Estimating breeding numbers and productivity of curlew and golden plover across the moorlands of the North Pennines and Yorkshire Dales

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Summary

- Great Britain holds important breeding populations of two species of iconic upland waders (66,000 pairs of curlew and 49,000 of golden plover).
- We carried out a modelling exercise to understand how changes in the extent of grouse moor management might impact breeding populations of these two wading bird species across a large area of northern England (including the North Pennines and the Yorkshire Dales).
- The modelling exercise conducted during the current study was based on data derived from bird surveys (following Brown & Shepherd, 1993) that were carried out in summer 2017 on 104 one-km squares, on 18 moorland estates in northern England and southern Scotland, during April to June 2017. Estates surveyed ranged from active grouse moors, with correspondingly high intensities of predator control and heather burning, to sites with only limited predator control and no grouse shooting or heather burning.
- From this previous study we were able to estimate how densities of ground nesting waders varied according to the degree of management of upland sites, finding approximately three times as many curlew territories and approximately four times as many golden plover territories per survey square on intensively managed grouse moors compared to other moors surveyed.
- We define the study area for our modelling work as land above 250m above sea level comprised of the following habitat types (heather, heather grassland, bog, acid grassland or calcareous grassland) across land encompassing Natural England's Pennine 'natural character area' and Yorkshire Dales National Park (3,257 km^2 in total).
- We estimated densities of breeding waders by using the known relationships for habitat, elevation and grouse moor management (predator control and burning) from our 2017 study sites to extrapolate across our study area.
- We estimated populations of Curlew and Golden Plover at 6161 (95% confidence intervals: 3,769-11,454) and 4544 pairs (95% confidence intervals: 2,047-11,691) respectively, across our study area. This represents 9% of the breeding populations of these species across Great Britain.
- Currently 78% of our study area is managed for red grouse (based on evidence of burnt strips indicative of this form of management).
- We found that found predator control was essential to maintain the current population sizes of curlew and golden plover in the study area, and a cessation of predator control across our study area would likely lead to a drop in numbers of curlew by 60% and golden plover by 79%.
- Based on the current populations estimated in our study area the following numbers of chicks produced each year would be: curlew 10,591 chicks per year (95% confidence intervals 4,672-18,872); golden plover 12,764 chicks per year (95% confidence intervals 8,569-17,740). Should

predator control cease this would result in an 87% decline in the number of curlew chicks and a 95% decline in the number of golden plover chicks.

- It is important to consider the magnitude of the changes to curlew and golden plover by predator control when decisions about upland land management are made (e.g post Brexit scenarios which might include changes to grouse moor management). However, such considerations should also be cognisant of the other implications of management for red grouse (e.g. negative impacts of strip burning on carbon storage and illegal persecution of raptors on grouse moors) when aiming for a balanced sustainable management system for grouse moorland.

Introduction

Moorland (or upland heathland), dominated by the dwarf-shrub, heather *Calluna vulgaris*, is a highly valued habitat in the UK. Such moors formed over the past 3,900 years, following the onset of extensive upland deforestation (Birks 1988) and are now maintained through management intervention, in particular, through use of fire or through grazing by domestic livestock (Gimingham 1995). Heather moorland in the UK is often managed to maximise populations of red grouse *Lagopus lagopus* as a gamebird (Moss 1989, Hudson 1995). Although not species-rich, the habitat hosts a range of highly specialised plant and invertebrate communities (Littlewood et al., 2006) and a unique bird assemblage (e.g. Thompson et al., 1995) and is designated as a UK Biodiversity Action Plan Priority Habitat (Anon 1995). The North Pennines area in particular holds some of the highest densities of ground nesting waders in the UK and also supports some of the UK's most intensely management grouse estates. The aim of the current project is to evaluate to what extent grouse moorland management supports substantial numbers of ground nesting waders across a study area comprising the North Pennines and Yorkshire Dales, and to what extent the numbers of ground nesting birds present could alter under scenarios of very different upland management (such as intensification, or cessation, of grouse estate management).

The moorland bird assemblage contains internationally important populations of some species. These include eight that are listed on Annex 1 of the EC 'Birds' Directive 79/409/EEC. Densities of some common species may be especially high including, possibly, the highest recorded densities globally of meadow pipit *Anthus pratensis* and skylark *Alauda arvensis* (Thompson et al., 1995). The recently published *Birds of Conservation Concern 4* (Eaton et al., 2016) highlights the precarious conservation status of several bird species that make regular use of moorland. Included on the Red List are Hen Harrier *Circus cyaneus*, Lapwing *Vanellus vanellus*, Curlew *Numenius arquata*, whilst the Amber List includes moorland birds such as Red Grouse, Dunlin *Calidris alpine* and Redshank *Tringa totanus*.

Grouse moor management involves interventions that are aimed at generating optimal conditions for grouse production. Principal among these, in terms of managing and shaping the landscape and habitat, is heather-burning. Heather is the principal food of adult red grouse. It is burned in a mosaic of patches on a rotation that ensures that heather of different ages is available for the grouse, especially young and nutritionally-rich heather. The other key management intervention, that directly shapes the make-up of the moorland fauna, is predator control. This involves removing or reducing populations of predatory birds and mammals that might affect survival rates of red grouse, especially of eggs and chicks. These two management interventions create habitat conditions and a low predator environment that may influence populations of other moorland bird species.

Several previous studies have investigated the link between moorland management and population densities and breeding productivity of moorland birds. For example, in northern England and eastern Scotland, Tharme et al. (2001) found golden plover and lapwing densities to be five times higher on moors managed for grouse shooting than on other moors, with red grouse and curlew densities being twice as high. Based on data collected between 1999 and 2003 from upland sites across Wales, northern England and southern Scotland, Buchanan et al. (in press) found that geographical location was the most important determinant of upland bird abundance but also that red grouse, golden plover and curlew abundances were higher where there was evidence of predator control. Similarly, across a range of sites in southern Scotland and the south Pennines, nesting success of curlew was positively correlated with gamekeeper density (Douglas et al., 2014). Further north, in the Scottish Highlands, red grouse and curlew were among bird species found to be especially associated with moors managed for grouse shooting with weaker associations also reported for golden plover and snipe (Newey et al., 2016). Some species have been found to be negatively associated with management for grouse shooting. Meadow pipit, skylark and carrion/hooded crow *Corvus corone* were each found in lower densities on grouse moors than other moors by Tharme et al (2001). Similarly, Newey et al (2016) reported negative associations with grouse moors for ring ouzel *Turdus torquatus*, meadow pipit, skylark and wheatear *Oenanthae oenanthae*. Some of the negative impacts from these two studies, especially for carrion/hooded crows, were probably due directly to predator control being carried out on grouse moors. For other species, it is likely that grouse moors are sub-optimal habitat compared to other upland areas or that heather-burning removes an important element of the habitat that is required by a species.

Teasing out specific influences of predator control and heather burning is difficult, as these two activities are usually carried out on the same sites. However, experimental treatments at single sites provide some evidence for such relative impacts. Under a low-level predator control regime in north Cumbria, for example, golden plover increased in number in the initial period after burning (Douglas et al., 2017). Most such studies assess only the presence of species on sites, and not their subsequent breeding success – which might lead to very different assessments of the conservation value of the different habitats. A rare example of assessing breeding success on moorland took place in Northumberland between 2001-2008. Under a continuation of a conventional heather-burning regime, predator control led to increases in breeding success of lapwing, golden plover, curlew, red grouse and meadow pipit, compared to areas without predator control (Fletcher et al., 2010). The study also recorded subsequent increases in breeding numbers of the first four named of these species.

Here we use data collected from recent surveys, undertaken in 2017 by Durham and Newcastle University, to estimate populations of breeding wading bird populations across the North Pennine uplands of England and southern Scotland. We base the predictive models generated by this data [paper shortly to be submitted to Journal of Applied Ecology (Littlewood et al., in prep) – delay caused by further investigation of use of satellite data on burning to check our findings from ground surveys and google earth were robust: in short the methods were robust but the remote sensed data took much longer than expected to analyse].

Here we explore a number of related aims and questions:

1. We estimate the breeding population of curlew and golden plover for a large area of northern England.
2. Using the statistical relationships from Littlewood et al., (in prep) we explore how changes in upland management associated with grouse moor management (explicitly predator control intensity) would impact populations of each species across our study area. We measure impact in two ways: (a) via relationships with density (which will be time lagged – see discussion); (b) productivity of each species.

Methods

1. Evaluating the drivers of curlew and golden plover population density

Study area i: 1 km square breeding bird surveys from 2017

One hundred and four squares, each measuring 1 km × 1 km, were selected from 18 upland estates in County Durham, Cumbria, East Lothian, Northumberland and the Scottish Borders (Fig. 1). Between one and twelve squares were surveyed per site; numbers per site being related to site extent and the extent of heather moorland on the estate. Survey squares were situated so as to reflect the range of conditions of heather moorland at a site. Survey squares were not located directly adjacent to each other, though some surveyed squares met at their corners, i.e. they did not share a common boundary. There was one exception to this, where a 500 m border was shared between two squares. Survey square selection was based on information received from local contacts (typically gamekeepers) about habitat types and their distribution across an estate; though decisions on which sites to survey were independent of local contacts. Squares that were largely dominated by heather were prioritised for surveying, though a minority of squares contained larger areas of grass-dominated habitats ("white ground"). No prior knowledge of the bird assemblages present on sites was used to inform the selection of squares for surveying.

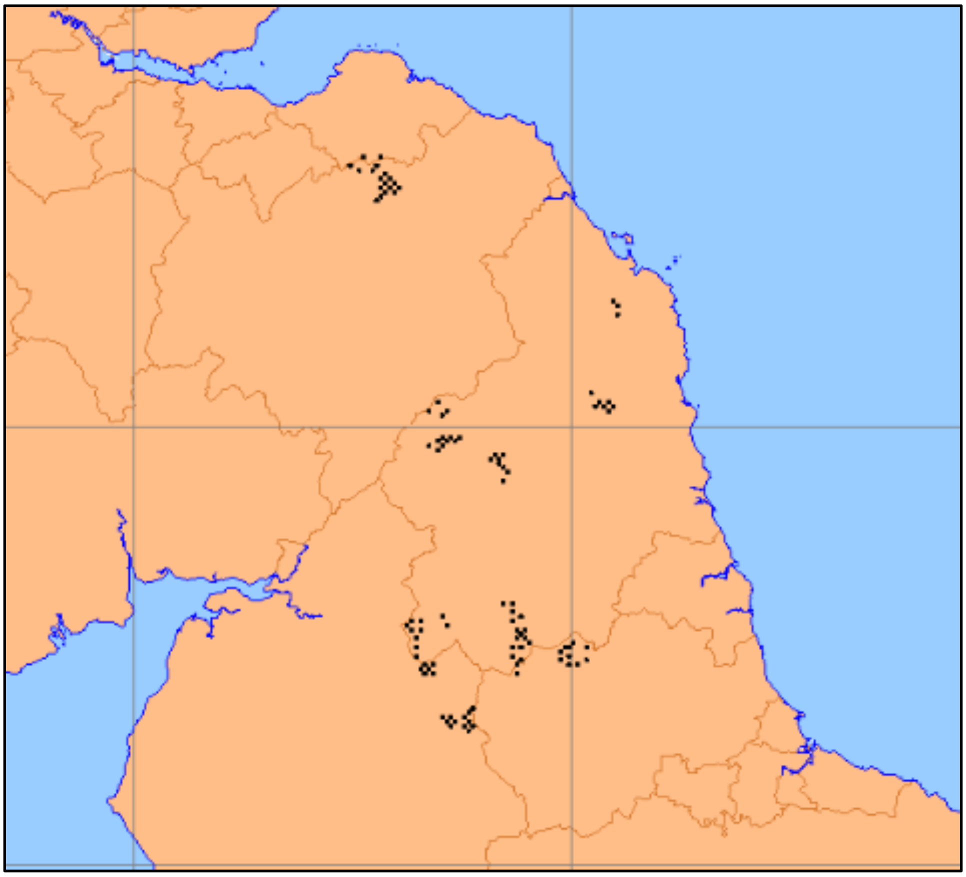

Figure 1. Location of the 104 squares surveyed across northern England and southern Scotland in 2017. The map shows UK National Grid 100 km grid lines and local authority boundaries, with the Solway Firth to the south-west and the North Sea to the north-east. The statistical relationships between golden plover and curlew and predator control were derived from these sites and applied to the area shown in Figure 2.

Bird survey fieldwork

Each 1 km square was surveyed using a method recommended by Brown & Shepherd (1993). This entails walking a route around the square that is likely to maximise bird encounters, within a 80 to 100-minute time duration. Thus, the route does not follow fixed transect lines but, instead, allows the surveyor to maximise route efficiency with respect to topography and to census all areas within the square that look likely to hold populations of breeding birds. Birds encountered (by sight or call or both) were recorded on a large-scale map along with standard species and breeding behaviour codes. Specific notation was used where two registrations of the same species were thought or known to relate to different individuals and also in situations where it was thought that a bird may have moved some distance between sightings, to avoid inflated estimates of bird numbers.

Each square was visited twice in the breeding season, once between 15 April and 21 May 2017 and once between 23 May and 26 June 2017. Second visits to a site was always at least 27 later than the initial visit (mean 36.1 days). This method ensures that both early and late breeding species are recorded adequately. Fieldwork was carried out between 8.30am and 6.00pm, thus avoiding periods of rapidly changing bird activity levels in the early mornings and evenings. Surveys were not carried out when winds exceeded force 5, in poor visibility or in rain in excess of lights spots. Surveying were suspended during periods of heavier rain and restarted after the rain had ceased. Surveys were carried out by three skilled field ornithologists and each square was visited by a different surveyor on the two visits.

Estimating territory numbers

Breeding bird territories were identified from the field maps compiled on each visit. For waders, birds present in breeding habitats and either alarm calling, in song or display, or exhibiting other breeding-associated behaviour were presumed to be occupying a breeding territory. A pair of birds in suitable habitat was also assumed to be on a territory but where a single bird was present and not displaying breeding associated behaviour, this was not counted as a separate territory. Likewise, congregations of likely non-breeding waders (such as early-season flocks of golden plover) were disregarded in estimating territory numbers. Notation on maps that indicated simultaneous observations, or birds thought by the fieldworker to be different, were used to determine which birds represented different territories. Where it was not possible to determine whether birds were likely to be the same or different individuals, an arbitrary cut-off of 500 m distance between map registrations was used to identify separate territories (Brown & Shepherd, 1993). Following estimation of the number of territories identified on each visit, the higher number was taken as the estimate for that square (following Calladine et al. (2009)).

Evaluating site management

Estate owners, tenants, agents, gamekeepers and managers were interviewed to quantify the time spent on predator control activity on each of the 18 sites. These estimates primarily comprised activities of gamekeepers employed on the estates, and to a lesser extent those carried out on the estates by tenant graziers and representatives from neighbouring estates operating with consent. These data were converted into estimates of the number of full-time equivalent staff exclusively carrying out predator control per 1000 ha.

The area of each survey square under burning management was estimated from GoogleEarth images. These were accessed in August 2017 and spanned the years 2003 to 2016, with 84% of images being from

2007 onwards. An absence of signs of burning in aerial images is likely to indicate that a site has not been burned for 20 years or more (Yallop et al., 2006). Whilst it is possible that burning may have been instigated on some areas since the images were taken, no substantial recent changes in burning management were reported during interviews with site contacts.

Seven estates, containing 54 of the survey squares, were managed as grouse moors with sustained predator control and heather burning. These are classed here as high-intensity management sites. The remaining 11 estates, containing 50 survey squares, were less actively managed for grouse shooting and, in some cases, no grouse shooting was practiced on the sites.

Estimating habitat and landscape variables

The extent of broad habitat types in each survey square was derived from a 25 m raster version of the UK Land Cover Map 2015 (Rowland et al., 2017). The most extensive habitats were: bog (38.7% of the total area surveyed), heather (30.5%), heather grassland (20.9%) and acid grassland (8.4%). Due to the relative similarity of vegetation in the first three of these categories, they were combined to form a single "heath habitats" variable. Slope and elevation data were calculated for each square from 30 m resolution elevation data downloaded from the United States Geological Survey Shuttle Radar Topography Mission (USGS, 2017). Mean elevation was calculated per 1 km survey square. Slope was calculated for each 30 m elevation pixel based on the elevation of the surrounding eight pixels. Three slope variables were creating by calculating the proportion of each square with slopes of less than 2°, 5° and 10°.

Statistical analyses

The abundances of curlew and golden plover were modelled individually in relation to the collated environmental variables using generalised linear mixed-effects models (GLMMs) fitted using the 'glmmTMB' function in R (R Core Team, 2017; Brooks et al. 2017). Zero-inflated Poisson models were used for each species, following exploration of dispersion and zero-inflation in their abundance data. Models were fitted with site-level random intercepts (n = 18), to account for non-independence among survey squares within each estate (see Fig. 1). Spatial autocorrelation in bird abundance, which might result from this clustering, was tested for using Moran's I statistic. Significant autocorrelation was identified for each species. Models were fitted with all possible combinations of environmental variables as predictors (see Supplementary Table S1), while not allowing co-occurrence of highly correlated variables (Pearson's correlation coefficient $r \geq 0.70$), which included predator control and burning ($r = 0.70$). All continuous predictors were standardised $[(x-\mu)/\sigma]$ to produce model coefficients comparable among predictors. For each species, models were selected with the most parsimonious combination of predictors, using the Akaike Information Criterion (AIC). Specifically, we considered models with $\Delta AIC \leq 6$ and lower than simpler nested models to have support (Richards, 2015), and included these in the top model set of each species. Additionally, Akaike model-averaged standardised coefficients were calculated across the top models for each species to illustrate the strength of evidence for different effects. Predictors occurring within the best performing model, and consistently throughout top model sets, were considered to have strong support.

Spatial autocorrelation was assessed in the residuals of the best performing model for each species using Moran's I statistic. No models had significant Moran's I statistics, indicating that the random intercept models adequately dealt with autocorrelation. Collinearity was assessed in the best performing models using variance inflation factors; no models contained predictors with variance inflation factors > 3 (Zuur, Ieno, & Elphick, 2010). The overall fit of each best model was evaluated using pseudo R^2, calculated as the squared correlation coefficient between fitted and observed values. Finally, we explored the potential for non-linear effects of management on bird abundance. Specifically, where predator control was selected in the best model, this model was refitted with a saturating effect of predator control of the form $a.(1\text{-}e^{-b.x})$, for which b was parameterised using one-dimensional optimisation, implemented using the 'optimize' function in R. The parsimony of these models was compared to that of the original models using AIC, and the best performing models selected (see Supplementary Table S2). The best performing model for each species was then taken forward to simulate the population sizes and productivities of these species across the North Pennines and Yorkshire Dales.

2. Estimating the populations and productivities of curlew and golden plover across the North Pennines and Yorkshire Dales

Study area ii: the North Pennines and Yorkshire Dales

The study area was defined as the uplands covering the North Pennines and Yorkshire Dales (Fig. 2). We delineated the North Pennines as the area enclosed by the outermost boundary of Natural England's North Pennines 'Area of Outstanding Natural Beauty' and 'Natural Character Area'. Similarly, we delineated the Yorkshire Dales as the area enclosed by the outermost boundary of Natural England's Yorkshire Dales National Park and Natural Character Area. We then restricted this region to the areas of suitable land-cover above the moorland line (i.e. we restricted our modelling to areas that could be potentially managed as grouse moors), which in England starts at approximately 250 m above sea level according to the Joint Nature Conservation Committee (JNCC, 2018). Specifically, we restricted our study area to 1 km squares with at least 10% of suitable land-cover (heath habitats, acid grassland or calcareous grassland) at elevations ≥ 250 m. The total area of this region is 4,086 km^2, of which 3,257 km^2 is covered by suitable upland habitat for breeding curlew and golden plover. The latter area was therefore used as the study area for this modelling work.

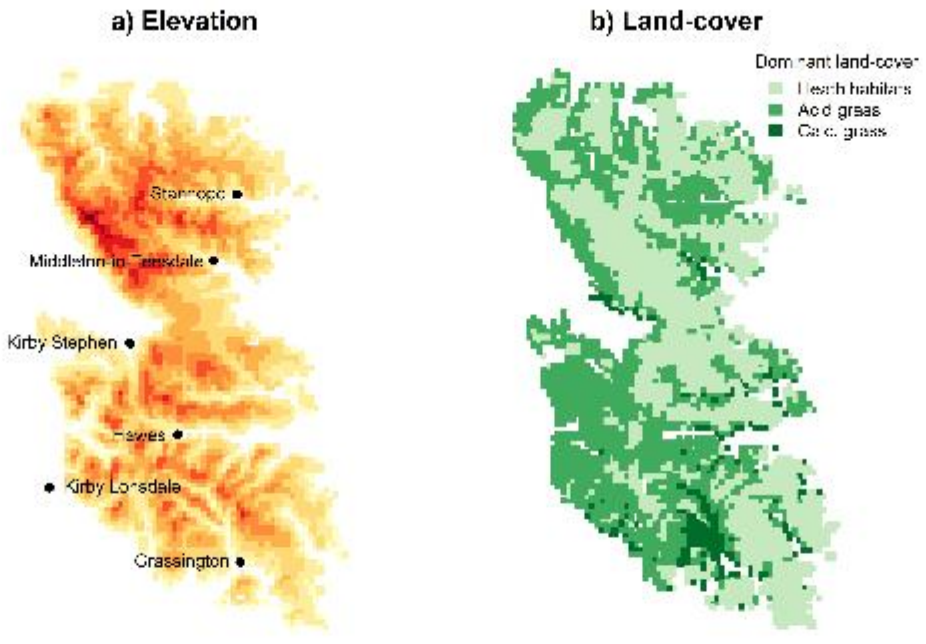

Figure 2. Extent of the region used in the current modelling study. Panel a) displays variation in elevation (with redder areas being higher) and the locations of major towns. Panel b) shows the dominant land-cover classes per 1 km square.

Estimating wider moorland management intensity and environmental variables

As for the analysis of our 104 1 km survey squares, the area of the study region (shown in Figure 2) under burning management was estimated from GoogleEarth images. This was performed at a coarser 5 km by 5 km resolution due the much larger area under investigation; area encompassed 223 5 km grid squares. Since 5 km squares often included areas of lowland or unsuitable land-cover, estimates of burning extent were made based on moorland habitat only. These estimates of burning extent were applied to all 1 km squares contained within each 5 km square. Importantly, these coarser estimates correlate well with burn extents estimated from 1 km data, across the 104 survey squares from 2017 (r = 0.80, P<0.0001).

Since no estimates of predator control activity were available across this wide area, we estimated predator control within each 1 km square based on the strong positive relationship between burning extent and predator control identified from the 2017 survey data. Specifically, we fitted zero-inflated Poisson linear mixed-effects models to the 2017 survey data using the 'glmmTMB' function in R, with predator control as the response variable, burn extent as a predictor and survey site as a random intercept. Using this model, we simulated variation in predator control activity across the North Pennines and Yorkshire Dales as a function of estimated variation burn extent.

As for our previous analysis, we used fine-scale land-cover and elevation data to estimate habitat type, elevation and slope at a 1 km scale across the study area.

Evaluating the potential effects of changes in management on population size and productivity

We use the best performing models of curlew and golden plover population density fitted to the 2017 survey data (see Supplementary Table S2) to simulate the population densities of these species across the North Pennines and Yorkshire Dales at a 1 km scale. In contrast to the 104 survey squares from 2017, which were dominated by suitable upland land-cover (mean 98% suitable land-cover), a number of the 1 km squares in the present study region contained lower proportions of suitable land-cover. As such, we adjusted our predicted population densities proportionally for any cells covered by less than 70% of suitable land-cover. Additionally, in contrast to the 2017 survey squares, a small proportion of the 1 km squares in this study area contained areas of calcareous grassland (see Fig. 2). Since calcareous grassland can harbour higher population densities of each species than heathland habitats or acid grassland, we corrected for elevated population densities in these squares using published estimates of population densities for each species on calcareous grassland (Williamson, 1968; Ratchliffe 1976). To account for the saturating effects of predator control in areas of calcareous grassland (which were identified for each species [see Fig. 3]), we applied different published density estimates depending on whether predator control fell above or below a threshold-level for each species. These predator control thresholds were determined from the turning points of the fitted predator control effects displayed in Fig. 3.

We summed the predicted 1 km-scale population densities to produce estimates of the current population size of each species across the study area. We quantified uncertainty in these population estimates using the 95% confidence intervals (95% CI) of the model predictions. Next, we estimated the productivity of each species across the study area based on their best estimate of population size. We used published estimates of clutch size (mean + 9%% CI; BTO, 2018) and the effect of predator control on the proportion of breeding pairs fledging young (mean + 9%% CI; Fletcher et al. 2010) to estimate the number of hatched chicks of each species per year. We used the same thresholds for predator control effects described previously, when applying the parameters for the proportion of breeding pairs fledging young.

Finally, we used the same procedure for estimating population size and productivity in three contrasting management scenarios to illustrate the potential effects of future changes in the management of UK uplands on populations of breeding waders. We developed three plausible scenarios of future management in our study area:

1. *Cessation of management*: all management of the uplands for grouse shooting ceases.
2. *Intermediate management intensity*: management intensity in all upland areas currently managed for grouse shooting is adjusted to intermediate levels. Areas that are currently unmanaged remain so.
3. *Maximum management intensity*: all suitable areas of the uplands are managed intensively for grouse shooting.

To test these scenarios, we adjusted our 1 km-scale estimates of management intensity across the North Pennines and Yorkshire Dales, and followed the previous procedure for simulating population size and productivity. Importantly, as we found evidence for a strong effect of predator control, but not burning extent (Littlewood et al., in prep), on each species, our scenarios were focused on adjustments of predator control. For scenario 2, predator control was reduced to the median levels recorded across the original survey squares in 2017 (0.44 FTE predator control 1000 ha^{-1}). For scenario 3, predator control was reduced to the maximum levels recorded across the 2017 survey squares (0.96 FTE predator control 1000 ha^{-1}).

Preliminary Results

Models of upland wader density

Our statistical models of curlew and golden plover density demonstrate strong evidence that predator control influences the densities of both species across our 104 1km survey squares in the uplands of northern England and southern Scotland (see Fig. 1 for location of sites from which these results were derived). This predictor had the strongest model-averaged coefficient for each species, and was selected in the best performing model (according to AIC) in each case (see Supplementary Table S2). The effect of predator control on each species was best described by a saturating function (Fig. 3), with marked increases in numbers to the presence of predator control but with little further responses to increasing levels of predator control. There was no strong evidence for effects of burning, which was not selected in any top model sets. Whilst the relative effects of predator control and burning could not be compared within the same models due to their collinearity, mean coefficients calculated across all models in which each occurred individually indicate much stronger effects of predator control than burning on the abundances of both species (see Supplementary Fig. S1). The only other variable selected in the best performing model of either species was a positive effect of elevation on golden plover numbers. The best performing model for each species was taken forward for use in the next stage of our analysis (the modelling work presented in this report), evaluating the potential effects of management scenarios on wader numbers across the uplands of northern England.

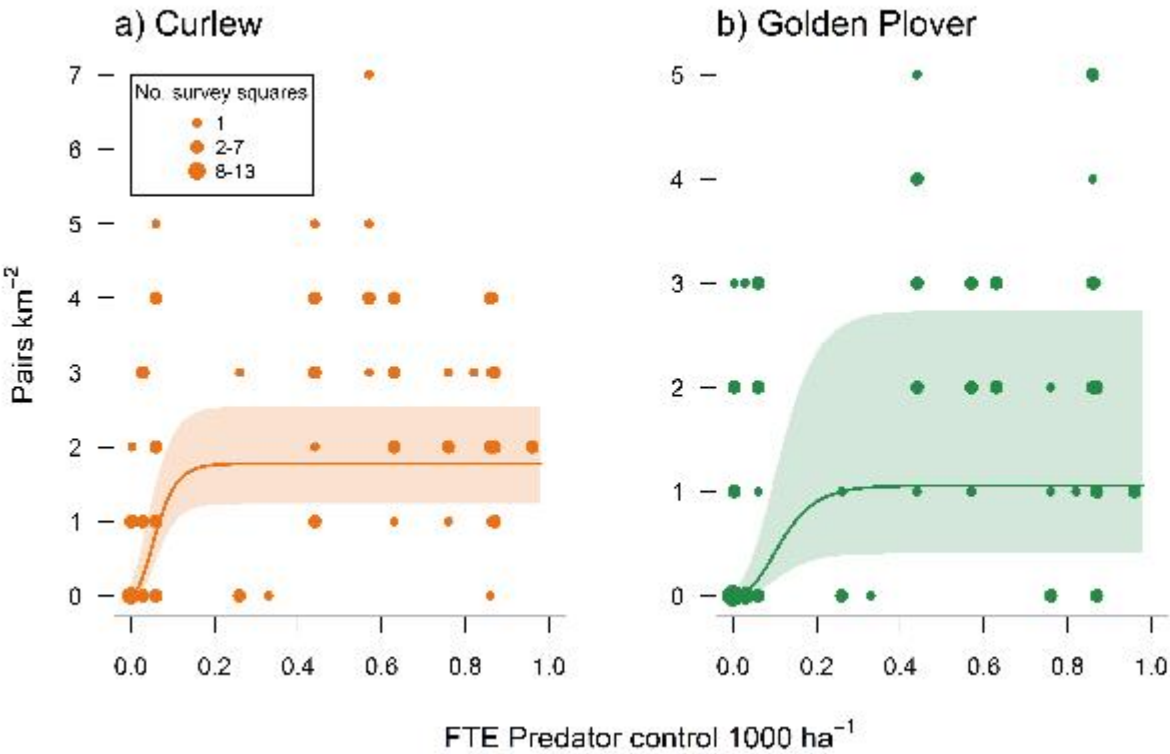

Figure 3. Responses of curlew and golden plover numbers to predator control intensity from statistical models fitted to data from 104 1km survey squares across the uplands of northern England and southern Scotland. FTE represents one person working full time as a gamekeeper responsible for predator control across an area of 1000 Hectares. Predator control was selected in the best performing model for each species. Lines indicate fitted estimates from the best performing models. Shaded areas represent 95% confidence intervals around these estimates. Fitted values were calculated for an average site, while setting any other predictors to mean values. The best performing models were fitted with saturating non-linear effects of predator control. Points represent individual 1km^2 census areas. Point sizes indicates the number of survey squares corresponding to each data point.

Potential effects of changes in management on upland wader populations

Study area

The study area selected for scenario-testing encompassed 4,086 km^2 of the uplands of the North Pennines and Yorkshire Dales (Fig. 2). We detected evidence of grouse moor management across 78% (2,527km^2) of the 3,257 km^2 of suitable upland moorland habitat covering the study area. Of this suitable upland habitat, we estimate that 32% (1,311 km^2) is under intensive moorland management (≥70% area with evidence of burning), while 38% (1,555 km^2) is under no or low intensity management (≤10% area with evidence of burning).

Effects of changes in management on population size

We used our fitted models to simulate the numbers of each species across the uplands of the study area, based on the relationships with predator control identified across our sample of survey squares. Summing our 1km modelled densities together, we estimate that there are currently 6,161 pairs of curlew (95% CI:

3,769-11,454) and 4,544 pairs of golden plover (95% CI: 2,047-11,691) across this our study area of 3,257 km^2 (Fig. 4). These estimates suggest that these populations represent 9% (95% CI: 6-17%) and 9% (95% CI: 4-24%) of the current UK breeding populations of each species (curlew: 66,000 pairs; golden plover: 49,000 pairs – both latest population size estimates from BTO website accessed on July 31st 2018). Next, we adjusted the intensity of management across the study area, in order to illustrate the potential effects of future changes in UK upland management on each species (Fig. 4). First, we evaluated how a decrease in management intensity would influence their populations. If all management for grouse shooting were to cease across the study area (scenario 1), we estimate that the populations of curlew and golden plover would decline by 60% (95% CI: 49-66%) and 79% (95% CI: 71-80%), respectively (curlew: 2,449 pairs [95% CI: 1,926-3,926]; golden plover: 958 pairs [95% CI: 600-2,287]). Second, we tested an intermediate management scenario (scenario 2), whereby the intensity of management for grouse shooting across the study area was adjusted to intermediate levels (i.e., the median levels recording across the 104 survey squares in 2017). Under this scenario, we estimate that the populations of curlew and golden plover would increase by 11% (95% CI: 10-12%) and 31% (95% CI: 30-32%), respectively (curlew: 6,870 pairs [95% CI: 4,161-12,879]; golden plover: 5,946 pairs [95% CI: 2,665-15,455]). Third we tested how an increase in management intensity, to the maximum levels record across our survey squares, would influence these populations (scenario 3). Under this scenario, we estimate that the populations of curlew and golden plover would increase by 33% (95% CI: 30-35%) and 67% (95% CI: 67-68%), respectively (curlew: 8,192 pairs [95% CI: 4,882-15,449]; golden plover: 7,578 pairs [95% CI: 3,417-19,630]).

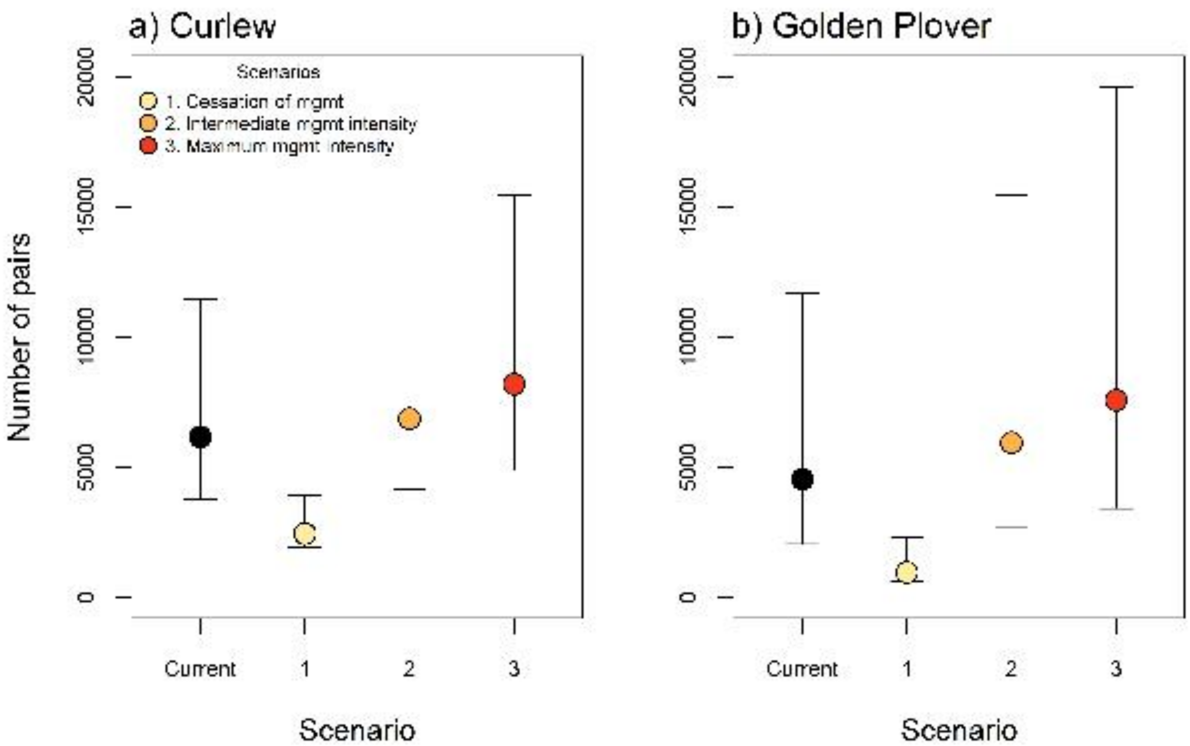

Figure 4. Potential effects of different plausible management scenarios on the populations of curlew and golden plover across the uplands of the North Pennines and Yorkshire Dales (study area of 3,257 km^2). These effects were simulated based on relationships between population density and predator control inferred from data from 104 1km survey squares across the uplands of northern England and southern

Scotland. Circles represent the best population estimates from fitted models. Bars represent 95% confidence intervals for these estimates.

Effects of changes in management on productivity

Finally, we combined our best estimates of population size from our model simulations with published estimates of the influence of predator control on the productivity of each species to illustrate the potential effects of changes in management on the productivity of each population (number of hatched chicks per year) (Fig. 5). We estimate that on average 10,591 curlew chicks (95% CI: 4,672-18,872) and 12,764 golden plover chicks (95% CI: 8,569-17,740) hatch per year across the uplands of the North Pennines and Yorkshire Dales at present. If all management for grouse shooting were to cease across the study area (scenario 1), we estimate that the numbers of curlew and golden plover chicks hatched per year would decline by 87% (95% CI: 83-96%) and 95% (92-99%), respectively (curlew: 1,367 chicks per year [95%CI: 205-3,183]; golden plover: 680 chicks per year [95% CI: 75-1,449]). If management intensity was adjusted to intermediate levels across the study area (scenario 2), we estimate that the numbers of curlew and golden plover chicks hatched per year would increase by 13% (95% CI: 13-13%) and 32% (95% CI: 32-33%), respectively (curlew: 11,935 chicks per year [95% CI: 5,282-21,234]; golden plover: 16,905 chicks per year [95% CI: 11,389-23,445]). Finally, if management intensity was increased to maximum levels across the study area (scenario 3), we estimate that the numbers of curlew and golden plover chicks hatched per year would increase by 47% (95% CI: 45-51%) and 75% (95% CI: 74-78%), respectively (curlew: 15,542 chicks per year [95% CI: 7,060-27,310]; golden plover: 22,393 chicks per year [95% CI: 15,245-30,846]).

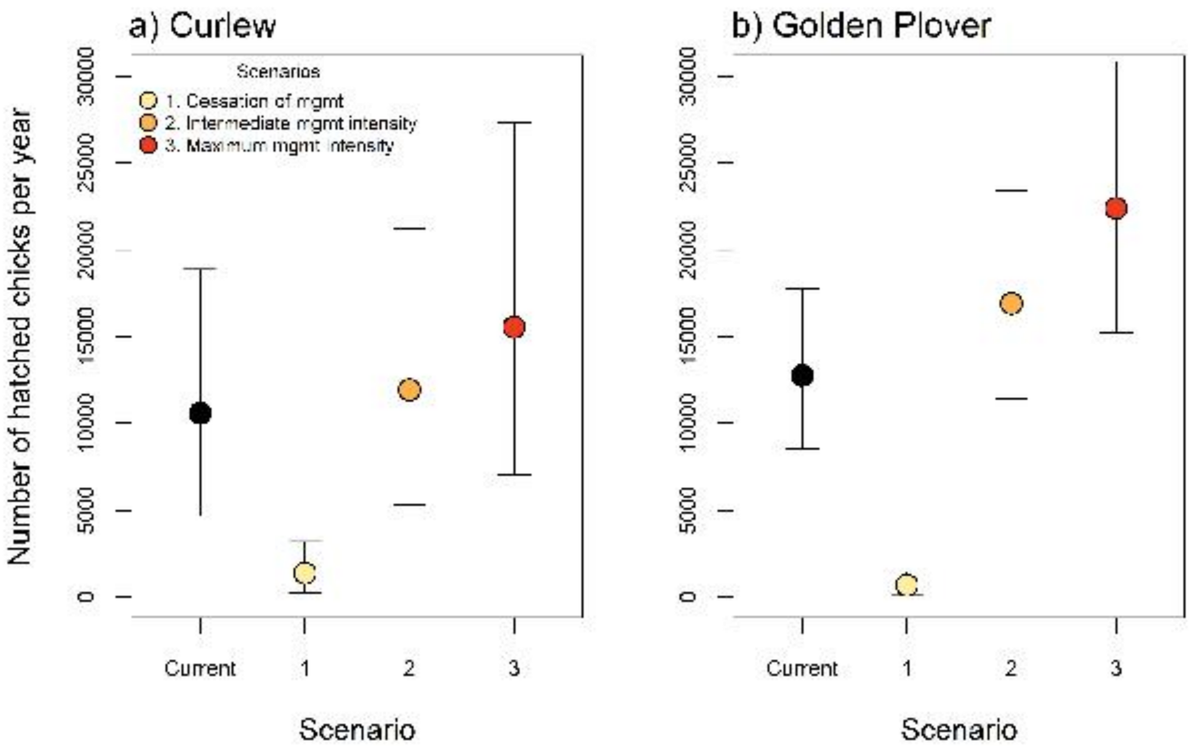

Figure 5. Potential effects of different plausible management scenarios on the productivities of curlew and golden plover across the uplands of the North Pennines and Yorkshire Dales (study area of 3,257 km^2). These effects were simulated based on relationships between population density and predator control inferred from data from 104 1km survey squares across the uplands of northern England and

southern Scotland, and published parameters on the productivity of each species. Circles represent the best population estimates from fitted models. Bars represent 95% confidence intervals for these estimates.

Preliminary discussion

Our previous field based study found that predator control on grouse moors was far more important in determining numbers of golden plover and curlew than burning (Littlewood et al. shortly to be submitted to Journal of Applied Ecology). The modelling study carried out in 2018 explores the implications of the relationships from the 2017 study to a regional population scale across the north Pennines and Yorkshire Dales (study area of 3,257 km^2).

Our main findings are that for our large study area in northern England (comprising suitable habitat for golden plover and curlew) there are likely to be substantial declines in the numbers of both species (60% for curlew and 79% for golden plover). This is a prediction based on existing data and should grouse moor management cease 'overnight' these predicted changes would take years before they were fully realised. We have not attempted to explore how quickly such changes would occur (as this is outside the remit of our work). This decline may be expected to be driven largely by the large scale declines in productivity which we find (87% and 95% declines in numbers of chicks produced across our study area by curlew and golden plover respectively) rather than loss of adult birds.

<u>Uncertainty</u>

We have presented our work with 95% confidence intervals to show the potential error around our estimates. Whilst these are large the relative changes in numbers are substantial and suggest large-scale changes would occur for our two study species with the sorts of larges changes in predator control that we have modelled. We will explore the uncertainty of our predictions in more detail in the remainder of the project.

<u>Broader implications of our study to date</u>

We have focussed on the impacts of predator control and burning (in Littlewood et al. in prep) and due to the former being of much more importance in determining numbers we have explored the extrapolations from changes in predator control. However, it is crucial that if grouse moor management is to adapt to current pressures for land management there is a need to minimise the negative impacts of burning on carbon storage and the issue of illegal raptor persecution on grouse moors needs to be addressed.

<u>Future work</u>

This study focussed on a study area in northern England but we will now use similar methods (based on data from other regions where available) to extrapolate similar impacts of changes in grouse moor management on curlew and golden plover across England as a whole and then Scotland.

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Supplementary Information

Table S1. Summary of predictor variables used in models of curlew and golden plover population density (used to derive predictive equations from 2017 data – Littlewood et al., in prep).

Variable name	Description	Data source
Burning extent	Estimated % of survey square under burning management	Google Earth 2003-2016
Elevation	Mean elevation of points in a 30 m grid	SRTM
Slope (<2°)	Proportion of cell with slope <2°	SRTM
Slope (<5°)	Proportion of cell with slope <5°	SRTM
Slope (<10°)	Proportion of cell with slope <10°	SRTM
Predator control	Full-time equivalent predator control per 1,000 Ha	Interviews with site contacts
Woodland	Woodland cover in the eight 1 km squares surrounding survey square	CEH Landcover 2015
Heath habitats	% cover of combined heather, heather grassland and bog	CEH Landcover 2015
Acid grassland	% cover in survey square	CEH Landcover 2015

Table S2. Parameter estimates and performance of top models of curlew and golden plover population density (used to derive predictive equations from 2017 data – Littlewood et al., in prep). All models were fitted with site-level random intercepts. Null models displayed for comparison.

a) Curlew

Model	**Predator control (P)**	***K***	**LL**	**AIC**
1	$0.79.(1-e^{-31.27*P})$	5	-154.02	0.00
2	0.56.P	4	-156.71	3.38
Null		3	-160.51	8.98

b) Golden Plover

Model	**Predator control (P)**	**Elevation**	***K***	**LL**	**AIC**
1	$1.04.(1-e^{-17.80*P})$	0.61	6	-125.67	0.00
2	0.79.P	0.45	5	-128.56	3.78
Null			3	-135.63	13.92

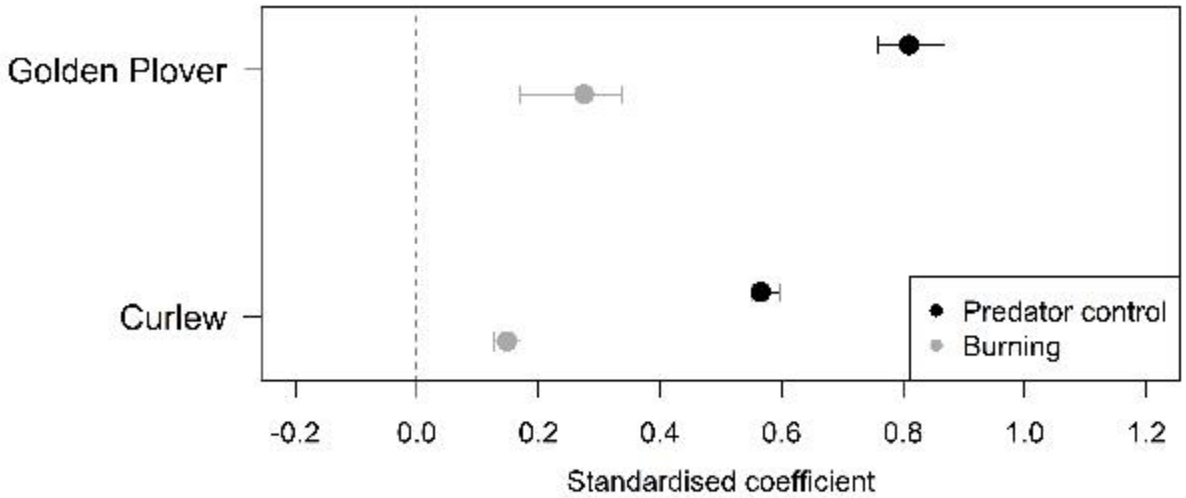

Figure S1. Standardised linear coefficients (i.e. scaled so effect sizes can be directly compared) for the effects of predator control and burning across models containing different combinations of predictors. Models containing both predictors together were not considered due to their high collinearity (r = 0.70). Points indicate means and lines indicate ranges.