Received: 28 January 2019 | Accepted: 28 June 2019
DOI: 10.1111/1365-2664.13470

RESEARCH ARTICLE

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

Road verges support pollinators in agricultural landscapes, but are diminished by heavy traffic and summer cutting

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Funding information
Natural Environment Research Council, Grant/Award Number: NE/L002434/1; Cornwall Area of Outstanding Natural Beauty unit

Handling Editor: Lucas Garibaldi

Abstract

1. Supporting pollinators in agricultural landscapes is important for reversing their global decline. Road verges and hedges are used by pollinators for feeding and reproduction, but few studies consider entire pollinator communities, and it remains unclear how they are distributed across adjacent verges, hedges and fields, or how they are affected by traffic and verge cutting.
2. We surveyed flowers and pollinators, using transect counts and pan traps, to explore the role of road verges and their associated hedges in supporting pollinators in an agricultural landscape in southwest England, and the impacts of traffic and verge cutting. At 19 sites, we surveyed the road verge (verge edge and verge centre), the verge hedge (both sides), a field hedge and the field interior.
3. Road verges and hedges had a much greater flower abundance, flower species richness and pollinator abundance than field interiors. Verge hedges had far less woody cover than field hedges, but greater flower species richness.
4. There were fewer pollinators along verge edges (next to roads) than along verge centres (2–11 m from roads) and fewer pollinators in road verges next to busier roads.
5. Road verges were generally cut once (in summer), and cuttings were never removed. There were substantially fewer flowers and pollinators in road verges that had been cut, even though surveys often took place many weeks after cutting.
6. *Synthesis and applications*. Road verges and their associated hedges can provide hotspots of resources for pollinators in agricultural landscapes, but their capacity to do so is reduced by heavy traffic and summer verge cutting. We recommend that beneficial management for pollinators should prioritize wider road verges (at least 2 m wide), roads with less traffic, and areas away from the immediate vicinity of the road. Where possible, verge cutting should not be carried out during peak flowering times.

KEYWORDS
bees, flies, hedgerows, hedges, highways, management, mowing, semi-natural habitat

1 | INTRODUCTION

Supporting biodiversity in agricultural landscapes is important for global nature conservation (Kremen & Merenlender, 2018), and for human economies due to the ecosystem services upon which agriculture relies (Zhang, Ricketts, Kremen, Carney, & Swinton, 2007). For example insect pollinators have experienced global declines (Potts et al., 2010), and while doing particularly poorly in farmland (Samuelson, Gill, Brown, & Leadbeater, 2018), they are often needed to pollinate crops (Klein et al., 2007). As field interiors provide few floral or nesting resources, semi-natural habitats are important for supporting pollinator populations (Senapathi, Goddard, Kunin, & Baldock, 2017).

In many countries, roads are bounded by verges and hedges that form an extensive network of semi-natural habitats across agricultural landscapes. Both road verges and hedges can be refuges for many taxa in otherwise resource-poor agricultural landscapes, including plants (Auestad et al., 2011; Staley et al., 2013), insects (Garratt, Senapathi, Coston, Mortimer, & Potts, 2017; Heneberg, Bogusch, & Řezáč, 2017), birds (Hinsley & Bellamy, 2000; Meunier, Verheyden, & Jouventin, 2000) and mammals (Jumeau, Boucharel, Handrich, & Burel, 2017; Pollard & Relton, 1970). They can also act as corridors for movement and dispersal (Tikka, Högmander, & Koski, 2001; Wehling & Diekmann, 2009). Plant communities in road verges and hedges produce flowers that provide nectar and pollen as food for insects (Hopwood, 2008; Jacobs et al., 2009; Munguira & Thomas, 1992), and studies have shown that they are important sources of floral resources at a landscape scale (Cole, Brocklehurst, Robertson, Harrison, & McCracken, 2017; Osgathorpe, Park, & Goulson, 2012), particularly in agricultural landscapes (Baude et al., 2016). However, no study has explored how pollinators are distributed at a local scale across adjacent road verges, hedges and fields.

Although the importance of hedges is well-known, there is increasing interest in road verges and their potential as a conservation resource (Gardiner, Riley, Bommarco, & Öckinger, 2018), especially given the large areas that they cover, for example an estimated 2,400 km^2 in Great Britain, or 1% of land (Plantlife, 2013). In Europe and North America, most rural road verges are cut once or twice per year, or not at all, though cuts are more frequent in some regions, and grazing, burning or herbicides are sometimes used (Bernes et al., 2017). However, there is growing mainstream pressure to change management to benefit wildlife, for example a public campaign by the charity Plantlife in Great Britain has received over 70,000 signatures and is providing management guidance to Councils (Plantlife, 2019). But there is a need for clarity on the impacts of traffic and verge cutting, which will determine how verges can best be utilized and managed.

The value of road verges as habitats for plants and pollinators is the result of low-intensity management, compared to regular grazing, tillage and chemical application in adjacent agricultural fields. Agricultural practices in field interiors can also affect adjacent hedges (Aude, Tybirk, & Bruus Pedersen, 2003), for example herbicide drift and fertilizer run-off may lead to a simplified flora (Staley et al., 2013). It is likely that hedges with fields on both sides, hereafter 'field hedges', are affected by agricultural practices to a greater extent than hedges with a road verge on one side, hereafter 'verge hedges'. This may lead to verge hedges having a greater capacity to support plant and pollinator communities than field hedges. For example Hanley and Wilkins (2015) found that the road-facing side of verge hedges contained a greater flower species richness, flower abundance and bumblebee abundance than the field-facing side. However, no research has compared verge hedges to field hedges.

Although road verges provide an opportunity for nature conservation, there is an array of impacts of roads and traffic that may negatively affect pollinators, including light pollution (Knop et al., 2017), noise pollution (Davis, Schroeder, Yeager, & Pearce, 2018) and traffic collision (Keilsohn, Narango, & Tallamy, 2018). This presents a management challenge to enhance the benefits of road verges to pollinators while reducing the negative impacts of roads and traffic. These negative effects are likely to be most prominent along the edge of the verge by the road, hereafter the 'verge edge', which may have management implications. Furthermore, as most of these negative effects are caused by traffic, they are likely to have a greater impact on busier roads, but no research has explored the impacts of traffic and proximity to roads on pollinator communities.

Road verge management affects their conservation value, though research has mostly focused on plants (Jakobsson, Bernes, Bullock, Verheyen, & Lindborg, 2018). A plot experiment along a single road verge found that cutting twice a year resulted in more flowers and insects than cutting once or no management (Noordijk, Delille, Schaffers, & Sýkora, 2009). It remains unclear, however, how these findings scale up because verge cutting results in the concurrent loss of floral resources across large areas, which probably impacts pollinators much more than suggested. To further understand the impacts of road verge cutting on pollinators, it is necessary to complement plot-scale experiments with larger scale studies.

In this study, we explore the role of road verges and their associated hedges in supporting insect pollinators in an agricultural landscape, and the impacts of traffic and verge cutting. We recorded flower and pollinator communities (orders: Hymenoptera, Diptera, Lepidoptera and Coleoptera) across the flowering season, in fields, hedges and different parts of road verges. Previous studies of road verges have often focused on single taxa (mostly Lepidoptera; e.g. Munguira & Thomas, 1992), few study sites (e.g. Noordijk et al., 2009), or do not explore the factors affecting pollinator communities in road verges (e.g. Cole et al., 2017). Our study is the first to explore the impacts of traffic and management on entire pollinator communities across a large number of sites. We tested the following hypotheses:

H1 *Road verges and hedges support a greater flower abundance, flower species richness and pollinator abundance than do field interiors.*

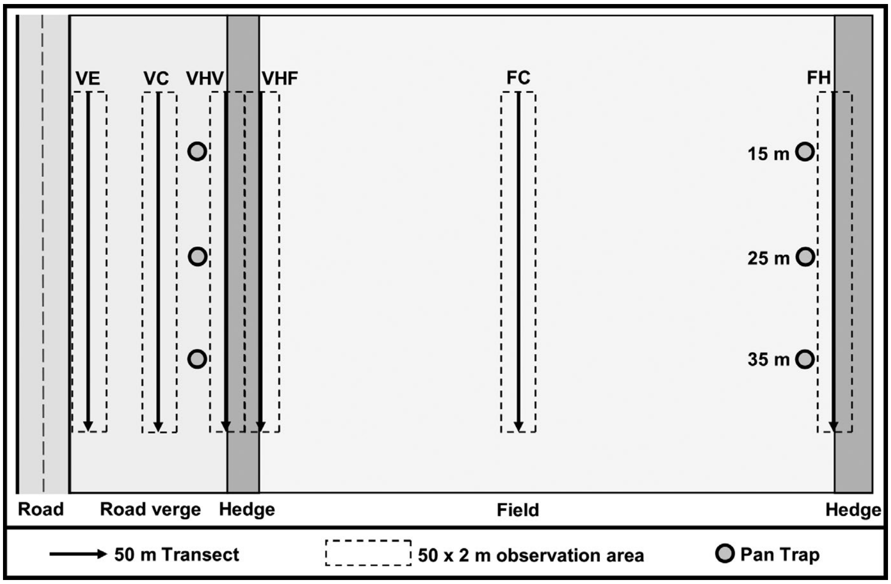

FIGURE 1 The sampling regime at each study site. The six transect locations refer to: verge edge (VE), verge centre (VC), verge hedge verge-facing side (VHV), verge hedge field-facing side (VHF), field centre (FC), and field hedge (FH). Surveys of flowers and pollinators were carried out at each transect in three survey rounds: spring, early summer and late summer. Pan traps were placed out once in summer for 48 hr

H2 *Verge hedges support a greater flower abundance flower species richness and pollinator abundance than do field hedges, because they are less exposed to agricultural practices.*

H3 *Verge edges have a lower flower abundance, flower species richness and pollinator abundance than do verge centres, because they are more exposed to traffic pollution and disturbance.*

H4 *Road verges next to busier roads have a lower flower abundance, flower species richness and pollinator abundance, because they are more exposed to traffic pollution and disturbance.*

H5 *Road verges that have been cut have a lower flower abundance, flower species richness and pollinator abundance.*

2 | MATERIALS AND METHODS

2.1 | Study sites

The study was carried out in 2018 at 19 study sites in Cornwall, United Kingdom (Appendix A). Study sites were selected based on: (a) Road type—not along a trunk road due to access restrictions and not in a residential area due to distinctive verge management; (b) Physical characteristics—road verge primarily consisting of grassland habitat, at least 5 m wide and 50 m long to allow the desired sampling regime, with adjacent farmland separated by a hedge rather than a fence; and (c) Safety—parking nearby and visibility for at least 75 m in both directions. A database of possible sites was created and, from this, permission was sought to access fields. Fields were those directly adjacent to the selected road verges, and were either arable or pasture, with a range of crops and management reflecting local agriculture. From this, we found 19 study sites that were at least 1 km apart. Road verges were 5–24 m wide. In the study area, most hedges are a characteristic regional style, called 'Cornish hedges'. They consist of a stone-faced earth bank (generally 1.5 m high and 1.5 m wide at the base) with herbaceous vegetation growing from the top and sides, with or without significant woody vegetation.

2.2 | Transect locations

At each study site, we set up 50 m transects at six locations (Figure 1): verge edge (VE)—in the verge, next to the road; verge centre (VC)—in the centre of the verge, between 2 and 11 m from the road, depending on the verge width; verge hedge verge-facing side (VHV)—in the verge, next to the verge hedge; verge hedge field-facing side (VHF)—in the field, next to the verge hedge; field centre (FC)—In the centre of the field; field hedge (FH)—in the field, next to the opposite hedge.

2.3 | Site characteristics

We measured the width of each road verge at distances of 5, 15, 25, 35 and 45 m along each verge centre, and calculated a mean value. We estimated the percentage cover of woody vegetation on the top of each verge hedge and field hedge transect to the nearest 10%. We measured traffic density by counting the number of vehicles passing by the road verge in either direction for 10 min, and repeated this on three separate days, between 09:00 and 16:30. During each site visit, road verge management was recorded, providing an estimated time of cutting that was accurate to within a two week period.

2.4 | Transects

We used transect surveys to compare the abundance and species richness of flowers, the abundance of pollinators and flower-pollinator interactions at the different transect locations. We refer to flower-visiting insects here as 'pollinators', though actual pollen transfer is not measured. Transect surveys were carried out during three rounds: spring (11/04/2018–04/05/2018), early summer (04/06/2018–22/06/2018) and late summer (01/08/2018–23/08/2018).

We recorded the identity and abundance of all species of flower along transects within 1 m either side (Figure 1). A floral unit was defined as one or multiple flowers that can be visited by an insect without having to fly between them, following Baldock et al. (2015).

Pollinator surveys were conducted when the wind speed was below Beaufort scale 5 and the temperature was above 17°C, or between 13–17°C if there was no more than 40% cloud cover (Pollard & Yates, 1993), except in the spring round when temperatures rarely met the minimum requirements. Temperature (°C) and wind speed (Beaufort scale) were recorded at the start of each survey. We walked each transect in both directions at a steady pace over 10 min and recorded all pollinators within 1 m either side of the transect and 2 m ahead. When a pollinator was observed visiting a flower, we also recorded the species of flower. Generally, bees, butterflies and hoverflies were identified to genus or species (if necessary taking voucher specimens), whereas beetles, non-syrphid flies and moths were identified to order (except for common and distinctive species) (full details in Appendix D). Given this variability in the level of taxonomic identification across and within groups, even for key groups such as bees and hoverflies, we did not calculate pollinator species richness from transect data, but instead used pan traps for this purpose (see below).

Sixteen plant species were excluded from further analyses because they had small flowers (< 5mm) that produce little nectar and pollen (Baude et al., 2016) and were rarely observed being visited by pollinators, or were horticultural varieties that are not visited by pollinators (Appendix E).

2.5 | Pan traps

Pan trap surveys were carried out in summer (17/07/2018–01/08/2018) to estimate the species richness of solitary bees and hoverflies in verge hedges and field hedges. At each study site, we placed pan traps along the verge hedge (verge-facing side) and field hedge (Figure 1), with three pan traps per transect, at distances of 10, 25 and 40 m. Pan traps were plastic dishes (radius 7.5 cm) that had been sprayed with fluorescent yellow paint. At each location, vegetation was flattened in a 1 m^2 area where necessary, to ensure pan traps were visible. Each pan trap was raised 6 cm from the ground. Pan traps were filled with water to a depth of 3 cm, and a drop of non-scented detergent was added to break surface tension. After 48 hr, the contents of the pan traps at 10 m and 40 m were collected and stored in 70% ethanol. If a pan trap had been disturbed, we collected the contents of the pan trap at 25 m instead (< 10% of cases), otherwise it was discarded. We identified all bees and hoverflies to species.

2.6 | Statistical Analyses

All statistical analyses were carried out in R 3.5.1 (R Core Team, 2018), using generalized linear mixed effects models (GLMM) ('lme4' package; Bates et al., 6). Models were initially fitted using Poisson error structure. Fixed effects were scaled (divided by 10 or 1,000) where necessary to allow model convergence and models were checked visually to meet assumptions. In one case, residuals showed heteroscedasticity so a negative binomial error structure was used. In each case, the link function was that which provided the lowest AIC. Models were tested for multicollinearity using variance inflation factors, which were < 5 in all cases.

For the transect data, we used two versions of the dataset to test different sets of hypotheses. In the first instance, we used the full dataset to test whether flower abundance, flower species richness and pollinator abundance were affected by transect locations (H1–H3, see Introduction). Flower abundance was modelled using a GLMM with negative binomial error structure. Flower species richness was modelled using a GLMM with Poisson error structure, log link function. Pollinator abundance was modelled using a GLMM with Poisson error structure and square root link function. In all cases, fixed effects included transect location and survey round, and the random effect was transect ID nested within site. In addition, the model for pollinator abundance included flower abundance divided by 1,000, wind speed (Beaufort scale) and temperature (°C) as fixed effects, and an observation-level random factor to address overdispersion. We did not include field type (arable or pasture) as a fixed effect because there were no apparent differences in the plotted data. The significance of the main effects and of pairwise contrasts between survey rounds and transect locations were assessed using likelihood ratio tests (LRT).

In the second instance, we used data for the verge edge and verge centre transects only, to test whether the abundance and species richness of flowers and pollinators in road verges were affected by traffic density, proximity to the road and verge cutting (H3–H5, see Introduction). All models were GLMM with Poisson error structure and square root link function, and fixed effects were survey round, distance from road (m) divided by 10, whether or not the verge had been cut during the study (Y/N), traffic density (vehicles 30 min^{-1}) divided by 10, and an interaction between traffic density and distance from road. The random effect was transect ID nested within site, and the models for flower abundance and pollinator abundance also had an observation-level random factor to address overdispersion. As above, the model for pollinator abundance had additional fixed effects of flower abundance divided by 1,000, wind speed and temperature. We used AICc to identify the best model ('MuMIn' package; Bartoń, 2016), whereby the best-fitting model was that with the lowest AICc. We considered models with ΔAICc < 2 and carried out model averaging on this top model set.

For the pan trap data, we explored whether there were differences in the species richness of hoverflies and solitary bees between verge hedges and field hedges (H2). We used a GLMM with Poisson error structure, square root link function and transect location as a fixed effect.

3 | RESULTS

We recorded 143 plant, 45 hoverfly, 28 solitary bee, 8 bumblebee, and 17 butterfly species, as well as many beetles and non-Syrphid flies (summarized in Appendices B–D, and species lists in Appendices E and F).

We present the results of the overall models, and then describe the relevant results for each hypothesis. Transect location and survey round significantly improved models for flower abundance, flower species richness and pollinator abundance (Table 1). An interaction between location and survey round did not significantly improve these models (Table 1), indicating relatively consistent patterns across survey rounds (Appendix G). Flower abundance, flower species richness and insect abundance were significantly different between each survey round and were greatest in early summer (Figure 2; Appendix H). Although pollinator abundance analyses will have been disproportionately affected by the response of non-Syrphid flies, which made up the greatest proportion of pollinators, patterns were similar across pollinator groups (Appendix I). Overall, verge hedges (verge-facing side) had more flowers and pollinators than verge edges or centres (Figure 2; Appendix H).

H1 *Road verges and hedges support a greater flower abundance, flower species richness and pollinator abundance than do field interiors.*

There was strong support for H1, with flower abundance, flower species richness and pollinator abundance all consistently low in field centres, and significantly lower than along all other transects (Figure 2; Appendices G and H).

H2 *Verge hedges support a greater lower abundance, flower species richness and pollinator abundance than do field hedges.*

There was partial support for H2. Verge hedges generally contained little woody cover compared to field hedges, with only 3 of 19 verge hedges containing more than 50% woody cover, compared to 12 of 19 field hedges. Flower species richness was significantly greater along verge hedges (verge-facing side) than along field hedges, but not flower abundance or insect abundance (Figure 2; Appendix H). There was some evidence that pollinator abundance was greater along the verge-facing side of verge hedges than along the field-facing side ($p = .0628$; Figure 2; Appendix H), but otherwise there were no significant differences between hedge transects (Figure 2; Appendix H). The models examining species richness in pan traps were not significantly improved by including transect location for either hoverflies (LRT $X^2 = .10$, $df = 4$, $p = .7524$) or solitary bees (LRT $X^2 = .85$, $df = 4$, $p = .3553$), indicating no significant differences between verge hedges (verge-facing side) and field hedges (Appendix J).

TABLE 1 The results of the likelihood ratio tests (LRT) testing the significance of the main effects for models assessing the impact of transect location and survey round on flower abundance, flower species richness and pollinator abundance

Model	Fixed effect	LRT X^2	*df*	*p*
Flower abundance	Location	49.73	5	<.0001
	Survey Round	58.61	2	<.0001
	Interaction	5.54	10	.8523
Flower species richness	Location	98.26	5	<.0001
	Survey Round	120.77	2	<.0001
	Interaction	14.38	10	.1565
Pollinator abundance	Location	92.95	5	<.0001
	Survey Round	39.77	2	<.0001
	Interaction	42.4	10	<.0001

H3 *Verge edges have a lower flower abundance, flower species richness and pollinator abundance than do verge centres.*

There was partial support for H3. Verge edges and verge centres often had different flower communities, with only four of the top 10 most common flower species at each being the same (Appendix C). Pollinator abundance was significantly lower along verge edges than along verge centres, but flower abundance and flower species richness were not significantly different (Figure 2; Appendix H).

H4 *Road verges next to busier roads have a lower flower abundance, flower species richness and pollinator abundance.*

There was strong support for H4. For the subset of the data that included only verge edge and verge centre transects, the best-fitting models for flower abundance, flower species richness and pollinator abundance included survey round, whether or not the verge had been cut and traffic density (Tables 2 and 3). The best-fitting models for pollinator abundance also included flower abundance and distance from the road (Tables 2 and 3). Traffic density ranged from 4 vehicles 30 min^{-1} to 708 vehicles 30 min^{-1} and had a significant positive, but small, effect on flower abundance and flower species richness (Appendix K). Pollinator abundance significantly decreased with increasing traffic and significantly increased with distance from the road (Figure 3).

H5 *Road verges that have been cut have a lower flower abundance, flower species richness and pollinator abundance.*

There was strong support for H5, with flower abundance, flower species richness and pollinator abundance being much lower in verges that had been cut (Figure 4), despite the fact that transect surveys generally took place weeks or months after cutting had taken place. Road verges at 17 of the 19 study sites were cut, and 15 of these were cut just once during the study. Cutting mostly took place within a 2-month period between late-May and mid-July. At 12 study sites, the entire width of the road verge was cut. At the other five study sites, only the verge edge was cut, though in two of these cases the rest of the verge was cut at a later date. Cuttings were never removed from verges.

4 | DISCUSSION

Our study has demonstrated that road verges and their associated hedges are important for supporting insect pollinators in agricultural landscapes, but that they are negatively affected by high

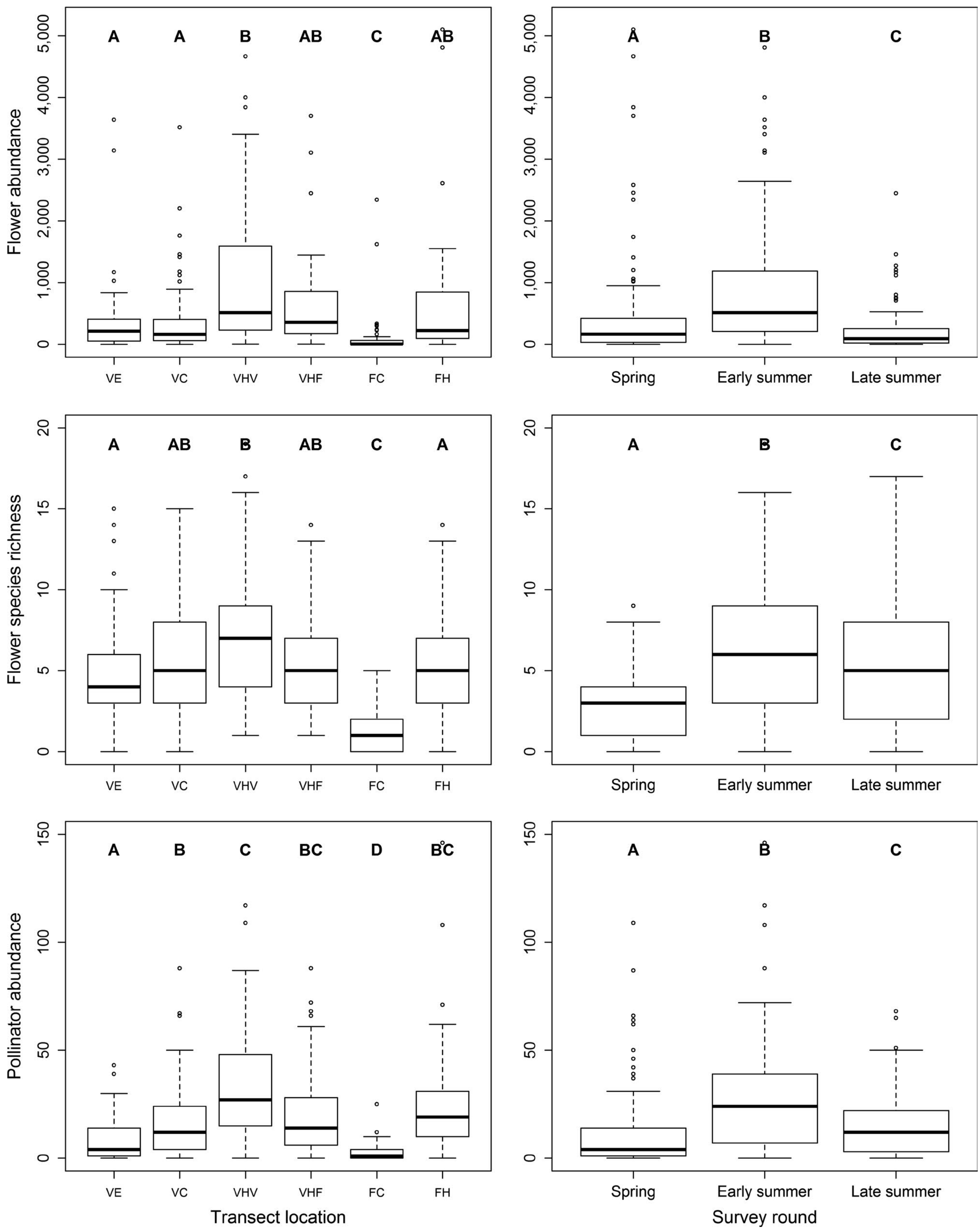

FIGURE 2 Flower abundance, flower species richness and pollinator abundance at each 50 × 2 m transect during each survey. In the left-hand plots, data points are grouped by transect location (*n* = 57 per boxplot). Transect locations are: verge edge (VE), verge centre (VC), verge hedge verge-facing side (VHV), verge hedge field-facing side (VHF), field centre (FC), and field hedge (FH) (see Figure 1). In the right-hand plots, data points are grouped by survey round (*n* = 114 per boxplot). Boxplots that do not share the same letter are significantly different pairwise contrasts ($p < .05$). Full model details are provided in Appendix H. Four outliers have been cropped from the top two plots for clarity of presentation (VHV. Early Summer = 7,185, FC. Early Summer = 6,330, FH. Spring = 7,418, and FH. Early Summer = 6,220)

TABLE 2 The best-fitting models (ΔAICc < 2.00) resulting from model selection of all possible combinations of terms from global models that assessed the impact of traffic density, proximity to road and verge cutting on flower abundance, flower species richness and pollinator abundance The models used the subset of the data that only included verge edge and verge centre transects. Conditional R^2 is not provided for the models of flower abundance and pollinator abundance because they contained an observation-level random factor to address overdispersion.

Model	Statistical Model	Fixed effects	Random effects	Intercept	*df*	logLik	AICc	Δ	weight	R^2	R^2 Cond.
Flower abundance	GLMM (Poisson, link = sqrt)	Survey round + verge cut	Site/transect ID + 1/ Observation	9.267	7	−764.042	1543.1	0.00	0.488	0.3147	n/a
		Survey round + verge cut + traffic/10	Site/transect ID + 1/ Observation	9.159	8	−763.662	1544.7	1.55	0.224	0.3191	n/a
	Global model: Survey round + distance to road/10 + verge cut + traffic/10 + traffic/10 * distance to road										
Flower species richness	GLMM (Poisson, link = sqrt)	Survey round + verge cut + traffic/10	Site/transect ID	1.769	7	−267.31	550.5	0.00	0.440	0.1211	0.2056
		Survey round + verge cut	Site/transect ID	1.957	6	−269.31	551.4	0.91	0.279	0.1110	0.2145
	Global model: Survey round + distance to road/10 + verge cut + traffic/10 + traffic/10 * distance to road										
Pollinator abundance	GLMM (Poisson, link = sqrt)	Flower abundance/1000 + survey round + distance to road/10 + verge cut + traffic/10	Site/transect ID + 1/ Observation	2.273	10	−384.781	791.7	0.00	0.177	0.3202	n/a
		Flower abundance/1000 + survey round + distance to road/10 + verge cut	Site/transect ID + 1/ Observation	1.957	9	−386.102	791.9	0.24	0.157	0.2989	n/a
		Flower abundance/1000 + survey round + temperature +distance to road/10 + verge cut + traffic/10	Site/transect ID + 1/ Observation	3.938	11	−383.770	792.1	0.43	0.143	0.3276	n/a
		Flower abundance/1000 + survey round + temperature + distance to road/10 + verge cut	Site/transect ID + 1/ Observation	3.072	10	−385.621	793.4	1.68	0.076	0.3002	n/a
	Global model: Flower abundance/1000 + survey round + wind +temperature + distance to road/10 + verge cut + traffic/10 + traffic/10 * distance to road										

TABLE 3 The coefficient estimates ± standard error (*SE*), confidence intervals (CI), test statistic values (*z*) and significance values (*p*) for the averaged model for: flower abundance, flower species richness and pollinator abundance. For each, the averaged model was taken from the top models with ΔAICc < 2.00 (Table 2). The models used the subset of the data that only included verge edge and verge centre transects

Model		Estimate ± *SE*	2.5% CI	97.5% CI	*z*	*p*
Flower abundance	(Intercept)	13.849 ± 2.1342	9.622	18.076	4.279	<.0001
	Verge cut (No–Yes)	−12.493 ± 2.6324	−17.712	−7.274	4.692	<.0001
	Survey round (1–2)	13.063 ± 2.2509	8.601	17.525	5.738	<.0001
	Survey round (1–3)	5.639 ± 2.9323	−0.174	−7.274	1.901	.0573
	Traffic	0.019 ± 0.0462	−0.073	0.110	0.393	.6920
Flower species richness	(Intercept)	1.842 ± 0.1696	1.507	2.177	10.777	<.0001
	Survey round (1–2)	0.988 ± 0.1298	0.731	1.245	7.526	<.0001
	Survey round (1–3)	0.911 ± 0.1743	0.565	1.256	5.168	<.0001
	Traffic	0.005 ± 0.0053	−0.005	0.344	0.945	.3440
	Verge cut (No–Yes)	−0.908 ± 0.1603	−1.226	−0.590	5.600	<.0001
Pollinator abundance	(Intercept)	2.722 ± 1.1270	0.501	4.945	2.402	.0163
	Distance to road	2.142 ± 0.5236	1.104	3.180	4.044	<.0001
	Flower abundance	0.848 ± 0.2635	0.325	1.370	3.180	.0015
	Survey round (1–2)	1.442 ± 0.5271	0.399	2.485	2.711	.0067
	Survey round (1–3)	1.152 ± 0.6010	−0.037	2.341	1.898	.0577
	Traffic	−0.010 ± 0.0112	−0.032	0.012	0.890	.3734
	Verge cut (No–Yes)	−1.596 ± 0.4492	−2.486	−0.705	3.512	.0004
	Temperature	−0.036 ± 0.0630	−0.160	0.089	0.563	.5737

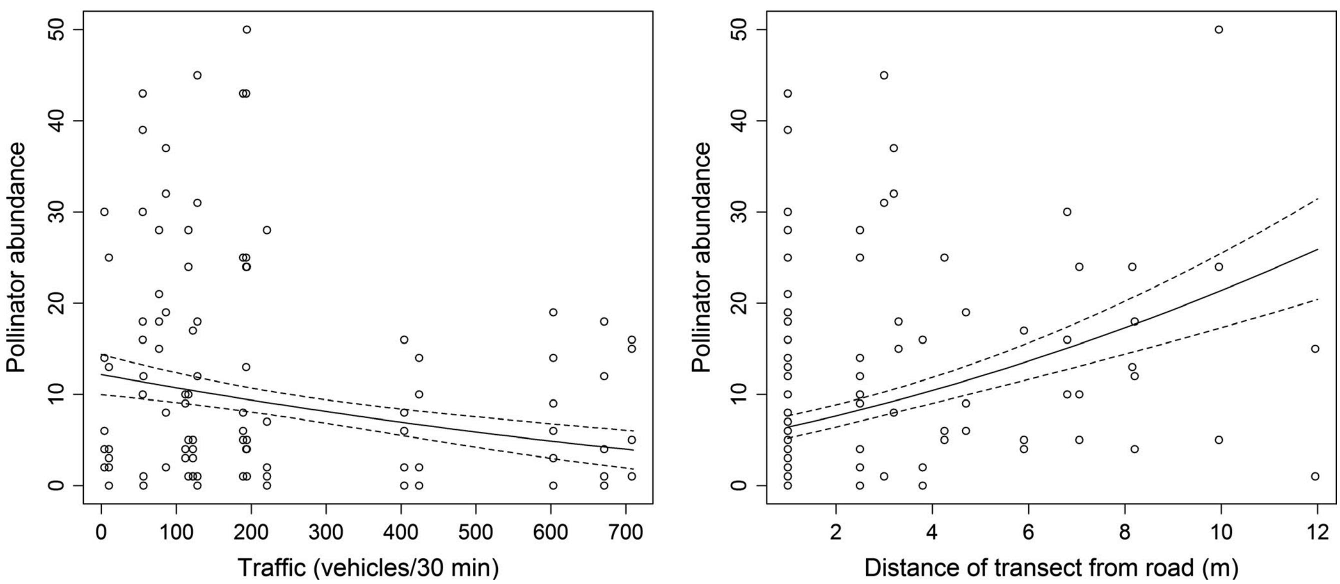

FIGURE 3 The impact of traffic density and distance from the road on pollinator abundance at each 50 × 2 m transect during each survey. Data are for verge edge and verge centre transects only, which was the subset of the data upon which analysis was carried out with these explanatory variables. Plotted lines are model predictions (mean ± *SE*). Full model details are provided in Tables 2 and 3. Four data points have been cropped for clarity of presentation (Traffic: $x = 4$, $y = 88$; $x = 193$, $y = 67$; $x = 708$, $y = 66$; Distance: $x = 2.50$, $y = 88$; $x = 8.15$, $y = 67$; $x = 11.95$, $y = 66$)

traffic densities and summer verge cutting. Specifically, verges and hedges provided a much greater abundance and species richness of flowers, and were associated with a much greater abundance of pollinators than field interiors. We recorded reasonable numbers of flowers in some fields at some times of year, for example in between rotational grazing in pastures and in arable fields when weeds had flowered, but these occurrences were rare, of short duration, and inconsistent across survey rounds. This suggests that

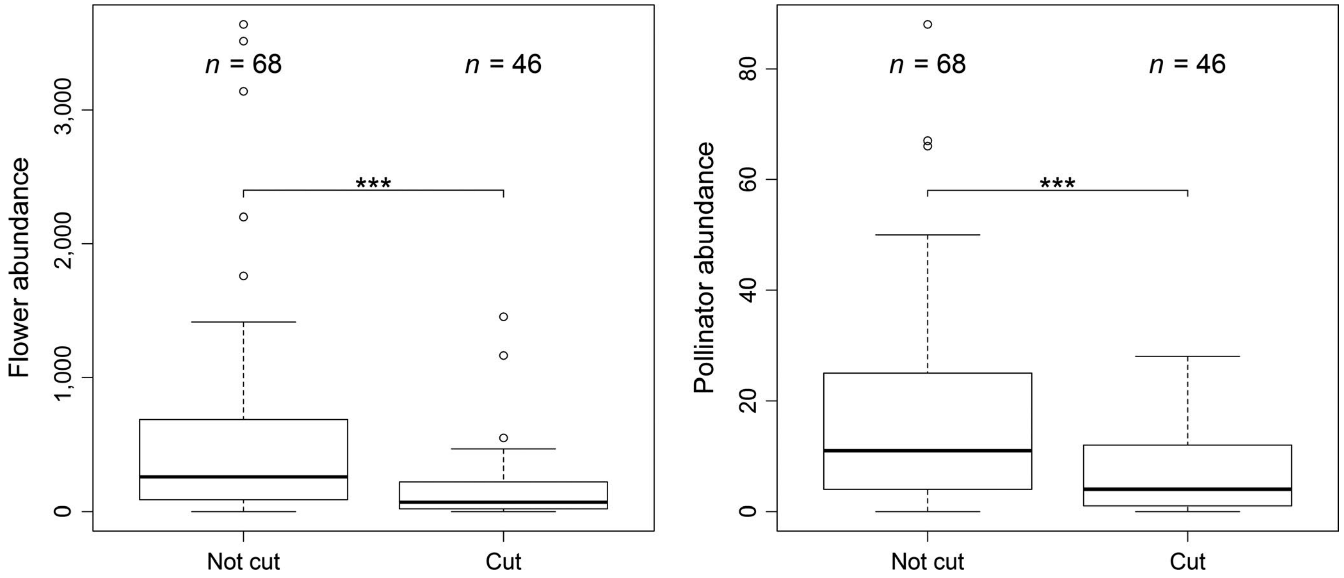

FIGURE 4 The impact of road verge cutting on flower abundance and pollinator abundance at each 50 × 2 m transect during each survey. Data are verge edge and verge centre transects only. Asterisks (***) indicate a significant difference between boxplots with $p < .001$. Full model details are provided in Tables 2 and 3

semi-natural habitats such as road verges and hedges are needed to provide a consistent source of forage for pollinators throughout the year. Furthermore, verge hedges provided more flowers and contained more pollinators than verge centres, and the flower communities also differed (Appendix C). The presence of both road verges and hedges should therefore result in greater overall floral diversity in the landscape, which can benefit pollinator diversity, nutrition and pollination (Ghazoul, 2006; Vaudo et al., 2015).

Sixty percent of flowers that were visited by pollinators comprised just five plant species: hogweed *Heracleum sphondylium*, bramble *Rubus fructicosus*, creeping buttercup *Ranunculus repens*, dandelion *Taraxacum* agg. and red campion *Silene dioica*, which suggests that a small number of common species are key in supporting pollinator communities in these habitats. Less common plant species are no doubt needed to support more specialist pollinator species, but it is important to enhance insect abundance as well as species richness, given reported declines in insect populations (Sánchez-Bayo & Wyckhuys, 2019).

Field hedges had a much greater cover of woody vegetation than verge hedges, which often had little or none. This seemed to be because verge hedges were more intensively managed. Despite this, there were no significant differences between verge hedges and field hedges in terms of flower abundance, pollinator abundance or species richness of solitary bees or hoverflies (H2). Although we only sampled species richness once at each site, the transect data suggest little difference between pollinator communities, probably because most pollinator species can easily move between nearby hedges. Although woody species such as blackthorn *Prunus spinosa* and hawthorn *Crataegus monogyna* provide a high abundance of flowers for short periods, they were only recorded during single survey rounds, so the presence of other wildflower species is likely to have compensated where woody vegetation was absent. There was, however, a greater species richness of flowers along verge hedges than field hedges (H2). The lower flower richness in field hedges may have been caused by the greater woody cover, and possibly a less diverse basal flora as a result of grazing, tillage, herbicide use or nutrient enrichment from fertilizer application (Hanley & Wilkins, 2015). Hanley and Wilkins (2015) found that the road-facing side of verge hedges contained greater flower species richness, flower abundance and bumblebee abundance than the field-facing side. We did not find such clear differences, which may be because farming practices were less intensive in our study fields. Overall, these findings suggest that plant and flower communities are different in verge hedges and field hedges, but that they support similar numbers of flowers and pollinators.

Contrary to H3, the abundance and species richness of flowers were similar between the verge edge and verge centre transects. However, plant and flower communities changed greatly within the first 1–2 metres from the road, and flower species richness was affected by the amount of traffic on the adjacent road. This is probably an impact of physical disturbance, nutrient enrichment from vehicle emissions, and other forms of pollution. Previous research has shown that vehicle emissions result in nitrogen deposition in road verge soils: busier roads have higher soil nitrogen levels, which decrease with distance from the road but still have a measurable effect at 10 m away (Truscott, Palmer, McGowan, Cape, & Smart, 2005). Truscott et al. (2005) also found that the first 1–2 m of the verge edge had more bare ground and ruderal plant species, as in our study. Future research should explore the relative impacts of different forms of traffic pollution and disturbance on plant and pollinator communities in road verges.

In support of H4, pollinator abundance in verges decreased with increasing traffic and increased with distance from the road. On the basis of our observations, we propose that this is primarily due to turbulence from passing road traffic, which makes it difficult for pollinators to forage at the verge edge, especially on busy roads. However, it may also have resulted directly from other forms of pollution, or indirectly due to the described differences in plant and flower communities. A study on honeybees showed that diesel exhaust pollution affected the odours of flowers that are used for foraging (Girling, Lusebrink, Farthing, Newman, & Poppy, 2013), and other roadside pollutants such as heavy metals can impact pollinators (Meindl & Ashman, 2013; Moroń et al., 2012), but have not yet been studied in the roadside environment. The finding suggests that: (a) Road verges that are only a few metres wide are of lower value to pollinators, unless along quiet roads, and (b) The first few metres of wider road verges are of lower value to pollinators.

Road verges that had been cut had many fewer flowers, flower species and pollinators (H5). It is obvious that cutting will initially result in a near-complete removal of flowers, but the numbers of flowers and pollinators were very low even weeks and months later. Grass cuttings were never collected, so road verge vegetation was covered in a thick thatch after cutting that was still visible months later and probably contributed to low flower abundances. Existing studies suggest that removing verge cuttings benefits plant and insect diversity (Jakobsson et al., 2018), and flower abundance (Noordijk et al., 2009). Our study illustrates negative effects of a widely used cutting regime on pollinators at a realistic site scale, but does not capture the direct mortality of pollinator eggs, larvae, pupae and adults during verge cutting, and provides a limited snapshot of a single year. In reality, verge cutting may have negative long-term impacts on pollinators that have not been studied here, or previously. Future research should carry out experimental manipulations of management at a site-level, using a large number of study sites, and monitor the long-term effects on pollinators.

Another limitation of our findings of the impacts of verge cutting is that the weather in the study year was particularly hot and dry, which may have accentuated the slow recovery of plant and flower communities. Our findings suggest that multiple cuts would be detrimental to flower production in drought years, at least if cuttings were not removed. This is an important consideration because climate change is predicted to increase the frequency of droughts, which reduce the overall availability of floral resources for pollinators (Phillips & Shaw et al., 2018). It is important that recommended management practices benefit pollinators in extreme weather years, as well as in typical years.

5 | CONCLUSIONS

In this study, we have shown that road verges and their associated hedges are important for supporting insect pollinators in agricultural landscapes, but their capacity to do so is reduced by heavy traffic and summer verge cutting. Generally entire road verges were cut in summer, regardless of whether it was necessary to do so to provide sight lines for road users, which suggests that there is significant opportunity in our study area to improve management for pollinators without conflict with safety requirements.

Our study is the first to show that busier roads have fewer pollinators in adjacent road verges, and that the verge edge next to the road contains fewer pollinators than the verge centre, probably due to turbulence and traffic pollution. In practice, given that pollinators do not use the verge edge as much, it may be beneficial to cut the first couple of metres from the road regularly for safety purposes if this means that areas further away from the road can be managed more favourably (with less cutting or better timing of cutting). Additionally, regularly cutting the verge edge will remove floral resources, which may reduce the proximity of pollinators to vehicles and subsequent road mortality resulting from collisions (Keilsohn et al., 2018).

On the basis of our findings, we recommend that management of road verges that aims to benefit pollinators should prioritize wider road verges (at least 2 m wide), lower traffic roads, and areas away from the immediate vicinity of the road. Where possible, verge cutting should not be carried out during peak flowering times, or otherwise road verges should not all be cut at the same time, as it results in a period of few flowers.

There is growing mainstream pressure to utilize road verges for nature conservation. Protecting florally diverse road verges that represent species-rich grasslands is important, but these are often the exception rather than the rule. Even modest improvements to the management of the overall network of road verges and hedges will provide major benefits for pollinator populations, given the large areas that they collectively cover.

ACKNOWLEDGEMENTS

We would like to thank Alice Lord for arranging contact with landowners, the land owners for permissions to access their land, Ros Shaw for commenting on the experimental design, Beth Roberts for assisting with statistics and Jess Knapp for commenting on a draft of the manuscript. BP was funded by a NERC GW4+ Doctoral Training Partnership studentship from the Natural Environment Research Council [NE/L002434/1], with additional funding from the Cornwall Area of Outstanding Natural Beauty unit. The manuscript was improved by comments from two anonymous reviewers.

AUTHORS' CONTRIBUTIONS

B.B.P. conceived the ideas, collected and analysed the data, and led the writing of the manuscript. All authors contributed to the ideas, methodology, interpretation of the results, manuscript drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the University of Exeter's institutional repository https://doi.org/10.24378/exe.1563 (Phillips, Gaston, Bullock, & Osborne, 2019).

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How to cite this article: Phillips BB, Gaston KJ, Bullock JM, Osborne JL. Road verges support pollinators in agricultural landscapes, but are diminished by heavy traffic and summer cutting. *J Appl Ecol*. 2019;56:2316–2327. https://doi.org/10.1111/1365-2664.13470