect stings and ticks (8 respondents), that accessibility needed to be maintained (5 respondents), that species choice should be sensitive, i.e. native, low water demands, local provenance, good for pollinators (4 respondents), that it could cause controversy (2 respondents), that meadows look messy in winter (2 respondents) and that disruption during the conversion should be minimised (1 respondent). We asked respondents to suggest alternatives to replacing lawn with wildflower meadow with the following response rate: herb lawn, moss lawn or living lawn (8), woodland (8), trees (8), no maintenance of current lawns (7), allotments (6), ponds (5), formal garden (3), flower border (2), scrub (2) and corn maze (1). Incidentally, Trinity College had a maze on its grounds in 1592 (Willis & Clark, 1886).

When asked if meadow planting could contribute to the University's sustainability goals, 164 of 170 respondents thought yes (96%). Of the six respondents who said no, two said meadow planting was tokenism only, and four did not elaborate. One said 'replacing a tiny area of ornamental lawn in Cambridge will not affect UK biodiversity in a serious way—there are better hills to die on'. A few who thought that meadow could contribute to sustainability goals also worried about tokenism, 'taking part in such a visible move towards sustainability will let colleges off the hook for more difficult and meaningful change and practices'. Thirteen respondents made comments around the positive impact being modest only (e.g. 'maybe on a local level', 'not as much as other interventions', 'bigger fish to fry'). On the other hand, 'huge impact' 'big impact' 'Yes!' 'definitely' 'much more' 'absolutely' 'of course' 'obviously' and 'I'm sure' appeared in 18 responses.

Twenty respondents highlighted meadow planting as an important sustainability leadership action that the University should take. 'The King's meadow is a very visible sign of positive change'. Respondents commented that planting meadows 'could change mindset about sad lawn culture' and would be 'a strong message that the university realises the importance of biodiversity in creating resilient ecosystems and preventing extinction'. One commented, 'The lawns are symbolic in many ways of Cambridge's link to tradition, and if this small element of tradition changes I am hopeful that tradition won't be such a barrier elsewhere'. Another thought that 'As a leading University, Cambridge has a responsibility, not only to the environment but also as an example to other universities to make biodiversity an important issue'. One respondent summarised, 'We need to abandon pointless traditions like lawns", while another had a simple message for us: 'Meadow good lawn bad save the planet'.

4 | DISCUSSION

4.1 | Value to wildlife

In spite of its diminutive dimensions and recent establishment, the meadow is of considerable and demonstrable value to wildlife. Compared with the remaining lawn, the meadow supports approximately three times more plant species and a much taller sward, which in turn supports three times more spider and bug species and individuals, while terrestrial invertebrate biomass is a massive 25 times higher in the meadow compared with the lawn. Bats were recorded three times more often over the meadow than the lawn. The meadow is attracting specialist species, like *Lygus pratensis*, a meadow specialist mirid bug with a southern but expanding distribution, and *Orthops kalmii* and *O. campestris*, both umbel-feeding mirid bugs abundant in July when the wild carrots were the dominant meadow plant. The weekly moth trap we run at the King's meadow also attracts a disproportionate number of grassland-specialist moth species, including rarities like *Noctua orbona* (Lunar Yellow Underwing), and meadow specialists like *Bucculatrix nigricomella* (Daisy Bentwing) (Marshall et al., 2022). Fourteen species with conservation designations were recorded in the meadow, more than twice that of the lawn. There are four times more declining plant species in the meadow than the lawn and two new records for Cambridgeshire: the eyebright species *Euphrasia confusa*, and the microfungus *Cercospora zebrina* on *Medicago arabica*. The decline in once-common arable weeds across the UK has been accompanied by a concomitant decline in their obligate fungal parasites (Preston, 2022). Of note at the King's meadow is *Puccinia cyani*, a rust species of cornflower *Centaurea cyanus* once considered 'extinct in the UK along with its host' (Termorshuizen & Swertz, 2011). This species, along with the powdery mildew *Peronospora agrostemmatis* (host plant corncockle *Agrostemma githago*), now seems to be enjoying a resurgence in wildflower mixes in Cambridgeshire and beyond (Preston, 2022).

Plant species composition and sward height were both found to be important drivers of invertebrate abundance in grassland systems, with most invertebrate orders found to be more abundant where vegetation height was longer than mown grassland (Norton et al., 2019). At King's, invertebrate body length was on average longer in the meadow than the lawn, and we suggest that the increased sward height of the meadow allows larger-bodied taxa to avoid bird predation, increasing all of species richness, abundance and biomass (Figure S1).

Previous studies have shown that plant diversity has a strong bottom-up effect on multitrophic ecosystems connected in food webs, with particularly strong effects on lower trophic levels like herbivores (Scherber et al., 2010). At King's, insectivorous bats at the top of the food chain were recorded three times more often over the meadow and the lawn, which we attribute to increased foraging activity associated with higher invertebrate biomass. The proximity of the river corridor probably increases the conspicuousness and attractiveness of the meadow to bats in compensation for its small size. The bottom-up control of restored species-rich meadows apparent at King's is encouraging from an urban restoration perspective, as it is relatively straightforward to manipulate plant species richness and sward height to give positive effects for other taxa.

The size of habitat patches and their connectivity have been identified as key to maintaining high levels of urban biodiversity (Beninde et al., 2015). In that meta-study, the smallest area considered necessary to sustain species numbers before they decreased exponentially was 1 ha. A small area (1.7 ha) of wildflower meadow had significantly higher insect abundance and species richness than a comparable amenity grassland (Hutchinson et al., 2020). At just 0.36 ha, the current meadow extent at King's is much smaller than is typical for previously studied grassland systems, although even 'mini-meadows' of just 2 × 2 m have been shown to have a positive impact on wildlife (Griffiths-Lee et al., 2022). To have recorded such dramatic and positive changes for biodiversity, across trophic levels, from so small an urban area is highly encouraging for future urban restoration projects. Connectivity depends on the taxon under study. A single night of small mammal trapping at the meadow in 2021 caught no animals, while one wood mouse was caught at Scholars' Piece. For small mammals, the meadow is probably a relatively isolated and inaccessible island of habitat, bounded by Clare College, the Gibbs building, the river and other college buildings. Bats and aerial insects on the other hand, including grassland specialist species, seem to have dispersed to make use of the area without problems.

Four of every five multicellular animals on the planet are nematodes, and their sensitivity to pollutants and environmental disturbance makes them an excellent indicator taxon for studying changes to ecosystems below-ground (Bongers & Ferris, 1999). At King's, there is no difference in nematode species richness, abundance nor functional guild composition in the meadow cf. lawn. The functional guild composition has values typical of managed grassland and agricultural systems (Berkelmans et al., 2003). Changes to below-ground fauna are expected to be slower than for above-ground fauna: differences in nematode communities along plant species diversity gradients have been reported after 15 years (Dietrich et al., 2021) and after 12 years (Viketoft et al., 2009). Over a seven-year study, nematode diversity was little influenced by plant diversity, and the faunal composition did not stabilise but changed continuously (Sohlenius et al., 2011). Our nematode datasets show similarly high heterogeneity in richness, abundance and to a lesser extent composition year-to-year and sample-to-sample. While sequencing costs prohibit denser sampling, inherent soil heterogeneity seems to have precluded the detection of any compositional changes in the early stages of meadow establishment, if they were there.

4.2 | Climate change mitigation

Reduced maintenance and fertilising associated with the meadow reduced emissions by 1.36 Mg CO_2-e per hectare per year compared with lawn. These estimates are similar to previous estimates of 1.0 and 1.6 Mg CO_2e/ha/year for turf on Swedish golf courses (Tidåker et al., 2017). Although the absolute CO_2-e emissions reduction is small relative to the College's total emissions of around 1600 Mg CO_2-e/year, it has been achieved with a cost saving of approximately £650/ha/year, and increased value to both people and wildlife.

Our small sample size did not reveal a significant difference in soil organic carbon between the lawn and meadow after 2 years, at least not in the top 10 cm. Deeper rooted species in the meadow compared with lawn may increase soil carbon <10 cm. Detecting changes in soil carbon stocks even over a 5-year period is very difficult, unless the carbon input change to the soil is very great (>20%) or the sampling density is very high (Smith, 2004). Our estimate of total meadow soil carbon stock of 123.55 Mg C/ha in the top 0–10 cm is high compared with literature values for calcareous grasslands and even higher for horticultural soil. Typical soil carbon stocks are approximately 69 Mg C/ha to a 15 cm depth (Carey et al., 2008) or approximately 51 Mg C/ha to a depth of 10 cm for upland calcareous grazing pasture (Niklaus et al., 2001). While we have no reason to doubt the reliability of our relative estimate of SOM concentration between meadow and lawn samples, our total estimate of soil carbon stock is likely prone to substantial measurement error associated with assumptions made for soil bulk density, organic matter-carbon conversion factor and stone content (Gregg et al., 2021). Under particular conditions, lawn may act as a net sink of atmospheric carbon (Velasco et al., 2016). Over the whole season, biogenic CO_2 fluxes from soil respiration far exceeded anthropogenic fluxes associated with mowing and other management (Lerman & Contosta, 2019). Soil CO_2 flux is, thus, an important part of the overall carbon budget of grassland and one that we have not studied at King's.

Reflectance increased by 25%–34% for meadow relative to lawn. Unmown lawn also had a higher reflectance (+25%) than formal lawn (data not presented), suggesting maintenance regime rather than species composition may be the key factor controlling reflectance. The meadow is dominated by white-flowered species throughout the flowering period (Austrian chamomile *Anthemis austriaca*, followed by ox-eye daisy *Leucanthemum vulgare* and carrot *Daucus carota*), although higher meadow reflectance was also observed during non-flowering periods. Alpine meadow plots with flowers removed manually had lower albedo and resultantly warmer soil temperatures than those with typical floral density (Iler et al., 2021). As the Cambridge Colleges' lawn area is 47.3 ha, or 1.3% of the city of Cambridge, relaxing the maintenance regime of formal lawns or replacing some of the plantings with meadow could increase reflectance and thus albedo, helping to maintain a cooler urban microclimate under future global warming (Yan et al., 2019).

4.3 | Society

Our survey respondents thought meadows provided greater aesthetic, educational and mental well-being services than lawns, as well as providing a stronger cultural connection, having higher religious/spiritual value, and being more inspirational than lawns. Meadows scored lower than lawns for recreational and practical services, emphasising the need for heterogeneity of planting within managed urban ecosystems. Access to green space has value for our health, mental (Fuller et al., 2007) and physical (Mitchell & Popham, 2008). The latter study demonstrated how income-related inequality in health was less pronounced where there was greater accessibility to green space, pertinent considering Cambridge is the most unequal city in the United Kingdom (CfC, 2018). Our respondents, who were overwhelmingly members of the collegiate university and mainly students, were acutely attuned to signals of land ownership and stewardship and the issue of unequal access to greenspace, themes that occurred frequently in open answers without prompting. It is relatively uncommon to accommodate hundreds of people in communal facilities where access to greenspace is so explicitly socially hierarchical and exclusionary. The strong support for meadow amongst our surveyed population may well be attributable in part to dissatisfaction with the current access to greenspace arrangements amongst the surveyed community and would not necessarily be expected amongst the city population overall, or in different cities. Additionally, the immense popularity of the meadow planting apparent in this cohort may not persist over time, if residents come to see this habitat as typical and, thus, less associated with novelty and action for the environment (Bullock et al., 2021). Where lawns were once used to demonstrate how much land one could keep out of productivity, it seems that they still have a symbolic significance around stewardship today, with respondents agreeing that meadow planting can be used to signal sustainability leadership.

Restoration and conservation efforts, especially within urban areas, should be a give-and-take between what is best for wildlife and what is best for people. Our survey showed that the local community would prefer a mixture of lawn and meadow, compared with either lawn or meadow monoculture, with only 1.4% preferring entirely lawn. More respondents found meadow or meadow-mix planting favourable when the option of paths and seated areas was added. Similar responses were recorded in Sweden, where residents valued lawn for playing, resting, picnicking, walking and socialising but overall preferred a variety of planted spaces that provided good conditions for different senses (sound, smell, touch and sight) and a range of activities (Ignatieva et al., 2017). In China, planted wildflower meadows have become a socially accepted landscape type, with respondents preferring meadows with a colourful and natural appearance (Jiang & Yuan, 2017).

5 | CONCLUSIONS

Establishing meadow in place of lawn at King's has improved wildlife value and reduced greenhouse gas emissions, while providing greater benefits to the college and wider Cambridge community at a lower cost. Our biodiversity study revealed that increased meadow planting in place of lawn would increase the value of the colleges and university estates to wildlife by about threefold. Wider meadow planting would have a positive impact on climate change mitigation efforts, saving around 1.36 Mg CO_2-e per converted hectare per year. Meadow planting would have additional climate change adaptation benefits including increased albedo via higher reflectances and a reduced urban heat island effect. The number of cuts required per year to maintain a lawn is expected to rise as growing seasons become longer under climate change (Sparks et al., 2007), while deeper-rooted perennial forb species are likely to better tolerate an intensified drought regime in Cambridge. These benefits have been achieved with a cost saving of approximately £650/ha/year. The Cambridge community proved overwhelmingly in favour of increased meadow planting on the college and University estates, with respondents happiest with a proposed mixture of hard-wearing lawn turf alongside more ecologically valuable and beautiful meadow planting. Respondents were clear that meadow planting should be in conjunction with maintaining or increasing access to greenspace for recreation, which is particularly salient for collegiate Cambridge where access to lawn has traditionally been restricted to senior members of the Colleges only. Alongside retaining lawn for practical recreation purposes, there was some support for maintaining the heritage aesthetic of Cambridge quads and lawns in some iconic settings, although no respondents suggested that King's should revert its Back Lawn meadow planting to lawn.

The University launched its Biodiversity Action Plan in November 2020 (Cambridge Green Challenge, 2020) and 2022, a Colleges Biodiversity Audit has been in preparation. These documents define a 10-year vision for biodiversity on the collegiate Cambridge estates, with an implementation plan and data-driven targets, efforts to which the positive results reported here can lend strong support. Cambridge respondents thought it was important that the University and Colleges should take a leadership role in the stewarding of their estates for nature and wildlife, supporting efforts by the City Council. This study takes an interdisciplinary approach, highlighting the value of small projects to local biodiversity, cultural services and carbon sequestration. Beyond Cambridge, an estimated 25% of the UK's urban area is grassland, and 84% of people live in urban areas. We suggest that meadow establishment in place of some lawn area is a small but worthwhile, and easily scalable, contribution to CO_2 emissions reductions, which brings substantial additional benefits for both people and wildlife.

AUTHOR CONTRIBUTIONS

Cicely A. M. Marshall: conceptualisation, methodology, software, formal analysis, investigation, resources, data curation, writing—original draft, writing—review and editing, visualisation, supervision, project administration, funding acquisition. **Matthew T. Wilkinson:** conceptualisation, methodology, investigation, data curation, resources. **Peter M. Hadfield:** conceptualisation, methodology, investigation, resources. **Steven M. Rogers:** methodology, investigation, resources, data curation, writing—review and editing. **Jonathan D. Shanklin:** methodology, investigation, data curation. **Brian C. Eversham:** conceptualisation, methodology, investigation, data curation. **Roberta Healey:** methodology, investigation, data curation. **Olaf P. Kranse:** methodology, investigation, data curation. **Chris D. Preston:** methodology, investigation, data curation. **Steven J. Coghill:** conceptualisation, resources. **Karris L. McGonigle:** conceptualisation, methodology, investigation, data curation. **Geoffrey D. Moggridge:** conceptualisation, resources. **Peter G. Pilbeam:** conceptualisation, methodology, investigation, data curation, resources. **Ana C. Marza:** conceptualisation, methodology, software, formal analysis, investigation, data curation. **Darinka Szigecsan:** methodology, investigation, data curation. **Jill Mitchell:** methodology, investigation, data curation. **Marcus A. Hicks:** methodology, investigation, data curation. **Sky M. Wallis:** methodology, investigation, data curation. **Zhifan Xu:** methodology, investigation, data curation. **Francesca Toccaceli:** investigation, data curation. **Calum M. McLennan:** investigation, data curation. **Sebastian Eves-van den Akker:** conceptualisation, methodology, software, formal analysis, investigation, resources, data curation, writing—review and editing, project administration, funding acquisition.

ACKNOWLEDGEMENTS

The authors acknowledge support from the Gatsby Charitable Foundation and King's College for two studentships. Work at the Crop Science Centre at the University of Cambridge is supported by BBSRC grants BB/R011311/1, BB/N021908/1 and BB/S006397/1. Cambridge Hub supported the interview questionnaire design via the Engage for Change programme. Cicely Marshall, Sebastian Eves-van den Akker, Geoffrey Moggridge, Steven Coghill, Sky Wallis, Francesca Toccaceli and Calum McLennan were members of King's College Cambridge at the time of the study (trustees, employees or students).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available from Dryad Digital Repository https://doi.org/10.5061/dryad.kd51c5bbb (Marshall et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Before-after-control-impact (BACI) hypothesis testing with ANOVA.

Table S2. Emissions and costs associated with the mowing and fertilising regimes of meadow and lawn in 2021, the two most carbon intensive management activities.
Table S3. Species seed mix planted on the Back Lawn in October 2019.
Figure S1. Pitfall biomass in 2021, showing the visual contrast between meadow traps (top row) and lawn traps (bottom row).
Figure S2. Images of the meadow and lawn used to calculate relative reflectance values.
Table S4. Relative reflectance values for analysed photographs.
Figure S3. Cambridge college greenspace, of which an estimated 56% (43.7 ha) is lawn.
Appendix S1. Survey questions.

How to cite this article: Marshall, C. A. M., Wilkinson, M. T., Hadfield, P. M., Rogers, S. M., Shanklin, J. D., Eversham, B. C., Healey, R., Kranse, O. P., Preston, C. D., Coghill, S. J., McGonigle, K. L., Moggridge, G. D., Pilbeam, P. G., Marza, A. C., Szigecsan, D., Mitchell, J., Hicks, M. A., Wallis, S. M., Xu, Z. ... Eves-van den Akker, S. (2023). Urban wildflower meadow planting for biodiversity, climate and society: An evaluation at King's College, Cambridge. *Ecological Solutions and Evidence*, *4*, e12243. https://doi.org/10.1002/2688-8319.12243