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Research article

A lidar based national model of hedgerows and other woody linear features in rural England

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ABSTRACT

Hedgerows and other woody linear features (WLF) are important semi-natural habitats, cultural features and potential carbon stores in farmland across several regions of the world, particularly Western Europe. Monitoring WLF has been limited by difficulties of mapping their extent and dimensions at large scales. Remote sensing can overcome such limitations by mapping WLF at high resolution at the national scale, but examples are few and generally more localized. We tested whether openly available, 1 m^2 resolution lidar could be used within a high-performance computing environment to model the extent and height of the WLF coverage in England. The results were compared with comprehensive ground truthing within 248 × 1 km^2 sample squares. There was close agreement (99.7 %) between the mean and total extent of WLF from the model and ground truthing squares, with 74 % of modelled WLF showing close alignment (<20 m distance) with ground truthed WLF. Total length of WLF in England was estimated as 641,079.8 km, with 29 % composed of trees/bushes taller than 6 m, and 61 % (389,439.3 km) corresponding to managed hedgerows of 1–6 m tall. Precise agreement between height classes in the model and sample squares was more modest (36 % of WLF lengths), but higher (60 %) if allowing a tolerance of ±1 height class for matching to accommodate temporal differences between lidar collection (2016–2021) and ground truthing (2022–2023). The model represents a significant improvement in mapping and monitoring WLF using openly available national lidar, and the limitations and potential opportunities are discussed.

1. Introduction

Field boundaries are important features in farmed landscapes, used for demarcating ownership and enclosing livestock and crops (Pollard et al., 1974; Wolton, 2024). By avoiding cultivation and direct inputs of agrochemicals, field boundaries can provide key habitat refuges for farmland biodiversity, which has declined after agricultural intensification from the early 20th Century (Sotherton and Self, 2000; Donald et al., 2006; Kleijn et al., 2011).

In parts of Europe, the Americas, Australia and China, woody linear features (WLF) are a dominant field boundary in farmed landscapes (Baudry et al., 2000). Hedgerows are a major component of WLF, and broadly defined as rows of woody shrubs and/or trees surrounding fields or pastures, which are managed by cutting to maintain their shape and integrity (Pollard et al., 1974). Hedgerows may also contain mature trees ('standards'), traditionally providing timber, forage and shelter. Other WLF can be self-sown bushes or trees along banks and fence-lines, or unmanaged hedgerows that have become fragmented or grown to into tall, uneven shrubs and trees (Wolton, 2024).

Hedgerows are particularly valued as key semi-natural farmland habitats and cultural features of rural landscapes in Britain, Ireland and France (Baudry et al., 2000; Oreszczyn and Lane, 2000; Wolton, 2024). The WLF densities can reach 17 km/km^2 (Mérot, 1999; Fuller et al., 2001), and are associated with approximately 600 wild plant species, 1500 insect species and 90 vertebrate species (UK Biodiversity Steering Group, 1995; Graham et al., 2018). Farmland hedgerows and other WLF provide shelter, foraging and breeding habitats in otherwise intensively managed landscapes (Hinsley and Bellamy, 2000; Redhead at el. 2013; Byrne & del Barco-Trillo, 2019), and are important habitat corridors for woodland species (Alderman et al., 2011; Finch et al., 2020; Litza et al.,

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2022). Additionally, WLF provide ecosystem services by supporting crop pollinators or pest controllers (Garratt et al., 2017, see also Albrecht et al., 2020), and physical structures to reduce soil erosion, water flow and nutrient runoff (Forman and Baudry, 1984; Wolton et al., 2014; Montgomery et al., 2020). Furthermore, hedgerows and other WLF can sequester significant amounts of carbon (e.g. up to 40 Mg C ha^{-1} from above-ground biomass of mature hedgerows), which contributes to net zero targets (Biffi et al., 2022, 2023, 2025).

Despite these benefits, within Britain the WLF network has been vulnerable to losses through destruction, or degradation from lack of management (Staley et al., 2023). The estimated length of managed hedgerows in Britain declined by 25 % between 1984 and 2023, although this was offset by an increase in unmanaged WLF and lines of trees (Norton et al., 2012, 2024). In 2023 the UK government stated an ambition to create or restore 72,420 km (45,000 miles) of hedgerows within England (Defra, 2023), requiring an effective strategy for implementation. It is therefore crucial to monitor the location, extent and condition of WLF to assess national targets and inform planning decisions, to safeguard the characteristic habitats and the ecosystem services they provide.

National inventories to estimate the length and dimensions of hedgerows and other WLF have been hampered by the complexity of mapping networks at the landscape scale, due to their narrow width, large extent and strongly three-dimensional structure. Field-based mapping of hedgerows and other WLF for an entire country has been logistically impractical and prohibitively expensive. Similarly, the use of aerial photography during the 20th Century was limited by available coverage (Graham et al., 2019). As such, the mapping of WLF has previously been restricted to sampling approaches, and then extrapolation or interpolation to achieve national estimates (Burel and Baudry, 1990; Barr and Gillespie, 2000; Staley et al., 2024). These issues have limited the ability of hedgerow inventories to target local actions, due to uncertainty and low resolution of the available information (Graham et al., 2019).

Advances in remote sensing and GIS can overcome limitations of scale and resolution to allow for the regional or national mapping of complete networks of hedgerows and other WLF (Graham et al., 2019). Scholefield et al. (2016) used NEXTMap digital elevation data, derived from synthetic aperture radar (SAR) and interferometry, to produce a model of Britain's WLF network, although this was produced at relatively coarse resolution (5 m) and did not include height information. In Germany, Muro et al. (2025) used 3 m resolution Planet surface reflectance data and low resolution (5 m) topographic elevation data to produce a national hedgerow map.

Airborne lidar (light detection and ranging) has also been used to produce three-dimensional models of WLF networks, including detailed height information, from the farm-scale to the county level at resolutions of 1–2 m (Redhead et al., 2013; Black et al., 2014; Broughton et al., 2017, 2021; Luscombe et al., 2023; Wolstenholme et al., 2025). Airborne lidar is a laser-scanning method that can achieve extensive coverage at sufficient resolution (e.g. 1 m or better) to characterize the location, length and height of WLF, potentially at the national scale (Graham et al., 2019). However, using lidar to produce a national inventory of WLF has so far been limited by the availability of high-resolution coverage at the national extent, and the ability to process the large volumes of data to reliably identify WLF and derive a linear network (Norton et al., 2024).

The increasing availability of non-commercial national lidar programmes in Europe (Florio et al., 2021), including for some constituent countries of Britain, has increasingly made it feasible to produce national inventories of WLF. In this study, we used a near-complete lidar coverage for England within a high-performance computing environment to produce a national model of the WLF network, depicting the feature locations, lengths and heights. The output was compared against ground truthing data collected during a national field survey of randomly stratified sample squares distributed across England, which provided a robust estimate of the model's accuracy. This allowed us to test whether our approach was a suitable alternative or complement to field-based surveying of WLF.

Producing a modelled inventory of England's WLF that contains height metrics, and which has comparable accuracy to ground surveys, offers a significant advance in the monitoring of hedgerows and WLF, overcoming some of the logistical constraints of ground surveys and potentially enabling more frequent monitoring of status and condition. Representing a new, repeatable baseline for future lidar re-surveys, our model can assist rural planning and national policies to conserve and expand WLF by focusing planting and management to maximize ecosystem services, habitats and connectivity. The model can also act as a case study for the use of openly available, national lidar for mapping WLF in other regions.

2. Methods

2.1. Lidar data availability

The source data for the lidar model were from the National Lidar Programme conducted by England's Environment Agency (EA; Defra, 2025). Airborne lidar data were captured from a fixed-wing aircraft in leaf-off conditions during 2016–2021 at a reported density of approximately 4 points per m^2. The lidar coverage included all of England (132,903 km^2), except for an area of approximately 24 × 25 km in North Yorkshire, which was excluded. The EA processed the point cloud to create a rasterized digital terrain model (DTM) and a first-return digital surface model (DSM). Both coverages had a 1 m^2 horizontal resolution, 1 cm vertical resolution and vertical accuracy of ± 15 cm, divided into 5 × 5 km tiles. A canopy height model (CHM) of 1 m^2 resolution was supplied by the EA, created by subtracting the DTM from the DSM.

2.2. Processing the CHM

We processed the CHM to create a WLF model in the R software environment on the LOTUS batch and parallel computing cluster that accesses the UK's JASMIN high-performance data analysis facility (Lawrence et al., 2013). LOTUS gives access to a cluster of 200 nodes/hosts with up to 48 cores per host and 1024 GB of RAM. The JASMIN facility is operated by the Science & Technology Facilities Council (STFC) on behalf of the Natural Environment Research Council (NERC).

The workflow is shown in Fig. 1 and described in detail below. First, all height values under 0.5 m in the CHM were removed to exclude ground vegetation, with remaining values reclassified into seven height classes (Table 1). Height classes were chosen for compatibility with those used in the long-running Countryside Survey monitoring programme (Maskell et al., 2008), which was the data source for ground truthing (see below). Greater precision of minimum height values (classes 1a, 1b and 1c) was given to allow users more flexibility in choosing minimum height values for linear woody features of interest.

Raster pixel values in the classified CHM were smoothed using modal filtering (11-pixel width), producing clumps of contiguous pixels with the same height class. This was done to reduce the processing burden while maintaining a realistic scale for bushes and trees. Pixels in clumps of ≤ 20 pixels and < 5 m from a pixel in a clump of 20 pixels or more were reclassified to the pixel value in the larger clump. This created a smoothed and classified CHM raster depicting feature heights, including buildings and non-linear woody vegetation.

2.3. Defining the spatial linear framework

The spatial linear framework used as the network of field boundaries, which defined the space potentially occupied by hedgerows and other WLF, was derived from the UKCEH Land Cover Map 2021 (LCM: land parcels GB (≥ 0.5 ha parcel size); Marston et al., 2022). Where WLF were present on the LCM polylines, the goal was for them to be segmented and

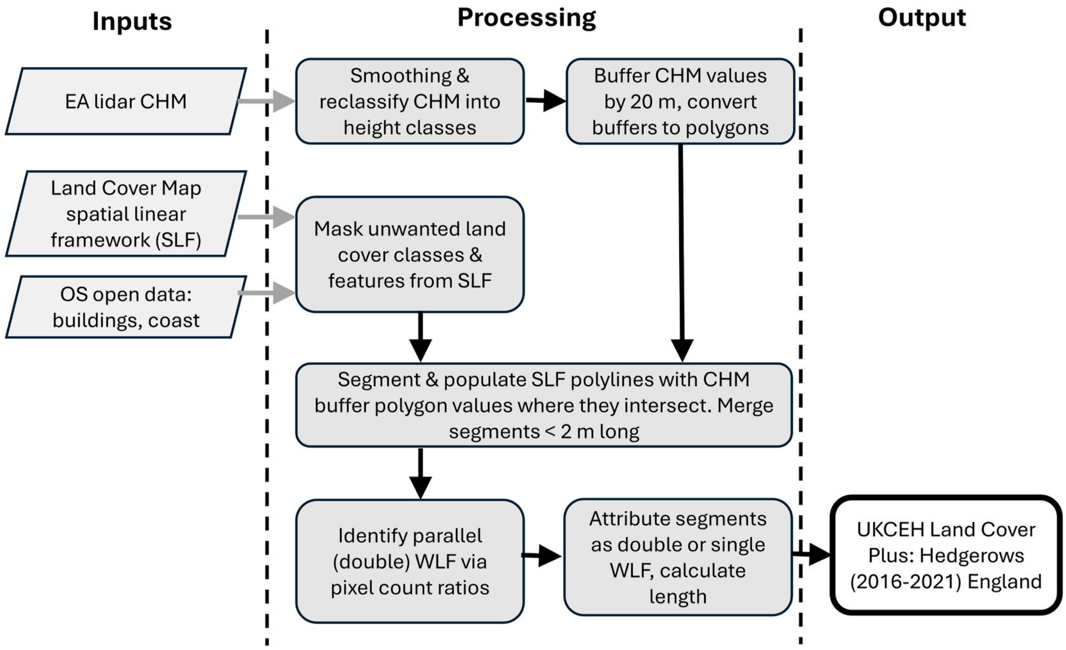

Fig. 1. The workflow used for creating the output hedgerows model: UKCEH Land Cover Plus: Hedgerows (2016–2021) England. The workflow used inputs of the Environment Agency (EA) lidar canopy height model (CHM; 1 m^2 resolution), the UKCEH Land Cover Map 2021, and the Ordnance Survey (OS) open data (see text for full details of source data and processing).

Table 1
Height classes used for categorizing woody linear features (WLF) in the lidar-derived hedgerows model and the Countryside Survey (CS) ground survey.

WLF height value (m)	model height class	CS height class
0.50–0.99	1a	0
1.00–1.49	1b	1
1.50–1.99	1c	1
2.00–2.99	2	2
3.00–3.99	3	3
4.00–5.99	4	4
≥ 6.00	6	6

populated with values from the processed CHM. To achieve this, the LCM linear framework was first masked to exclude boundary polylines that coincided with land cover classes that would likely result in misclassification of WLF. A mask was produced from LCM polygons that comprised woodland, mountain/moor/heath, saltwater, freshwater, coastal, urban and suburban areas, which covered a total of 96,832 km^2. This reduced the likelihood of including CHM features that were not WLF, such as walls, buildings and woodland edges, which were considered much more likely than WLF in those land cover types.

Masking was also applied within 50 m of the tidal high-water mark to exclude coastal cliffs/rocks. Buildings not already in the masked LCM classes, such as farmsteads, were derived from open data products (Ordnance Survey Limited, 2025a) and masked with a 5 m buffer applied to exclude garden/yard infrastructure. Masking of all these areas from the spatial framework was intended to avoid substantial type I errors, while sacrificing few genuine WLF. The resulting coverage of the output model would therefore comprise all enclosed land, predominantly in England's lowland farmed landscape where most WLF exist (Staley et al., 2023), and which totalled approximately 35,000 km^2.

2.4. Attributing WLF to the spatial framework

The spatial framework polylines may not exactly align with equivalent WLF in the rasterized CHM, as they were drawn from different sources, so we applied a tolerance/buffer when assigning WLF to the spatial framework. This was achieved by assigning all CHM cells without data and within 20 m of a cell with data to the value of the nearest cell with data. This 20 m buffer value was chosen after preliminary analyses suggested the best trade-off between true and false positives. The resultant raster was converted to polygons and overlain with the polylines of the masked spatial framework. Polylines were retained and attributed with the height class of the corresponding polygon if segments coincided at least 0.9 proportion of their length within a CHM polygon. Segments less than 2 m long were merged with the dominant adjoining polyline to reduce unnecessary fragmentation, whilst extraneous sections under 2 m in length were deleted.

To identify parallel hedgerows or tree lines, such as those on either side of a road or lane (which the spatial framework usually generalized to a single polyline), we used the following routine: layers were produced from the rasterized CHM to count pixels within a radius of 10 m (filter10) or 20 m (filter20) of each pixel. At the greater search radius (filter20), a WLF with a parallel feature on the opposite side of a road, for example, would encounter more pixels to count than a single-line WLF that has no parallel feature. As such, for parallel WLF the filter20 raster would be expected to have a relatively far higher pixel count than for single WLF. Dividing the resulting rasters (filter20/filter10) then gave a ratio raster, with higher output ratio values of 2.5–4.0 considered as parallel features and given a value of 2, and other values being assigned as 1. The polyline sections were then buffered to 15 m and each buffer polygon was attributed as a single (Single) or double (isDouble) WLF based on the modal value (either 2 or 1) of the intersecting ratio raster pixels in each polygon.

Further attributes were applied to roadside WLF: a vector coverage of England's road network (Ordnance Survey Limited, 2025b) was buffered to 20 m. Where a polyline segment had at least 0.75 proportion of its length within the road buffer then it was considered a roadside WLF and attributed as 'isRoadside'. Further classifying label attributes were added to aid WLF interpretation: where the attributes isDouble and isRoadside were both true then a label of 'Double hedge' was given, indicating two parallel WLF on either side of a road. Where isDouble was true and isRoadside was false then the label given was 'Probable wide single hedge', indicating a wide hedgerow or tree line with a broad canopy. Where isDouble was false and isRoadside was true or false then the label was 'Single hedge'. The attributes for each linear feature segment are shown in Table 2.

The final classified and labelled polylines were clipped to the extent of the original EA 5 km tiles and then merged into 10 km tiles. Polyline segments touching the 5 km tile edges within the 10 km tile were combined into a single feature if they had the same attributes, and a further attribute of polyline segment length was calculated and applied. The output product was UKCEH Land Cover Plus: Hedgerows (2016–2021) England (Broughton et al., 2024), hereafter the 'hedgerows model'. Processing time to generate the full model was approximately 1–2 days, depending on other jobs running in the cluster.

2.5. Ground truthing survey and comparison

The model output was compared against ground truthing in 248 squares (1 km^2 each) distributed across England, which coincided within the hedgerow model coverage. The 1 km^2 squares were surveyed by trained fieldworkers in 2022–2023 using the Countryside Survey (CS) methodology (Wood et al., 2017; Norton et al., 2024). The CS is a national periodic monitoring scheme for Great Britain that surveys habitats and physical features, including WLF, within a stratified sample of 1 km^2 squares (Maskell et al., 2008).

Within CS squares the WLF polylines were mapped and categorized into height classes (Table 1), including features at least 20 m long and a maximum of 5 m wide. Linear woodland strips wider than 5 m, such as field boundary shelterbelts and roadside trees, were also recorded and included as WLF in analyses after deriving the length of their long axis as a polyline. The spatial linear framework used for CS mapping was derived from the same OS (Ordnance Survey) data used for the LCM framework, and also for our hedgerows model. However, in both frameworks the surveyors or original processing sometimes reshaped features and caused divergence in the location of boundaries.

The hedgerows model was compared with CS WLF in several ways. Firstly, the total length of WLF in each of the 248 CS squares was compared with WLF from the hedgerow model in the same squares. These were compared using the same criteria, excluding any CS features that fell within the land cover masks used in the hedgerows model. Secondly, a 20 m buffer was applied around the CS WLF, and the hedgerows model features were clipped within this buffer. The buffer distance (matching the 20 m tolerance used when assigning WLF to the spatial framework) allowed for deviation in the location of field boundaries between the original CS and LCM spatial frameworks, possibly resulting from surveyors adjusting the position or shape of features during ground observations. For each CS square, the total length of hedgerow model features within the 20 m buffers were compared with the CS WLF from which the buffers were derived. This was a more detailed test of whether CS features had closely aligned features in the hedgerow model.

Finally, the height classes of the CS and hedgerow model features were compared by taking the midpoint of each hedgerow WLF segment, to represent the whole segment, and comparing its height class to that of the nearest CS WLF, within the corresponding 20 m buffer. Because the hedgerow model had a higher precision of height values than the CS WLF, with more height classes, the comparison was typically comparing multiple segment midpoints against the CS single linear feature that they were aligned with inside the 20 m buffer. The proportion of the model's WLF segments whose height class tallied with the adjacent CS WLF height class could then be calculated.

Table 2
Attributes given to each segment of a WLF in the hedgerows model.

Attribute	Description
section	Unique number of each segment
hghtcls	Height class
isDb	'isDouble': interpreted as double (parallel) features
isRd	'isRoad': interpreted as a feature lying alongside a road
hlength	Length (metres) of the feature segment
label	Interpreted feature type, derived from Boolean terms of isDb and isRd attributes

2.6. Statistical analyses

The length of all WLF in each 1 km^2 square was calculated for the hedgerows model and the CS survey, and separately for the length of the hedgerows model features within the 20 m tolerance buffers of the CS features. Paired tests gave a statistical comparison between the total WLF lengths across all 248 squares. A Bland-Altman plot visualized the comparison of the feature lengths between CS ground surveys and the hedgerows model in each survey square. A Bland-Altman plot is a graphical method to show the agreement between values derived from two different survey methods or measurement techniques. Our plot depicts the mean of each pair of values of WLF total length for each square, plotted against the difference between them, where the 95 % limits of agreement are shown as two standard deviations of the mean difference (Myles and Cui, 2007).

To compare feature height values, we quantified the agreement between the height class of each feature in the hedgerows model versus the corresponding feature in the CS survey data. Comparisons used the CS height classes (Table 1), and we calculated the total number of the hedgerow model feature midpoints that agreed (true positives) or disagreed (false negatives and false positives) with their corresponding CS features in having the same height class. From these values we calculated the recall (true positive divided by (true positive + false negative)) and precision (true positive divided by (true positive + false positive)) for each CS height class and all classes combined. We also calculated the overall agreement expressed as feature lengths (represented by the midpoints).

Due to the potential disparity in the dates of data collection between the lidar and CS surveys, we repeated the overall height comparison agreement for feature lengths, but allowed for a difference of one height class in the hedgerows model from the corresponding CS height class. Hence, a height class of 2, 3 or 4 in the hedgerow model would be considered as agreement for a corresponding class of 3 in the CS data (i.e. class 3 $\pm$ 1). The proportion of all WLF and their lengths in the hedgerows model that agreed with the corresponding CS height class was then derived, with and without the class tolerance.

We further calculated the range of height class disagreement between the hedgerow model and the CS features by calculating the summed lengths of WLF for each deviation from the CS height class. This was achieved by subtracting the hedgerows model height class of the feature midpoint from the corresponding CS feature height class. These calculations would show whether any deviation of height class from 0 (agreement) was biased towards an underestimation (values 1 to 6) or an overestimation (values −1 to −6) of the hedgerows model.

3. Results

3.1. WLF distribution

The hedgerows model coverage for England comprised 1470 individual 10 km tiles (Fig. 2), totalling 9.51 Gb in file size, containing WLF with a total length of 641,079.8 km for all height classes above 0.5 m tall. The distribution of WLF by height class showed that 29 % was trees and bushes taller than 6 m (Table 3), while 61 % (389,439.3 km) was in the height range of 1–6 m that broadly corresponded to managed hedgerows.

The distribution of WLF was uneven across England, with higher densities (> 6 km/km^2) in the west and southwest (Fig. 3). Low densities (< 2 km/km^2) occurred in counties with large urban conurbations, including Greater London, West Midlands (Birmingham) and Bristol, which were mostly masked from the analysis. However, relatively low densities of WLF (2–4 km/km^2) were also apparent in predominantly

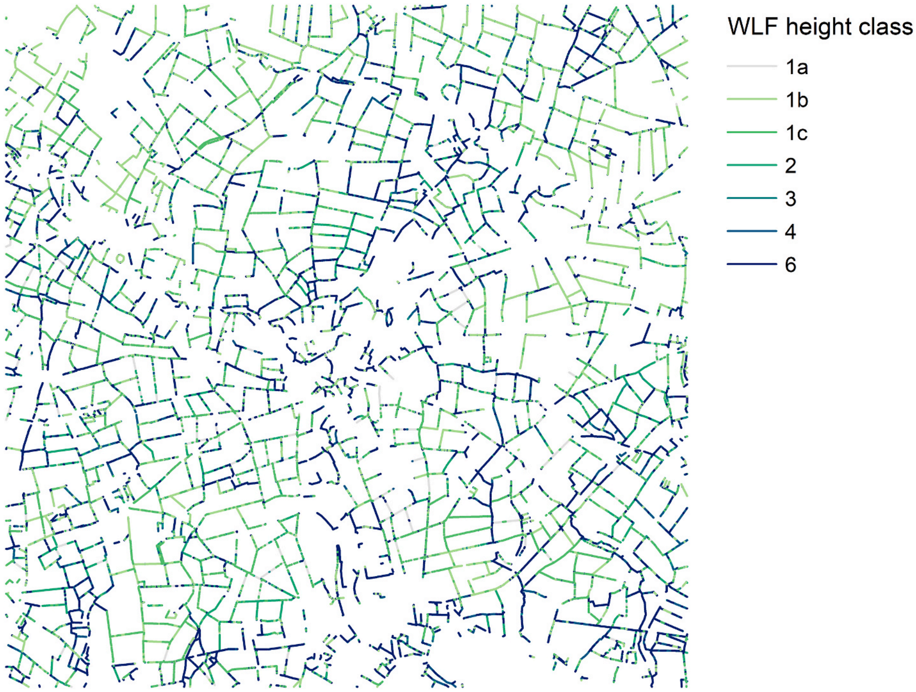

Fig. 2. Example of a 10 × 10 km tile of the hedgerows model output (Ordnance Survey square SP10), where WLF are colour-coded by height class. For height class interpretations, see Table 1. The tile is oriented north (top) on the UK National Grid.

Table 3
Length and density of WLF in the England hedgerows model, categorized by height. The area of England used to calculate density (132,903 km^2) did not exclude the masked area used in processing, which was presumed to contain negligible WLF.

Height class	Height range m	Length km	% of WLF length	Density km/km^2
1a	0.50–0.99	66,866.0	10.4	0.5
1b	1.00–1.49	114,715.8	17.9	0.9
1c	1.50–1.99	103,600.9	16.2	0.8
2	2.00–2.99	73,427.8	11.5	0.6
3	3.00–3.99	24,389.4	3.8	0.2
4	4.00–5.99	73,305.4	11.4	0.6
6	6.00 ≥	184,774.5	28.8	1.4
–	Total	641,079.8	100.0	4.8

rural counties of northeast England (e.g. Northumberland, Durham), eastern England (e.g. Lincolnshire, Cambridgeshire) and southern England (e.g. Hampshire, Surrey). For several of these counties (Northumberland, Hampshire, Surrey), the low densities of WLF coincided with a high coverage of woodland (Marston et al., 2022), which likely constrained the area of farmland that could host WLF. However, other rural counties with low densities of WLF also had limited woodland cover (Cambridgeshire, Lincolnshire), indicating that WLF were genuinely scarce even on extensive farmland.

3.2. Comparison of modelled WLF extent with CS ground truthing

For all 248 CS survey squares, the total length of WLF in the hedgerows model (1319.4 km) was almost the same (99.7 %) as the total length of CS features from the ground truthing (1324.0 km). A paired *t*-test showed no statistical difference (two-tailed: $P = 0.88$) between the total length of features per square in the hedgerows model (mean 5320.3 m ± 2857.0 SD) versus the CS data (mean 5338.5 m ± 3214.7 SD), with a strong correlation ($r = 0.82$) between them. The Bland-Altman plot displayed a good agreement between the two measurements across all squares (Fig. 4), with the mean difference being −18 m

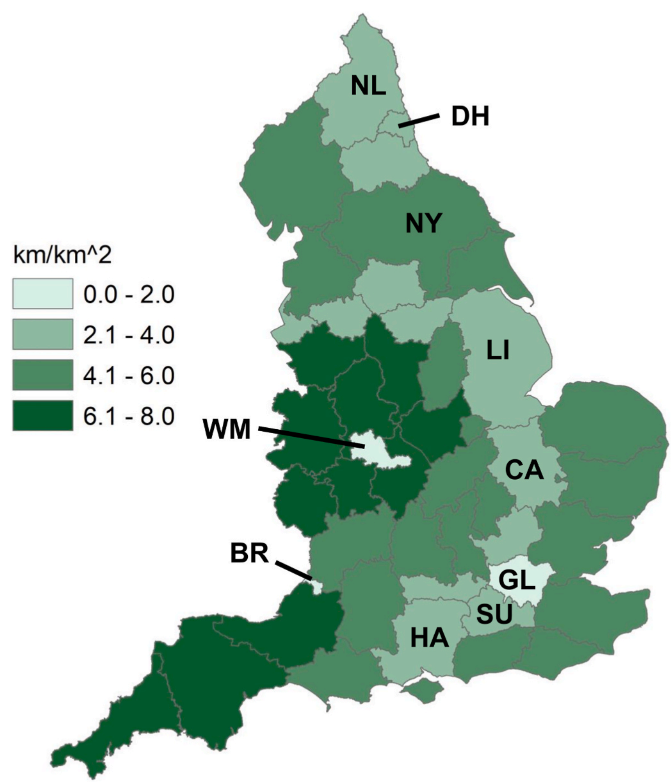

Fig. 3. The density of WLF (km/km^2) in administrative counties of England. Labels refer to counties mentioned in the text: NL = Northumberland, DH = Durham, NY = North Yorkshire, LI = Lincolnshire, CA = Cambridgeshire, WM = West Midlands, BR = Bristol, GL = Greater London, SU = Surrey, HA = Hampshire.

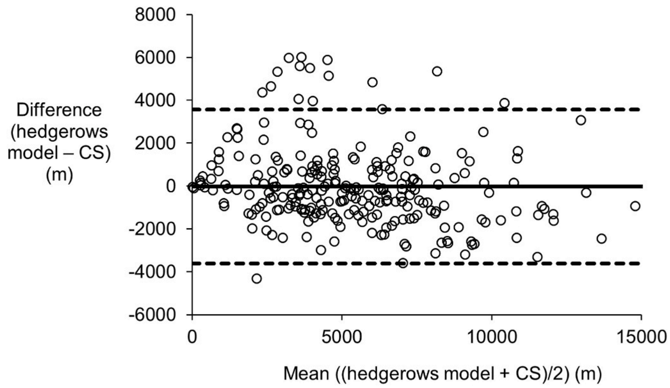

Fig. 4. Bland-Altman plot of the total length of features within 248 survey squares of 1 km^2 each, as derived from the hedgerows model and from the CS ground survey. The solid horizontal line shows the mean difference for all paired values (−18.3 m) and dashed lines are the 95 % limits of agreement. Points nearer the mean line show greater agreement between the hedgerows model and CS ground survey, while those beyond the 95 % limits show relatively low agreement.

and the 95 % limits of agreement falling within −3613 m to +3576 m.

Within individual squares the difference in the total length of WLF between the hedgerows model and the CS data was mostly within ± 30 %, although there was a very large discrepancy in some squares, with the model predicting up to 5996 % more length of WLF (Fig. 5). Of the 20 squares (8 %) showing the greatest discrepancy of more than 200 % between the hedgerows model and the CS data, most (14) were in upland regions of northern or southwest England. All of these 20 squares involved a substantial overestimate of WLF by the hedgerows model; on visually checking the modelled WLF against satellite imagery, the major reason appeared to be that networks of drystone walls used as livestock barriers were misclassified as WLF.

For WLF lengths in each square that fell within the 20 m tolerance buffer applied to the CS features, a paired *t*-test showed a significant difference (two-tailed: $P < 0.01$) between the length of WLF in the hedgerows model (mean 3918.7 m ± 2751.0 SD) and the CS data (mean 5338.5 m ± 3214.7 SD). However, there was a very strong correlation ($r = 0.95$) between the length of WLF from both sources across the 248 squares. This comparison indicated that 26 % of the length of WLF in the hedgerows model was more than 20 m away from any feature in the CS data, but the remaining 74 % of WLF length in the hedgerow model was closely associated with CS features, being aligned within 20 m.

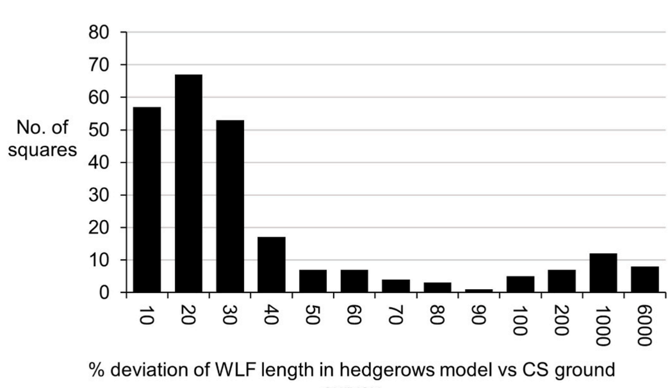

Fig. 5. The percentage difference between the length of WLF in the hedgerows model compared to the CS ground survey, summarised for the 248 survey squares.

3.3. Comparing WLF heights

The hedgerows model contained 35,025 sample midpoints of WLF segments (total length 829.3 km) that fell within the 20 m buffer of CS features, and where a height class attribute was available for both the hedgerow model and the CS data. Only 30 % of the hedgerows model points agreed exactly with the height class of the corresponding CS feature, which represented the overall recall and precision (both returning a value of 0.30, see supplementary material). Individual height classes varied somewhat in their agreement, with model height classes 1b and 1c (CS class 1: 1.00–1.99 m tall) having the highest recall and precision, and those in model class 1a (CS class 0: 0.50–0.99 m tall) having the lowest values (see supplementary material, Table S1).

The overall agreement between CS and the model height classes translated to 36 % of the total WLF length (Fig. 6). When the height class tolerance was applied to allow for one height class deviation either side of the correct class, then the agreement increased to 56 % of WLF samples, or 60 % of the total WLF length. Where there was disagreement in WLF height classes, those of the CS data tended to be taller than corresponding values in the hedgerows model, most frequently by one or two classes (Fig. 6).

4. Discussion

The hedgerows model was successful in rendering a lidar CHM raster into a national network of WLF polylines (Broughton et al., 2024). The model provided a baseline inventory of WLF length and location and also a novel height classification that was compatible with Britain's long-running CS monitoring program, complementing the ground-based surveys (Norton et al., 2024).

The modest resolution of the original lidar, captured at around 4 points per m^2 and processed as a 1 m^2 raster, was apparently sufficient to detect most WLF, with British hedgerows averaging at least 2.4 m wide (Norton et al., 2024). The modest resolution also helped to limit the processing demands, so was a useful trade-off of detail versus practicality, although the data volume still required a high-performance computing facility.

Our hedgerows model estimated a total extent of WLF in England of 641,079.8 km in 2016–2021, at an average density of 4.8 km/km^2. This figure compared well (115.3 %) with the national estimate of 556,000 km for England's WLF in 2022/2023, derived from sampling and interpolation in the CS (Norton et al., 2024). When considering only WLF in the hedgerows model that corresponded to the 1–6 m height

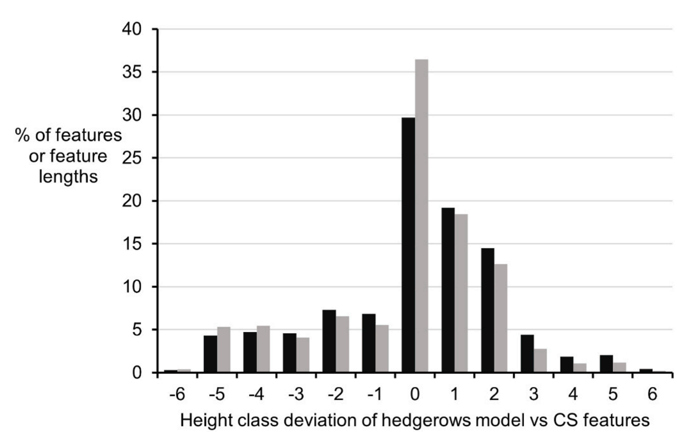

Fig. 6. Distribution of differences between the corresponding height class of WLF in the hedgerows model and CS data, for the number of WLF features (black) and the length of WLF features (grey). A deviation of 0 means agreement between the height class in the two sources for the same WLF, a negative value means the feature's height class in the hedgerows model exceeds the CS, and a positive value means the CS height class exceeds the hedgerows model.

range of managed hedgerows, the modelled estimate of 389,439 km was very close (103.0 %) to the 378,000 km estimated by the CS (Norton et al., 2024).

For the more detailed comparison between WLF in the hedgerows model and the 248 sample squares used for ground truthing, there was remarkably close agreement in the total length of WLF (99.7 %), and a strong correlation between them ($r = 0.82$) on a square-by-square basis. Some of the more extremes of over- or underestimation of WLF lengths in particular squares (Fig. 5) may have cancelled out each other when deriving this overall metric. Indeed, on a per-feature basis there was a somewhat lower (74 %) agreement in close alignment (< 20 m apart) between WLF in the hedgerows model and the CS ground truthing. Nevertheless, the results generally indicated that the hedgerow model performed well against the CS ground truthing when depicting WLF and managed hedgerow extent, with the results being highly comparable for a large proportion of the survey squares.

The comparisons with CS showed that the hedgerows model was a significant improvement on previous attempts to create a WLF model within Britain using remote sensing data. Creating a national model based on SAR, Scholefield et al. (2016) achieved a 58 % agreement of WLF extent when compared to CS survey data. In smaller sampling areas, Luscombe et al. (2023) achieved an agreement of 63–98 % between WLF models (derived from 2 m resolution lidar) and manually digitised features from aerial imagery. All of these studies, including ours, pre-emptively masked out areas or land-cover types known to generate excessive error (such as moorland and coastal strips), to improve results.

For our hedgerows model, where the WLF extent in sample squares did deviate strongly from the CS survey, this was primarily due to the model over-estimating WLF that were not recorded by CS, assuming the latter estimate was more accurate. A major cause of this disparity appeared to be a misclassification in the hedgerows model of upland networks of drystone walls. Although the masking of upland pasture and moorland was aimed at minimizing this effect, the inclusion of some wall networks on lower pastoral areas was unavoidable. Despite drystone walls generally being less than 1 m wide, this could be inflated by tall herbage alongside, and some walls were evidently captured by the lidar and were present within the coverage. Similar false positives for drystone walls were found by Luscombe et al. (2023), along with solar panel arrays, although our use of a linear framework of field boundaries eliminated the incorporation of in-field features.

Future improvements to the model could include the integration of high-resolution multi-band optical data, to assist with distinguishing WLF from drystone walls via differences in their reflectance. Spectral imagery was used by Aksoy et al. (2010; normalized difference vegetation index) and Muro et al. (2025; visible and near-infrared) to distinguish WLF from non-vegetated linear features. This was not attempted for the hedgerows model, however, as at the time of processing there was no freely available and contemporary data at a comparable resolution (1 m^2) and extent (all of England).

The hedgerows model was less successful in determining WLF height than for characterizing their extent, with a lower agreement of height classes compared to the CS data. This was somewhat expected, firstly, due to the temporal mismatch between data collection of the lidar and CS surveys, of up to six years. Hedgerow management generally involves mechanical trimming, as often as every year, with tall hedges and lines of trees being subject to periodic cutting that would substantially reduce their height. Subsequent re-growth between cuts could accrue more than a metre of vegetation; indeed, agri-environmental policies in England have incentivised less frequent hedgerow management (Natural England, 2013a, 2013b), resulting in more substantial, periodic cuts. As such, vegetation growth or management could have significantly affected WLF dimensions between the lidar and CS ground surveys.

A further source of height disparity may stem from differences in precision and accuracy when WLF height was assessed by a surveyor on the ground versus the lidar instrument. For example, the relatively low resolution of the lidar data (4 points per m^2) may have allowed penetration of sparse twigs or branches at the tops of WLF, which a surveyor may have perceived differently and included within the feature height. Surveyors may have also estimated or generalized height values across a longer stretch of a WLF than the scale of the lidar precision. There was some evidence that the recall and precision of WLF heights varied by class (see supplementary material), with some classes apparently performing better or worse than others. However, as sources of error should have applied in the same way to all height classes (which were subjective height bands and not natural breaks), we are unable to account for any such differences.

When allowance was given for the factors underlying potential disparity, by accepting a greater tolerance of height classes in the comparisons, the overall agreement between the hedgerows model and the CS survey features (all height classes combined) was substantially improved, averaging at 60 % of the WLF extent, but this meant a rather broad allowance of 3 m or more in vertical height. Nevertheless, there are very few studies validating the height categories of WLF derived from remote sensing against ground truthing. In one example, Broughton et al. (2017) reported a 73 % agreement between WLF height classes in a lidar-derived model for southwest England, compared to ground-truthed height estimates. However, that study involved different lidar data and processing, and limited ground truthing compared to our hedgerows model. Due to the novelty of a large-scale assessment of a lidar-derived model versus ground truthing, the performance of our hedgerows model is difficult to contextualize.

If assuming that the CS ground truthing was definitive in representing accurate WLF height values at the time of the lidar surveys, then the results showed that the hedgerows model tended to underestimate the WLF height classes. Overcoming the issues underlying the disparity (such as the temporal mismatch of surveys) would require very contemporaneous data collection within the same season for the lidar and ground truthing, which would be logistically impractical at such a scale. Because the dynamics of hedgerows management over one or several years means their height can change by several metres (Croxton et al., 2004; Staley et al., 2015), such variation seems inevitable where ground truthing and remote sensing cannot be closely synchronized.

Since the release of our hedgerows model in 2024 (Broughton et al., 2024), two other UK commercial products were launched that mapped hedgerows or WLF, including Bluesky International Limited's National Hedgerow Map (NHM™, https://bluesky-world.com/national-hedgerow-map/) and the Ordnance Survey's Field Boundary layer (https://docs.os.uk/osngd/data-structure/structures/structure-features/field-boundary). These products were created using stereo aerial photography, spectral imagery and/or lidar, and their specifications differ substantially from each other and our hedgerows model in their spatial elements (e.g. polylines or polygons), height parameters and underlying spatial resolutions. Validation information for these datasets is also not publicly available for comparison.

As such, a plurality of WLF mapping products is emerging that vary in their availability (e.g. purely commercial or free licensing for academic and/or public sector use), and also their spatial extent and integration with other proprietary data products. As it is based on the same spatial framework, our hedgerows model integrates seamlessly with a range of widely used UKCEH data products, including the UKCEH Land Cover Maps (e.g. Marston et al., 2022) and annual crop maps (Upcott et al., 2023). The hedgerows model therefore has a unique niche that contributes to a more comprehensive representation of England's rural landscape.

National-scale mapping of WLF networks using remote sensing has enormous potential as a monitoring, planning, management and research tool. For example, our model identifies English counties (Fig. 3) or smaller administrative areas with low densities of WLF, which could be targeted for planting to improve biodiversity and cultural services (Oreszczyn and Lane, 2000; Graham et al., 2018; Staley et al., 2023). Within a planning framework, where hedgerows are lost to development then a comprehensive WLF model enables the losses to be quantified, and new areas identified for appropriate design and enforcement of mitigation or offsetting (Hanson and Olsson, 2023; Thornhill et al., 2025). At a finer resolution, our model could identify gaps in the WLF networks to direct planting at the field or farm-scale to reduce water runoff, soil erosion and nutrient loss (Forman and Baudry, 1984; Wolton et al., 2014; Montgomery et al., 2020). Identifying outgrown hedgerows in the 4.0–5.9 m or $\geq$ 6 m height classes within our model could target WLF for restoration to bring back into management (Staley et al., 2023, 2024). The model could also assist with managing a diverse height distribution of WLF as habitats for farmland biodiversity (Hinsley and Bellamy, 2000; Broughton et al., 2021) and to ensure habitat connectivity for bats and birds (Alderman et al., 2011; Finch et al., 2020). Importantly, on a national scale the comprehensive mapping of WLF could also facilitate estimates of current (or future) potential carbon sequestration and storage, contributing to net zero targets (Biffi et al., 2022, 2023).

A major ambition for remote sensing models is to provide spatially explicit information on the WLF stock and its changes to complement, upscale or reduce the reliance on labour-intensive ground-based surveys (Norton et al., 2024). Although remote sensing is now capable of modelling the extent of WLF, as shown by the close agreement between the hedgerows model and the CS ground truthing in sample squares, the modelling of WLF heights comparable to ground surveys is less established. Furthermore, many variables of WLF condition that are currently recorded by ground truthing remain beyond the scope of routine remote sensing at the national scale, such as determining hedgerow species composition and vegetation structure for assessing habitat condition or management type (Staley et al., 2020).

These limitations mean that remote sensing is unable to fully replace large-scale ground surveys in the near future, and still benefits from aligned field surveys for validation, as demonstrated here. The current value of remote sensing perhaps lies not in fully replacing WLF ground surveys, but in better targeting to aid contextualisation and upscaling of results, while increasing the accuracy of further modelling through combined approaches (Rhodes et al., 2015). Advances in data capture and processing power will continue to improve remote sensing capability, but there are trade-offs with costs of data acquisition, storage and analysis, and identifying the best combinations of data types should be a key goal. One uncertainty to address is the ability of public sector agencies to resource repeated national campaigns of data collection (like the EA's National Lidar Programme) for the rolling monitoring of WLF change, e.g. 5-yearly. Commercial data products are increasingly providing this capability, but affordability may then be a barrier for many public sector agencies, conservation charities, academia and research institutes, and the extent of ground truthing validation is unlikely to be as comprehensive as in the CS survey.

5. Conclusions

Despite some limitations, our hedgerows model demonstrated how non-commercial lidar data could be processed to successfully produce a national model that well-represented WLF extent, and also provide a moderate representation of the height profile. However, the data volume for a national-scale model required processing within a high-performance computing environment, while validation required extensive ground truthing from national survey data. Nevertheless, the methodology represented a progression and improved accuracy from previous attempts at creating national models of WLF within Britain (e.g. Scholefield at el. 2016). The resulting data product of a national WLF coverage for rural England (Broughton et al., 2024) has significant potential value for planning, conservation and monitoring.

Despite the remaining limitations with our methodology, the ongoing capture and increasing availability of extensive lidar data for Europe (Florio et al., 2021) allows a similar or improved approach to be repeated for England and other countries. However, assessing the detailed condition and species composition of hedgerows and other WLF using large-scale remote sensing remains a challenge. Where possible, synchronized and representative field data should be available to validate such models (for feature extent and dimensions) and provide additional information on WLF type and condition.

CRediT authorship contribution statement

Richard K. Broughton: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rich J. Burkmar:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Morag E. McCracken:** Writing – review & editing, Project administration, Methodology, Investigation. **Nadine Mitschunas:** Writing – review & editing, Validation, Investigation. **Lisa R. Norton:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Denise W. Pallett:** Writing – review & editing, Validation, Investigation. **Justine Patton:** Writing – review & editing, Validation, Investigation. **John W. Redhead:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jo T. Staley:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Claire M. Wood:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Richard F. Pywell:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Data accessibility

The UKCEH hedgerows model is available from the EIDC repository: https://doi.org/10.5285/d90a3733-2949-4dfa-8ac2-a88aef8699be. The model is freely licensed for most UK academic and public sector use, or under a commercial license for private sector use. The lidar source data for England are publicly available without restriction from the EA National LIDAR Programme: https://www.data.gov.uk/dataset/f0db0249-f17b-4036-9e65-309148c97ce4/national-lidar-programme. Coding and scripts are not publicly available due to commercial sensitivity. Countryside Survey ground-truthing source data are sensitive due to privacy and access agreements, but licensing agreements are possible on request: https://www.ceh.ac.uk/our-science/projects/cs-policy.

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.jenvman.2025.126705.

Data availability

The data that has been used is confidential.

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