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Vehicular tracks and the influence of land use and habitat protection in the British uplands

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1. Introduction

Upland areas contain a number of fragile soil types that include immature Lithosols and Regosols (Pearsall, 1950; Bibby, 1984; Gordon et al., 2001), Folic Histosols (Fox and Tarnocai, 2011) and carbon-rich peats (Fibric Histosols (FAO, 1988); Bragg and Tallis, 2001). The landscapes overlying these soils also support a range of ecologically sensitive habitats of both national and global importance (Ratcliffe and Thompson, 1988; Thompson et al., 1995; EEA, 2010). Together these provide other ecosystem services including: water provision and regulation (Viviroli and Weingartner, 2004); field sports (Simmons, 2003); tourism (Fredman and Heberlein, 2005); renewable energy production (Thompson et al., 2005); agriculture (Mansfield, 2011); and commercial forestry (Bunce et al., 2014). Mountains cover 25% of the Earth’s land surface but the ecological value and importance of upland ecosystems are often disproportionate to their extent. In the UK, for example, despite covering <30% of the land by area, uplands contain almost 60% of the national designated Natura 2000 sites (EEA, 2010).

Upland environments are vulnerable to anthropogenic threats encompassing multiple spatial scales. The global and regional impacts of climate change (Gallego-Sala and Prentice, 2013) and atmospheric pollution (Caporn and Emmett, 2009) interact with more localised threats such as land management (Clutterbuck and Yallop, 2010), domestic livestock production (Chico et al., 2019), and recreation (Kincey and Challis, 2010; Pickering et al., 2011). Changes in agricultural practices and upland utilisation create a requirement for increased vehicular access, often in areas well beyond the official road networks, which increases the potential for damage and degradation of upland ecosystems (Lindsay et al., 2016).

Both surfaced and unsurfaced vehicle tracks can have significant adverse environmental impacts including: soil disturbance (Bayfield et al., 1984); soil compaction (Sack and da Luz, 2003); peat subsidence (Wawrzyczek et al., 2018); reduced soil moisture (Charman and Pollard, 1995); and increased surface runoff (Ziegler and Giambelluca, 1997), erosion (Gager and Conacher, 2001; McHugh, 2007) and sediment delivery (Fahey and Coker, 1989; Ziegler et al., 2004). The latter can alter downstream flow regimes, water quality and aquatic habitats (Arp and Simmons, 2012). Vehicle use has also been linked to the spread of invasive species (Rooney, 2005), reduced soil microfauna (Kevan et al., 1995; Niwranski et al., 2002), elevated risk to the establishment and movement of vulnerable animal species (Mammides et al., 2016), and persistent loss of vegetation cover (Bayfield et al., 1984). Even limited use in some habitats may have measurable consequences. In upland tundra, for example, the single passage of a tracked vehicle in summer can impact plant community structure for decades (Forbes, 1988). Even where unsurfaced tracks are later abandoned, the rapidity and extent of vegetation recovery is dependent on the communities affected. Heathland and grassland vegetation in the uplands may respond rapidly, whereas more sensitive communities such as on blanket bog frequently fail to show recovery 24 years after abandonment (Charman and Pollard, 1995).

Given the extent of these environmental impacts, and existing concerns for upland biodiversity and habitat condition (Amar et al., 2012; Ohlemüller et al., 2008; Thirgood and Redpath., 2009), it is perhaps not surprising that vehicle tracks in the uplands have been a contentious issue for several decades (Prior and Raemakers, 2006). Conservationists and recreational users are generally opposed to the development of tracks, particularly expressing concern over their development in designated areas (e.g. Watson, 2011; Brown, 2013). It might be reasonably expected, therefore, that vehicle use in upland areas would be controlled by legislation. In the United States off-road vehicle (ORV) use is commonly permitted in restricted upland zones, but only on designated trails within specific time periods (e.g. Sack and da Luz, 2003). ORV users are also required to obtain permits to use designated trails (e.g. National Park Service, 2014). However, in countries such as Great Britain there are currently no controls on *ad hoc* ORV travel across upland areas.

In the case of surfaced tracks in Great Britain, the situation is more complex. The provision, rearrangement or replacement of a private way associated with some activities, such as renewable energy production (Wawrzyczek et al., 2018), are regarded as developments requiring planning permission from the Local Planning Authority (LPA). However, this does not apply if the purpose of the track is for agriculture or forestry in non-protected areas. Planning legislation covering Great Britain considers surfaced tracks for agriculture or forestry as permitted developments (UK Government, 1990; 2014). Under this legislation, developers are only required to seek prior notification from the LPA to determine whether prior approval is needed in respect of the design, manner of construction or route of the private way. Where new surfaced tracks or historical routes requiring significant alteration are proposed in areas protected by conservation legislation, the position is different and consent by the relevant national Statutory Nature Conservation Body (SNCB) is required.

Given the sensitivity of the upland soil/habitat matrix, it might be expected that SNCBs would use legislation to keep the extent of vehicle tracks in areas of conservation importance to a minimum. While generic land cover within upland areas is routinely reported through land cover mapping (e.g. Feranec et al., 2007; EEA, 2017; Rowland et al., 2017), the extent to which sensitive upland habitats and soils are impacted by vehicle tracks is currently not known or monitored. As such, there is currently no quantitative reporting of the extent or location of tracks in upland areas with which to judge either the real importance of this issue or the success of current controls.

The aim of this study was to address this deficiency by providing, for the first time, quantitative estimates of the current extent of vehicular tracks across a sample of the uplands of Great Britain and to judge their impact by land cover, soil type (specifically blanket peat) and protective habitat designation. Land cover classes included grass/sedge dominated, heather dominated (managed and unmanaged), heather-grass vegetation, broadleaf woodland and ‘other’ (exposed rock and mining/quarries). We also used an information theory approach (Burnham and Anderson 2002) to formulate a set of *a priori* models to predict the presence and extent of surfaced vehicular tracks as a function of land cover, protected status, extent of blanket peat, proximity to areas of human population and altitude to identify drivers most strongly influencing vehicular track development in upland Britain.

2. Methods

2.1. GB upland area and study sample

Digital vector data providing land classification of Great Britain were obtained from Countryside Survey (CS) mapping (Wood, 2013). Environmental Zones designated as ‘Uplands’ for England and Wales, and ‘True Uplands’ for Scotland were selected as representative of upland habitat across mainland Great Britain (Fig. 1; 58,045 km^2). National Grid Reference mapping data were obtained from Ordnance Survey (OS) and 10 km x 10 km grid squares (‘OS grid squares’ hereafter) were used as primary study sample units. Using ArcGIS, OS grid squares were intersected with the CS upland zones and the mean upland coverage by OS grid square determined. A sample area of 2% has been shown to produce good results for estimating the extent of management burning in upland areas (Yallop et al., 2006). For this study, the number of grid squares required to provide a 5% sample of CS upland for each country were randomly selected using the Geospatial Modelling Environment (GME) package in R (version 3.5.2; R Development Core Team 2018). This procedure identified 10-27 sample

OS grid squares for each country that contained a sample of 5.4 - 5.7% of CS upland for each country (Table 1).

Sample OS grid squares and the extent of CS upland within each grid square were assessed using imagery and OS mapping overlays in Google Earth (GE). Environmental Zones in CS data are classified by environmental variables, including climate, altitude and slope (Bunce et al., 1996) and created at a resolution of 1 km. For consistent assessment, the upland extent in all sample squares was revised at finer-scale to only include areas of land above the limit of agricultural enclosure or, for remote areas where no enclosure was present, only land above the OS 250 m contour marked on 1:50000 scale mapping (Ratcliffe and Thompson, 1988; Backshall et al., 2001; Table 1). Reservoirs covering areas larger than 1 km^2 that fell within the upland sample areas were excluded, and the coverage of imagery for all sample squares (ranging from 2007 to 2016) was digitised and attributed by year (Supplemental Table 1).

2.2. Identification and mapping of vehicle tracks

Vehicle tracks were digitised as linear features visible in the most recent imagery available in GE and recorded as either surfaced or unsurfaced in appearance. The primary identifying feature of unsurfaced tracks was the presence of parallel lines/tyre marks extending for distances greater than 100 m, with reduced or altered plant growth (Fig. 2a) and erosion of soil/substrate (Fig. 2b) visible along their length. Surfaced tracks were identified from the uniform, bright appearance that contrasts with the surrounding landscape and arises from the application of surfacing material (Fig. 2b). All footpaths and roads marked on OS mapping were additionally mapped and used to avoid false identification of these features, particularly surfaced or paved footpaths (Buckley, 2018). However, some sections of unsurfaced track were coincident with the location of footpaths recorded on OS mapping and where these extended for distances greater than 100 m, these sections of footpath were additionally assigned as a vehicle track.

Mapping of tracks was not undertaken in areas of coniferous plantation due to tracks being obscured by the tree canopy. Tyre tracks within mowing lines associated with vegetation cutting in heather-dominated areas (see Fig. 2b) were considered single use and were also excluded from mapping and statistical reporting.

2.3. *Classification of land cover*

Areas of major upland vegetation type (coniferous plantation, broadleaf woodland, ericaceous (predominantly *Calluna vulgaris* L.) and grass/sedge dominated vegetation (Yallop and Clutterbuck, 2009)) were digitised for the upland extent in each sample square using imagery in GE. In addition, *Calluna* dominated vegetation was separated into areas with and without visible evidence of prescribed fire management (Yallop et al., 2006; see Fig. 2b), areas where no dominant community of *Calluna* or grass/sedge could be visually determined were mapped as heather-grass vegetation, and further classes of exposed rock (such as mountain crags (Ellis et al., 1996) and limestone pavement (Goldie, 1993)), and areas of quarry/mining activity were recorded as 'other'.

The length of each mapped track was examined in GE, even where this led outside the sample grid square, and it was noted where these led to, or continued past, a building (e.g. house, sheep pen), plantation, quarry, pylon/radio mast, wind farm or reservoir. It was not possible to determine whether these tracks were created for these features or if the tracks were already present and had since been adopted for additional use. These tracks were, therefore, attributed as multi-use tracks

(Prior and Raemakers, 2006) and included in analysis. Track and land cover data were exported to ArcGIS for spatial analysis.

2.4. Areas of designated protection and blanket peat

Conservation legislation covering the British uplands includes both European-wide and national protective designations. Natura 2000 is the largest coordinated network of protected sites in the World protecting over 1000 rare and threatened animal and plant species and 200 habitat types (European Commission, 2008). Founded on two key pieces of European Union legislation – the 1979 Birds Directive 2009/147/EC (formerly 79/409/EEC) and the 1992 Habitats Directive 92/43/EEC – Natura 2000 designates Special Protection Areas (SPA) and Special Areas of Conservation (SAC) respectively. Under the UK's Wildlife and Countryside Act 1981 (JNCC, 2015), sites with features of special interest such as wildlife, geology and landforms are designated and protected as Sites of Specific Scientific Interest (SSSI). Digital vector data containing the extent of all SPA, SAC and SSSI were obtained from respective SNCB's and merged to create an extent of combined 'designated protected area'.

Digital vector soil data for England and Wales were obtained from the National Soil Resources Institute (NSRI, 2001) and for Scotland from the James Hutton Institute (JHI, 2013). Soil units identified as blanket peat were extracted for each country (1011a-b and 1013a-b for England and Wales; 4, 124, 215 and 604-606 for Scotland; Table 1). Blanket peat soils were selected as they account for around 50% of the UK total soil carbon (Milne and Brown, 1997) and can support globally important blanket bog habitat (Lindsay et al., 1988). Only half (54%) of blanket peat in the sample lies within areas of protective designation (Table 1).

2.5. Data summary

Surfaced and unsurfaced track data were intersected with land cover, area of designation and area of blanket peat to determine track length (km) and density of tracks (km km^{-2}) for all combinations. Mapped footpath data were intersected with areas of designation and areas of blanket peat. As the squares contained different amounts of upland, the weighted arithmetic mean and weighted sample variance of track density for all squares were calculated to report statistics on track type and density.

2.6. Determination of covariates

Information on geographical location, proximity to human habitation and altitude were included in models to identify the most important predictors of the presence and density of surfaced tracks. To improve the resolution of geographical information for analysis, a grid comprising 1 x 1 km squares was created for the extent of the sample area using ArcGIS.

The geographical location of the centroid of each 1 km square was determined in latitude and longitude (decimal degrees in WGS84). Postcodes covering mainland Great Britain were obtained from OS Code-Point OpenData, and the distance from the centroid of each 1 km square to the nearest postcode determined. Mean altitude for the area of upland contained in each 1 km square was determined from OS Land-Form PANORAMA elevation data (50 m resolution). The 1 km grid squares were subsequently intersected with surfaced track data, land cover, areas of designation and areas of blanket peat.

2.6.1. Statistical analysis

Data were modelled using R (version 3.5.2; R Development Core Team 2018) with models fitted in a Bayesian framework using Integrated Nested Laplace Approximation (R-INLA; Rue et al. 2017). We used an information theory approach (Burnham and Anderson 2002), formulating 18 ecologically plausible alternative models (Table 2), with the best-fitting models identified based on Watanabe-Akaike Information Criterion (WAIC) (Vehtari et al. 2017). This was not an exhaustive list of models but was considered a coherent list of competing hypotheses. For the variable 'country', data for England and Wales were pooled due to imbalance (deviation from orthogonality).

Bayesian inference is robust in dealing with relatively complex datasets like the one in the present study, specifically unbalanced data, an inherent lack of dependency due to repeated measures at sampling sites, and a highly varied non-normal response variable. Bayesian models are flexible in allowing the estimation of a posterior distribution of differences between parameters and across levels of factors. These are relatively straightforward procedures using Bayesian inference, but extremely problematic in a frequentist framework (Zuur et al. 2014; Kruschke 2015), notwithstanding more general reservations in using frequentist analyses (Burnham and Anderson 2014). Integrated Nested Laplace Approximation (INLA) is an increasingly popular package in R for Bayesian inference. INLA is a deterministic Bayesian method, which means results are repeatable, in contrast to probabilistic methods. It permits a wide range of functions to be fitted, is relatively simple to use and is computationally efficient.

Data for density of tracks were zero inflated. To accommodate this data structure, we used a hurdle model. Hurdle models are partitioned into two parts, with a binary process modelling probability of an event, and a second process modelling the magnitude of an event (Hilbe 2014). In the case of track data, we compared each 1 km square without surfaced tracks to those with surfaced tracks using a binary (Bernoulli) process, while for zero-truncated data we used a gamma distribution to accommodate a continuous and strictly positive data distribution (Zuur et al. 2014). This modeling approach enabled us to separately identify which models best explained: 1. the probability of surfaced vehicle tracks in 1 km squares; 2. the density of surfaced tracks in 1 km squares where tracks occurred. Standard error of the regression (*S*), the standard distance between observations and the fitted model, was used as a measure of model goodness-of-fit.

3. Results

3.1. Sample area

The total area sampled comprised 5.5% (3195 km^2) of the area identified as upland in CS data for mainland Great Britain. This provided a revised 2332 km^2 of the British uplands delimited to land above the limit of agricultural enclosure or above the OS 250 m contour. 18% of this area was found to be coniferous plantation (Table 1), resulting in the upland sample assessed here totalling 1910 km^2. Within this sample, 36% comprised areas with protective habitat designation (679 km^2) and 16% areas of blanket peat (301 km^2). These represent between 4.1-6.4% and 3.2-5.9% of the total area of protected habitat and blanket peat in CS upland data respectively (Table 1).

3.2. Track distribution and type

A total length of 2104 km of vehicular track visible in imagery dating from 2007 to 2016 was identified in the sampled area (Table 3), which equates to a mean (± SE) track density of 1.10 ± 0.15 km km^{-2} across the British uplands. The majority (1538 km) were classified as unsurfaced and 27% (566 km) surfaced (Table 3). The mean density of all tracks mapped in both England (2.17 ± 0.14 km km^{-2}) and Wales (2.19 ± 0.42 km km^{-2}) is four times greater than the mean density of all tracks mapped in Scotland (0.56 ± 0.12 km km^{-2}).

The density of surfaced tracks mapped in Scotland (0.22 ± 0.05 km km^{-2}) was lower than those mapped in both England (0.40 ± 0.07 km km^{-2}) and Wales (0.50 ± 0.05 km km^{-2}). However, as a proportion of all tracks mapped, twice the amount of tracks in Scotland (40%) were surfaced compared to 19% and 23% of tracks for England and Wales respectively (Table 3).

3.3. Tracks by land cover, designation and blanket peat

Assessment of land cover across the whole sample shows that the highest mean density of tracks (1.76 ± 0.18 km km^{-2}) exists within areas of managed heather (Table 4), 65% greater than the density of tracks identified in unmanaged heather (1.07 ± 0.18 km km^{-2}) and grass-dominated areas (1.07 ± 0.17 km km^{-2}). The density of tracks in heather-grass vegetation, broadleaf woodland and other land cover (rock outcrops and quarries) were all at least 25% lower than the mean density across the entire upland sample, with the lowest density recorded on 'other' land cover (0.32 ± 0.16 km km^{-2}; Table 4). Split by track type, the highest mean density of both unsurfaced (1.23 ± 0.17 km km^{-2}) and surfaced tracks (0.52 ± 0.06 km km^{-2}) were found within areas of managed heather (Table 4). Country level statistics are presented in Supplemental Table 2.

Comparison of the extent of tracks within and outside of designated areas are presented in Supplemental Table 3. The highest density of surfaced tracks in designated areas was identified in areas of managed heather (0.39-0.52 km km^{-2}; Supplemental Table 4). This surfaced track density is higher than the mean surfaced track density across the whole sample in each country (Table 3) and in Scotland the density of surfaced tracks in managed heather (0.39 ± 0.05 km km^{-2}) is almost twice the density of surfaced tracks in non-designated areas (0.26 ± 0.07 km km^{-2}; Supplemental Table 4).

The extent of tracks by soil type are presented in Supplemental Table 5. In Scotland and Wales, the highest density of surfaced tracks on blanket peat was identified in areas of managed heather (0.69-1.24 km km^{-2}; Supplemental Table 6). This surfaced track density is 2-3 times greater than the mean surfaced track density on other soils in both countries (0.23-0.55 km km^{-2}).

3.4. Models

3.4.1. Probability of surfaced tracks

The best-fitting model, determined by WAIC, to predict the probability of the presence or absence of surfaced tracks in each 1 km square grid square was model M18 (Table 2), which took the form:

$$Ptrack_{ij} \sim Binomial(\pi_{ij})$$

$$E(Ptrack_{ij}) = \pi_{ij} \text{ where } var(Ptrack_{ij}) = \pi_{ij} \times (1 - \pi_{ij})$$

$$logit(\pi_{ij}) = \eta_{ij}$$

$$\eta_{ij} = \beta_1 + \beta_2 \times dist_{ij} \times \beta_3 \times alt_{ij} + \beta_4 \times grass_{ij} + \beta_5 \times mheath_{ij} + block_j$$

$$block_j \sim N(0, \sigma^2_{block})$$

Where $Ptrack_{ij}$ is the probability π of 1 km square i showing visible evidence of tracks in 10 km square (*block*) j. The variable $dist_{ij}$ is a continuous covariate representing distance to postcode (km), alt_{ij} is a continuous covariate representing altitude (m), $grass_{ij}$ is a continuous covariate equating with area of grass-dominated areas (km^2), and $mheath_{ij}$ is a continuous covariate equating with area of managed heather (km^2). Exploratory analyses demonstrated dependency in the data among 1 km squares from the same 10 km squares. To accommodate this dependency in the data, the random intercept $block_j$ was included to introduce a correlation structure between observations for different 1 km squares from the same 10 km square, with variance σ_{block} distributed normally and equal to 0.

The model predicted statistically important positive relationships between the probability of surfaced tracks and the area of grass-dominated vegetation and managed heather (Table 5; Figs 3A-B). There was a statistically important negative interaction between the effects of distance to postcode and altitude on the probability of tracks; with a negative effect of altitude on the probability of tracks limited by proximity to areas of population (Table 6; Fig. 4). The standard error of the regression (*S*) was estimated to be 0.62 (95% credible intervals 0.35-1.00). Thus, 95% of model predictions for the probability of an average 1 km^2 block being surfaced was estimated to lie between 0.35-1.00.

3.4.2. Extent of surfaced tracks

For zero-truncated data, the best-fitting model to predict the density tracks in each 1 km square grid square was model M14 (Table 2). The fitted model took the form:

$$Dtrack_{ij} \sim Gamma(\mu_{ij}, \phi)$$

$$E(Dtrack_{ij}) = \mu_{ij} \text{ and } var(Dtrack_{ij}) = \frac{\mu_{ij}^2}{\phi}$$

$$log(\mu_{ij}) = \eta_{ij}$$

$$\eta_{ij} = \beta_1 + \beta_2 \times grass_{ij} \times \beta_3 \times mheath_{ij} + block_j$$

$$block_j \sim N(0, \sigma_{block}^2)$$

Where $Dtrack_{ij}$ is the density of tracks in 1 km square *i* in 10 km square (*block*) *j*, assuming a gamma distribution with mean μ and precision ϕ. The variables $grass_{ij}$ and $mheath_{ij}$ were continuous covariates representing area (km^2) of grass-dominated vegetation and managed heather, respectively. $Block_j$ was included as a random intercept in the model. The model predicted statistically important positive effects of both area of grass-dominated vegetation and managed heather (Table 6; Figs 5A-B). S was 1.4 km (CrI 1.3-1.5); 95% of model predictions lay between 1.3-1.5 km of surfaced track for an average 1 km^2 block.

4. Discussion

This is the first study to make a national assessment of the extent of vehicular tracks in upland areas. By examining an approximately 5% sample of the uplands of Great Britain we provide an estimate of the length of tracks in current use broken down by track type, land cover, soil type and protective designation. Using an information theory approach, we formulated a set of *a priori* alternative models to enable inclusion of geographical and topographical variables to compare alternative predictors of track presence and length.

4.1. Presence and extent of upland tracks

The length of all vehicular tracks mapped (2104 km) was six times greater than the length of footpath marked on OS mapping (355 km; Supplemental Table 7), indicating that the British uplands may currently be accessed to a far higher degree by motorised vehicles than walkers. Although footpath erosion can be significant in creating gullies (Kincey and Challis, 2010), erosion caused by vehicles is five times greater (McHugh, 2007) and it is concerning to note that 25% of the length of footpaths marked on OS mapping showed evidence of being used by vehicles (Supplemental Table 7). The extent of track mapped in the sample equates to a mean density of vehicle track in the British uplands of 1.10 ± 0.15 km km^{-2}, and although environmental impacts of tracks are widely reported (Bayfield et al., 1984; Forbes, 1988; Charman and Pollard, 1995; Sack and da Luz, 2003; Wawrzyczek et al., 2018) there is little published information on the extent of upland tracks elsewhere with which to compare the density estimated here. However, this mean density of vehicle tracks is over seven times greater than the density of ORV tracks mapped in the area surrounding Lake Johnstone, Western Australia (0.15 km km^{-2}; Westcott and Andrew, 2015). Given that this comparatively low level of track density has raised concerns over damage to features of conservation value at this location (Westcott and Andrew, 2015), it is concerning to note that the mean density of tracks in the uplands of England (2.17 ± 0.14 km km^{-2}) and Wales (2.19 ± 0.42 km km^{-2}) is over 14 times greater. The density of vehicle tracks in the British uplands is equally striking when compared to the density of the public road network, which in the UK equates to 0.17 km km^{-2} (Knoema, 2011).

Ecological and environmental damage resulting from vehicle tracks has been noted in upland areas worldwide including in other parts of Europe (Heras and Infante, 2018), Canada (Kevan et al., 1995), North America (Arp and Simmons, 2012; Sack and Da Luz, 2003), Thailand (Ziegler et al., 2004) and New Zealand (Fahey & Coker, 1989). In the absence of data on the actual extent of vehicle tracks it is not possible to assess whether upland areas are accessed by vehicles at these levels globally. It is worth noting that the ecological impacts of vehicle traffic, such as the effect of dust on vegetation and the blockage of wildlife corridors, typically extend for distances >100 m from roads (Forman, 2000). Assessments of road networks globally indicate that around 80% of the Earth's land surface is roadless (i.e. >1 km from a road; Ibisch et al., 2016). However, the roadless area is fragmented into 600,000 patches of which more than half are <1 km^2 in size (Ibisch et al., 2016), but it is not clear which habitats are impacted most. Given that mountainous areas cover 25% of the Earth's surface (Thompson et al., 2005), this highlights an urgent need for wider quantification of track extent to understand if globally important upland habitats and soils are experiencing higher pressure of vehicles than other areas.

The lower density of tracks mapped in Scotland in this study (0.56 ± 0.12 km km^{-2}) most likely reflects the more remote nature of the Scottish uplands, with 85% of the population of mainland GB located in

England and Wales (ONS, 2018). The inference that more remote areas are less accessible and are less likely to have tracks is supported by the identification of a negative interaction between the effects of distance to postcode and altitude on the probability of surfaced track in the best-fitting Bernoulli model (Fig. 4). However, none of the models predicting track presence based solely on remoteness (M01-M05) were identified as the best-fitting model, and land cover proved a better predictor of the presence and extent of tracks (Table 6).

4.2. Extent of tracks by land cover

The highest density of tracks was associated with areas of heather-dominated vegetation managed by burning or cutting, an activity undertaken for grouse shooting (Table 3). This effect was positive, with a greater extent of surfaced tracks associated with a larger area of managed heather (Fig. 3A). A comparable effect was seen with the area of grass-dominated vegetation typically associated with sheep farming (Table 3; Fig. 3B). However, these overall statistics are slightly biased by the proportion of upland in GB that lie within Scotland (67% of the sample), although country (model M03) and geographic location (model M06) were not identified as important covariates predicting track presence or extent. While the mean density of both surfaced and unsurfaced tracks in managed heather in Scotland is more than twice the density of tracks mapped in any other land cover, in England and Wales high densities of tracks were identified in several land covers, particularly grass-dominated vegetation and areas of heather-dominated vegetation (with and without signs of management; Supplemental Table 2).

4.3. Tracks by protective designation

Given the national and global importance of designated upland habitats, our findings suggest that the density of surfaced and unsurfaced tracks is lower in areas of conservation importance than outside (Supplemental Table 3). However, our analysis reveals this pattern to be more complex. The prediction of model M10 (Table 2) supports the value of designation in protecting these sites, with a negative relationship between the probability of encountering surfaced tracks and the extent of protection for a given 1 km^2; mean (credible intervals) -0.13 (-0.25 to -0.01). However, where surfaced tracks occur, the area protected is unrelated to the extent of surfaced tracks; mean (credible intervals) -0.03 (-0.10 to 0.04). The implication of this finding is that protected status is effective in limiting the establishment of surfaced tracks in a given location, but once surfaced tracks are constructed, their further development appears not to be constrained by its protected status.

Examining designated areas by land cover revealed that the highest densities of surfaced tracks in all three countries (0.39-0.52 km km^{-2}) occur in areas of managed heather. In Scotland this figure is higher than the mean density of surfaced tracks outside of designated areas. We recognise that some tracks may pass through one land cover to access other land cover beyond. However, the proportion of surfaced tracks that were classified as multi-use showed that in England the majority (76%) of surfaced tracks in designated areas of managed heather were constructed solely for access to that habitat. In both Scotland and Wales this figure was 100% (Supplemental Table 8). These data indicate significant pressure, as a result of land use or management that is not for ecological or conservation activities, is being imposed on 'protected' areas. Notably, if only sites with some degree of protection are examined, our overall finding that the area of managed heather and grass-dominated vegetation predict the probability and extent of surfaced tracks is still supported (results not shown).

Overall then, designation of protected status may not be the most efficient tool for managing track development in upland areas. Protection is not a component of any of the best-fitting models we examined, with both the presence and extent of surfaced tracks driven primarily by the extent of managed heather and grass-dominated vegetation. While protection may be efficient in constraining the development of new surfaced tracks, we found no evidence that it limits their extent once established in an area. By extrapolation, based on the 14,046 km^2 of protected habitats located in upland Britain (Table 1), we estimate that 13,864 ± 3,827 km of vehicular track (2,572 ± 200 km surfaced) currently exists in areas of conservation interest (Supplemental Table 9).

4.4. *Tracks on blanket peat*

For the areas of blanket peat mapped that do not fall under protective designation (46%), there is currently no conservation legislation for tracks with which to assess the success of protection. This shortcoming may explain why the area of blanket peat (M11) was not identified as an important covariate predicting track presence or extent (Table 5). However, restoration of peatlands is now widely recognised as a key initiative to mitigate the impacts of climate change and help countries meet zero net carbon targets (CCC, 2020). Understanding the level of vehicular activity on blanket peat is, therefore, key to planning restoration strategies. We estimate that 6,820 ± 1,118 km of vehicular track exist on the 6,855 km^2 of blanket peat in upland Britain (Table 1; Supplemental Table 10) and found that 36% of unsurfaced footpaths on blanket peat show evidence of vehicular use (Supplemental Table 7).

4.5. *Policy implications*

Despite presumptions that protected habitats and sensitive soils would see little surfaced track usage, we show that land cover, regardless of protection, is a key driver of track presence and extent in the British uplands. The length of surfaced track constructed over areas of conservation interest and on blanket peat is concerning. Current legislation implies that all the tracks mapped in areas of designated habitat constructed since 1981 received consent from the relevant SNCB. This legislation also implies that all these constructed tracks would also have received either full planning permission or have been approved as a permitted development by the LPA. It is worth noting that tracks for purposes other than farming or forestry, such as access to game sport, have never been permitted developments (Prior and Raemakers, 2006). Unfortunately, we have no way of confirming whether the tracks identified in our study are legally permissive, but enforcement actions for unconsented surfaced tracks in designated upland sites have been undertaken in both England (Natural England, 2020) and Scotland (Cairngorms NPA, 2019).

On the assumption that full planning permission was granted for the surfaced tracks mapped in designated areas of managed heather in this study, these data raise questions as to whether consideration of the potential impacts of tracks on designated areas by LPAs and SNCBs are appropriate. Many unsurfaced tracks are transient features that if left unused may allow recovery of the habitat (Charman and Pollard, 1995), but constructed/surfaced tracks are now physical components of the upland landscape. There is a clear requirement for vehicular access for ecological improvement of upland areas and for hill farming activities, but we suggest that legislation for surfaced tracks, at the least, is reviewed. As vehicle damage to blanket bog has also resulted in several enforcement actions requiring habitat restoration (Natural England, 2020), the *ad hoc* use of vehicles on blanket peat may also need inclusion in upland track legislation. Both these measures are urgently required to protect and preserve the sensitive soils and habitats in upland Britain.

The accessibility of open source aerial photography enabled mapping of vehicle tracks across a range of land cover and also enabled the upland envelope to be refined. This approach allowed geographical variation in the upland limit across Great Britain to be accounted. The identification of vehicular activity in designated areas that is not facilitating ecological improvement highlights a clear need for wider quantification of the extent of tracks in uplands globally. Such assessment will determine how protective habitat designation is working more widely. The approach adopted in this study could be applied to any upland landscape.

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Figure 1. Location of study sample squares and Countryside Survey upland areas.

Figure 2. Appearance of tracks (surfaced and unsurfaced) and mow lines in imagery on Google Earth.

Figure 3. (A) Posterior mean fitted probability of surfaced tracks as a function of area of grassland (km^{-2}); (B) Area of managed heather (km^{-2}). Shaded area is the 95% credible intervals. Points are observed data for individual 1 km^2 blocks.

Figure 4. Posterior mean fitted probability of surfaced tracks as a function of altitude for upland sites 10 km, 2.5 km and 0.5 km from the centroid of each 1 km square to the nearest postcode. Shaded area is the 95% credible intervals. Points are observed data for individual 1 km^2 blocks.

Figure 5. (A) Posterior mean length of surfaced tracks as a function of area of managed heather (km^{-2}); (B) Area of grassland (km^{-2}). Shaded area is the 95% credible intervals. Points are observed data for individual 1 km^2 blocks.

Tables

Table 1. Upland areas in Great Britain (* excluding Northern Ireland) from Countryside Survey (CS) data and proportions sampled for mapping of extent of tracks.

	England	Scotland	Wales	Great Britain*
CS Data				
Total CS upland (km^2)	15739	32034	10272	58045
Sample OS grid squares	15	27	10	52
CS upland in sample (km^2)	860	1749	586	3195
Proportion of CS upland sampled (%)	5.4	5.5	5.7	5.5
CS upland with SSSI/SAC/SPA designation (km^2)	4196	8187	1663	14046
Proportion CS upland designated (%)	27	26	16	24
CS upland blanket peat (km^2)	2738	3472	644	6855
Proportion CS upland blanket peat (%)	17	11	6	12
Revised sample above agricultural enclosure or 250 m				
Revised upland sample extent (km^2)	505	1555	272	2332
Area with protective habitat designation (km^2)	270	340	75	685
Proportion of upland sample with designation (%)	53	22	27	24
Revised sample excluding plantation				
Revised upland sample squares excluding plantation	13	26	9	48
Revised upland sample excluding plantation (km^2)	423	1272	215	1910
Proportion of upland sample that is plantation (%)	16	18	21	18
Protected habitat designation				
Protected area designation (km^2)	270	335	74	679
Proportion of upland sample with designation (%)	64	26	35	36
Proportion of designation mapped (%)	6.4	4.1	4.5	4.8
Soil				

Blanket peat (km²)	161	112	28	301
Proportion of upland sample that is blanket peat (%)	38	9	13	16
Proportion of blanket peat in designated areas (%)	71	21	93	54
Proportion of upland blanket peat mapped (%)	5.9	3.2	4.3	4.4
Land Cover				
Grass/sedge dominated	171	708	173	1052
Unmanaged heather (Heather U)	28	96	9	134
Managed heather (Heather M)	124	194	7	325
Heather/grass vegetation	77	171	16	264
Broadleaf woodland	6	36	9	51
Other	16	67	<1	84

Table 2. *A priori* models to predict probability and extent of vehicle tracks in upland areas of Great Britain.

Model	Model formulation	Model description/justification
M01	distance to postcode	Proximity to human population positively associated with tracks
M02	altitude	Altitude negatively associated with tracks
M03	country	Differences in land use, altitude and human population density between countries
M04	distance x altitude	Shorter distances to population coupled with low altitude positively associated with tracks
M05	distance x altitude x country	Shorter distances to population coupled with low altitude positively associated with tracks and varies among countries
M06	latitude x longitude	Geographic location positively associated with tracks
M07	area of grassland	Grazing positively associated with tracks
M08	area of managed heather	Heather management positively associated with tracks
M09	area of unmanaged heather	Heather habitat positively associated with tracks
M10	area of protected habitat	Lack of protective designation positively associated with tracks
M11	area of blanket peat	Blanket peat negatively associated with tracks
M12	area of protected habitat + area of managed heather	Lack of protective designation and heather management positively associated with tracks
M13	area of protected habitat + area of unmanaged heather	Lack of protective designation and heather habitat positively associated with tracks
M14	area of grassland + area of managed heather	Grazing and heather management positively associated with tracks
M15	area of grassland x country + area of managed heather x country	Grazing and heather habitat positively associated with tracks and the effects of each vary between counties
M16	area of grassland + distance x altitude	Grazing and shorter distances to population coupled with low altitude positively associated with tracks
M17	area managed heather + distance x altitude	Managed heather and shorter distances to population coupled with low altitude positively associated with tracks
M18	area of grassland + area of managed heather + distance x	Grazing, managed heather and shorter distances to population coupled with low altitude positively

altitude	associated with tracks

Table 3. Extent of tracks (total length and density) across sample of upland areas in mainland Great Britain.

Sample area	Upland area (km^{2})	All tracks		Unsurfaced		Surfaced	
		Length (km)	Mean (± SE) density (km km^{-2})	Length (km)	Mean (± SE) density (km km^{-2})	Length (km)	Mean (± SE) density (km km^{-2})
England	423	920	2.17 (± 0.14)	748	1.77 (± 0.13)	171	0.40 (± 0.07)
Scotland	1272	712	0.56 (± 0.12)	426	0.33 (± 0.30)	286	0.22 (± 0.05)
Wales	215	472	2.19 (± 0.42)	364	1.69 (± 0.38)	108	0.50 (± 0.14)
GB	1910	2104	1.10 (± 0.15)	1538	0.81 (± 0.13)	566	0.29 (± 0.04)

Table 4. Extent of tracks (total length and density) by land cover across sample of upland areas in mainland Great Britain.

Sample area	Upland area (km^2)	All tracks Length (km)	All tracks Mean (± SE) density (km km^{-2})	Unsurfaced Length (km)	Unsurfaced Mean (± SE) density (km km^{-2})	Surfaced Length (km)	Surfaced Mean (± SE) density (km km^{-2})
Grass	1052	1130	1.07 (± 0.17)	833	0.79 (± 0.15)	296	0.28 (± 0.04)
Heather U	134	143	1.07 (± 0.18)	112	0.84 (± 0.17)	30	0.22 (± 0.04)
Heather M	325	573	1.76 (± 0.18)	401	1.23 (± 0.17)	172	0.52 (± 0.06)
Heather/grass	264	197	0.75 (± 0.16)	150	0.57 (± 0.14)	47	0.18 (± 0.04)
Broadleaf	51	35	0.68 (± 0.19)	19	0.38 (± 0.13)	15	0.31 (± 0.12)
Other	84	27	0.32 (± 0.16)	22	0.26 (± 0.14)	5	0.06 (± 0.06)

Table 5. Fit of *a priori* models to predict the presence and extent of upland surfaced tracks. WAIC is Watanabe-Akaike Information Criterion score, Δ*i* is delta WAIC, ω is WAIC weighting.

Presence of surfaced tracks				Extent of surfaced tracks			
model	WAIC	Δ*i*	ω	model	WAIC	Δ*i*	ω
M18	2673	0	1.00	M14	980	0.0	0.63
M05	2729	56.1	0.00	M18	982	2.0	0.23
M16	2730	57.7	0.00	M15	983	3.1	0.14
M17	2731	58.5	0.00	M12	1014	33.9	0.00
M04	2759	86.6	0.00	M08	1015	35.2	0.00
M15	2771	97.9	0.00	M17	1015	35.2	0.00
M14	2783	110.3	0.00	M16	1020	40.0	0.00
M12	2810	137.4	0.00	M07	1022	42.4	0.00
M02	2817	144.4	0.00	M02	1027	47.1	0.00
M08	2822	149.1	0.00	M04	1027	47.4	0.00
M07	2829	156.1	0.00	M05	1028	48.2	0.00
M10	2847	174.7	0.00	M01	1029	49.3	0.00
M03	2851	178.1	0.00	M13	1031	51.2	0.00
M13	2851	178.1	0.00	M03	1032	52.4	0.00
M11	2852	179.0	0.00	M09	1033	53.1	0.00
M09	2853	180.2	0.00	M10	1034	53.9	0.00
M01	2853	180.5	0.00	M11	1034	54.4	0.00
M06	2853	180.5	0.00	M06	1035	55.5	0.00

Table 6. Posterior mean estimates of surfaced tracks for the best-fitting hurdle model using INLA with sampling block fitted as a random intercept. Occurrence data were fitted to a Bernoulli distribution, frequency data were fitted to a gamma distribution. CrI are the Bayesian credible intervals. Credible intervals that do not encompass zero in bold to indicate statistical importance.

	Occurrence model (M18)			Frequency model (M14)		
Parameter	Posterior mean	Lower CrI	Upper CrI	Posterior mean	Lower CrI	Upper CrI
Intercept	**-1.10**	**-1.53**	**-0.68**	**-0.39**	**-0.45**	**-0.33**
Grassland	**0.52**	**0.38**	**0.66**	**0.23**	**0.16**	**0.30**
Managed heather	**0.50**	**0.38**	**0.62**	**0.20**	**0.15**	**0.26**
Distance	0.10	-0.09	0.29	-	-	-
Altitude	**-0.61**	**-0.77**	**-0.46**	-	-	-
Distance x altitude	**-0.30**	**-0.44**	**-0.16**	-	-	-

Author contributions

Ben Clutterbuck: Conceptualization, Methodology, Validation, Writing – Original Draft, Visualization. **Wilmie Burton**: Investigation, Data Curation, Writing – Original Draft. **Richard Yarnell**: Conceptualization, Methodology, Writing – Original Draft. **Carl Smith**: Formal Analysis, Writing – Review & Editing, Visualization.

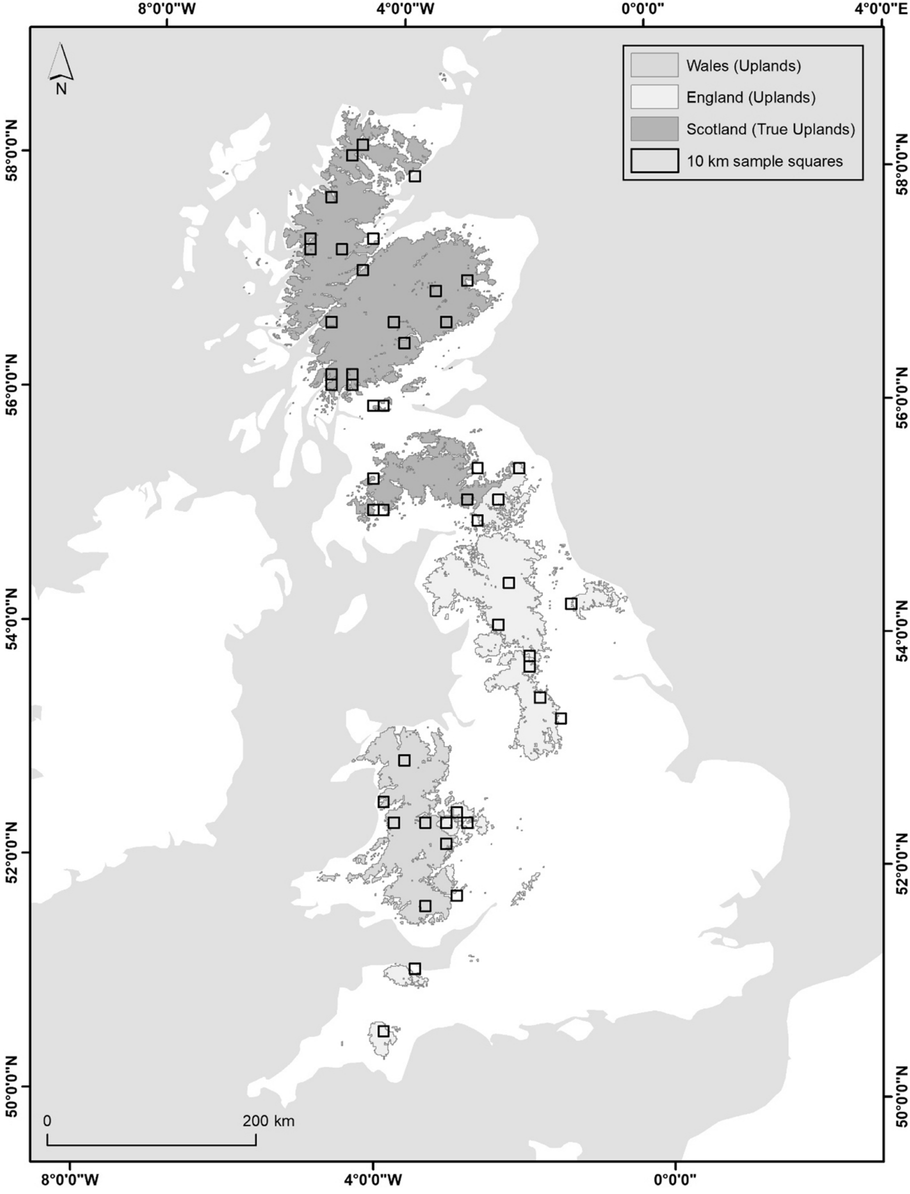
Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- First assessment of the extent of vehicle tracks in sensitive upland habitats
- Wide-ranging vehicular track networks exist in the British uplands
- Land use appears to be driving the presence of surfaced tracks in protected areas
- We recommend a review of upland track legislation in GB to protect these habitats
- Wider assessment of upland tracks is required globally



8°0'0"W
4°0'0"W
0°0'0"
4°0'0"E
58°0'0"N
56°0'0"N
54°0'0"N
52°0'0"N
50°0'0"N
N
Wales (Uplands)
England (Uplands)
Scotland (True Uplands)
10 km sample squares
0
200 km

Figure 1

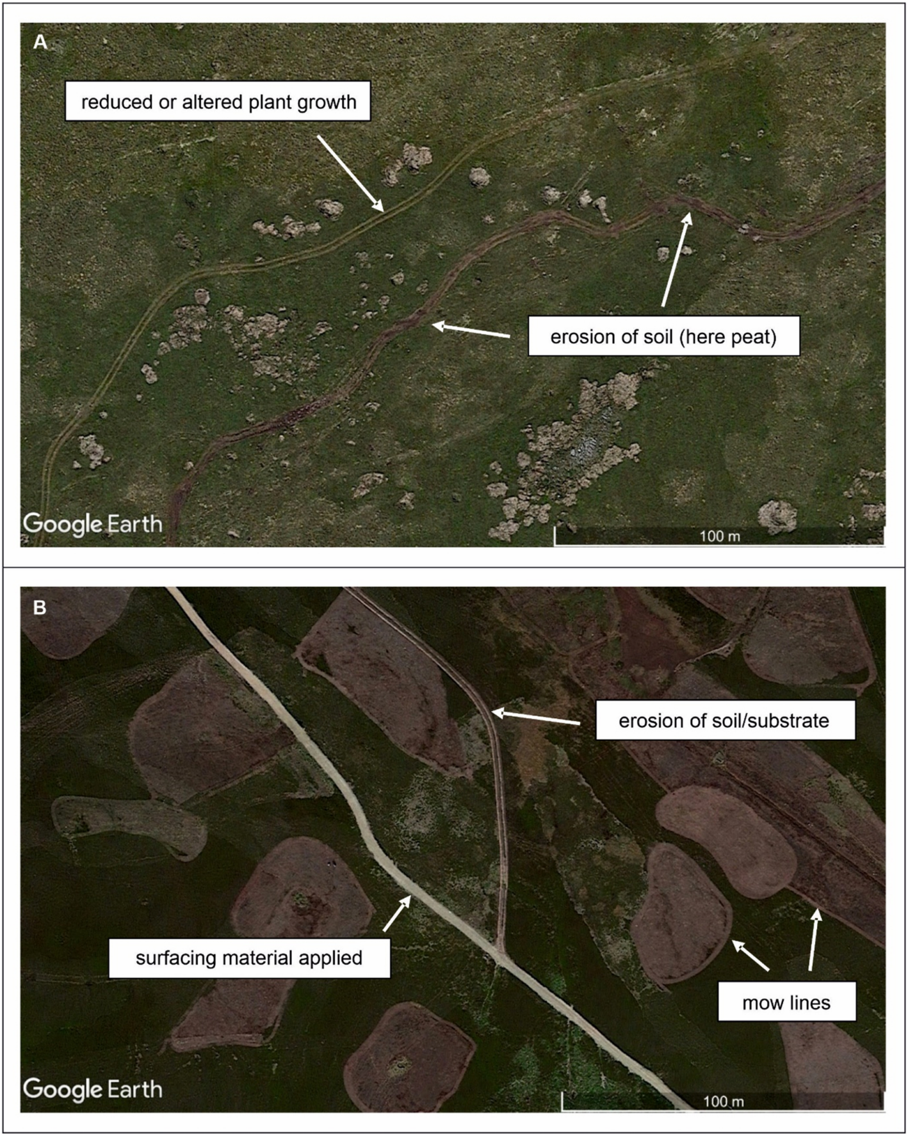

A
reduced or altered plant growth
erosion of soil (here peat)
Google Earth
100 m
B
erosion of soil/substrate
surfacing material applied
mow lines
Google Earth
100 m

Figure 2

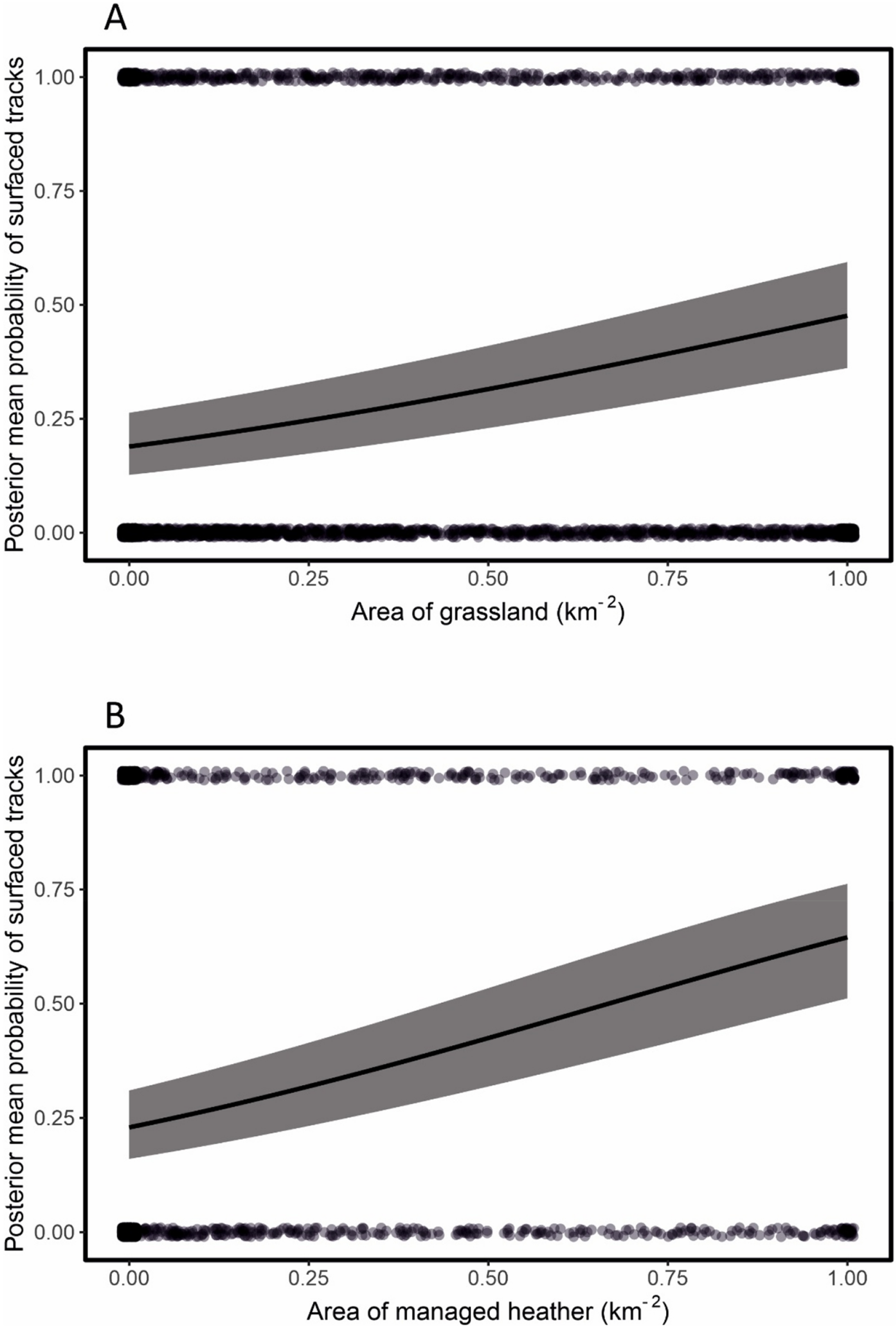
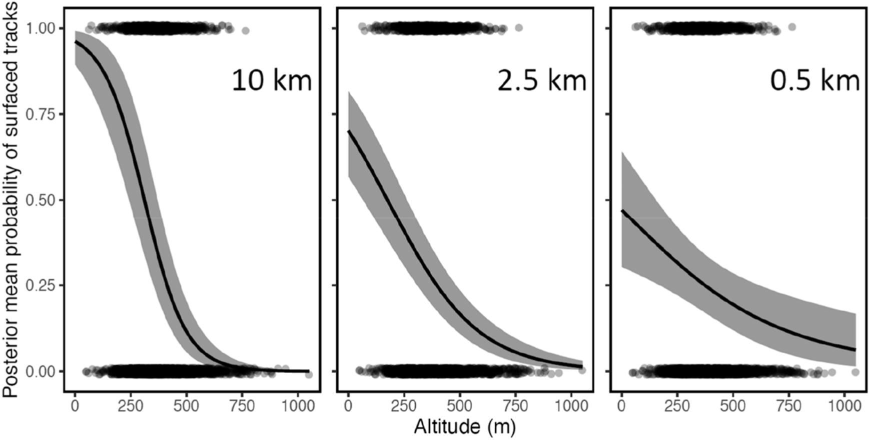

A
Posterior mean probability of surfaced tracks
1.00
0.75
0.50
0.25
0.00
0.00
0.25
0.50
0.75
1.00
Area of grassland (km^{-2})
B
Posterior mean probability of surfaced tracks
1.00
0.75
0.50
0.25
0.00
0.00
0.25
0.50
0.75
1.00
Area of managed heather (km^{-2})

Figure 3



Posterior mean probability of surfaced tracks
1.00
0.75
0.50
0.25
0.00
10 km
2.5 km
0.5 km
0
250
500
750
1000
Altitude (m)

Figure 4

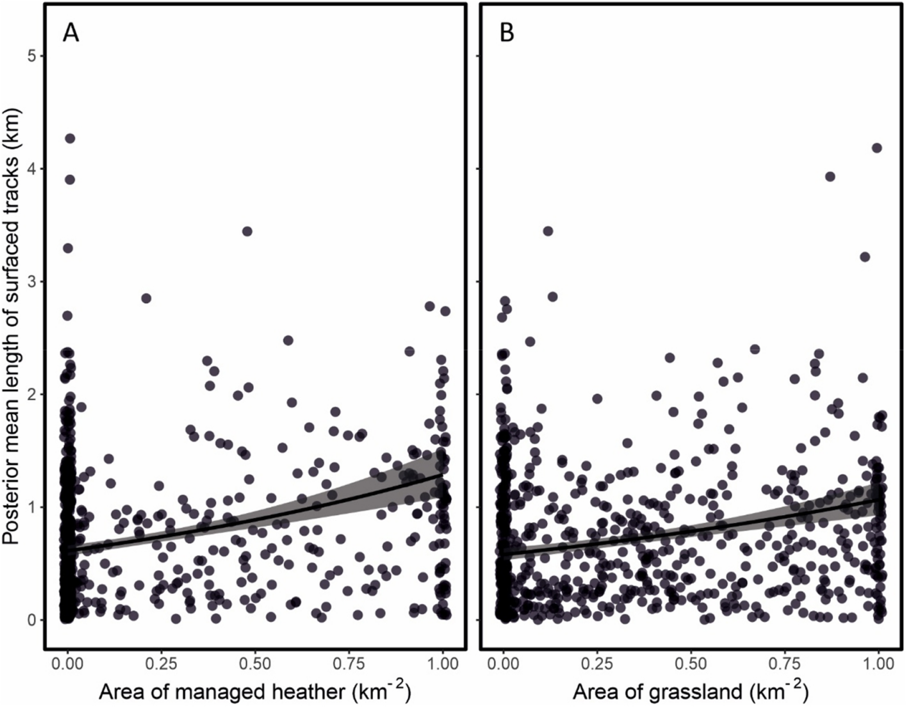

A
B
Posterior mean length of surfaced tracks (km)
0
1
2
3
4
5
0.00
0.25
0.50
0.75
1.00
Area of managed heather (km^{-2})
Area of grassland (km^{-2})

Figure 5