The changing environment of conservation conflict: geese and farming in Scotland

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ABSTRACT

1. Conflict between conservation objectives and human livelihoods is ubiquitous and can be highly damaging, but the processes generating it are poorly understood. Ecological elements are central to conservation conflict, and changes in their dynamics – for instance due to anthropogenic environmental change – are likely to influence the emergence of serious human-wildlife impacts and, consequently, social conflict.
2. We used mixed-effects models to examine the drivers of historic spatio-temporal dynamics in numbers of Greenland barnacle geese (*Branta leucopsis*) on the Scottish island of Islay to identify the ecological processes that have shaped the environment in which conflict between goose conservation and agriculture has been triggered.
3. Barnacle goose numbers on Islay increased from 20,000 to 43,000 between the 1987/88 and 2015/16 seasons. Over the same period, the area of improved grassland increased, the number of sheep decreased and the climate warmed.
4. Goose population growth was strongly linked to the increasing area of improved grassland, which provided geese with more high quality forage. Changing climatic conditions, particularly warming temperatures on Islay and breeding grounds in Greenland, have also boosted goose numbers.
5. As the goose population has grown, farms have supported geese more frequently and in larger numbers, with subsequent damaging effects. The creation of high-quality grassland appears to have largely driven damage by geese. Our analysis also reveals the drivers of spatial variation in goose impacts: geese were more likely to occur on farms closer to roosts and those with more improved grassland. As geese numbers have increased they have spread to previously less favoured farms.
6. *Synthesis and applications*. Our study demonstrates the primary role of habitat modification in the emergence of conflict between goose conservation and agriculture, alongside a secondary role of climate change. Our research illustrates the value of exploring socio-ecological history to understand the processes leading to conservation conflict. In doing so, we identify those elements that are more controllable, such as local habitat management, and

less controllable, such as climate change, but which both need to be taken into account when managing conservation conflict.

Keywords: barnacle geese, climate change, conservation conflict, goose conservation conflict, grass damage, habitat modification, human-wildlife conflict, Islay, population dynamics, spatial ecology

INTRODUCTION

Conservation conflict – conflict between stakeholders representing biodiversity conservation and those representing other interests (e.g. food production) – is widespread globally (Redpath *et al*. 2013, 2015). Such conflict can be highly damaging to both biodiversity and livelihoods, so represents a key challenge for society (Sillero-Zubiri, Sukumar & Treves 2007). Human-wildlife conflict researchers have often focused on quantifying the negative impacts of wildlife on humans and vice-versa (Woodroffe, Thirgood & Rabinowitz 2005). In contrast, research into the processes leading to the emergence of serious impacts and, in turn, conflict between stakeholders, is currently scarce (Young *et al*. 2010). Such research could provide new insight into why conflict emerges and how it can be managed.

While conflict is clearly a social phenomenon, it emerges from environments comprising both socio-economic and natural elements, and can be triggered by change in any of these, such as wildlife population growth or decreases in the market values of crops, if they result in impacts perceived to be unacceptable by one or more parties (Young *et al*. 2010). In particular, ecological elements (e.g., species, ecosystems) are central to conflicts, but such ecological temporal dynamics tend to be studied in isolation rather than in interaction with human activities (Redpath & Sutherland 2015). Encouragingly, conflict studies are starting to combine ecological and human dynamics over short time-scales (e.g., Simonsen *et al*. 2016). Historic applied ecological data represents a potentially valuable resource for studying how environmental change has contributed to the development of conservation conflicts, by revealing how historic management and natural resource use by humans have shaped the ecological context of conflict (Lambert 2015).

The analysis of spatial historic data could additionally reveal why conflict is more likely to emerge in certain areas. The potential for conflict varies considerably due to spatial variation in social, economic and ecological factors (White *et al*. 2009). The latter can play a prominent role, for instance by influencing the severity of negative impacts of wildlife experienced by humans. For example, livestock depredation by wild carnivores can be more frequent in areas with more favourable habitat for wild prey, leading to a greater potential for conflict (Treves *et al*. 2004). Such spatial variation is often highly skewed, with only a small proportion of stakeholders experiencing serious negative consequences (Naughton-Treves 1998; Michalski *et al*. 2006). In this case, only farms located within large wilderness areas may experience high rates of livestock depredation (Michalski *et al*. 2006). Approaches based on spatial historic data could reveal how these skewed spatial patterns have evolved, and how they may lead to conflict in the future.

Here, we used 29-year and 18-year ecological time-series to examine how environmental change has contributed to the emergence of conflict over the conservation of Greenland barnacle geese (*Branta leucopsis*) and agriculture on the Scottish island of Islay. Migratory waterbird populations are regarded as a high conservation priority due to their strong reliance on restricted sites along their migration routes; environmental change at a single site can negatively impact an entire population (Kirby *et al*. 2008). Indeed, Greenland barnacle geese are an Annex I species on the European Union (EU) Birds Directive. Islay is an important site for this species, supporting more than half of the world's population during the non-breeding season (56% of 81,000 in 2013; Mitchell & Hall 2013). Birds arrive in early October from breeding grounds in eastern Greenland, via staging grounds in Iceland, and leave Islay by mid-April (Fig. 1a). Many goose populations are growing throughout the northern hemisphere, and are feeding increasingly in agricultural rather than natural habitats (e.g., Gauthier *et al*. 2005; Van Eerden *et al*. 2005), causing substantial economic damage to grassland and arable crops (Owen 1990). In such areas, conflict between conservationists and farming bodies is common (Fox *et al.* 2016). This is the case on Islay, where barnacle geese feed predominantly on farmed grassland and form large flocks that cause substantial damage to grass yields (Percival & Houston 1992). Barnacle goose numbers on Islay more than doubled from around

20,000 in 1987/88 to 43,000 in 2015/16 (Fig. 2a), contributing to growing conflict among stakeholders, including conservation groups, farmers and the governmental organisation in charge of goose management, Scottish Natural Heritage (SNH; McKenzie & Shaw 2017). To date, management of goose conservation-agriculture conflict on Islay and elsewhere has generally focused on reducing agricultural damage caused by geese. Coordinated approaches combining habitat management of goose refuges, scaring geese from agricultural areas, and payment of compensation to farmers experiencing grass and crop damage have seen some success in areas such as the Netherlands, Norway and Sweden (Cope, Vickery & Rowcliffe 2005; Fox *et al.* 2016). However, increasing goose numbers can outstrip both the size of refuges and the level of funding for compensation, necessitating population regulation through sport hunting (Madsen *et al.* 2017) or, more controversially, culling, as has been applied on Islay (McKenzie & Shaw 2017).

To understand how the environment has shaped the conflict over time, we investigated the drivers of increasing goose numbers on Islay, at two spatial scales. First, we examined the factors that have driven increases in total barnacle goose abundance on Islay (hereafter, 'population-scale analysis'), relating goose numbers to historic land-use and climate data for Islay and breeding grounds in Greenland. Increasing goose numbers across North America and western Europe are thought to have been caused by a combination of agricultural intensification (e.g., Van Eerden *et al.* 2005), release from hunting pressure (Menu, Gauthier & Reed 2002) and climate change, such as warming temperatures (e.g., Gauthier *et al.* 2005), though the relative importance of these drivers is unclear and likely to vary among species and regions. Here, we tested four non-mutually exclusive hypotheses for population increases, assuming that effects would act primarily via increasing forage availability and/or quality. We tested whether population increases resulted from:

1. Increases in improved grassland availability on Islay following agricultural improvements
2. Increases in improved grassland availability on Islay due to reductions in sheep densities
3. Warming and drying climate on Islay
4. Warming and drying climate at breeding grounds in Greenland

We then examined how changes in goose abundance have influenced the distribution of geese across different farms, (hereafter, 'farm-scale analysis'), testing three hypotheses. We tested whether geese occurred more frequently and in greater numbers:

5. When the population was larger
6. On farms with more improved grassland
7. On farms closer to roosting sites

MATERIALS AND METHODS

Study area

Islay is an island of 62,000ha situated in the Inner Hebrides of western Scotland (Fig. 1). Islay's landscape is dominated by agriculture (56,000ha), predominantly rough grazing and farmed grassland supporting sheep and cattle. In 1992, a government-funded goose management scheme was initiated on Islay, partially compensating farmers for economic losses from goose damage. From 2000, farmers were also allowed to protect parts of their farm by scaring geese, which in certain cases included licensed shooting of geese. However, steep increases in goose numbers during the early 2000s, combined with growing costs of farming and reductions in funding for compensation, resulted in geese causing serious economic damage to Islay's agricultural economy (currently estimated at £1.6 million per annum). In 2014, a new goose management strategy was implemented by SNH and the Scottish Government, which aimed to reduce goose damage by 25-30% by reducing barnacle goose numbers (SNH 2014). Since 2014, between 1,000 and 2,700 barnacle geese have been culled on Islay each year. This has contributed to an escalation in conflict between SNH, farmers and conservation organisations on Islay, with the Royal Society for the Protection of Birds and Wildfowl and Wetlands Trust lodging a formal complaint to the European Commission in 2015 over the culling programme.

Data collection and statistical analysis

Goose abundance data

Population censuses across the wintering range of Greenland barnacle geese are undertaken every five years, using ground and aerial surveys (Mitchell & Hall 2013). More frequent surveys are undertaken at a number of key wintering sites, including Islay. We used data from island-wide ground surveys of Islay's overwintering barnacle geese, carried out by SNH multiple times each year, generally in November, December, January and March (*n*=101). These provided estimates of total goose numbers on Islay for the period 1987-2016 and farm-specific goose numbers for the period 1998-2016. Surveys were conducted twice over consecutive days and averaged to produce a more reliable estimate of total barnacle goose abundance. They were carried out by five pairs of trained surveyors in vehicles around five pre-defined routes of sub-areas of Islay and were conducted simultaneously on each route, with care taken to avoid double counting both within and among sub-areas by monitoring the movements of flocks during surveys. Geese were counted from vehicles using binoculars and spotting scopes, at distances of 20m-2km. The farms occupied by geese were recorded according to a system of unique field codes, using maps of the study area.

Population-scale analysis

To test hypotheses 1-4, we acquired land-use and climate data for the period 1985-2015. We obtained Islay land-use data from the Scottish Government (http://www.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/Datasets). We used data on annual variation in sheep numbers on Islay, collected by the annual June Scottish Agricultural census, and in the area of improved grassland on Islay (defined as grassland that has previously been reseeded), collected by the Agricultural census (1985-2008) and from Single Farm Application forms (2009-2015). We used monthly climate data for the West Scotland from the Met Office to represent Islay's climate (http://www.metoffice.gov.uk/climate/uk/summaries/datasets), calculating mean daily temperature and total precipitation during the barnacle goose non-breeding season (October-March). We used monthly climate data from Danmarkshavn meteorological station, which lies within the barnacle goose breeding range in eastern Greenland (74.48°N; 18.98°W), to represent breeding ground climate (http://research.dmi.dk/publications/other-publications/reports/). We calculated mean daily temperature and total precipitation for two important periods during breeding for arctic goose reproduction and post-fledging survival (e.g., Dickey, Gauthier & Cadieux 2008): in early spring (May) when geese have recently arrived and are egg laying, and late summer (August) when geese are brood rearing and preparing to leave. We considered predictors at time-lags of 1-3 years, assuming that predictors would influence abundance via lagged, and possibly additive, effects on survival and recruitment. Time-lags of t-1 represent, for Greenland, the climate during the breeding season directly preceding abundance surveys on Islay and, for Islay, the climate/land-use during the previous year's non-breeding season on Islay. Greenland$_{t\text{-}3}$ and Islay$_{t\text{-}2}$ predictors allow for delayed cohort effects on the future reproduction of juveniles, which reach sexual maturity at 2 years (Forslund & Larsson 1992; see Fig. S1 in Supporting Information for an illustration of the timing of predictors). Environmental conditions experienced in early life by arctic-breeding geese can influence survival (van der Jeugd & Larsson 1998) and reproduction in later life (Sedinger, Flint & Lindberg 1995). See Table 1 for a summary of all predictors and their hypothesised effects.

We fitted linear mixed-effects regressions between barnacle goose abundance and predictors, including a random intercept for survey month, using the 'lme' function in R (Pinheiro *et al.* 2016; R Core Team 2016). We fitted models with maximum likelihood and scaled variables to produce standardised coefficients. We considered separate improved grassland coefficients for pre-2009 and post-2009 time-periods, using an interaction with a categorical variable representing time-period. This was because, whilst improved grassland is defined in the same way on the data collection forms for these periods, more guidance on differences between improved grassland and rough grazing is provided on Single Farm Application Forms (post-2009), resulting in slightly different classifications of improved grassland between the two periods (Fig. 2b). We fitted models with 'AR-1' autocorrelation structures to account for temporal autocorrelation in model residuals. We considered models of increasing complexity, fitting models containing all possible combinations of predictors for Islay land-use, Islay climate and Greenland climate (Table 1) for a given number of predictors, until the addition of an extra predictor did not produce a parsimonious model according to Akaike's

Information Criterion (AIC). We assessed models with ΔAIC ≤6 and lower than simpler nested models to have some support (Richards 2015), and considered predictors occurring in all these 'top models' to have strong support. We visualised relationships between goose abundance and these predictors using partial-effect plots, which display response-predictor relationships while accounting statistically for the effects of other predictors in a model. This is done by plotting $r(x|\text{other predictors})$ against $r(y|\text{other predictors})$, where $r(x|\text{others})$ are residuals of a model regressing predictor x against all other predictors (but not response y) and $r(y|\text{others})$ are residuals of a model regressing y against all predictors except for x.

Farm-scale analysis

To test hypotheses 5-7, we fitted models exploring the influences of Islay goose abundance, farm-specific improved grassland area and farm-specific distance to nearest roost on barnacle goose numbers on farms. To test the effect of abundance, we used the total abundance estimates corresponding to farm-scale goose numbers. We calculated distance to roost as the Euclidean distance between a farm's centroid and the nearest barnacle goose roost. There are three main night-time roosting sites on Islay, composed predominantly of saltmarsh and inter-tidal mudflats, used by the majority of barnacle geese (see Fig. 1b). We calculated mean area of improved grassland (grassland reseeded within the past seven years) on farms using data provided by the Islay goose management scheme. See Table 1 for a summary of these predictors.

We used a hurdle modelling procedure, first fitting models exploring drivers of probability of goose occurrence during a survey on farms, using presence-absence data (hereafter, 'occurrence models'), and second fitting models exploring the drivers of their numbers when they were present, using presence-only count data (hereafter, 'count models'). This procedure allowed us to investigate the processes generating goose occurrence and numbers separately. We fitted models using linear mixed-effects regressions, including random intercepts for survey year and farm ID (n=103) using the 'glmer' function in R (Bates *et al.* 2015). We fitted models with maximum likelihood, using binomial and Poisson error structures for occurrence and count models, respectively. We tested for spatial autocorrelation per survey in the responses and residuals by calculating Moran's I statistic, to determine the ability of models to explain any spatial autocorrelation in the responses. There were low levels of autocorrelation in the data, with significant spatial autocorrelation in farm-specific occurrences and counts, respectively, on only 18% (21/120) and 5% (6/120) of surveys. There were similarly low levels of autocorrelation in the residuals of the best occurrence (16%) and count models (4%).

To test hypothesis 5, we first fitted models with total barnacle goose abundance as a fixed effect. We included farm ID random coefficients for the effect of abundance, to account for variation in this effect among farms. We included linear and quadratic effects of day of year to account for seasonal changes in goose spatial aggregation potentially resulting from depletion in grass availability. We fitted models with the scaled predictors together, separately and both absent, identifying the best model using AIC. Next, to test hypotheses 6 and 7, we extracted the farm-specific intercepts/coefficients (i.e., $\beta_{\text{Population}} + \gamma_{\text{Farm}}$) from the best models, and fitted post-hoc models exploring the effects of improved grassland area and distance to roost on variation among farms in i) goose occurrence/number (farm-specific intercepts) and ii) the effect of Islay abundance on occurrence/number (farm-specific coeffcients). We used non-linear regression, implemented with the ‘nlsLM’ function in R (Elzhov *et al.* 2013), considering linear and curvilinear effects of the form ax^b for each scaled predictor. As before, we selected the best models using AIC.

For all models, we assessed model fit using R^2 (Nakagawa & Schielzeth 2013) and collinearity using variance inflation factors, accepting those <3 (Zuur, Ieno & Elphick 2010).

RESULTS

Population-scale analysis

The best model of barnacle goose abundance (R^2=0.86) showed that population increases were linked primarily to changes in land-use on Islay, but were also associated with climate variation on Islay and Greenland (Fig. 3-4). All top models contained predictors of Islay land-use, Islay climate and Greenland climate (Fig. 3; Table S1). The area of improved grassland on Islay two years previously was by far the strongest predictor of goose abundance (Fig. 3 & 4a); this predictor was selected in all top models and its partial effect (R^2=0.67) was more than four times stronger than any other. This supports hypothesis 1, suggesting that the area of improved grassland on Islay – which increased by

45% between 1987 and 2004 (Fig. 2b) – has boosted goose numbers by roughly 6,000 per 1,000ha increase in grassland. In contrast, there was no evidence for hypothesis 2 – a negative effect of sheep numbers – despite a 40% decrease in sheep numbers on Islay from 78,500 to 47,000 between 1998 and 2011 (Fig. 2c).

We found strong evidence for a positive effect of Islay temperature on abundance, operating at both one and two year time-lags, thus supporting hypothesis 3 (Fig. 3 & 4b). Both time-lags were present in all top models (Fig. 3), with a 1ºC increase at a one year time-lag boosting goose numbers by roughly 3,000. We also detected weaker, negative effects of Islay precipitation at one and two year time-lags, with goose numbers decreasing by 700 (t_1) and 900 (t_2) per 100mm increase in precipitation. Both time-lags featured in the best model, but not all top models (Fig. 3; Table S1). Islay's October-March temperature and precipitation exhibited increasing, though non-significant, trends during the study period (see Fig. S2). Spring and late summer climatic conditions at breeding grounds were also associated with goose abundance, providing some support for hypothesis 4, although effect sizes were generally weaker than for Islay climate (Fig. 3 & 4c). There was evidence for a moderate positive effect of August temperature (2,300 more geese per 1ºC increase) and a weaker negative effect of August precipitation (1,100 fewer geese per 10mm increase) during the breeding season directly preceding goose surveys; these effects are present in all top models. A weak negative effect of precipitation at a two year time-lag was also present in all top models. These effects indicate that warmer and drier periods preceding migration from breeding grounds influenced recruitment positively. August breeding ground temperatures have become significantly warmer, from an average of 2.2ºC in 1985 to 3.6ºC in 2015, but there has been no significant change in precipitation (see Fig. S2). There was some evidence of positive effects of spring breeding ground precipitation and temperature on goose abundance (Fig. 3; Table S1), in particular suggesting delayed positive effects of wet springs on recruitment. However these effects were not present in all top models (Fig. 3; Table S1).

Farm-scale analysis

The best models describing the number and occurrence probability of geese at a farm level contained positive effects of goose abundance, thus supporting hypothesis 5 (Fig. 5; Table S2). Our models estimated that, for a 10% growth in the population, probability of occurrence and abundance on an average farm increased by 5% and 9%, respectively. The best models also contained quadratic effects of day (Table S2). The probability of goose occurrence on farms increased from the start of the season, peaking in February-March before declining later in the season (see Fig. S3). In contrast, the number of geese recorded per farm showed a slight decline during the season, suggesting that geese spread out over more farms.

Variation in farm-specific intercepts from both occurrence and count models was linked primarily to the area of improved grassland on farms, thus supporting hypothesis 6. Geese were more likely to occur and to do so in greater numbers on farms with more improved grassland (Fig. 6a & c; Table 2a). For example, geese were present on farms with 10ha and 100ha of improved grassland, respectively, during 7% and 79% of surveys, at average abundances of 160 and 1,400. There was also evidence for negative effects of distance to roost in both models, indicating that geese were more likely to occur and to do so in greater numbers on farms nearer roosts, thus supporting hypothesis 7 (Fig. 6b & d; Table 2a). For example, geese were present on farms 1km and 8km from roosts, respectively, during 43% and 23% of surveys, at average abundances of 580 and 190.

While the effect of Islay goose abundance on farm-scale goose occurrence and number was positive on average, it varied in strength and direction among different farms when random effects are considered (Fig. 7). In the best occurrence model, 2 out of the 104 farms had negative abundance coefficients – indicating decreasing occurrence probability as total abundance has increased – whilst for the remaining 98%, positive coefficients varied considerably, between 0.12 and 2.47 (mean, 1.16). Even greater variation was present in the count model where 21% of farms have negative abundance coefficients and the remaining 79% vary by several orders of magnitude, between 0.09 and 11.65 (mean, 2.00). We were able to identify the drivers of farm-specific variation for occurrence models, but not count models. We detected a negative effect of improved grassland area and a positive curvilinear effect of distance to roost on farm-specific abundance coefficients for occurrence probability (Table 2b). This suggests that goose occurrence became more likely on farms with less improved grassland and those further from roosts, as goose abundance increased (Fig. 7).

DISCUSSION

This study illustrates how environmental change can shape the ecological dynamics underlying the emergence of conservation conflict. The growth of Islay's barnacle goose population was strongly linked to changing farming practice, specifically improvements to grassland, and was also associated with climate warming. As goose abundance increased, farmers experienced geese on their farms with greater frequency and in larger numbers, and geese spread to previously less favoured farms. By revealing the drivers of goose numbers experienced by farmers, our analysis explained how spatial patterns of human-wildlife impacts can evolve.

Drivers of goose population dynamics

Increases in the number of barnacle geese on Islay were associated with environmental conditions at different stages of this species' annual cycle. We identified lagged effects of land-cover and climate experienced during the non-breeding season on Islay and of climate experienced during the breeding season on Greenland. Of these, the strongest driver of abundance was the area of improved grassland on Islay. This concurs with other studies implicating agricultural intensification as a likely driver of increasing goose populations (e.g., Abraham, Jefferies & Alisauskas 2005; Fox *et al*. 2005). Increased application of Nitrogen-based fertilisers during the 20th century, in Europe encouraged by production subsidies paid through the Common Agricultural Policy until 2003, has created areas of pasture significantly higher in protein and digestibility than natural goose foraging areas (van Eerden *et al*. 2005). On Islay, some of the increases in high-quality grassland were driven by the EU funded Agricultural Development Programme for the Scottish islands, which commenced in 1987 (McKenzie & Shaw 2017). The increase in improved grassland has probably increased Islay's goose carrying capacity, providing geese with 'escape' from density-dependent survival. Density-dependence may have acted in recent years, with goose numbers fluctuating around 40,000 and increases in improved grassland slowing. Goose abundance correlated most strongly with improved grassland at a two-year time-lag, suggesting that cohort effects may also be acting on survival and reproduction. Cohorts born prior to non-breeding seasons when improved grassland is abundant may produce more offspring when they breed for the first time two years later. Increased immigration from neighbouring non-breeding sites could also be playing a role in population growth in Islay. However, populations have also increased at neighbouring sites and the total population overwintering on Islay has remained constant during the period of population increase (WWT range-wide surveys: 1999, 0.65; 2003, 0.65; 2008, 0.64; Mitchell & Hall 2013), suggesting that a strong role of immigration is unlikely.

We identified secondary climatic effects on goose abundance. In particular, abundance was higher following warmer and drier non-breeding seasons. This is probably linked to effects on forage quality: during colder winters grass protein content can be lower (Therkildsen & Madsen 2000), while during wet winters, grass availability may be lower due the combined effects of waterlogging and trampling by geese damaging grass (Kahl & Samson 1984). We detected positive effects of warm and dry weather during the early and late breeding season on Greenland. In particular, abundance was higher following warmer, drier Augusts. Cold, potentially snowy, periods late in the breeding season can result in brood losses due to hypothermia (Dickey, Gauthier & Cadieux 2008). The presence of climate effects reveals that external, uncontrollable, factors can play a role in shaping the environmental context of conflicts.

We detected no effect of decreasing competition with sheep on goose abundance, though it is possible that such an effect would only acted during the latter part of the study period – when sheep numbers decreased dramatically – and was not detected as a result. Prior to 1998, there was an increasing trend in sheep numbers, largely matching the trend in improved grassland. Another potential driver of abundance increases is the implementation of stricter population protection and subsequent reductions in hunting. However, the protection of barnacle geese by the EU's 1979 Bird's Directive and the UK's 1981 Wildlife and Countryside Act occurred a number of years prior to this study's time-period. Any population recovery would likely be evident for only a short period following cessation of hunting, as has been shown for other goose species (Fox *et al.* 2005; Gauthier *et al.* 2005).

Drivers of farm-scale goose dynamics

As the population has grown, goose numbers on farms have increased and their distribution has spread over a wider area. These relationships provide a link between the drivers of goose population dynamics and their spatial dynamics at a scale experienced by stakeholders. The creation of high-quality grassland was the principal driver of goose population growth and was thus likely to be responsible for the problem of serious grass damage by geese (relationships between local goose abundance and damage are probably simple; Fox *et al.* 2016).

The farm-specific intercept models also reveal that farms with more improved grassland were more likely to support large numbers of geese, supporting the population-scale results. Such farms are likely to have larger carrying capacities. Additionally, geese are known to graze more intensely on more productive pasture (e.g., Ydenberg & Prins 1981). Geese were also more likely to occur on farms closer to roosts. In order to minimize energy expenditure, geese preferentially forage closest to roosts and only move further afield when these resources become depleted, as has been identified in a range of goose species including barnacle geese (Si *et al.* 2011). These results go some way in explaining why goose impacts vary between farmers and illustrate how skewed impacts on stakeholders – a common feature of conservation conflicts (e.g., Naughton-Treves 1998; Cope, Vickery & Rowcliffe 2005) – can emerge. It should be noted that, while the occurrence model explained a large proportion of variation in farm-specific intercepts (R^2=0.69), the count model explained much less (R^2=0.09). There are likely to be a range of other factors contributing to variation in goose numbers among farms, such as scaring intensity and the quality of grassland.

Our analysis also shows how the Islay case-study has evolved over time; the effects of abundance on farm-scale goose occurrence and number were highly variable. Interestingly, farms with less improved grassland and further from roosts – which were less likely to support geese on average – became more likely to harbour geese as the population increased. This could be because forage is becoming more depleted on preferred farms, forcing geese to forage more frequently on farms further from roosts and those with less improved grassland. As a result, a wider range of farms may have experienced goose damage as the population has grown.

Linking drivers of ecological dynamics to management of conflict

By exploring the socio-ecological history of this conflict, we identified that the contemporary problem of damage to grass by geese on Islay is largely an unforeseen consequence of historic improvements in grass productivity. This illustrates that changes in land management by humans can be a key driver of environmental change contributing to the emergence of conflict. While conservationists have often expressed concern over the negative impacts of agricultural intensification on biodiversity and wildlife populations (e.g., Donald, Green & Heath 2001), our study illustrates how inadvertent positive impacts of agricultural management on wildlife populations can ultimately be damaging for conservation interests. Proactive responses to initial population increases could prevent human-wildlife impacts from reaching conflict levels and be more cost-effective than reactive interventions (Drechsler, Eppink & Wätzold 2011). Managers need to tackle emerging conflicts early not only to prevent stakeholders positions from becoming entrenched, for example by working closely with stakeholders to find shared solutions as carried out for geese in Norway and Denmark (Tombre, Eythórsson & Madsen 2013), but also to prevent impacts from wildlife reaching levels that are challenging and costly to manage.

We found that uncontrollable external processes such as climate change can influence the environmental context underlying conservation conflict. Managers should consider such processes when planning interventions. This could be achieved using predictive modelling frameworks such as management strategy evaluation (MSE), an approach gaining popularity in conservation (Bunnefeld, Hoshino & Milner-Gulland 2011). MSE combines models of natural dynamics with those for monitoring and management, incorporating the various uncertainties of complex socio-ecological systems. The use of shooting as a population-reduction tool on Islay has resulted in the escalation in conflict between stakeholder groups. An alternative strategy could be coordinated reductions in grassland productivity, through decreased reseeding frequencies and fertiliser application, in order to reduce the carrying capacity of the island. The effectiveness of these strategies could depend on climate, for example if reductions in goose numbers from culling were offset by increases in recruitment due to milder breeding conditions. Using MSE it would be possible to take into account the influence of climate change on the effectiveness of these competing management strategies.

The gathering of ecological and social evidence is recognised as an important step along the roadmap to conflict management (Redpath *et al.* 2013). However, in many cases, management interventions are put in place before the drivers of conflict are fully understood. The suitability of different management options will depend on the unique ecological and socio-economic characteristics of a particular region (Henle *et al.* 2008), including historic changes in these characteristics (Lambert 2015). As such, studies like ours provide an important step in understanding how conflict emerges and how to manage it. For waterbird populations, such studies can inform how to manage populations at the centre of conflicts sustainably, in order to pursue the African-Eurasian Waterbird Agreement (AEWA 2015). It is uncertain how the Islay case-study will develop in the future following the UK's decision to leave the EU. Brexit could potentially lead to change in the protection status of barnacle geese in the UK, however this could open up new options for the management of this conflict.

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AUTHORS' CONTRIBUTIONS

NB, AK, SR and TM formulated the question. TM conducted the analysis and wrote the paper. All authors contributed to revisions.

DATA ACCESSIBILITY

The data used in this study are available from Dryad Digital Repository.

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Tables

Table 1. Summary of model predictors, including the time-lags considered, the hypotheses they relate to and their hypothesised effects on goose numbers.

Analysis	Name	Description	Mean (range)	Time-lags	Hypothesis	Effect
Population-scale	$\text{Grass}_{\text{Islay}}$	Area of improved grassland on Islay	7,040ha (5,331-8,331)	*t*-1; *t*-2	1	+
	$\text{Sheep}_{\text{Islay}}$	Number of sheep on Islay	65,913 (47,040-78,537)	*t*-1; *t*-2	2	-
	$\text{Temp}_{\text{Islay}}$	Mean Islay October-March temperature	5.0°C (3.5-6.5)	*t*-1; *t*-2	3	+
	$\text{Precip}_{\text{Islay}}$	Total Islay October-March precipitation	1,105mm (829-1,462)	*t*-1; *t*-2	3	-
	Temp_{Aug}	Mean August Greenland temperature	2.9°C (1.1-5.2)	*t*-1; *t*-2; *t*-3	4	+
	$\text{Precip}_{\text{Aug}}$	Total August Greenland precipitation	16.6mm (0.2-63.7)	*t*-1; *t*-2; *t*-3	4	-
	Temp_{May}	Mean May Greenland temperature	-6.4°C (-8.8- -3.3)	*t*-1; *t*-2; *t*-3	4	+
	$\text{Precip}_{\text{May}}$	Total May Greenland precipitation	6.2mm (0-19.8)	*t*-1; *t*-2; *t*-3	4	-
Stakeholder-scale	$\text{Abund}_{\text{Islay}}$	Islay barnacle goose abundance	41,400 (28,500-53,000)	None	5	+
	$\text{Grass}_{\text{Farm}}$	Area of improved grassland on farm	39.7ha (0-152.5ha)	None	6	+
	$\text{Roost}_{\text{Farm}}$	Distance to roost from farm	4.6km (0.2-13.9)	None	7	-

Table 2. Best models of farm-specific intercepts (a) and coefficients for the effect of Islay barnacle goose abundance (b). Standardised coefficients, numbers of parameters (*K*), log-likelihoods (LL), ΔAIC and R^2 are displayed. Null models are displayed for comparison, or in the case that they are the most parsimonious. See Table 1 for descriptions of predictors.

a) Farm-specific intercept models

	Occurrence		**Count**	
	Best	**Null**	**Best**	**Null**
$\text{Grass}_{\text{Farm}}$	$3.25x^{0.66}$		1.28	
$\text{Roost}_{\text{Farm}}$	$-5.34x^{0.09}$		-0.89	
K	5	2	4	2
LL	-158.36	-219.58	-263.80	-268.34
ΔAIC	0.00	116.44	0.00	5.09
R^2	0.69	-	0.09	-

b) Farm-specific abundance coefficient models

	Occurrence		**Count**
	Best	**Null**	**Null**
$\text{Grass}_{\text{Farm}}$	-0.15		
$\text{Roost}_{\text{Farm}}$	$1.34x^{0.16}$		
K	4	2	2
LL	-61.02	-72.28	-251.18
ΔAIC	0.00	18.52	0.00
R^2	0.19	-	-

FIGURE LEGENDS

Figure 1. The distribution and abundance of Greenland barnacle geese across their range (a) and on Islay, including distributions of roosting sites (b). Goose abundances at wintering sites were calculated using Wildfowl and Wetlands Trust survey data (Mitchell & Hall 2013). Goose density per hectare of farmland on Islay was calculated using Scottish Natural Heritage survey data.

Figure 2. Annual variation in barnacle goose mean abundance on Islay (a), area of improved grassland on Islay (b), number of sheep on Islay (c) and temperature on Islay and Greenland (d). Where relevant, years represent the starting years of wintering seasons e.g., 2015 for the 2015-16 season.

Figure 3. Standardised coefficients ± 95% confidence intervals for the best model of Islay barnacle goose abundance, according to AIC. See Table 1 for descriptions of predictors.

Figure 4. Partial effects of selected environmental predictors on Islay barnacle goose abundance. R^2 displayed for each partial effect. See Table 1 for descriptions of predictors.

Figure 5. Fitted effects of Islay barnacle goose abundance on farm-scale barnacle goose probability of occurrence (a) and number (b), from best occurrence and count models. Shaded areas represent fitted values ± standard errors. Models were fitted for an average farm, with day set to an intermediate level (5th December).

Figure 6. Fitted effects of mean area of improved grassland and distance to nearest roosting site on farm-scale barnacle goose probability of occurrence (a-b) and number (c-d). Points are farm-specific estimates from the best occurrence and count models. Lines are produced by incorporating the relationships between farm-specific intercepts and grassland/distance to roost (see Table 2a) into the fitted estimates. Models were fitted with abundance and day set to intermediate levels (4,000; 5th December).

Figure 7. Percentage change in farm-scale probability of barnacle goose occurrence with Islay goose abundance, for farms with varying improved grassland area (a) and proximity to roosting site (b).

Fitted lines are produced by incorporating the relationships between farm-specific intercepts/slopes and grassland/distance to roost (see Table 2) into the fitted estimates of the best occurrence model. Models were fitted with day set to an intermediate level (5th December).

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

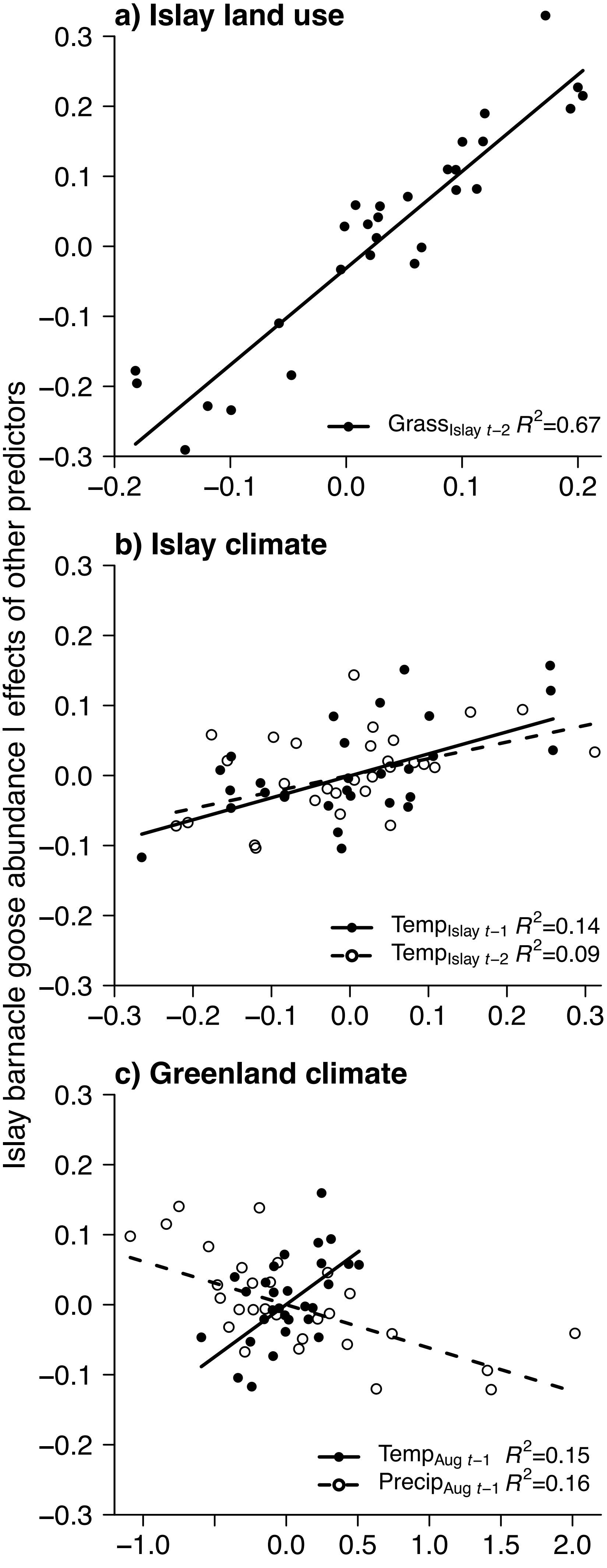
Table S1. Population-scale model selection table.

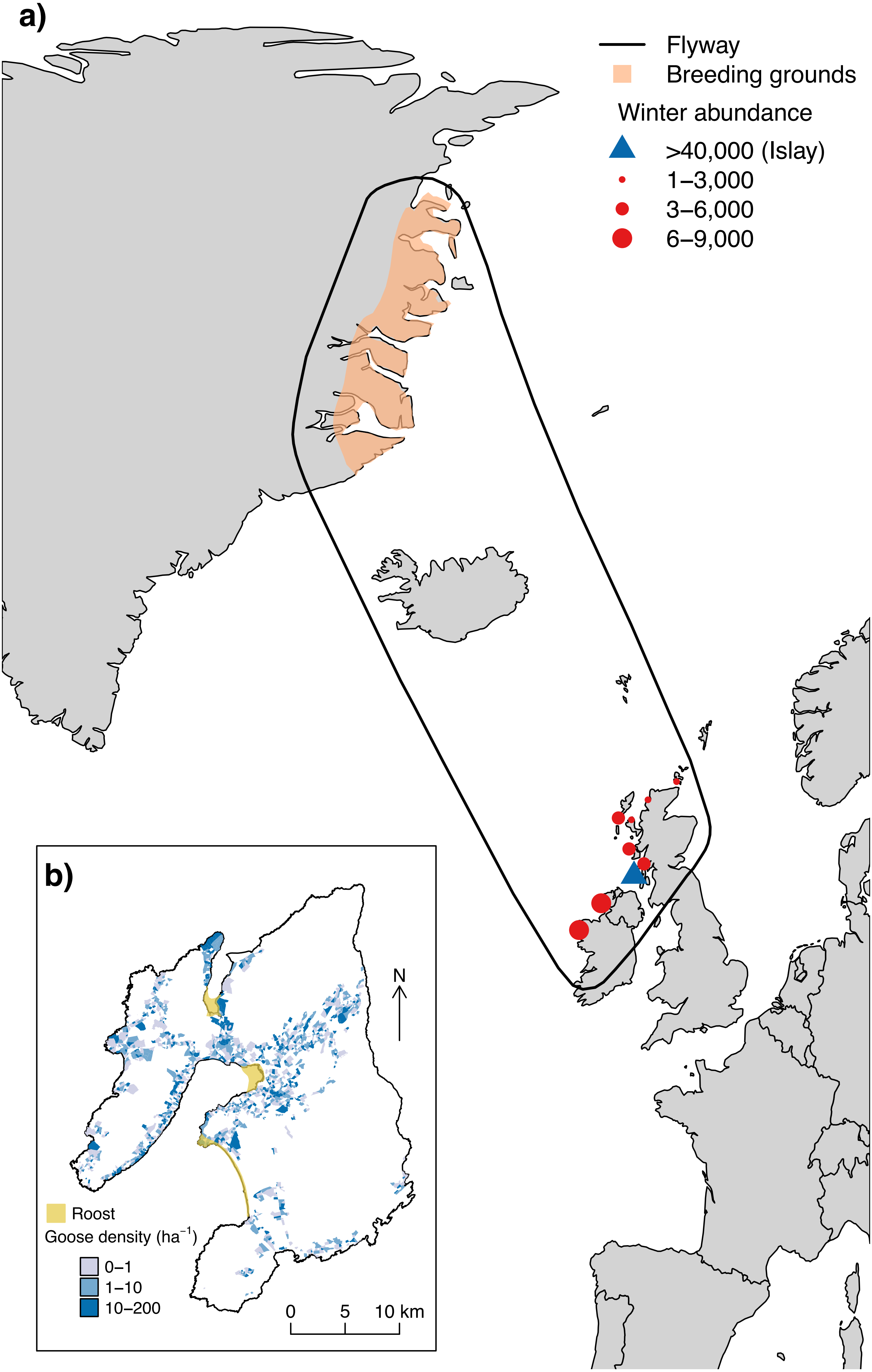
Table S2. Farm-scale model selection table.

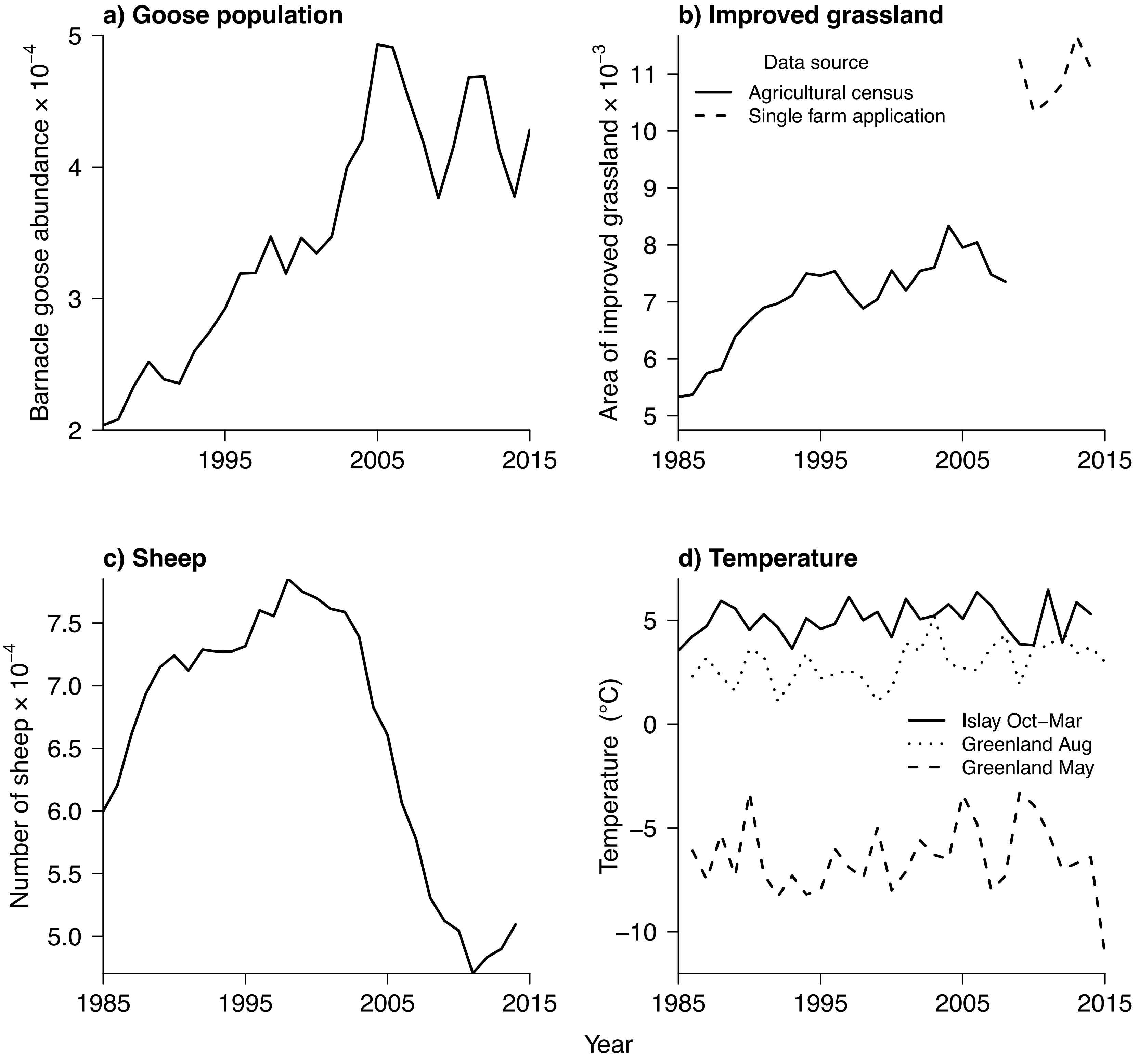
Fig. S1. Relative timings of variables.

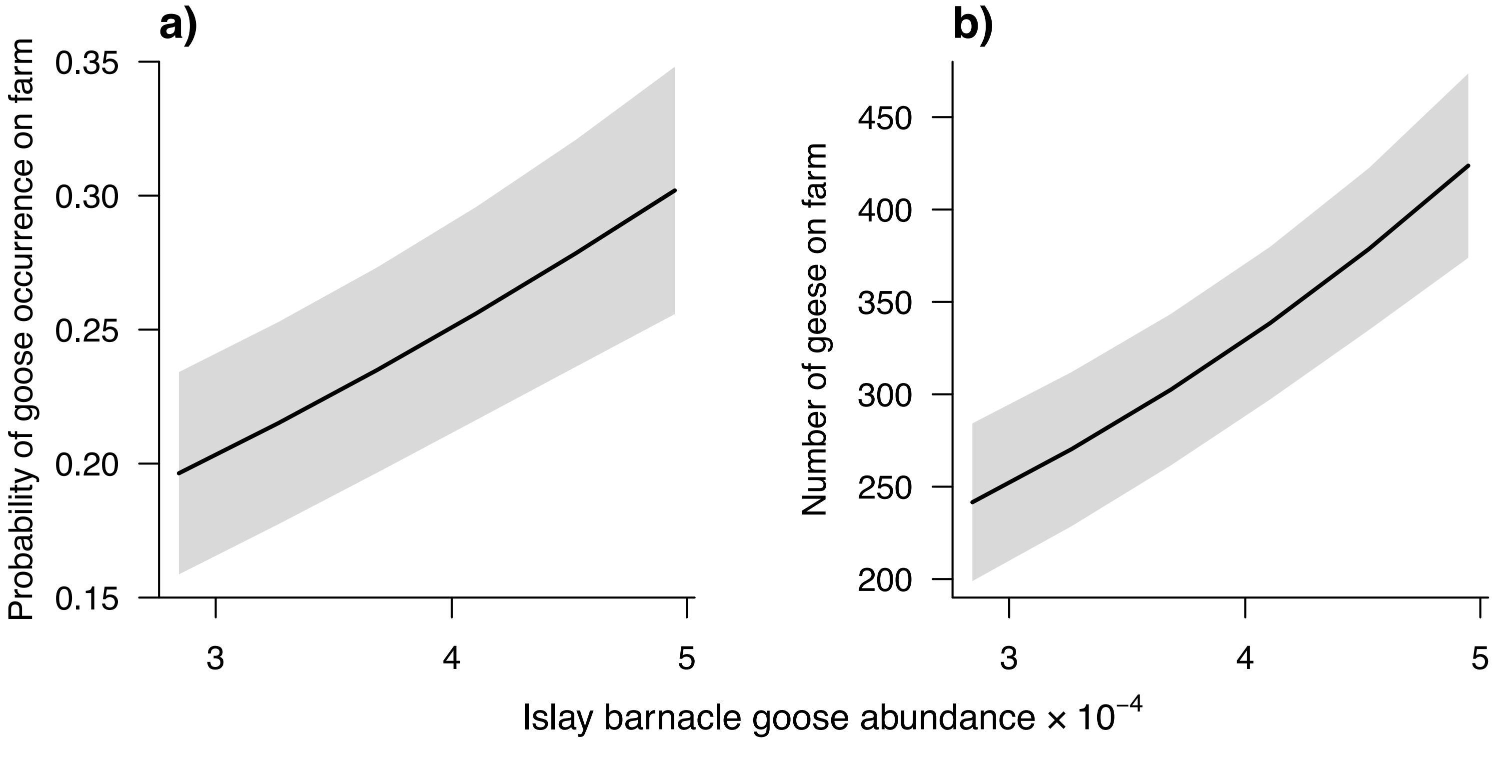
Fig. S2. Temporal trends in climatic variables.

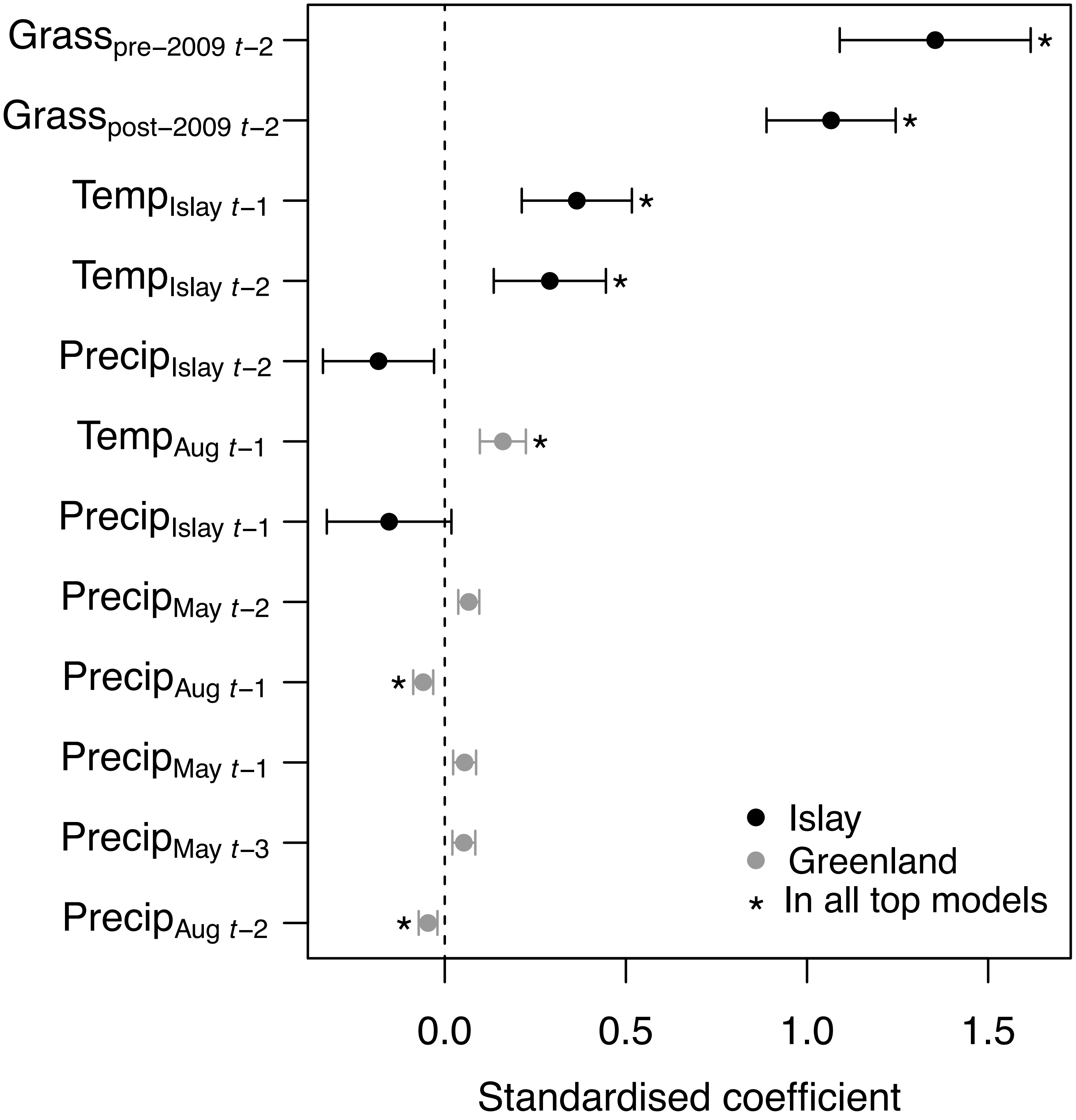
Fig. S3. Influence of day on farm-scale goose numbers.

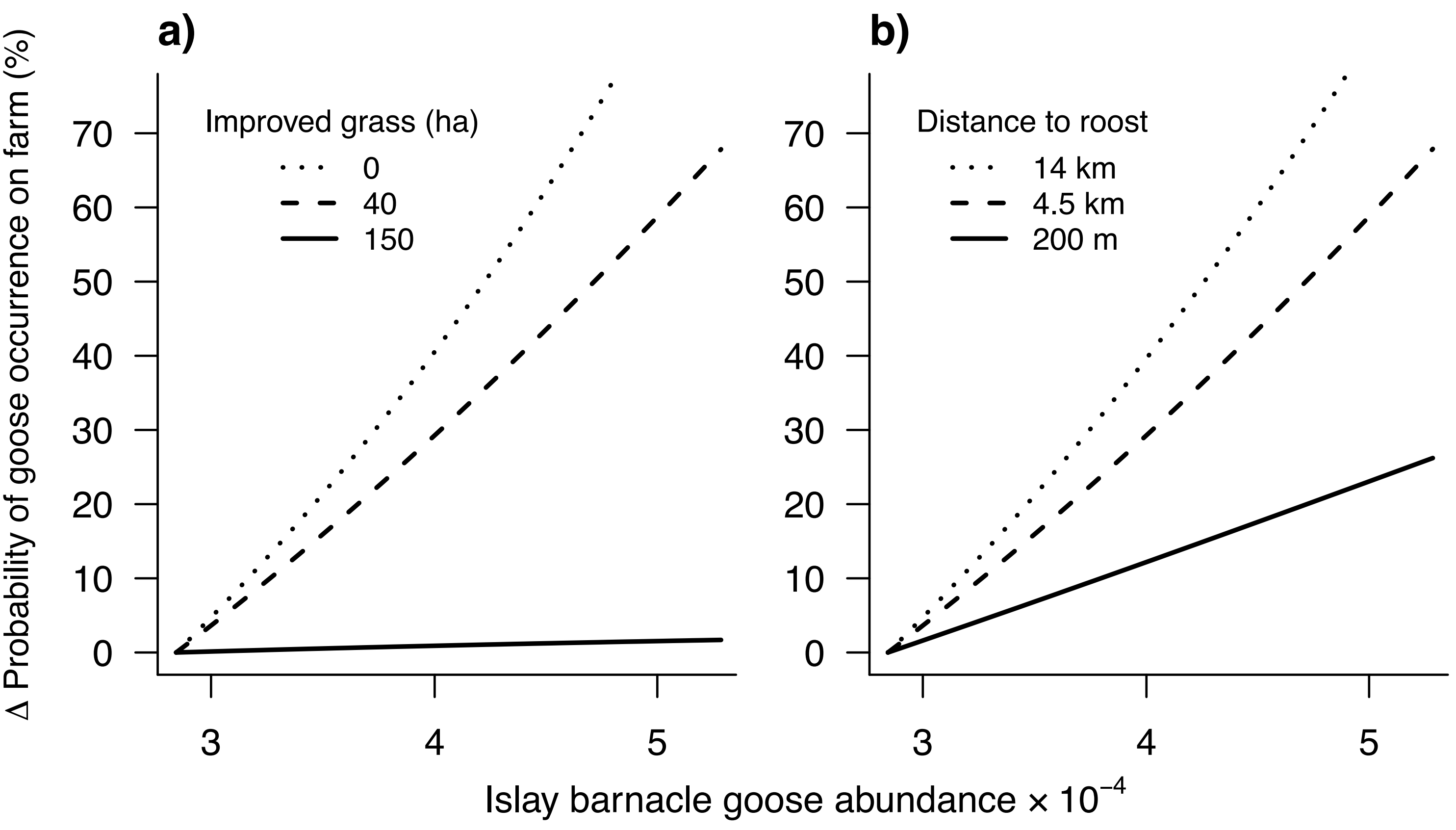

a) Islay land use
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
Grass$_{\text{Islay } t-2}$ R^2=0.67
−0.2
−0.1
0.0
0.1
0.2
b) Islay climate
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
Temp$_{\text{Islay } t-1}$ R^2=0.14
Temp$_{\text{Islay } t-2}$ R^2=0.09
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
c) Greenland climate
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
Temp$_{\text{Aug } t-1}$ R^2=0.15
Precip$_{\text{Aug } t-1}$ R^2=0.16
−1.0
0.0
0.5
1.0
1.5
2.0
Islay barnacle goose abundance | effects of other predictors
Predictor | effects of other predictors

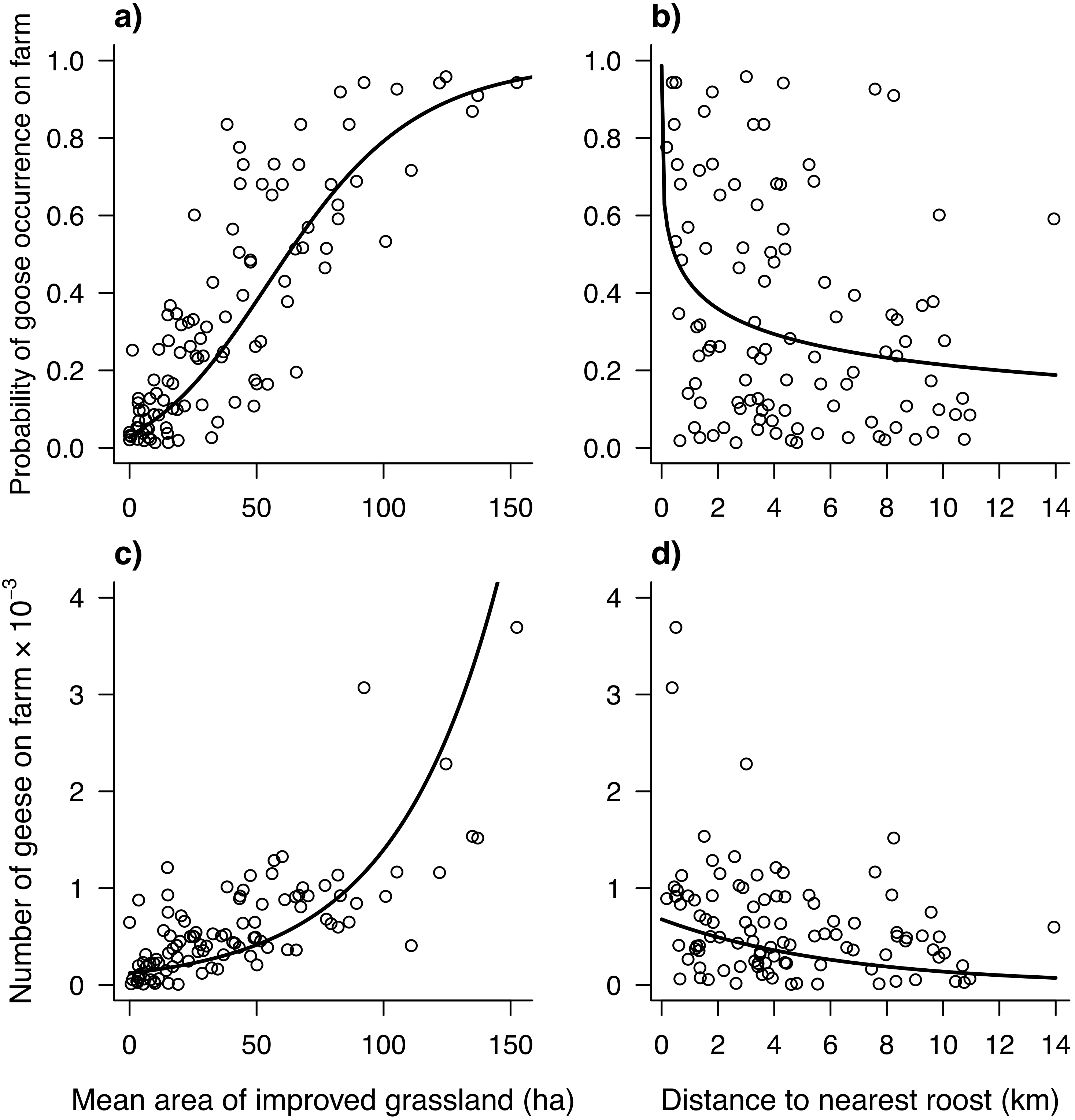

a)
Flyway
Breeding grounds
Winter abundance
>40,000 (Islay)
1–3,000
3–6,000
6–9,000
b)
N
Roost
Goose density (ha^{-1})
0–1
1–10
10–200
0
5
10 km


a) Goose population
Barnacle goose abundance × 10^{-4}
2
3
4
5
1995
2005
2015
b) Improved grassland
Area of improved grassland × 10^{-3}
5
6
7
8
9
10
11
Data source
Agricultural census
Single farm application
1985
1995
2005
2015
c) Sheep
Number of sheep × 10^{-4}
5.0
5.5
6.0
6.5
7.0
7.5
1985
1995
2005
2015
d) Temperature
Temperature (°C)
−10
−5
0
5
Islay Oct–Mar
Greenland Aug
Greenland May
1985
1995
2005
2015
Year


a)
b)
Probability of goose occurrence on farm
0.35
0.30
0.25
0.20
0.15
Number of geese on farm
450
400
350
300
250
200
3
4
5
3
4
5
Islay barnacle goose abundance × 10⁻⁴


Grass pre−2009 t−2
Grass post−2009 t−2
Temp Islay t−1
Temp Islay t−2
Precip Islay t−2
Temp Aug t−1
Precip Islay t−1
Precip May t−2
Precip Aug t−1
Precip May t−1
Precip May t−3
Precip Aug t−2
0.0
0.5
1.0
1.5
Standardised coefficient
Islay
Greenland
In all top models


a)
b)
Improved grass (ha)
0
40
150
Distance to roost
14 km
4.5 km
200 m
Δ Probability of goose occurrence on farm (%)
0
10
20
30
40
50
60
70
3
4
5
Islay barnacle goose abundance × 10^−4


a)
b)
Probability of goose occurrence on farm
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
0
2
4
6
8
10
12
14
c)
d)
Number of geese on farm × 10^{-3}
4
3
2
1
0
0
50
100
150
0
2
4
6
8
10
12
14
Mean area of improved grassland (ha)
Distance to nearest roost (km)