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Research Paper

Road verge extent and habitat composition across Great Britain

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HIGHLIGHTS

- There is growing interest in enhancing road verges for nature.
- We present a novel method for characterising and classifying road verges remotely.
- We use satellite and ground-level imagery from Google Earth and Google Street View.
- Road verges cover 1.2% of land in Great Britain, of which 27.5% is frequently mown.
- Opportunities to enhance verges for nature include reduced mowing and tree planting.

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ABSTRACT

There is growing societal and scientific interest in enhancing road verges for nature and the environment. This is partly because they are estimated to cover large areas in some regions. Yet, to our knowledge, there has been no quantitative assessment of national road verge extent, or of the habitats they encompass. We present a novel method for characterising and classifying road verges remotely. We use this to evaluate the extent and habitat composition of road verges across Great Britain, and to identify opportunities for improving verges for nature and the environment.

We use stratified random sampling of freely-available road maps combined with satellite (Google Earth) and ground-level imagery (Google Street View). Overall, we estimate that there are 2,579 km^2 (2,149-3,010 km^2) of road verges across Great Britain, equivalent to 1.2% of land area, of which 707 km^2 (27.47%) is short, frequently-mown grassland, 1,062 km^2 (40.87%) is regular grassland, 480 km^2 (18.73%) is woodland, and 272 km^2 (10.66%) is scrub. By comparison, we estimate that there are 3,694 km^2 of hard road surfaces across Great Britain, equivalent to 1.8% of land. Only 27% of frequently-mown grassland verges contained trees, indicating potential for planting trees and shrubs to provide environmental benefits.

Our findings suggest that there are significant opportunities to enhance (i) verges along major roads, because these constitute a disproportionately large area of road verge and have the widest verges, and (ii) frequently-mown grassland verges for example by, where appropriate, reducing mowing frequencies and/or planting trees. Our method can be used, adapted and further developed by others, for example to assess road verges across other regions, and to assess verge habitat composition in greater detail.

1. Introduction

Land scarcity presents a major obstacle towards resolving many environmental issues. Conversion of forests, grasslands and wetlands to agricultural and urban land uses has degraded natural systems and the benefits that they provide to people (IPBES, 2019). Addressing global environmental issues such as biodiversity loss and climate change therefore depends to a large extent on finding land on which to restore habitats (IPBES, 2019; Strassburg et al., 2020). This is a major challenge in many regions, requiring innovative approaches that create multi-functional spaces. Road verges – the land that borders road networks – offer one such opportunity.

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There is growing societal and scientific interest in enhancing road verges for nature (Gardiner et al., 2018) and to provide other environmental benefits, such as carbon sequestration, improved air quality and flood reduction (O'Sullivan et al., 2017; Phillips et al., 2020a; Salmond et al., 2016; Säumel et al., 2016). Road verges present a major opportunity because they are estimated to cover large areas that are owned and managed by relatively few stakeholders, which are also usually public bodies – namely local and regional government and associated highways organisations. For example, in Great Britain road verges have been estimated to cover 2,400 km^2 (Plantlife, 2013). This assumes an average of 3 m of verge either side of roads. However, to our knowledge, there has been no formal quantitative assessment of national road verge extent, or of the habitats that verges encompass. Such an assessment is important for determining the current and future capacity of road verges to benefit nature and the environment. It can also provide practical insights into how road verges can be enhanced for this purpose.

Recent developments in freely available sources of big data, such as satellite imagery (e.g. Google Earth), provide opportunities to record and monitor land use easily and remotely. This potential is even greater around roads due to the availability of Google Street View, which provides panoramic ground-level imagery for the majority of public roads across many countries. Google Street View has been shown to provide reliable measures for audits of neighbourhood environments (Kelly et al., 2013; Rundle et al., 2011), which can be extracted far more rapidly than by on-the-ground surveys. It has been used for a wide variety of research (Rzotkiewicz et al., 2018), for example surveying street trees (Berland and Lange, 2017), amounts of street-level urban greenery (Li et al., 2015), pollinator habitats in people's gardens (Burr et al., 2018), and invasive alien plants along roads (Kotowska et al., 2021). Yet, its potential for assessing road verge habitats has not yet been realised.

In this study, we carry out an assessment of road verges across Great Britain. We use stratified random sampling of road maps in combination with satellite (Google Earth) and ground-level imagery (Google Street View). Specifically, we explore the potential of this approach for characterising and classifying road verges by using it to determine the extent and habitat composition of road verges across Great Britain. From this information, we identify opportunities for improving verges for nature and the environment. The findings of the study are important for identifying the current and future capacity of road verges to benefit nature and the environment at a regional and national scale. We provide practical insights for enhancing verges as multi-functional green spaces, with particular relevance for urban areas and densely-populated regions, where land scarcity is an issue.

2. Materials and methods

Here, we define a road verge as the soft surface (unpaved, consisting of vegetation, bare ground or similar) bordering roads, separating them from the surrounding landscape (often bounded by a fence, wall or hedge) or from another road (e.g. a roundabout or vegetated median), apparently owned and managed by local or national government, but excluding non-linear blocks of greenspace that clearly exist for recreational purposes (e.g. public parks).

2.1. Road verge sampling

We used stratified random sampling to assess the extent and characteristics of road verges across Great Britain. Sampling was carried out in QGIS 3.4.15 (QGIS Development Team, 2020) using freely-available data from OS OpenData (Ordnance Survey, 2020a): OS Open Roads and OS Boundary-Line; and CORINE Land Cover (Copernicus, 2018). OS Open Roads is a vector map of all public roads, including information on road classification. OS Boundary-Line includes polygons of Great Britain's administrative regions. CLC 2018 is a vector map of land use for European countries from satellite imagery, using 44 land use classes, grouped into five main categories: 1) artificial surfaces, 2) agricultural areas, 3) forests and semi-natural areas, 4) wetlands and 5) water bodies. First, we merged component layers of OS Open Roads into a single polyline. We excluded Local Access, Restricted Local Access and Secondary Access roads because these are generally privately-owned roads that are not maintained at the public expense by highway authorities (Ordnance Survey, 2020b) and so are not included in the UK government's road length estimates for Great Britain (Department for Transport, 2020). We separated out roads that formed part of the Strategic Road Network (trunk roads, consisting of motorways and the most 'significant' A-roads) and used this as a sampling stratum. These roads are managed by national (rather than local authorities), via organisations such as Highways England, and typically have the widest road verges.

We used OS Boundary-Line to split Great Britain into its 11 administrative regions: South East, London, North West, East of England, West Midlands, South West, Yorkshire and the Humber, East Midlands, North East, Scotland and Wales (Fig. 1a), and clipped the remaining road network for each administrative region. Urban road verges are often distinct in their form and management, so we further divided each administrative region's road network into urban and rural roads using CLC 2018. We considered urban areas to be all 'artificial surfaces' land use classes, and rural areas to be all 'agricultural areas', 'forest and semi-natural areas', 'wetlands' and 'water bodies' land use classes (Bossard et al., 2000). This resulted in an urban and a rural road network for each of the 11 administrative regions, plus the Strategic Road Network – a total of 23 strata (Fig. 1b; Table 1).

We generated 1,000 random sampling points stratified across the 23 strata (Fig. 1c-d). The number of points per stratum was determined by the length of road in the stratum as a proportion of the total length of road for Great Britain (Table 1). The minimum distance between these points was 76 m, with 99% of points more than 250 m from other points and 95% of points more than 1 km from other points (distance to nearest point (mean ± *SD*): 6,745 ± 5,951 m). Rural roads in the London administrative region constituted just 0.12% of total road length – a single allocated sampling point – so we combined the urban and rural sampling strata for London. Otherwise, the number of sampling points per stratum ranged from 17 to 87 (Table 1). Sampling points were merged into a single shapefile.

2.2. Measuring road, verge and landscape characteristics

For each sampling point, we extracted the coordinates, road name, road class, administrative region and whether it was classified as urban or rural (see Appendix A). We summarised surrounding land use by creating a 100 m buffer around each point, then extracting the percentage of each land use class within the buffer using CLC 2018. We combined land use classes to give an overall percentage area within each buffer that consisted of land use classes in each of the five main CLC 2018 land use categories: 'artificial surfaces', 'agricultural areas', 'forests and semi-natural areas', 'wetlands' and 'waterbodies' (Copernicus, 2018).

We randomised the order of the points so those in the same sampling stratum were not sampled sequentially, then assigned each point a new unique ID from 1 to 1,000. For each point, we assigned a side of a road to survey by alternating between N, E, S and W, and choosing the side of the road that was closest to the allocated bearing. We then used a detailed protocol and criteria for measuring road and road verge characteristics at each point using satellite imagery from Google Earth and ground-level imagery from Google Street View (see Appendix A). This included measurements of road, pavement, other hard surfaces, verge and vegetated median widths, and of the type and width of each habitat that formed the road verge. Measurements were taken using Google Earth, whilst Google Street View was used to confirm boundaries and habitats, which are often unclear using satellite imagery alone.

Habitats were broadly classified as lawn (short, frequently-mown

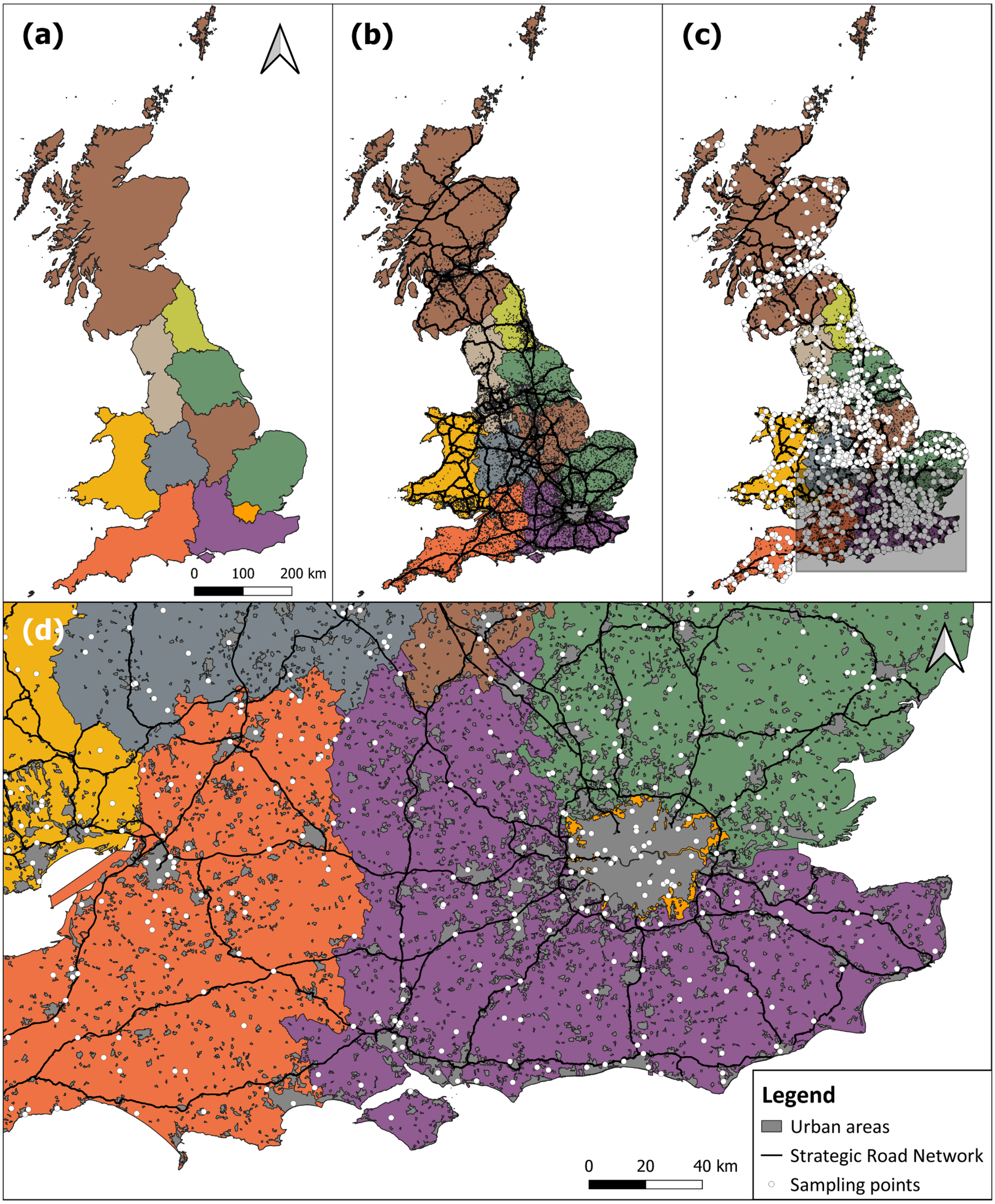

Fig. 1. Maps of (a) the 11 administrative regions of Great Britain, (b) the areas that were defined as urban (grey) and rural (colours) within each, and the Strategic Road Network (black), which formed the 23 sampling strata for stratified random sampling, and (c-d) the 1,000 sampling points. The number of sampling points per strata was determined by the length of road in the strata as a proportion of the total length of road for Great Britain (Table 1).

grassland), grassland (less frequently-mown, i.e. apparently mown just once or twice per year, or not mown at all), scrub, woodland, bare ground, horticulture (e.g. flower beds), or scattered trees. Strictly speaking, these are types of land cover, but we refer to them as habitats because we consider them within the context of nature conservation. We used these broad habitat classes because they could easily be distinguished using ground-level (and to a lesser extent satellite) imagery, whilst differentiating more specific habitat types (e.g. different grassland habitats) is difficult and beyond the scope of this study. Habitat widths were measured as shown in Fig. 2.

We recorded the type of outer boundary that separated the road verge from the surrounding landscape (e.g. fence/wall/building, garden, hedge, trees, scrub, greenspace). To account for uncertainty when the boundary was unclear (e.g. when there was a transition of scrub or woodland separating the road verge from the surrounding landscape), we measured the width of the 'ambiguous boundary' that potentially included part of the road verge, i.e. we partitioned the 'certain' versus the 'uncertain' verge width to provide a measure of uncertainty (see Figs. 3 and 4). To avoid double counting any area of road verge when scaling up our measurements to estimate road verge extent, we

Table 1
The 23 sampling strata used for the stratified random sampling of road verges, consisting of the 11 administrative regions of Great Britain divided into urban and rural areas, plus the Strategic Road Network (trunk roads). The number of allocated sampling points within each stratum was determined by the total road length in the stratum as a proportion of the total road length of Great Britain. The final number of points was the number following removal of points that we considered to be private roads (i.e. those that had been misclassified in OS Open Roads).

Stratum		Land area (km^2)	OS Open Roads road length (km)	UK Government estimated road length (km)[1]	% greater estimate in OS Open Roads	% of GB road network	Allocated sampling points	Final sampling points (points removed)
North East	Urban	900.05	9,798.21	15,995	6.00	2.29	23	23
	Rural	7,782.48	7,156.73			1.67	17	17
North West	Urban	2,160.61	23,852.37	36,355	5.22	5.57	56	56
	Rural	12,769.74	14,399.64			3.36	34	34
Yorkshire and the Humber	Urban	1,793.02	18,562.48	31,317	8.06	4.34	43	43
	Rural	13,779.64	15,277.32			3.57	36	36
East Midlands	Urban	1,713.95	16,179.13	30,978	9.35	3.78	38	37 (1)
	Rural	14,106.52	17,694.92			4.13	41	38 (3)
West Midlands	Urban	1,793.29	17,813.12	32,401	6.73	4.16	42	42
	Rural	11,220.38	16,768.58			3.92	39	39
East of England	Urban	2,153.90	19,600.21	38,989	9.82	4.58	46	45 (1)
	Rural	17,431.81	23,217.76			5.42	54	54
London	Urban	1,339.21	14,414.74	14,753	1.16	3.37	34	35[2]
	Rural	256.08	509.60			0.12	1	
South East	Urban	3,135.56	28,432.73	47,044	8.81	6.64	66	66
	Rural	16,276.64	22,756.26			5.32	53	53
South West	Urban	1,962.28	19,611.80	49,298	8.02	4.58	46	46
	Rural	22,438.84	33,639.77			7.86	78	75 (3)
Scotland	Urban	2,535.12	21,919.42	55,925	5.69	5.12	51	51
	Rural	77,699.36	37,186.12			8.69	87	85 (2)
Wales	Urban	1,235.79	11,997.55	32,145	7.48	2.80	28	28
	Rural	19,997.64	22,552.33			5.27	53	53
Strategic Road Network	n/a	14,778.49	12,395	19.23	3.45	34	34	
	Total		428,119.28	397,596	7.68	100.00	1,000	990 (10)

[1]Department for Transport (2020). Road lengths statistics (RDL). https://www.gov.uk/government/statistical-data-sets/road-length-statistics-rdl
[2]Rural roads in the London administrative region constituted just 0.12% of total road length – a single allocated sampling point – so we combined the urban and rural sampling strata for London

partitioned verges to ensure that a particular area of verge was only attributable to a single road (e.g. Fig. 4e) or, in the case of a road verge bounded on two opposite sides by roads, noted that the verge was attributable to multiple roads and accounted for this when scaling up (Fig. 4c).

We tested the protocol on 50 sampling points, then refined it to improve functionality and to address ambiguity. Data were then collected for the 1,000 sampling points, which were divided between three data collectors. To ensure reliability of measurements, the two additional data collectors were trained by the lead author using 20 examples covering a diversity of scenarios, then were tested on a separate 10 examples (see Appendix A). Results were assessed for agreement between data collectors (interrater reliability) using the Intraclass Correlation Coefficient (ICC) – a scale of 0 to 1, reflecting no agreement to perfect agreement (Shrout and Fleiss, 1979). We calculated ICC in R 3.6.2 (R Core Team, 2019) using the 'irr' package (Gamer et al., 2019) and a two-way mixed-effects model (Koo and Li, 2016). The first test resulted in only moderate agreement for measures of verge widths (ICC = 0.505), so further training was provided. A second test of a new set of 10 examples resulted in excellent agreement (ICC = 0.977), after which the main data collection was conducted. Perceived ambiguity in measurements was highlighted and discussed amongst the three data collectors, and the protocol further refined as required. In addition, 10 randomly selected sampling points were separately measured by multiple data collectors for every 100 points measured (for the first 400 sampling points), and resulted in good overall agreement (ICC = 0.736). Occasionally, it was difficult to take measurements (e.g. due to no Google Street View imagery, tree canopy obscuring satellite imagery, or poor-quality satellite imagery). In these cases, we used an apparently similar, nearby visible section of the road when available, or otherwise estimated based on the available satellite imagery. This was better than not using the sampling point because exclusion may have introduced systematic bias against small road types (where Google Street View is less likely to be available) in more remote areas (where satellite imagery is more often of lower quality), which are likely to have smaller road verges.

2.3. Estimating road verge extent

We excluded 10 sampling points (1%) that we considered to be private roads (i.e. those that had been misclassified in OS Open Roads), for example because they were a dirt or gravel road/track, were a dead-end road leading to a farm or property, or were a forestry road (Table 1). This did not explain the 7.68% greater estimated total road length from OS Open Roads compared to that from UK Government data (Table 1; Department for Transport, 2020). We expect that this may be due to the way that roads are divided at junctions, roundabouts and slipways in OS Open Roads (because estimates were 1–10% greater for regional strata, but 19% greater for the Strategic Road Network stratum) (Table 1). Because our sampling method was based on the distribution of roads and points in OS Open Roads, we used the associated road lengths to estimate road verge extent for Great Britain, but reduced estimates by 1% to account for the described misclassification of some roads. To account for uncertainty in road verge boundaries when measuring each road verge width, we calculated a lower, upper and 'reasoned' estimate of road verge extent for Great Britain. First, we calculated the road verge width (lower, upper and reasoned estimate) for each sampling point using Table 2. We then multiplied the estimate for each sampling point by two (because the road verge was only measured for one side of the road), except for road verges that were bordered by another road (e.g. slipways and separate roads, rather than verges in between opposing lanes of traffic, which we classified as a vegetated median), because only half of the road verge could be attributed to each road. Next, we added the vegetated median width. For each stratum, we calculated the mean road verge width, then multiplied by the total length of road to get a total area of road verge (Table 1). Finally, we added the total area of road verge for

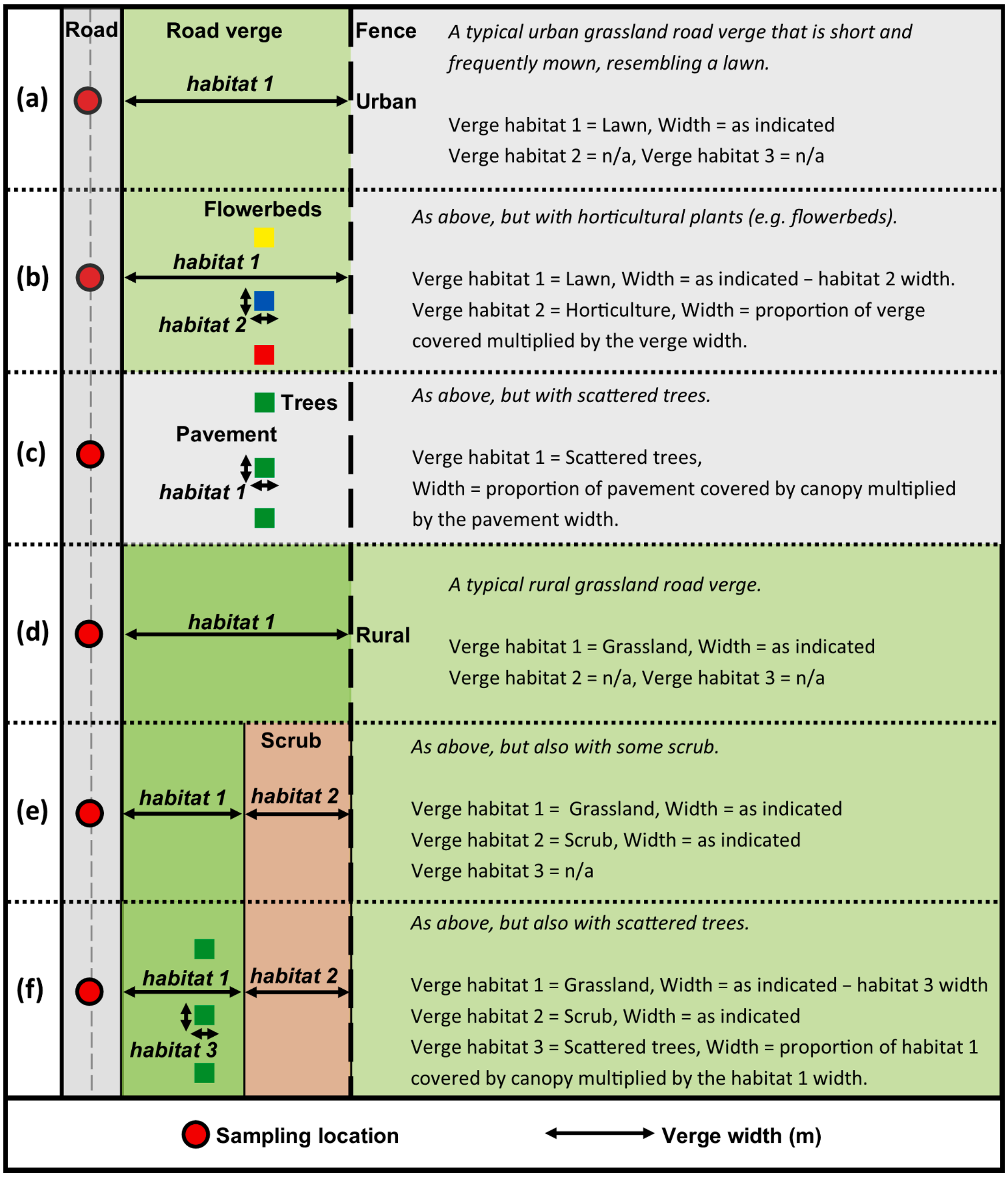

Fig. 2. Examples for determining road verge habitats and their widths.

each stratum together to get a lower, upper and reasoned estimate for the total area of road verge in Great Britain. To estimate the extent of road and other associated hard surfaces, we added together the road, pavement and other hard surface widths for each point, calculated an overall mean, then multiplied by the total length of road for Great Britain.

2.4. Estimating road verge habitat areas

We estimated the area of each road verge habitat using similar lower, upper and reasoned estimates to account for uncertainty in road verge boundaries. For the lower estimate, we calculated an overall percentage area of each verge habitat that made up the verge width, then multiplied these percentages by the lower estimate for the total area of road verge. The reasoned and upper estimates used the lower estimate, but additionally attributed half or all, respectively, of the habitats that made up the uncertain verge boundary (as described in Table 2). We made a generalising assumption about the habitat type for each uncertain road verge boundary type – assuming grassland for field margin boundaries, scrub for hedge boundaries, lawn for greenspace boundaries, and woodland for tree boundaries.

3. Results

3.1. Potential of Google Earth and Google Street View for characterising and classifying road verges

Google Earth imagery was available for all sampling points, though image quality was variable and not always adequate to take measurements without the addition of Google Street View. However, Google Street View imagery was available for 96% of sampling points, with 22% of imagery taken since 2019, 33% since 2018, and 46% since 2015 (Appendix A).

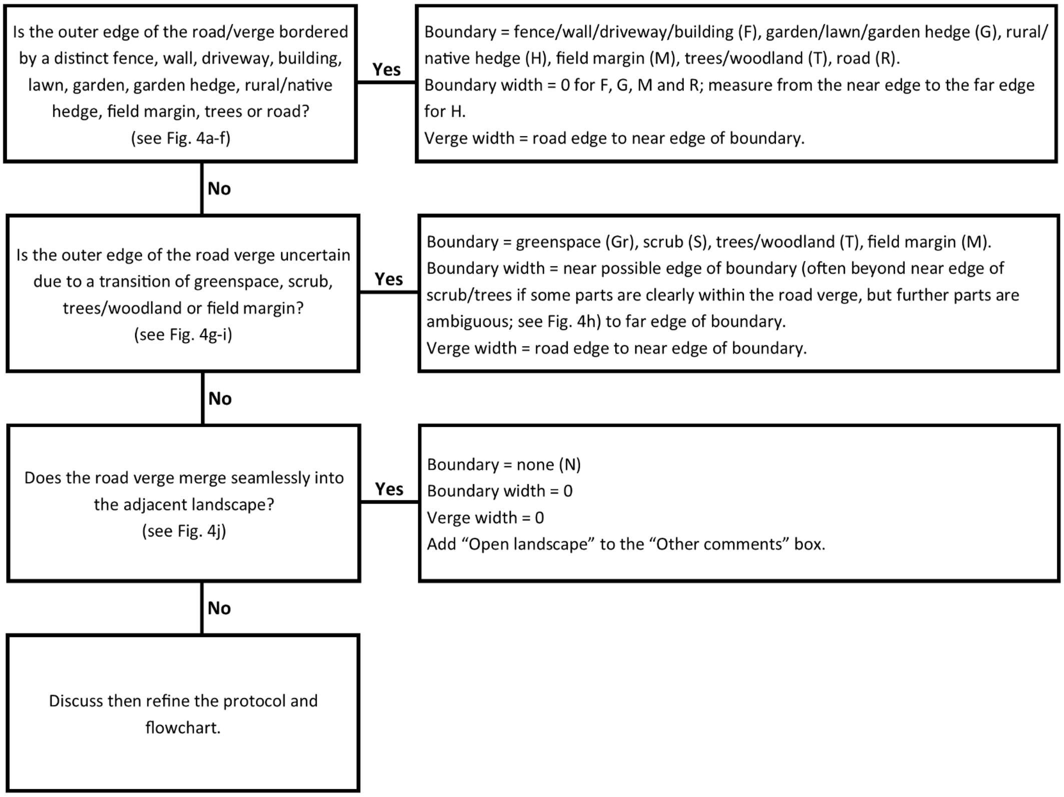

Fig. 3. Decision tree for deciding the boundary of a road verge when measuring road verge width.

3.2. Extent of road verges across Great Britain

Of the sampled points, 35% were located along distinctly rural roads, 47% were located along distinctly urban roads, whilst 18% were located along roads in the rural–urban fringe (e.g. at the edge of cities and towns, or in villages) (Fig. 5). Most roads were classified as minor roads (32%) or local roads (44%), whilst 14% were classified as A-roads, 9% as B-roads and 0.5% as motorways (Fig. 5). Average widths (mean ± *SD*) were 6.4 ± 3.6 m for roads, 1.8 ± 2.1 m for pavements, and 0.5 ± 1.5 m for other associated hard surfaces – a total mean width of hard road surfaces of 8.7 ± 5.1 m. Overall, this resulted in an estimated 3,694 km^2 of publicly-owned hard road surfaces across Great Britain, equivalent to 1.8% of land. The vast majority of land within a 100 m radius of the sampled points was agricultural or artificial surfaces, whilst only 8.9%, 7.5%, 5.9%, and 3.9% of points contained more than 0%, 10%, 25%, and 50% of forest, semi-natural, wetland or water bodies habitats within 100 m.

Fifty-four percent of sampling points had a road verge, with an average width of 6.8 ± 9.9 m (mean ± *SD*; lower–upper estimate: 5.9–7.8 m, median = 3.4 m, maximum = 90 m) (Fig. 5; Table 3). Road verges were far more common in rural areas than in urban areas (80% versus 30% of roadsides), though they were on average wider along urban roads than along rural roads (mean ± *SD* (lower–upper estimate): urban 8.0 ± 9.6 m (7.1–8.9 m), rural 6.2 ± 12.5 m (5.3–7.1 m)) (Fig. 5). Verges were also more common, and larger, along higher traffic volume road types (motorways, A-roads and B-roads) (Fig. 5).

Overall, we estimate that the total area of road verge in Great Britain is 2,579 km^2 (lower–upper estimate: 2,149–3,010 km^2), equivalent to 1.2% of land (Table 3). Of this, 29% is located in urban areas, 49% in rural areas, and 23% in the rural–urban fringe that is intermediate in form. In urban areas, we estimate that verges cover 879 km^2, equivalent to 4.2% of urban land. Across the sampling strata, the Strategic Road Network (which consists of the more major roads) holds by far the greatest share (18.4%) of road verge area. This is nearly double that of any other of our strata across Great Britain (Table 3), despite comprising only 3.5% of total road length (Table 1), and is a result of verges along the Strategic Road Network being much wider (Fig. 5).

3.3. Habitat composition of road verges across Great Britain

We estimate that 707 km^2 (27.5%) of road verge area is short, frequently-mown grassland (lawn), 1,062 km^2 (40.9%) is regular grassland, 480 km^2 (18.7%) is woodland, and 272 km^2 (10.7%) is scrub, whilst wetland, horticulture and bare ground make up the remaining 59 km^2 (2.3%) (Fig. 6; Table 4). 56% of lawn verges were found in urban areas, whilst 98% were found in either urban or rural–urban fringe areas. Overall, only 27% of lawn verges contained trees. Of all lawn verges, 65% were greater than 2 m wide, 34% were greater than 5 m wide, and 19% were greater than 10 m wide, of which only 39%, 30% and 24%, respectively, contained trees (Fig. 6).

4. Discussion

There is growing societal and scientific interest in using road verges for nature conservation (Gardiner et al., 2018) and to provide other environmental benefits (Phillips et al., 2020a). This study has presented a detailed and robust method for using Google Earth and Google Street View to characterise and classify road verges, and for estimating their extent and habitat composition at a regional and national scale. Below, we discuss the potential of our method, the findings, and practical insights for improving road verges for nature and the environment.

4.1. Google Earth and Street View as environmental tools for monitoring roads and road verges

Overall, the study shows that Google Earth and Google Street View offer major, untapped potential for addressing environmental questions relating to roads and road verges. Our method can be used, adapted and

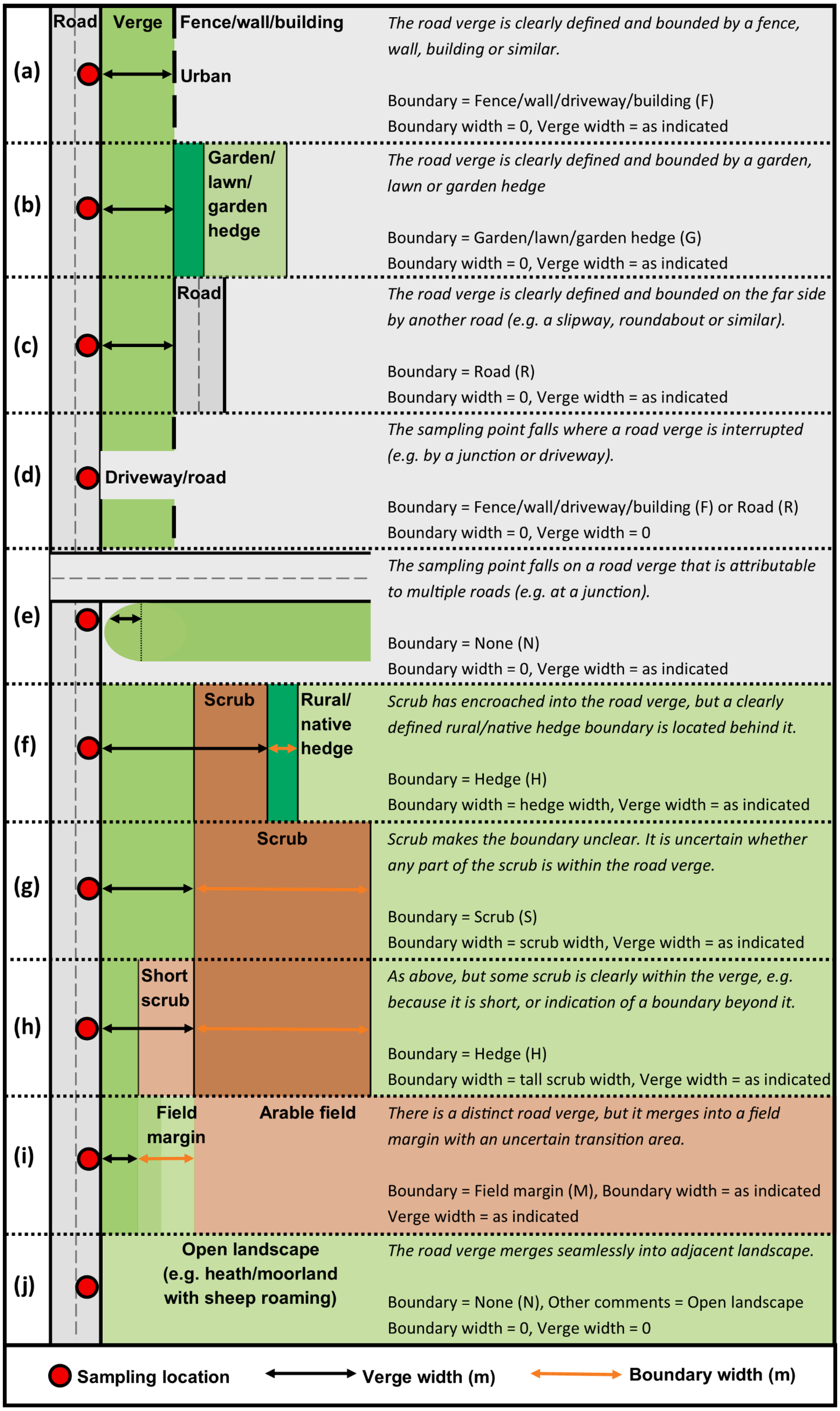

Fig. 4. Examples for determining the boundary of a road verge, and the widths of the road verge and boundary.

Table 2
Method for calculating the lower, reasoned and upper estimate of road verge width for each sampling point.

Estimate	Calculation of road verge width (m)	Assumptions
Lower	Verge width	1. Ambiguous boundaries are not part of the road verge.
Reasoned	If boundary = H or S: Verge width + (boundary width –1.5)/2 If boundary ≠ H or S: Verge width + boundary width/2	1. All native hedge (H) and scrub (S) boundaries contain an underlying hedge of width 1.5 m,[1] which has encroached equally into the road verge and adjacent land. 2. Half of all other ambiguous boundaries are part of the road verge.
Upper	If boundary = H or S: Verge width + (boundary width –1.5) If boundary ≠ H or S: Verge width + boundary width	1. All native hedge (H) and scrub (S) boundaries contain an underlying hedge of width 1.5 m,[1] which has encroached into the road verge, but not into the adjacent land. 2. All other ambiguous boundaries are part of the road verge.

[1]Department for Environment, Food & Rural Affairs (2011). Hedgerow Survey Handbook https://www.gov.uk/government/publications/hedgerow-survey-handbook

further developed by others, for example to assess road verges across other regions, and to assess verge habitat composition in greater detail. More generally, we have demonstrated the potential of using large, freely-available sources of satellite and ground-level imagery (Google Earth and Google Street View) to answer environmental questions relating to roads and road verges. Specifically, Google Street View imagery was available for 96% of sampling points, with 22% of imagery taken since 2019 (33% since 2018, 46% since 2015). It should be noted that many countries, particularly in Africa and Asia, currently have only minimal coverage of Google Street View imagery, which limits adoption of our approach, though this will likely improve in the future.

In the UK, Google Street View imagery has now been collected for more than 10 years, so it would be valuable to carry out a longitudinal study to see if and how road verge habitats are changing. Furthermore, developments in automating image analysis via machine learning (Lamba et al., 2019) can help to make better use of these data sources. This could be used by highways authorities and nature conservation organisations to provide finer resolution information on the species and habitats that are present in road verges (e.g. different grassland habitats as indicated by distinctive plant indicator species, rather than the very coarse habitat classification that we used), to assess roadside habitats automatically, and to monitor changes over time. However, potential applications extend to other environmental issues relating to roads, such as monitoring of roadkill (Shilling et al., 2020). The potential to do so is constantly increasing in response to the accumulating archive of Google Street View imagery.

4.2. The extent and habitat composition of road verges in Great Britain

Overall, we estimate that there are 2,579 km^2 (2,149–3,010 km^2) of road verges across Great Britain, equivalent to 1.2% of land, which validates a previous approximation of 2,400 km^2 (Plantlife, 2013). In urban areas, we estimate that road verges cover 4.2% of land, compared to the 29.5% of urban land covered by residential gardens, and the 7.1% of land covered by other green spaces in Great Britain (Office for National Statistics, 2019). This suggests that road verges are a major contributor to urban green space, as found in previous studies (Marshall et al., 2019). We have also assessed the habitats that make up this considerable area, of which an estimated 707 km^2 is frequently-mown grassland, 1,062 km^2 is regular grassland, 480 km^2 is woodland, and 272 km^2 is scrub.

Given that land scarcity is a major obstacle towards resolving many environmental issues, road verges offer a considerable opportunity to achieve ambitions around nature conservation, carbon sequestration and urban greening. For example, 1,769 km^2 of grassland road verge is similar to the total area of semi-natural grassland remaining in Great Britain (Bullock et al., 2011), so enhancement of verge habitats could make an important contribution to grassland restoration (Auestad et al., 2016). More generally, road verges are likely a significant component of 'green infrastructure' – providing habitats, connectivity, and other environmental benefits in human-dominated landscapes (Phillips et al., 2020a). For example, the 4.2% of land that verges cover in urban areas could be enhanced to benefit local people, for example to provide cooling during warm weather, to reduce storm water runoff, and to provide aesthetic and health benefits by providing access to nature (O'Sullivan et al., 2017; Salmond et al., 2016; Säumel et al., 2016).

In most cases, there was very little semi-natural habitat within a 100 m radius of roads. This demonstrates the importance of road verges for providing such habitats in anthropogenic landscapes. It also provides further evidence that older road verges are often remnant habitat patches that act as refugia (Auffret and Lindgren, 2020; Cousins, 2006; Fekete et al., 2020). For more recently-built roads, it suggests that verges have primarily replaced agricultural and urban land-uses. Furthermore, whilst discussion of road verges often focuses on grasslands, particularly on those that are frequently mown, our findings show that road verges in Great Britain include significant amounts of other habitats such as scrub and woodland.

In addition to the area covered by road verges, we estimate that there are 3,694 km^2 of hard road surfaces across Great Britain, equivalent to 1.8% of land. The hard and soft areas relating to roads therefore collectively cover around 3% of land. Yet, the actual extent of roads and road verges is much greater than this because we excluded private roads (local access, restricted local access and secondary access roads), of which there is a roughly equivalent additional length of road – a further 294,196 km, compared to 428,119 km of public roads (Ordnance Survey, 2020b). For our purposes, assessment of private roads is more difficult (because Google Street View is often unavailable) and less useful (because it would be difficult to influence their management on a significant scale). However, including private roads is likely to result in a total estimated area attributable to roads and road verges nearing 5% of land in Great Britain.

4.3. Practical insights for improving road verges for nature and the environment

Our study provides several practical insights about opportunities to enhance the road verge network for nature and the environment. In general, changes in road verge management that result in even modest improvements (e.g. optimised mowing regimes; Jakobsson et al., 2018) will provide substantial benefits if they can be implemented across a significant proportion of the road network, given the area of land that road verges collectively cover. However, we suggest three specific opportunities.

First, many road verges are relatively wide – approximately half are 3 m wide or more – which makes them target candidates for enhancement. Wider road verges are important from a nature conservation

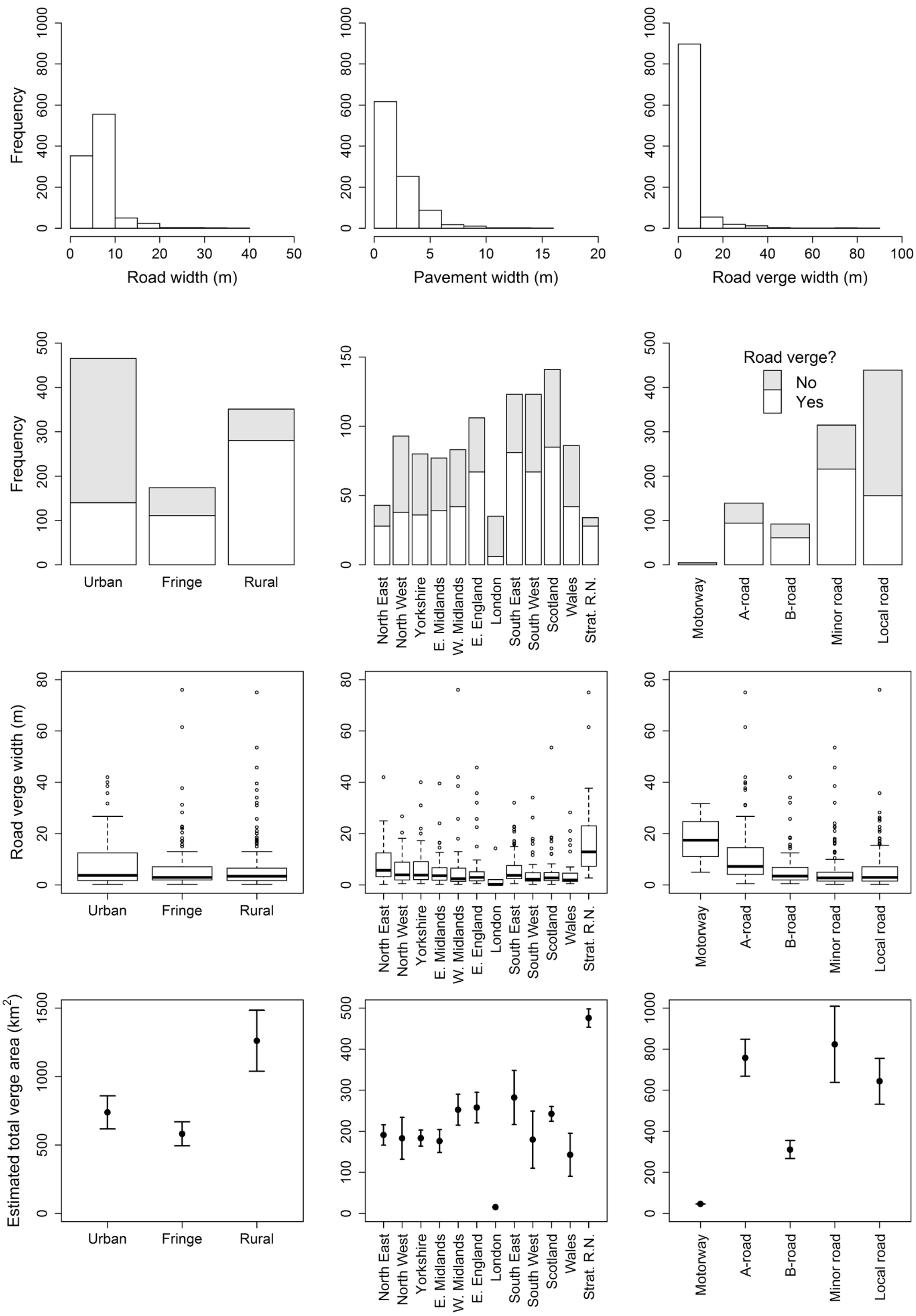

Fig. 5. Road and road verge characteristics at the sampled points ($n = 990$). 'Fringe' refers to roads located at the rural–urban fringe (e.g. at the edge of cities and towns, or in villages). For the boxplots, data are the 'reasoned' estimate, and are only presented for sampling points that had a road verge, with one outlier removed for clarity of presentation: a 90 m road verge along a rural minor road in Scotland. In the bottom three plots, error bars are the lower–upper estimates around the reasoned estimate. Names of Great Britain's administrative regions are abbreviated ('Strat. R. N.' is the Strategic Road Network; see Table 1).

perspective because they can sustain richer plant and insect communities (Monasterolo et al., 2020; Phillips et al., 2020b). The road-facing edges of verges, which constitute a greater proportion of narrow verges, are also more exposed to pollution, are less used by insects (Phillips et al., 2021; 2019), and put animals (including insects, amphibians, reptiles, birds and mammals) at greater risk of being hit by vehicles (Orłowski, 2008; Plante et al., 2019; Skórka et al., 2013). From a practical perspective, verge edges often need to be cut frequently to maintain safety and visibility for road users, and larger, wider road verges provide greater opportunity to carry out enhancements at scale.

Table 3
Estimated mean road verge width (including and excluding sampling points where no verge was present), mean total verge width (including both sides of the road and vegetated median), and the resulting estimated total road verge area, for each stratum, and overall for Great Britain. For each, we provide a 'reasoned' estimated (est.) as well as a lower and upper estimate (see Materials & methods; Table 2).

Stratum		Mean verge width (inc. verge absent) (m)		Mean verge width (exc. verge absent) (m)		Mean total verge width (m)		Total verge area (km^2)	
		est.	lower–upper	est.	lower–upper	est.	lower–upper	est.	lower–upper
North East	Urban	6.5	5.3–7.7	11.6	9.4–13.7	10.7	8.3–13.1	104	81–127
	Rural	5.0	4.9–5.1	6.5	6.4–6.7	12.3	12.1–12.5	87	86–89
North West	Urban	2.1	1.3–2.9	9.8	6.2–13.4	4.0	2.4–5.5	94	57–130
	Rural	3.3	2.8–3.8	4.6	3.9–5.4	6.2	5.2–7.3	89	74–104
Yorkshire and the Humber	Urban	2.3	2.3–2.3	10.0	10.0–10.1	3.3	3.3–3.4	61	61–62
	Rural	4.5	3.8–5.1	6.4	5.5–7.3	8.1	6.8–9.4	122	103–141
East Midlands	Urban	1.7	1.7–1.7	6.3	6.2–6.4	2.4	2.3–2.4	38	37–38
	Rural	4.6	3.9–5.4	6.3	5.2–7.3	7.9	6.4–9.5	138	111–166
West Midlands	Urban	3.8	3.1–4.6	14.6	11.7–17.6	6.4	4.9–8.0	113	86–140
	Rural	4.1	3.8–4.4	5.5	5.1–6.0	8.4	7.8–9.0	139	129–150
East of England	Urban	1.8	1.7–1.9	4.5	4.2–4.8	2.8	2.6–3.1	55	50–59
	Rural	5.1	4.4–5.8	6.5	5.6–7.4	8.8	7.4–10.2	203	171–235
London	All	0.6	0.5–0.8	2.9	2.8–3.0	1.1	0.8–1.4	15	11–20
South East	Urban	3.7	3.4–4.1	7.3	7.1–7.5	6.1	5.5–6.7	3	3–3
	Rural	5.2	4.0–6.3	6.1	4.7–7.4	9.9	7.6–12.2	279	213–344
South West	Urban	1.6	1.2–2.0	4.4	3.3–5.4	2.5	1.7–3.3	57	39–75
	Rural	3.2	1.9–4.5	4.6	2.8–6.3	6.3	3.6–9.0	122	71–174
Scotland	Urban	1.3	1.2–1.3	4.9	4.9–4.9	2.4	2.3–2.6	81	76–87
	Rural	4.6	4.3–4.9	5.8	5.4–6.1	7.4	6.8–8.0	161	148–174
Wales	Urban	1.4	0.9–1.9	13.2	8.7–17.7	2.1	1.1–3.0	76	41–112
	Rural	3.1	2.4–3.8	4.4	3.5–5.4	5.6	4.2–7.0	66	50–83
Strategic Road Network		15.3	14.8–15.8	18.6	18.0–19.2	21.3	20.3–22.3	475	453–498
	Overall	3.7	3.2–4.3	6.8	5.9–7.8	6.4	5.3–7.4	2,580	2,149–3,010

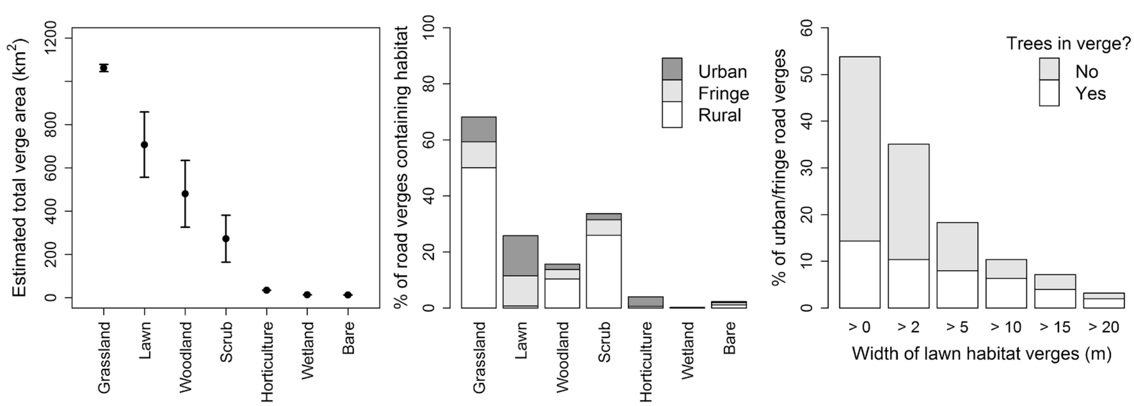

Fig. 6. The total areas and frequencies of different road verge habitats. The 'lawn' habitat refers to short, frequently-mown grassland, whilst 'bare' refers to bare ground. We present the percentage of lawn road verges (of different widths) containing trees as an indicator of the potential for planting trees to provide environmental benefits. Error bars are the lower–upper estimates around the reasoned estimate.

Table 4
Estimated total area of each road verge habitat across Great Britain. For each, we provide a 'reasoned' estimated (est.) as well as a lower and upper estimate (see Materials & methods; Table 2).

Habitat type	% of total verge area		Total verge area (km^2)	
	est.	lower–upper	est.	lower–upper
Grassland	40.9	48.6–35.4	1062	1045–1078
Lawn (frequently-mown grassland)	27.5	25.9–28.6	707	556–858
Woodland	18.7	15.1–21.3	480	325–634
Scrub	10.7	7.6–12.8	272	164–381
Horticulture (e.g. flower beds)	1.3	1.6–1.1	34	34–34
Wetland	0.5	0.6–0.4	13	13–13
Bare ground	0.5	0.6–0.4	12	12–12
Total	100.0	100.0–100.0	2,580	2,149–3,010

Second, the Strategic Road Network (major roads managed nationally, by organisations such as Highways England) provides the greatest opportunity for environmental enhancement on road verges because it holds the greatest share of road verge area (18.4%), despite comprising just 3.5% of total road length. This is because these roads are far more likely to contain road verges, and those verges are, on average, much wider than for other road types. Enhancements need to be carried out strategically to balance the greater barrier effects (Jacobson et al., 2016), levels of pollution and risks of wildlife-vehicle collisions along these high traffic volume road types (Forman et al., 2003; Phillips et al., 2020b). However, their wider verges mean that habitat improvements can be set back from the road edge to reduce these risks. Otherwise, wider road verges on roads with lower traffic volumes, whilst less common, should be prioritised for enhancement because they somewhat overcome these issues.

Third, the estimated 707 km^2 of frequently-mown grassland, which is primarily located in urban areas, offers various opportunities for environmental enhancement. Most simply, reducing mowing frequencies (e.g. to just once or twice per year, where possible) would provide more flowers for pollinators, allow plants to set seed, and create structural diversity for other animals (Jakobsson et al., 2018; O'Sullivan et al., 2017; Phillips et al., 2020b; 2020a;; Watson et al., 2020). Whilst the road-facing edges of verges are often necessarily cut for safety reasons (e.g. to maintain visibility), less frequent mowing is often possible, and could save money due to reduced maintenance costs (Phillips et al., 2020a; Watson et al., 2020). Whilst reduced mowing is perceived as untidy by some portions of the public, a recent Europe-wide study found that most people were favourable about such management when within well-defined areas, for example by regularly mowing edges (Fischer et al., 2020). In addition, only 27% of frequently-mown grassland verges contained trees, yet many were wide enough to accommodate them. Planting trees in some of these road verges could provide a wide range of benefits for people, nature and the environment (Salmond et al., 2016), and contribute towards UK government tree planting ambitions (Defra, 2018). From a practical perspective, this needs to be balanced against the costs of establishment and maintenance, and potential conflicts, such as reduced landscape view and risks related to reduced visibility and damage to infrastructure from tree roots and branches (Phillips et al., 2020a; Säumel et al., 2016). Again, wider road verges are most appropriate because trees and their roots, branches and leaves are less likely to pose such risks when positioned further back from the road edge. Furthermore, these conflicts could be overcome, and environmental benefits maximised, through strategic selection of tree species (O'Sullivan et al., 2017).

Data availability

All data supporting the results are provided in the manuscript and supplementary material.

CRediT authorship contribution statement

Benjamin B. Phillips: Conceptualization, Methodology, Investigation, Visualization, Formal analysis, Writing - original draft, Writing - review & editing. **Anila Navaratnam:** Investigation. **Joel Hooper:** Investigation. **James M. Bullock:** Methodology, Writing - review & editing, Supervision. **Juliet L. Osborne:** Methodology, Writing - review & editing, Supervision. **Kevin J. Gaston:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104159.

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