

Stoat (*Mustela erminea*) on the Orkney Islands – assessing the risks to native species





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COMMISSIONED REPORT

Commissioned Report No. 871

Stoat (*Mustela erminea*) on the Orkney Islands – assessing the risks to native species

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COMMISSIONED REPORT

Summary

Stoat (*Mustela erminea*) on the Orkney Islands – assessing risks to native species

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Keywords

Orkney vole; stoat; hen harrier; short-eared owl; predator-prey interactions.

Background

Stoats (*Mustela erminea*) were first recorded on Orkney in 2010 following an assumed accidental introduction. Stoats are native to mainland Britain where they prey on a variety of mammals, birds and their eggs. Stoats are invasive in New Zealand and have caused the decline or extinction of many native birds. In some areas of New Zealand, the impact of stoats is exacerbated by outbreaks in mouse populations occurring in response to masting events in native beech forests. Predator-prey interactions, for example between mustelids and rodents, can result in reciprocal feedback involving numerical and functional responses and population cycles. In systems where alternative prey is scarce, the predator population will recurrently collapse then rebuild in response to depletion and recovery of their main prey. However, in systems where alternative prey is abundant the impact of predation on the preferred prey can trap it at constantly low density, with any rise being cancelled by increased predation.

The Orkney vole (*Microtus arvalis orcadensis*) is an important prey species for several nationally important populations of raptors on Orkney including hen harriers (*Circus cyaneus*) and short-eared owls (*Asio flammeus*). It is feared that the introduction of stoats may lead to a depletion of Orkney voles which in turn could affect the predators that depend on them. This study set out to assess the potential impact of stoats on the ecology of Orkney, in particular to the Orkney vole population, the vole-eating raptors and the potential alternative prey for stoats.

Main findings

- We have inferred from records of stoat sightings that stoats are likely to be distributed throughout Mainland Orkney and connected islands will be occupied by stoats now, or in the very near future.
- We found no evidence of cyclic patterns in vole abundance in Orkney in the past though we found evidence of some inter-annual variability of limited amplitude and frequency. This implies that Orkney voles have been providing a relatively steady supply of food to hen harriers and short-eared owls, including at critical times in their life cycles.
- We have presented and evaluated three plausible scenarios regarding the potential outcome for the impact of stoats on Orkney ecology. We consider the most likely outcome of a long-term impact of stoats on Orkney to be that Orkney vole populations will

become permanently reduced to lower average densities. This is because a range of alternative prey are available to stoats, stoats have intrinsic high mobility, and there are no top predators that would impose a mortality cost to stoat mobility should they exploit several prey in different habitats.

- We also consider the likelihood of such a scenario having a major detrimental effect on harriers and short-eared owls through depletion of a key prey and high predation on ground nesting birds.
- If, as we expect, the introduction of stoats in the Orkney ecosystem results in changes in vole dynamics, such changes are highly likely to result in a significant deterioration in the condition of species that are the designated features of Special Protection Areas. It can be considered highly likely, on the basis that stoats are opportunistic predators that direct predation of ground nesting waders by stoats will occur in those protected areas.
- We advise that averting further spatial expansion and, more damaging, further increase in abundance in stoats requires rapid and decisive intervention. We strongly recommend that stoat management should be accompanied by regular monitoring of key components of the ecosystem in Orkney, according to a formal adaptive management framework. Such a programme would provide ongoing improvements in understanding of the system being managed and of the effectiveness of management action in delivering the desired outcome. We provide details of these recommendations.

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Table of Contents		Page
1.	INTRODUCTION	1
2.	METHODS	4
3.	RESULTS	7
3.1	Review of relevant evidence regarding the predator/prey relationship between hen harriers and short-eared owls and the Orkney vole	7
3.2	Review (and map) the history of colonisation of Orkney by stoats from trapping records, sightings etc.	7
3.3	Review the evidence for population cycling in Orkney vole populations and how this might influence the introduced stoat population	13
3.4	Review the evidence of rabbit populations on Mainland Orkney and assess how this might influence the likely prey to be taken by stoats, such as Orkney vole and ground nesting waders	20
3.5	Assess the degree or risk that introduced stoats pose to the island ecology of Orkney, with an emphasis on vulnerable prey species such as Orkney vole	23
4.	DISCUSSION	27
4.1	Review of relevant evidence regarding the predator/prey relationship between hen harriers and short-eared owls and the Orkney vole	27
4.2	Review (and map) the history of colonisation of Orkney by stoats from trapping records, sightings etc.	27
4.3	Review the evidence for population cycling in Orkney vole populations and how this might influence the introduced stoat population	28
4.4	Review the evidence of rabbit populations on Mainland Orkney and assess how this might influence the likely prey to be taken by stoats, such as Orkney vole and ground nesting waders	30
4.5	Assess the degree or risk that introduced stoats pose to the island ecology of Orkney, with an emphasis on vulnerable prey species such as Orkney vole	30
5.	REFERENCES	33

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1. INTRODUCTION

The purpose of this research was to investigate potential impacts of introduced stoats (*Mustela erminea*) on the ecology of the Orkney Islands. Stoats are not native to Orkney and were first reported on the islands in 2010. Over the past five years the population on Mainland Orkney has increased. This study will evaluate the degree of risk that stoats pose to other species on Orkney including the Orkney vole (*Microtus arvalis orcadensis*), hen harrier (*Circus cyaneus*), short-eared owl (*Asio flammeus*) and other ground nesting birds as well as the relationships between them.

The Orkney vole is a sub-species of the common vole (*Microtus arvalis*) found across Continental Europe (Reynolds, 1992). Orkney voles are much larger than their Continental relatives, with males weighing up to 85g compared to 25g for Continental common voles. They are also much larger than field voles (*Microtus agrestis*), the only *Microtus* vole found in mainland Britain. Their fecundity is much reduced compared to their mainland European ancestors (Gorman & Reynolds, 2008). Orkney voles have been present in the archipelago since at least 5100 bp 5,100 years ago, having been introduced by human, probably from Belgium (Martínková *et al.*, 2013). They are found on several islands including Mainland, South Ronaldsay, Rousay, Sanday and Westray but are not found on Hoy (Gorman & Reynolds, 2008). A small, unlicensed introduction to Eday is reported to have taken place in the last 20 years. They are present in most habitats in Orkney except arable land and grazed pastures but reach their highest population densities (up to 570 voles per hectare) in old peat cuttings and rough grassland (Reynolds, 1992). Studies of Orkney voles in the late 1980s and early 1990s concluded that the populations were relatively stable (Reynolds, 1992), which would make this population stand out relative to most other *Microtus* vole populations which typically have irruptive or cyclically fluctuating dynamics (Taitt & Krebs, 1985).

Orkney voles are an important prey item for raptors including hen harriers, short-eared owls and kestrels (*Falco tinnunculus*). Short-eared owls are particularly dependent on voles, which comprise 78 – 100% of the total prey items consumed in the breeding season and up to 72% in the winter diet (Reynolds, 1992). Short-eared owls hunt both during the day and at night and synchronise their hunting activity with peaks in vole activity (Reynolds & Gorman, 1999). Hen harriers have a more varied diet, which includes significant proportions of lagomorphs and birds though voles are still an important dietary component, particularly in spring (Amar, 2001; Redpath *et al.*, 2002). In southern Scotland, abundance and clutch size (but not fledging success) of hen harriers were significantly correlated with field vole abundance (Redpath *et al.*, 2002).

Hen harriers in the U.K. are legally protected at a national and international level but are still persecuted in some areas (Amar & Redpath, 2002). Illegal persecution contributed to their virtual extinction on mainland Britain in the early twentieth century but hen harrier populations on the Orkney Islands remained and are likely to have contributed to the recolonisation of Britain in the 1930s and 1940s (Amar & Redpath, 2002). The Orkney Mainland Moors Special Protection Area (SPA) is designated under European and domestic legislation and is home to one of the largest and densest hen harrier populations in Britain (SNH, 2015). It also supports significant numbers of breeding short-eared owls and red-throated divers (*Gavia stellata*) (SNH, 2015). In addition, the site is designated as a Site of Special Scientific Interest (SSSI) and in combination with three other SSSIs on Mainland Orkney, supports a wide variety of breeding and non-breeding waders and wildfowl (SNH, 2015).

Stoats are small mustelids (males weigh up to c.470g, females c.300g), that are native in the northern Holarctic, including Great Britain (McDonald & King, 2008). Stoats live in a variety of habitats that offer suitable prey and sufficient cover but tend to avoid open areas

(McDonald & King, 2008). Studies of stoat diet have highlighted a variety of prey including rabbits, rodents, game birds, waders, chicks and eggs which may vary seasonally according to prey availability (McDonald *et al.*, 2000; McDonald & King, 2008). They have also been seen to kill hen harrier chicks (Redpath pers. obs.). The impact of stoats on their prey populations will vary. Stoats were introduced to New Zealand from Britain in the 1880s as a biological control for rabbits (McDonald & King, 2008) but instead have had a devastating impact on native species on the mainland and offshore islands (e.g. Dowding & Murphy, 2001; O'Donnell, 1996; O'Donnell & Hoare; 2012). Outbreaks of mice following seed masting events in New Zealand beech forests result in elevated numbers of stoats which in turn increased predation on native birds (King, 1983). These masting events were associated with rainfall (Tompkins *et al.*, 2013). Because of their impact on native prey, Stoat belongs to the 100 world's worst invasive species (Global Invasive species database, 2015).

The reproductive strategy of stoats makes it an ideal species for invading new areas. Females are sexually mature at 2 – 3 weeks and can be mated whilst still in the nest. Fertilised eggs develop into blastocysts but implantation (and subsequent embryonic development) can be delayed for 9 – 10 months (McDonald & King, 2008) thus meaning that the chances of a female being pregnant at the time of introduction or invasion to a new area are high. Reinvansion of areas previously eradicated of stoats is a continual threat and carries a high risk to native fauna (Veale *et al.*, 2012).

In Europe and North America, the stoat and other *Mustela* relatives are associated with cyclic fluctuations of vole and lemming populations (Graham & Lambin, 2002; Gilg *et al.*, 2003; Hellstedt *et al.*, 2006). In those localities, predator-prey interactions often result in reciprocal feedback that involves numerical (changes in abundance reflecting variation in reproduction and survival) and functional responses (variation in intake rate in relation to prey density). Combined with the variable impact of other predators, predation can exceed the production by voles, resulting in prey depletion and eventually a decline in the predator population. This sequence of events results in regular cycles repeated every 3-4 years, without any environmentally induced variation in primary productivity (Gilg *et al.*, 2003; Hellstedt *et al.*, 2006; but see Graham & Lambin, 2002).

An essential feature of a system where such predator prey cycles develop is the low availability of alternative prey to mustelids, such that depletion of their main vole prey is followed by reproductive failure and starvation which precipitates a collapse in mustelid numbers that had built up during the period of high vole abundance. The pattern of predation, and importance of prey switching, depends on the size, range and seasonal availability of different prey and the match between their body size and that of the dominant prey. In Fennoscandia, stoats are variously described as rodent specialist or semi-generalist predators in various parts of their range. This is because their larger size gives them access to a wider range of prey than the smaller least weasel (*Mustela nivalis nivalis*) whose size is approximately equal to that of its vole prey. Thus the realised degree of specialism of stoats is an important consideration when attempting to predict its impact.

The population dynamics of Orkney voles are relevant to the likely impact of stoats on Orkney ecology not only because of the direct impact of stoat predation on voles but because of the potential impact on the alternative prey for stoats that could be targeted if either vole abundance decreases and/or stoat abundance increases. Given stoats are notorious predators of eggs and chicks (McDonald & King, 2008), this potential impact might be severe, but this will depend upon how tightly stoat demography and distribution is tied to vole abundance.

The importance of vole presence on Orkney is a key distinction between the likely impact of stoats on Orkney and the apparent lack of major impact of introduced stoats on Shetland. The introduction of stoats to Shetland is much longer established (17th Century), and records

are ongoing but occasional from Mainland Shetland and Muckle Roe, and rare, incidental or absent from other islands (McDonald & King, 2008). Stoat populations on Shetland have not increased to high densities and their observed impacts have not been especially marked, though it is likely that any impacts were incurred early on in their history on these islands. This lack of a large population or large current impact is most likely because of the lack of a reliable prey base on Shetland on which stoat breeding can capitalise. This is the key difference between Shetland and Orkney, in that voles provide a high quality, accessible and reliable food source for stoats, especially for breeding females (McDonald *et al.*, 2000).

In this study, we addressed five questions posed by SNH in order to reach conclusions about the potential impact of stoats on Orkney and to evaluate how stoats could interact with other species. The questions are outlined below and are used to structure the results and discussion of this report.

1. Review of relevant evidence regarding the predator-prey relationships between hen harriers and short-eared owls and the Orkney vole.
2. Review (and map) the history of colonisation of Orkney by stoats from trapping records, sightings, etc.
3. Review the evidence for population cycling in Orkney vole populations and how this might influence the introduced stoat population.
4. Review the evidence of rabbit populations on Mainland Orkney and assess how this might influence the likely prey to be taken by stoats, such as Orkney vole and ground nesting waders.
5. Assess the degree of risk that introduced stoats pose to the island ecology of Orkney, with an emphasis on vulnerable prey species such as Orkney vole.

2. METHODS

In order to address the questions set by SNH we had to assemble various datasets from numerous sources.

Stoat records

All records of stoat sightings were obtained from SNH. The National Biodiversity Network (NBN) was searched for additional records of stoats in Orkney but there was none. The records were categorised as reliable (confirmed), possible and inconclusive by SNH staff, who based their judgement on the description of the record that was given to them at the time of reporting. The sightings were mapped using the exact locations reported to SNH. We also calculated a conservative distribution of stoats based on these records by adding a 1 km buffer to all reported sightings that were judged as reliable. The frequency of reported sightings per month and year were calculated and compared to dates of media events (provided by SNH) that were used to raise awareness of stoats in Orkney. We allocated each sighting to a season to look for seasonal differences in the distribution of stoat sightings (spring: March – May, summer: June – August, autumn: September – November, winter: December – February).

Vole populations

To tackle the question of cyclicity in vole populations we searched for data relating to surveys of vole abundance in Orkney. RSPB held the longest, most consistent dataset of vole surveys on Mainland Orkney which spanned from 1999 – 2014 (data missing in 2009 and 2013). These surveys were conducted in three areas of West Mainland (around Birsay Moors), with four transects in each area. Vole presence or absence was recorded within quadrats along each transect. Data from these surveys were supplemented with additional surveys that had been conducted as part of a number of different projects, using similar monitoring methods. All surveys that contributed data were conducted in summer (primarily July/August). Data from Arjun Amar (1998 and 1999) were collected as part of his PhD project (Amar, 2001) and from Tom Langhorne (2014) as part of his honours project (Langhorne, 2015), both based at the University of Aberdeen. The remaining data were taken from surveys commissioned in 2005, 2006 and 2007 for monitoring as part of the Orkney Hen Harrier Scheme (OHHS). This scheme was aimed at reversing the decline of hen harriers in Orkney by increasing the area of rough grassland and prey abundance close to hen harrier nesting areas (Crossley, 2005). A breakdown of the data contributions from each source is shown in Table 1.

Transects from each data source were categorised by habitat (moorland, rough grass, pasture) and the proportion of quadrats with positive signs of vole presence in each transect was calculated. The proportion of positive quadrats within each habitat was then standardized to account for differences in sources and survey areas. This gave us a score of vole abundance. Quadrat size and transect length was variable between studies and the signs of vole presence included from the presence of dropping or feeding remains (e.g. grass clippings). Vole population growth rate was calculated using the change in abundance from one year to the next using the formula $\ln N_t / \ln N_{t-1}$, where N_t was vole abundance at year t . This calculation was only possible where there were at least two consecutive years of data and hence could not be calculated for 2009, 2010, 2013 or 2014.

Hen harrier breeding

Owing to the fact that the available data on vole abundance were somewhat sparse and collected using non-standardised methods, we also chose to analyse the breeding data of hen harriers as a proxy for vole abundance. This is in the knowledge that although hen harriers are not vole specialists, the availability of voles is strongly correlated with clutch size in various studies (Hamerstrom, 1979; Korpimaki, 1985; Simmons *et al.*, 1986; Redpath *et al.*, 2002). We therefore assumed that clutch size would vary in relation to vole populations.

Data on the breeding activity of hen harriers were obtained under contract from the Orkney Raptor Study Group ((Williams, 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012; 2013; Williams & Branscombe, 2014) for the years 2002 – 2014 and from the RSPB for 2001. We used information on the year, location, clutch size and overall outcome of each nest (success or failure) to analyse the breeding activity of hen harriers in Orkney from 2001 – 2014. We used data from nests in Mainland Orkney and Rousay because these islands are occupied by voles. Data from Hoy were excluded because there are neither voles nor stoats on Hoy and until recently few pairs of harriers. In order to determine if there was spatial variation in breeding success across Orkney we conducted spatial autocorrelation analyses on the clutch size of hen harrier nests. If no spatial autocorrelation was found then we were safe to assume that data from across Mainland Orkney and Rousay could be pooled and any results would be applicable to the whole area. Analyses of clutch size and nest success from 2001 – 2014 looked for variation that could be attributed to fluctuations in vole abundance.

Short-eared owl breeding

Data for the breeding activity of short-eared owls were also obtained from ORSG via the Orkney Bird Reports from 2003 – 2013 and for an area of West Mainland surveyed by Stuart Williams and Brian Ribbands (ORSG) from 2010 – 2014. Short-eared owls are notoriously difficult to monitor without causing disturbance (Calladine *et al.*, 2008) and so there were limited data on clutch size and nest success. Instead we chose to use the number of pairs recorded in the breeding season as a measure of breeding condition (Reynolds, 1992; Village, 1987; Korpimaki & Norrdahl, 1991).

Rabbit populations

Data on the distribution of rabbits were obtained from the Orkney Wildlife Information Record Centre (OWIRC) and from the National Biodiversity Network (NBN). Data from NBN were submitted by the Biological Records Centre, British Trust for Ornithology, People's Trust for Endangered Species and the Mammal Society. Overall, we had 158 records of rabbits on Mainland Orkney from 1962 – 2014. Landscape coverage of rough grassland and improved grassland were derived from the Land Cover Map 2007 data for the UK (Morton *et al.*, 2011). Each rabbit and stoat record was assigned a value (ha km⁻²) for rough grass and improved grass according to the 1 km square that the record was located in. This information was then used to make a basic habitat assessment and compare the occurrence of rabbit records in each grassland type with the occurrence of stoat sightings in each grassland type.

Risk analysis

The final objective posed by SNH was an assessment of the degree or risk that introduced stoats pose to the island ecology of Orkney, with an emphasis on vulnerable prey species such as Orkney vole. We chose to present three scenarios that addressed potential outcomes and impacts for the stoat population and other species in Orkney, along with our opinions on the likelihood of each scenario occurring.

All statistical and spatial analyses were conducted using the statistical software "R" (R Core Team, 2013) and geographical information software ArcGIS 10.2.1.

Table 1. Outline of the data from vole surveys across Mainland Orkney provided by different sources.

Year	Contributor	No. of survey transects in each habitat		
		Moorland	Rough grass	Pasture
1998	A. Amar	3	3	3
1999	A. Amar	2	3	3
	RSPB	8	4	
2000	RSPB	8	4	
2001	RSPB	8	4	
2002	RSPB	8	4	
2003	RSPB	8	4	
2004	RSPB	8	4	
2005	RSPB	8	4	
	OHHS		12	23
2006	RSPB	8	4	
	OHHS		11	17
2007	RSPB	8	4	
	OHHS		11	18
2008	RSPB	8	4	
2009	No data			
2010	RSPB	8	4	
2011	RSPB	8	4	
2012	RSPB	8	4	
2013	No data			
2014	RSPB	4		
	T. Langhorne	23	22	

3. RESULTS

3.1 Review of relevant evidence regarding the predator/prey relationship between hen harriers and short-eared owls and the Orkney vole

In many parts of their range, the diet, density and clutch size of hen harriers appears to be determined by the abundance of voles (Hamerstrom, 1979; Korpimaki, 1985; Simmons *et al.*, 1986). Voles form an important component of the diet in spring when birds are settling on their breeding territories and in the summer when they are feeding chicks (e.g. Simmons *et al.*, 1986; Barnard *et al.*, 1987). In Scotland, where the majority of British harriers breed, field voles are an important component of the diet especially in winter and spring and harrier numbers and clutch size are strongly correlated with vole abundance (Redpath *et al.*, 2002). Although fledging success tended to be greater in years of vole increase than in years of vole decline, fledging success was not significantly correlated with the relative abundance of voles, or with the abundance of meadow pipits (*Anthus pratensis*) or red grouse (*Lagopus lagopus scotica*) chicks.

Picozzi (1980) found that voles formed a small proportion (4%) of hen harrier food items during the breeding season on Orkney, although this may have been a slight underestimate. Males tended to catch more voles than females. In contrast, Balfour and MacDonald (1970) found that voles formed 37% of food items. Whether this difference reflects variation in vole abundance is unclear. Picozzi (1980) considered that voles were likely to be much more important prey items during winter and spring. The absence of harriers from Shetland and the low numbers on Hoy, where voles are absent, both suggest that voles are an important prey item for harriers. Moreover, on Orkney, harriers showed a preference for hunting on rough grass, probably as a consequence of the higher abundance of Orkney voles in this versus alternative habitats, such as heather or pasture (Amar & Redpath, 2005). Amar and Redpath (2002) recently demonstrated that harriers on Orkney were limited by food availability. Although the population has since recovered, further reductions in food, may have potentially serious consequences for the population.

In mainland Scotland, short-eared owl abundance was strongly correlated with field vole abundance (Village, 1987). Similarly in mainland Europe, abundance, and the number of young short-eared owls and kestrels fledged were strongly correlated with the abundance of field voles and common voles in spring (Korpimaki & Norrdahl, 1991). In Orkney, voles figure prominently in the diet of these owls, forming more than 60% prey items (Gorman & Reynolds, 1993). In addition, owls time their hunting activity to match the activity of voles (Reynolds & Gorman, 1999).

In summary, this evidence suggests that stoats may have an indirect impact on hen harriers and short-eared owls if they reduce the numbers of voles available to hen harriers, especially before and during the early breeding season.

3.2 Review (and map) the history of colonisation of Orkney by stoats from trapping records, sightings etc.

There have been 380 sightings of stoats that were confirmed as reliable by SNH and a further 13 possible sightings reported since 2010. An additional 14 reports were deemed inconclusive by SNH staff. These inconclusive reports were a mixture of circumstantial evidence (e.g. dead poultry assumed to be killed by stoats) and assumed observer error. The number of reports has shown an accelerating increase (Figure 2). Most reports were of sightings of live stoats although a small number (7%) were reports of dead animals, mostly road kill.

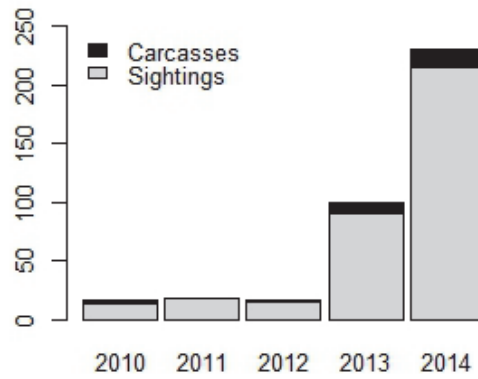


Figure 1. Number of records of stoat sightings or carcasses reported each year to SNH.

The total distribution of sightings that were judged as reliable (confirmed) and possible are mapped in Figure 2 (393 sightings in total). All sightings but one were on the mainland, Burray and South Ronaldsay. The outlying possible sighting was recorded in Westray in August 2013. No further records have been made on outlying islands.

We have mapped the history of colonisation of stoats in Orkney using the records judged as reliable by SNH. The following maps (Figure 3) show the sightings reported each year as well as the cumulative distribution of all sightings up to that point in time. Our aim was to identify if there were any areas where sightings were not repeatedly recorded from 2010 - 2014. The area of this conservative estimate of cumulative distribution was plotted against time to demonstrate the continual spread of stoats since 2010.

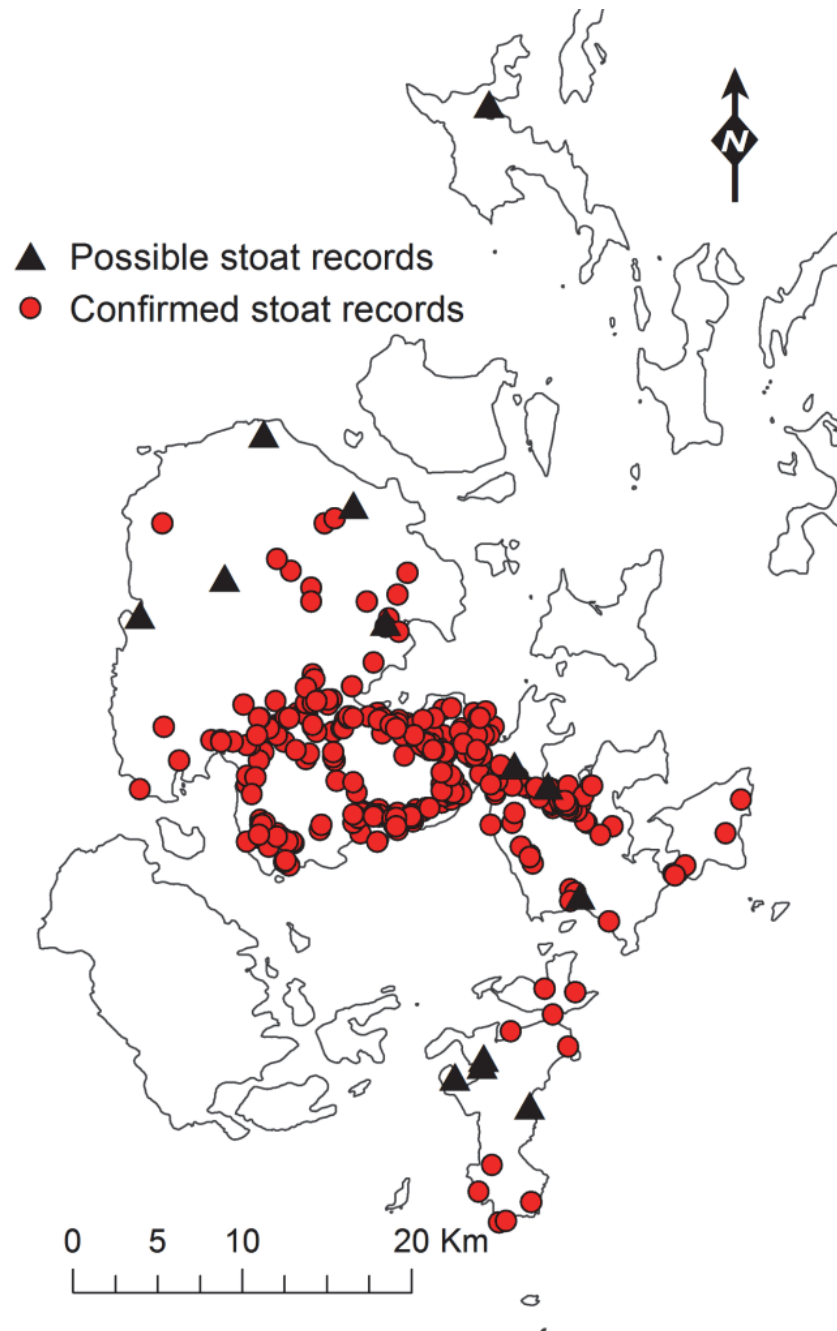


Figure 2. Distribution of stoat records collected between 2010 and 2014, judged as reliable (confirmed) (380 sightings) or possible (13 sightings) by SNH staff.

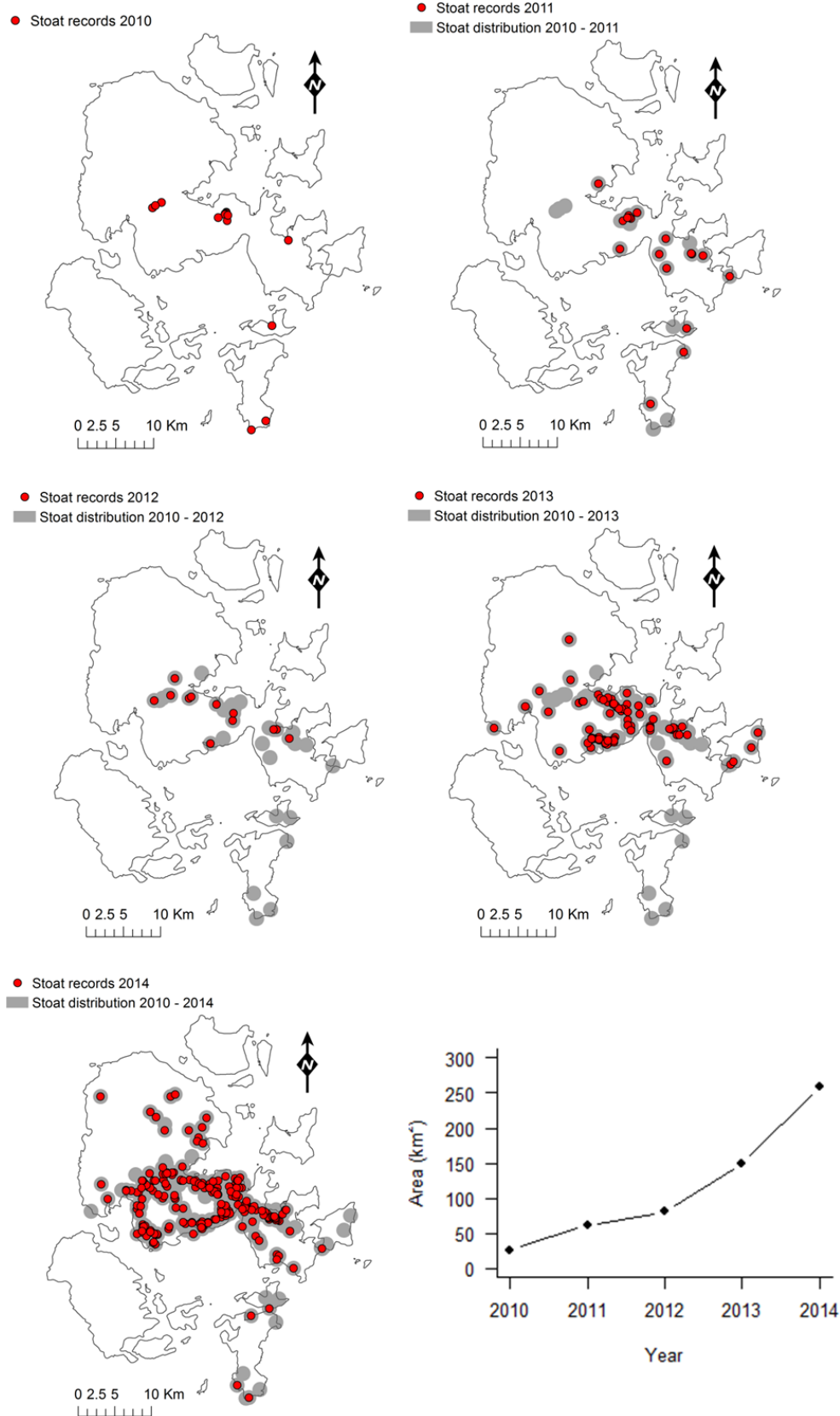


Figure 3. History of reporting of stoat sightings in Orkney from 2010 to 2014. Red dots represent sightings or carcasses reported that year and confirmed by SNH to be reliable. Grey areas represent the cumulative distribution of stoat sighting records. The area is that derived from reported sightings and will not reflect the actual distribution of stoats.

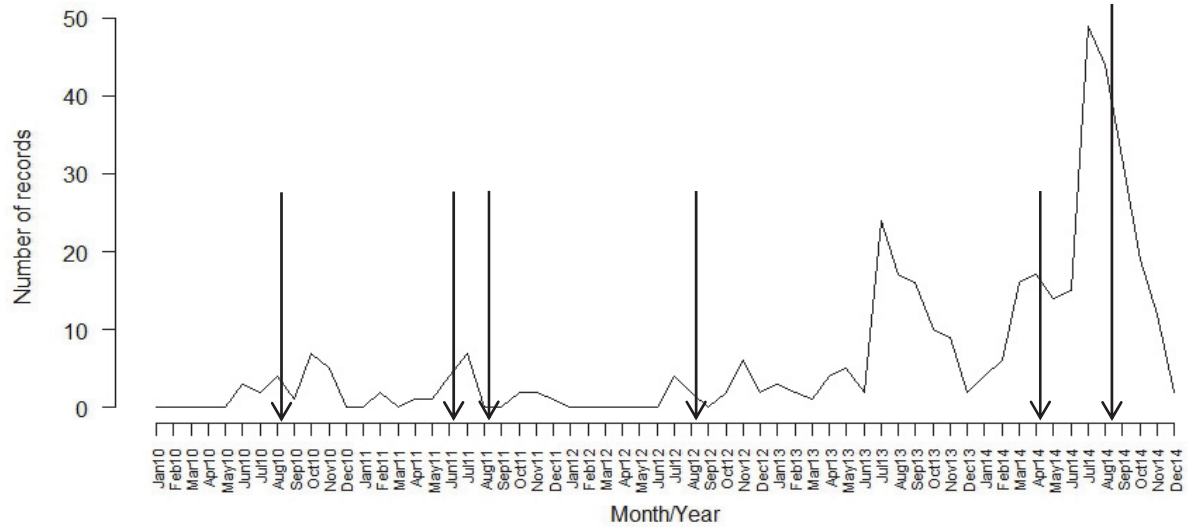


Figure 4. Number of records by month and timing of media events (arrows) raising awareness of stoats on Orkney.

We calculated the number of stoat sightings reported each month from 2010 to the end of 2014 and can clearly see an increase in reports over time. We also recorded timings of media events aimed at raising awareness of stoats on Orkney to see if there was any influence of publicity on public reporting of stoat sightings (Figure 4). Media events were not obviously followed by peaks in reported sightings. Rather there were obvious seasonal peaks in July of 2011 – 2014. We investigated the number and distribution of sightings reported each season (spring: March – May, summer: June – August, autumn: September – November, winter: December – February) (Figure 5). Most records were submitted in summer. In terms of distribution, most areas were covered by reports of sightings in all seasons although a few areas in the north of west mainland only had reports in. In Burray and north of South Ronaldsay there were no sightings of stoats in summer.

A map of the distribution of stoat sightings in relation to the road network on Orkney mainland implied that most locations of stoat sightings were close to roads (Figure 6). In fact, 36% of records were located within 50 m of a road and 63% within 100m of a road (Figure 7).

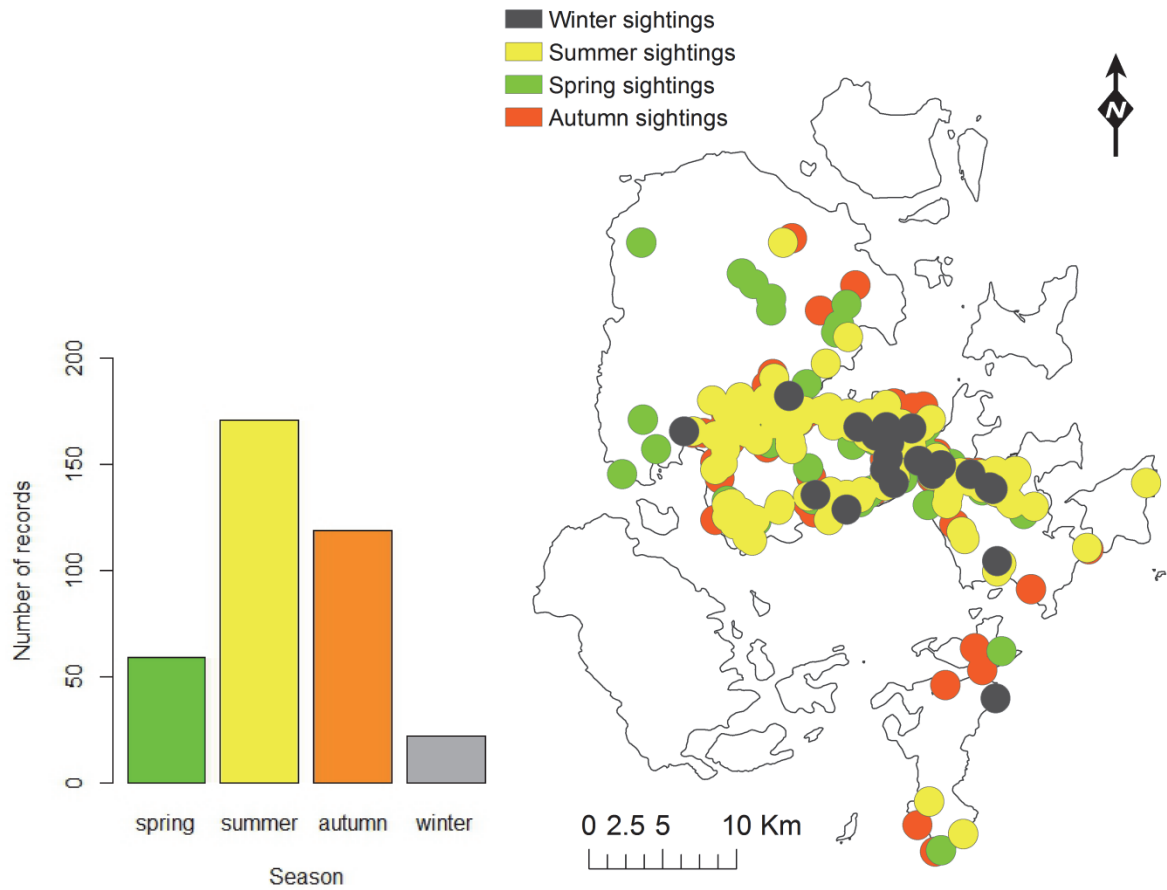


Figure 5. Number of records of stoat sightings in each season, across all years and a map of the distribution of sightings reported each season.

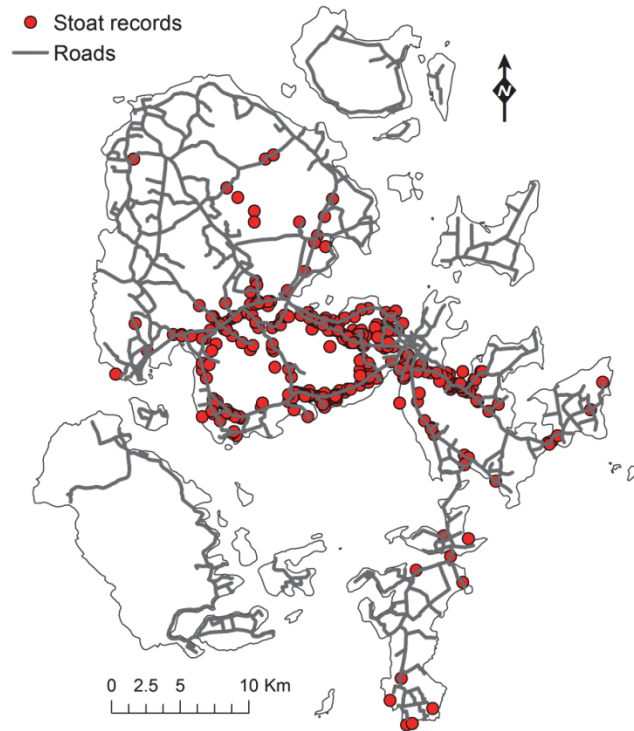


Figure 6. Distribution of stoat records compared to the road network on Orkney.

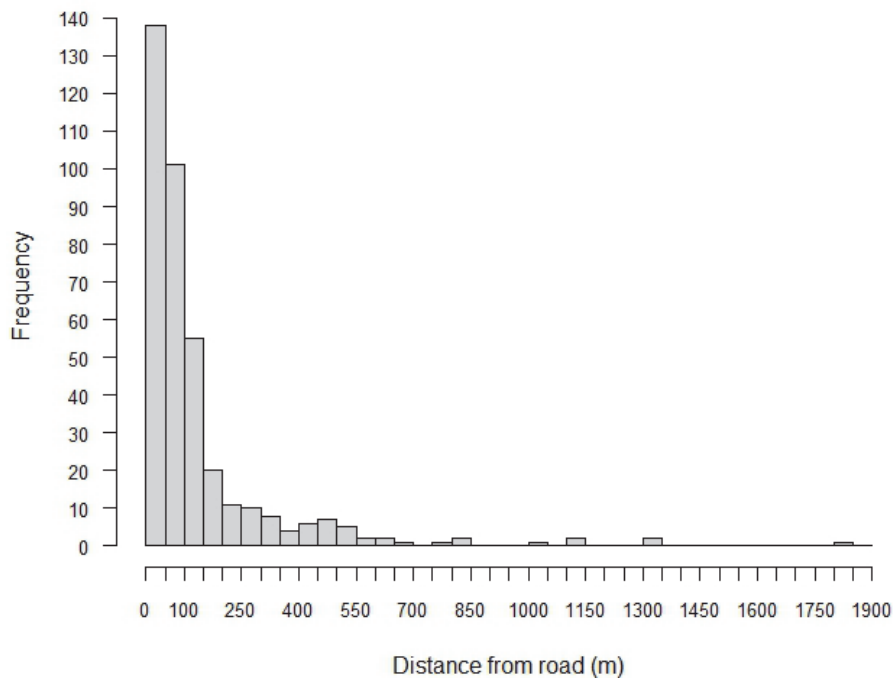


Figure 7. Frequency of stoat records locations at increasing distance from roads.

3.3 Review the evidence for population cycling in Orkney vole populations and how this might influence the introduced stoat population

We first chose to analyse the breeding data of hen harriers as a proxy for vole abundance. We initially checked the assumption that there was no spatial autocorrelation in clutch size for hen harriers across mainland Orkney and Rousay, i.e. that variation in clutch size was randomly distributed throughout the area. We found no obvious decline in spatial autocorrelation in clutch size with distance within years or across all years of available data (2001-2014) (Mantel test: correlation = 0.05) (Figure 8). Because this analysis implies that factors influencing hen harrier clutch size fluctuate synchronously over Orkney allowed us to pool data from all areas of Orkney mainland and Rousay for maximising power in subsequent analyses. The maximum distance between any two nests was 28.6 km. Almost three quarters (73%) of pairwise distances were within 15 km.

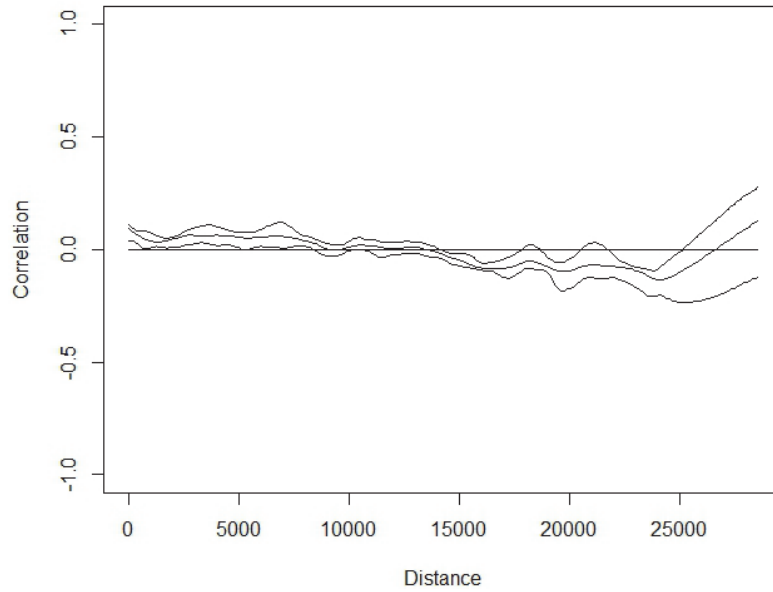


Figure 8. Correlation of clutch size with distance (in metres) with confidence intervals.

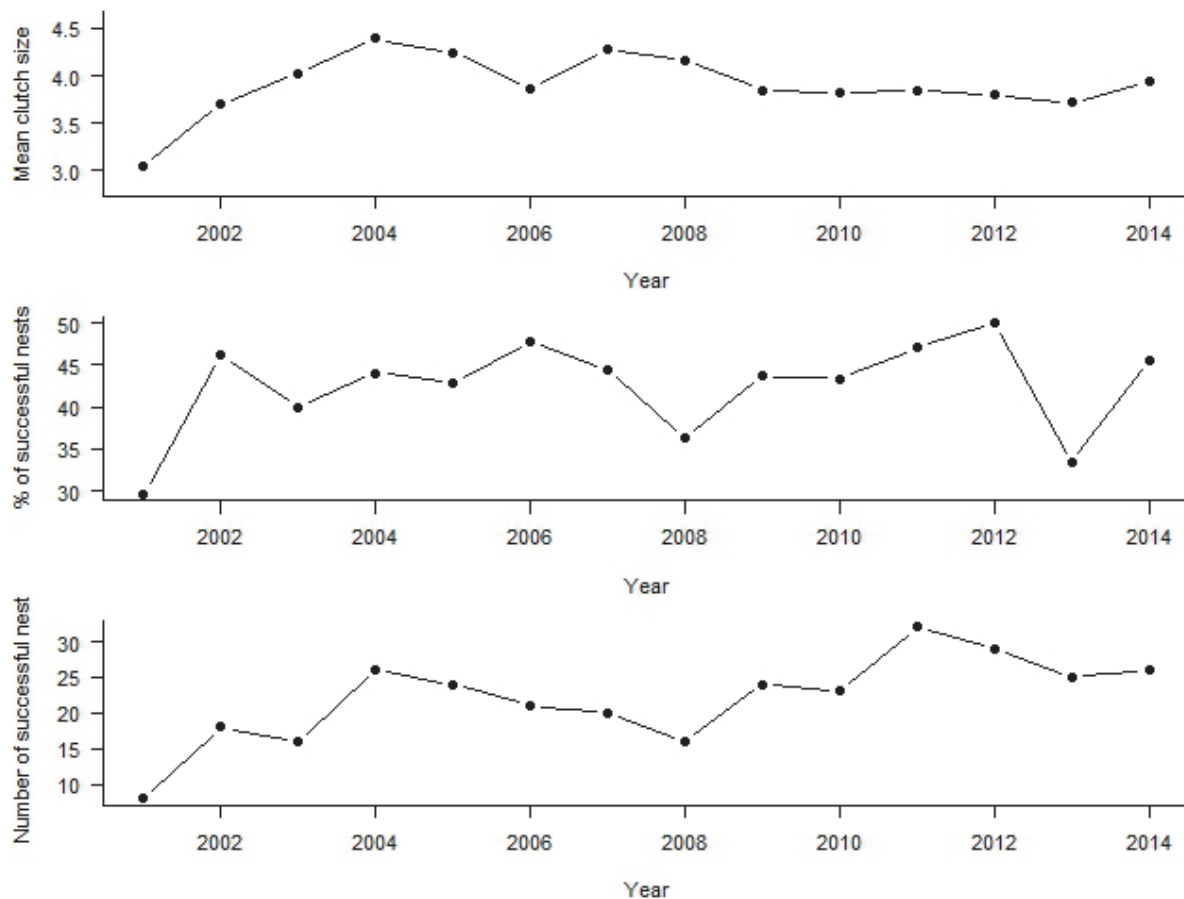


Figure 9. Mean clutch size, proportion of successful nests and total number of successful nests for hen harriers in Orkney across the mainland and Rousay from 2001 to 2014.

A lack of variation in clutch size between 2003 and 2014 suggested that vole abundance was not a controlling factor in clutch size and maybe that there was minimal variation in vole abundance throughout these years (Figure 9). We also looked at the number of successful

nests (those which fledged chicks) as a proportion of the total number of nests found each year. Survey effort was not constant throughout the time period and therefore the increasing number of successful nests could not necessarily be attributed to an overall increase in nest building. The proportion of nests that were successful each year was most variable, and particularly high in 2012 and with low values in 2001, 2008 and 2013 (Figure 9). A variety of factors could be contributing to this including, in addition to any influence of vole supply, weather, availability of non-vole prey during the chick rearing stage and levels of polygyny, which itself could reflect hen harrier productivity in previous years. Mean clutch size was not correlated with the proportion of successful nests ($r = 0.42$, $p = 0.13$) suggesting that overall, the outcome (success or failure) of hen harrier nests on Orkney is not related to the number of eggs laid in a nest.

An example of hen harrier clutch size in Langholm, Dumfries and Galloway, demonstrates variation in response to cyclic vole populations and is shown in Figure 10 as a comparison to hen harrier clutch size in Orkney. There is an obvious peak in mean clutch size followed by a decrease for two years before increasing again. This follows the peaks and troughs of the vole population (Redpath *et al.*, 2002).

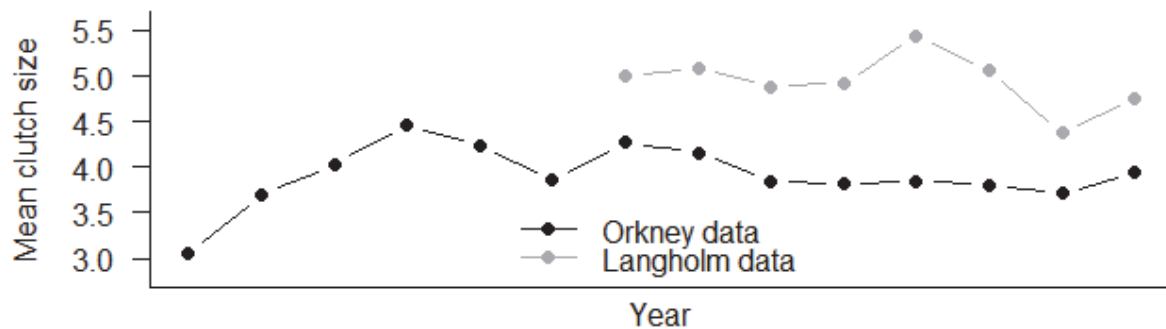


Figure 10. Mean clutch size for a hen harrier population in an area with cyclic vole abundance (Langholm data) compared to mean clutch size for hen harriers in Orkney.

Results from vole surveys from various sources were amalgamated to create a time series of vole abundance from 1998 – 2014 (data missing in 2009 and 2013) (Figure 11). Results were categorised by habitat (moorland, rough grass or pasture) and standardised within each habitat category to account for differences in survey techniques and areas. All surveys were conducted in summer. There was no significant decline in vole abundance through time ($R^2 = 0.1$, $F_{1,13} = 2.6$, $p = 0.1$) however the mean abundance of voles before 2010 was significantly higher than the mean abundance after 2010 ($t_{10} = 3.9$, $p = 0.001$).

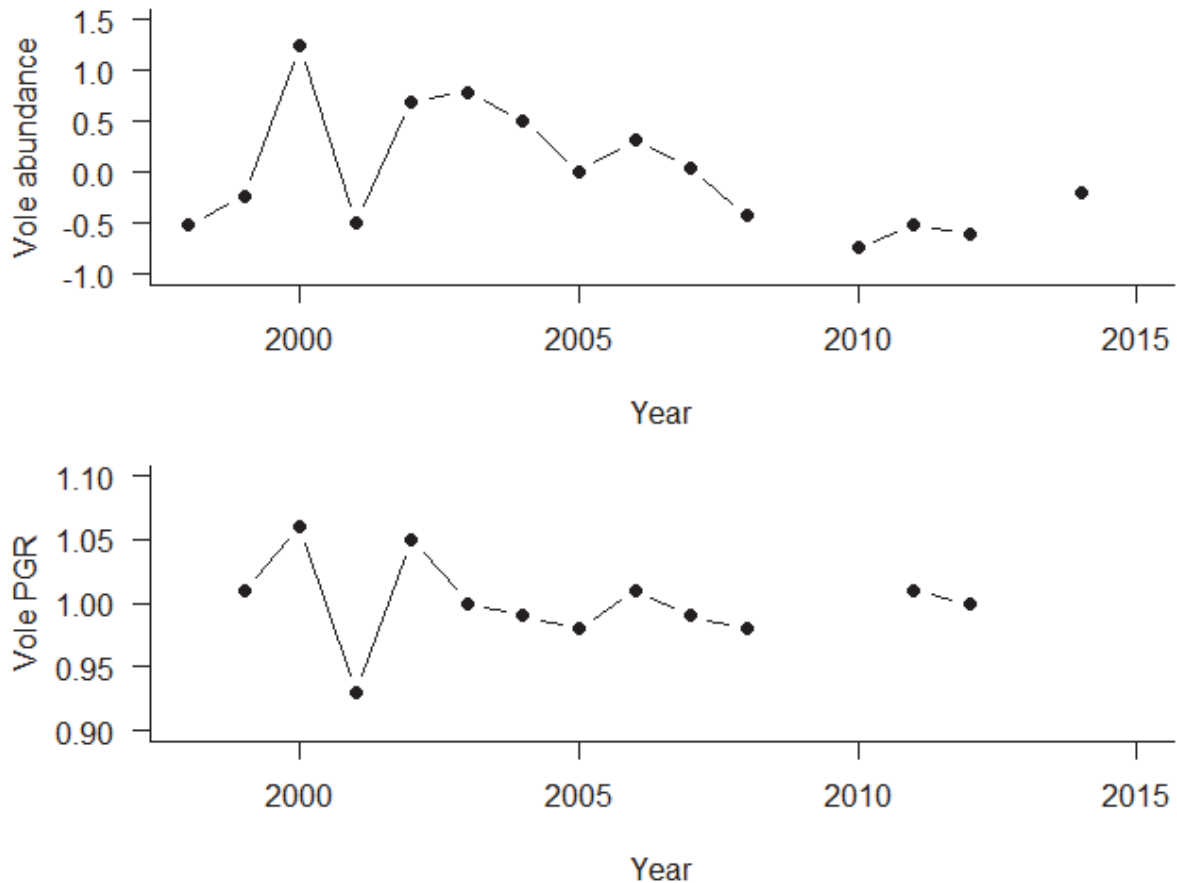


Figure 11. Vole abundance (top) and vole population growth rate (PGR) (bottom) in Mainland Orkney from 1998 – 2014. Abundance was standardised within each survey to account for data from different sources and survey designs.

We analysed this time series of data to identify any lags which could indicate a temporal pattern in vole abundance. Figure 12 shows estimates of the autocorrelation function (ACF) for the time series on the y-axis and lag time (at one year intervals) on the x-axis. The dashed lines illustrate the 5% significance bands. None of the estimates for the ACF at any year are significant and so we can conclude that there is no temporal pattern in vole abundance from 1998 – 2014. We repeated this exercise using growth rate of the vole population. This showed a one year lag with a significant negative correlation of 0.62.

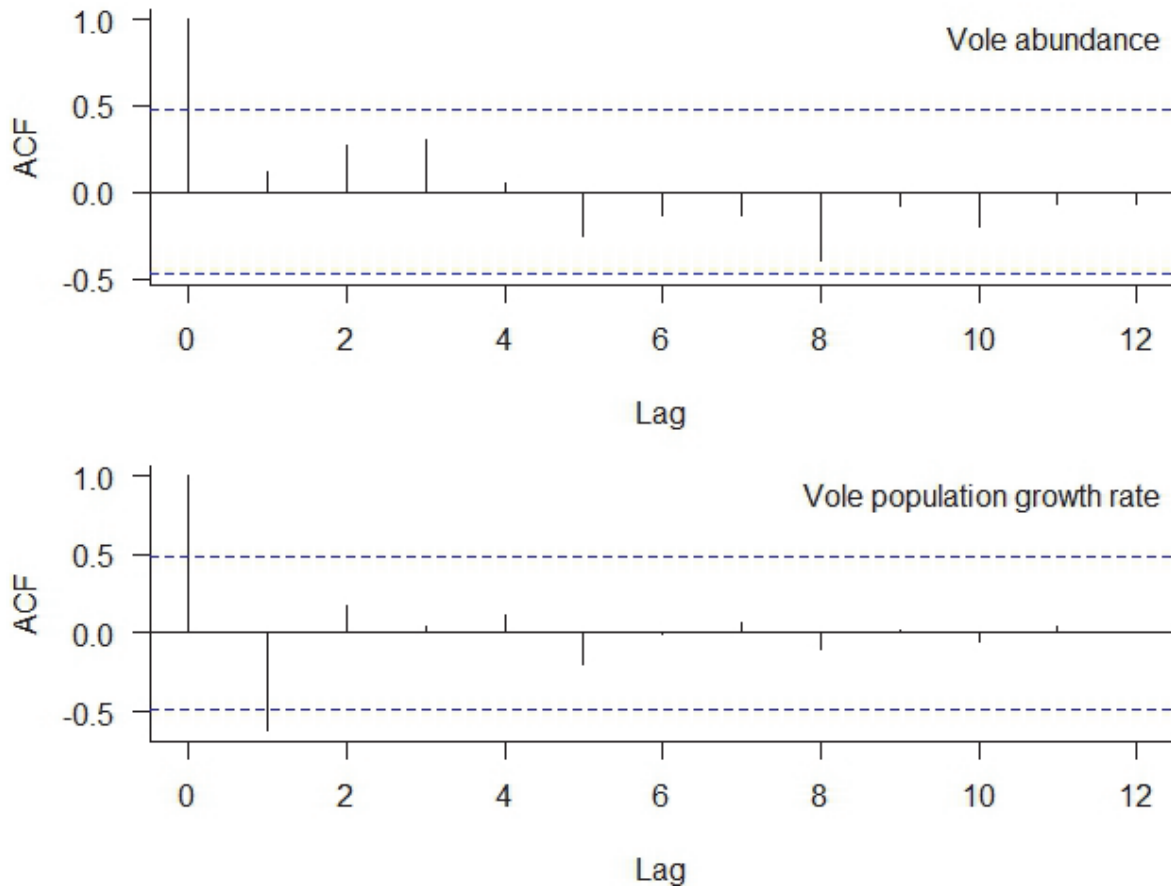


Figure 12. Estimates of autocorrelation function for time series of data for vole abundance and vole population growth rate at lags of one year intervals.

After concluding from the analyses of the available data that there were no obvious cyclic patterns in vole abundance in Orkney we sought to ascertain whether the abundance of voles, as reflected by the index we derived, had any direct bearing on the breeding output of hen harriers and short-eared owls.

We found no significant correlation between vole abundance and hen harrier clutch size ($P = 0.41$, $p = 0.18$) or between vole abundance and proportion of successful nests ($P = -0.06$, $p = 0.87$). There was also no correlation between vole population growth rate and hen harrier clutch size ($P = -0.29$, $p = 0.42$) but there was a significant positive correlation between vole population growth (from year $t-1$ to t .) and proportion of successful nests (at year t) ($P = 0.76$, $p = 0.01$) (Figure 13, 14).

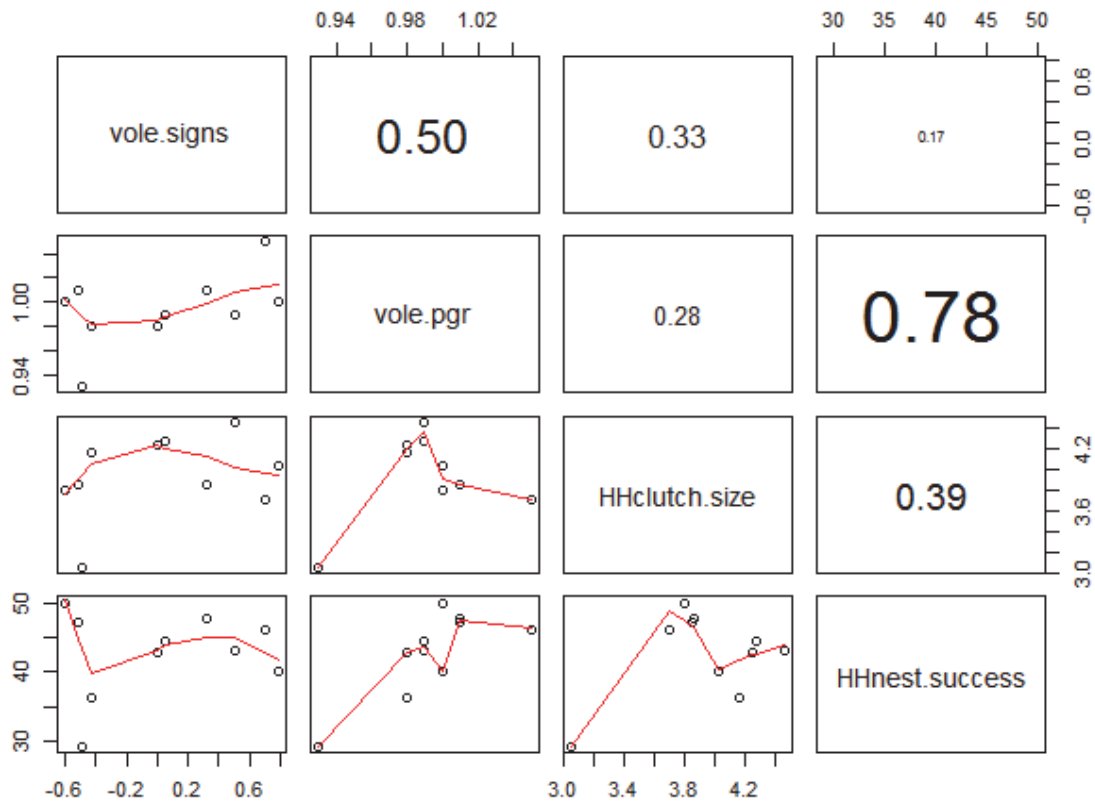


Figure 13. Pairs plot demonstrating correlations (below diagonal) and correlation coefficients (above diagonal) between vole abundance (vole.signs), vole population growth rate (vole.pgr), hen harrier clutch size (HHclutch.size) and proportion of successful nests (HHnest.success). The size of the text above the diagonal corresponds to the strength of the correlation.

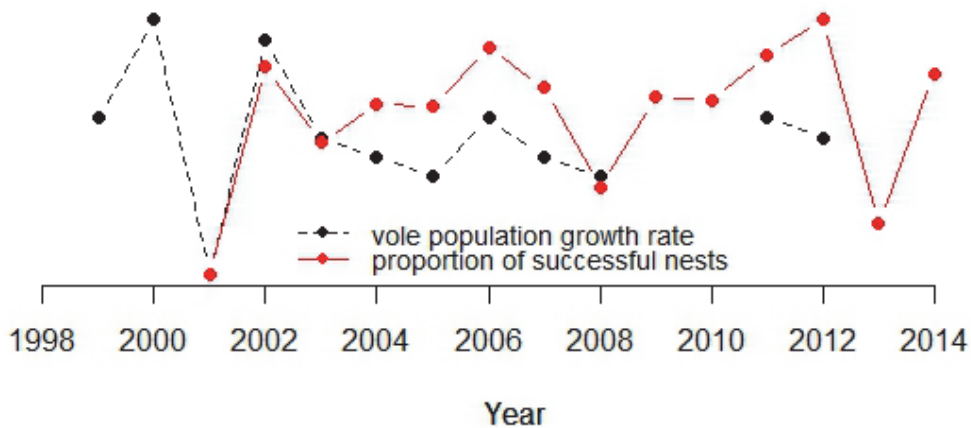


Figure 14. Overall trends in vole population growth and proportion of successful hen harrier nests in Orkney.

Data for breeding activity in short-eared owls were less comprehensive. Using annual accounts from the Orkney Bird Reports from 2003 – 2013, we calculated the likely number of pairs of short-eared owls seen on territories throughout the breeding season. The number of pairs recorded each year significantly increased with time ($R^2 = 0.55$, $F_{1,9} = 13.43$, $p = 0.005$)

but this is likely to be due, in part, to increasing survey effort. We also analysed a subset of the data from the north of west Mainland where more intensive surveys had been conducted by Stuart Williams and Brian Ribbands from the Orkney raptor study group. However these data only spanned 2010 – 2014 and access to 2012 data was limited by a confidentiality agreement and so it was difficult to interpret any pattern in breeding pair numbers (Figure 15).

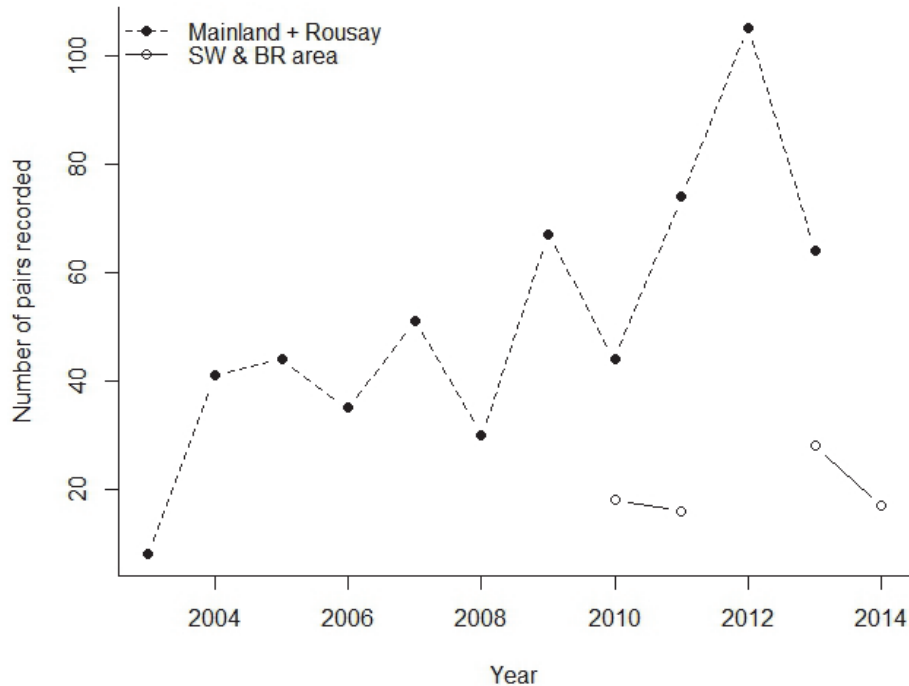


Figure 15. Number of pairs of short-eared owls recorded during the breeding season across Mainland Orkney and Rousay and in the area surveyed by Stuart Williams (SW) and Brian Ribbands (BR).

In order to analyse the number of short-eared owl pairs for evidence of a cyclic pattern and to remove the possible effect of observer effort we conducted an autocorrelation function on a time series of the residuals of the linear regression of number of owl pairs against year. None of the autocorrelation function estimates were significant which suggests that there was no temporal pattern in the number of short-eared owl pairs on Mainland and Rousay from 2003 – 2013 (Figure 16).

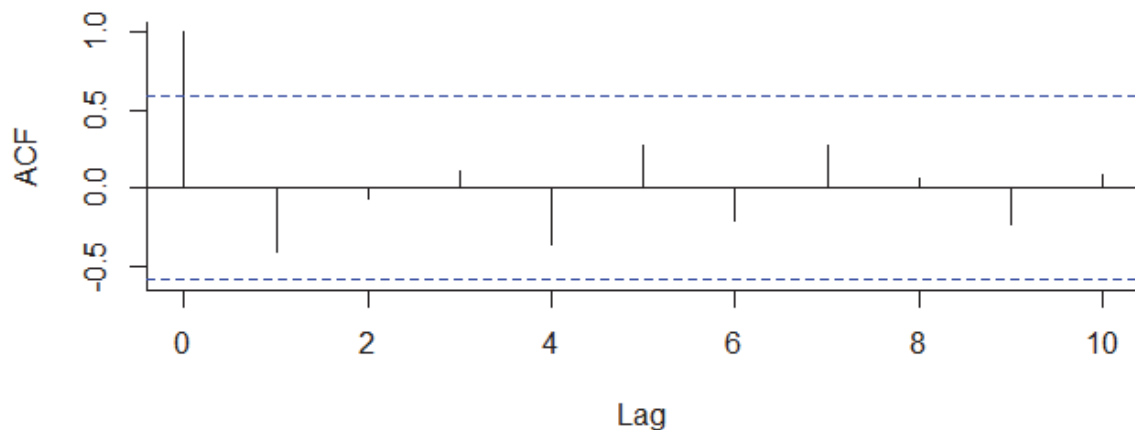


Figure 16. Estimates of autocorrelation function for time series of residuals for short-eared owl pairs at lags of one year intervals.

No significant correlations were found between vole abundance, vole population growth rate and number of owl pairs recorded on Mainland and Rousay. Although not significant, there was a near significant negative correlation between vole abundance and number of owl pairs ($P = -0.64$, $p = 0.07$), which is surprising and confounded by effort (Figure 17). However, there was a reported increase in owl survey coverage from 2009 onwards and so this is likely to bias the number of owl pairs recorded.

In 2013 there was an obvious decrease in number of owl pairs recorded and the proportion of hen harrier nests that were successful. Clutch size for hen harriers was not affected in the same way. Unfortunately we do not have any data from vole surveys in that year and so it is not possible to detect whether the low breeding success was related to abundance of voles.

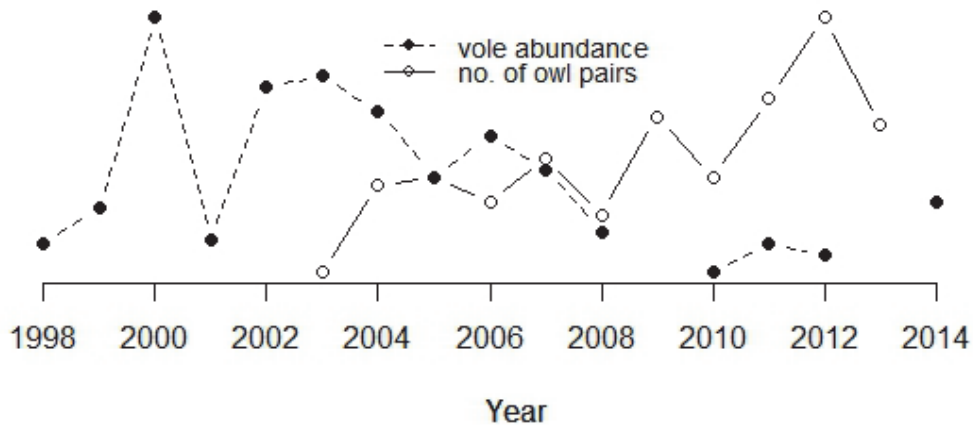


Figure 17. Overall trends in vole population growth and proportion of successful short-eared owl nests in Orkney.

3.4 Review the evidence of rabbit populations on Mainland Orkney and assess how this might influence the likely prey to be taken by stoats, such as Orkney vole and ground nesting waders

We mapped the available records for rabbits on Mainland Orkney and overlaid this on our map of the distribution of stoat records collated from 2010 – 2014 and locations of protected sites for breeding and non-breeding birds (Figure 18).

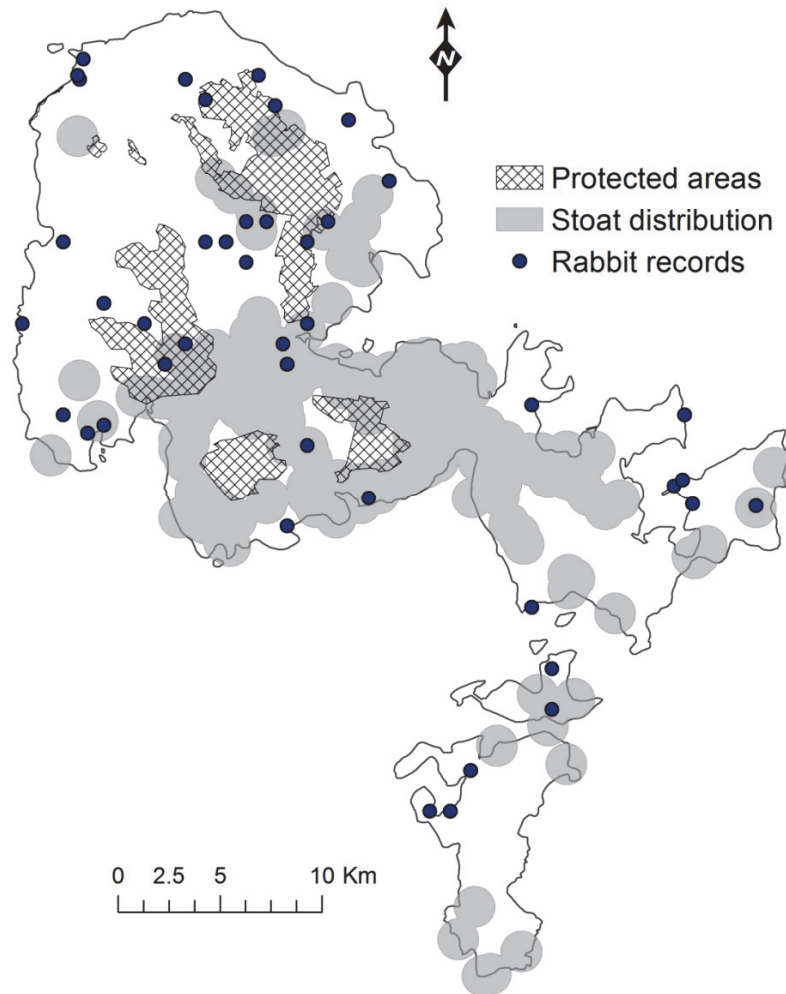


Figure 18. Map of the distribution of stoat sightings (records from 2010 – 2014 with 1 km buffer) and rabbit records in Orkney in relation to areas protected for breeding birds. The areas include Special Protection Areas (SPAs) designated for hen harriers, short-eared owls and red throated divers and Sites of Special Scientific Interest (SSSI) designated for assemblages of breeding and non-breeding birds. Note that both the areas for stoats and rabbits represent only the reported sightings and so are likely to underrepresent the distribution of both species.

In order to establish whether rabbit and stoat sightings were reported from similar habitats, we performed some basic habitat analyses. The area (ha) of improved and rough grassland that was within the 1 km square surrounding each stoat and rabbit record was calculated. This was intended to be used as a rough guide to habitat preferences of the two species and also to assess whether or not there was an overlap in where both species were seen and reported. The frequency of occurrence (as a proportion) of each grass type was graphed to illustrate the availability and range of areas of grasses per 1 km² on Mainland Orkney. Figures 19 and 20 represent the frequency of stoat and rabbit records found at increasing areas of improved and rough grassland. For stoats, the peak in records occurred in areas with 30 – 40 ha of improved grass per 1 km² whereas for rabbits there were two peaks: 0 – 10 ha km⁻² and 30 – 50 ha km⁻². Stoats were most commonly recorded in areas of rough grassland greater than 20 ha km⁻² whereas rabbits were primarily recorded in areas of rough grass coverage less than 20 ha km⁻², with a peak at 10 – 20 ha km⁻². This suggests that although rabbits are less likely, and stoats more likely to be seen in areas of high rough grass, there is no obvious distinction between the habitats in which stoats and rabbits have been seen and reported.

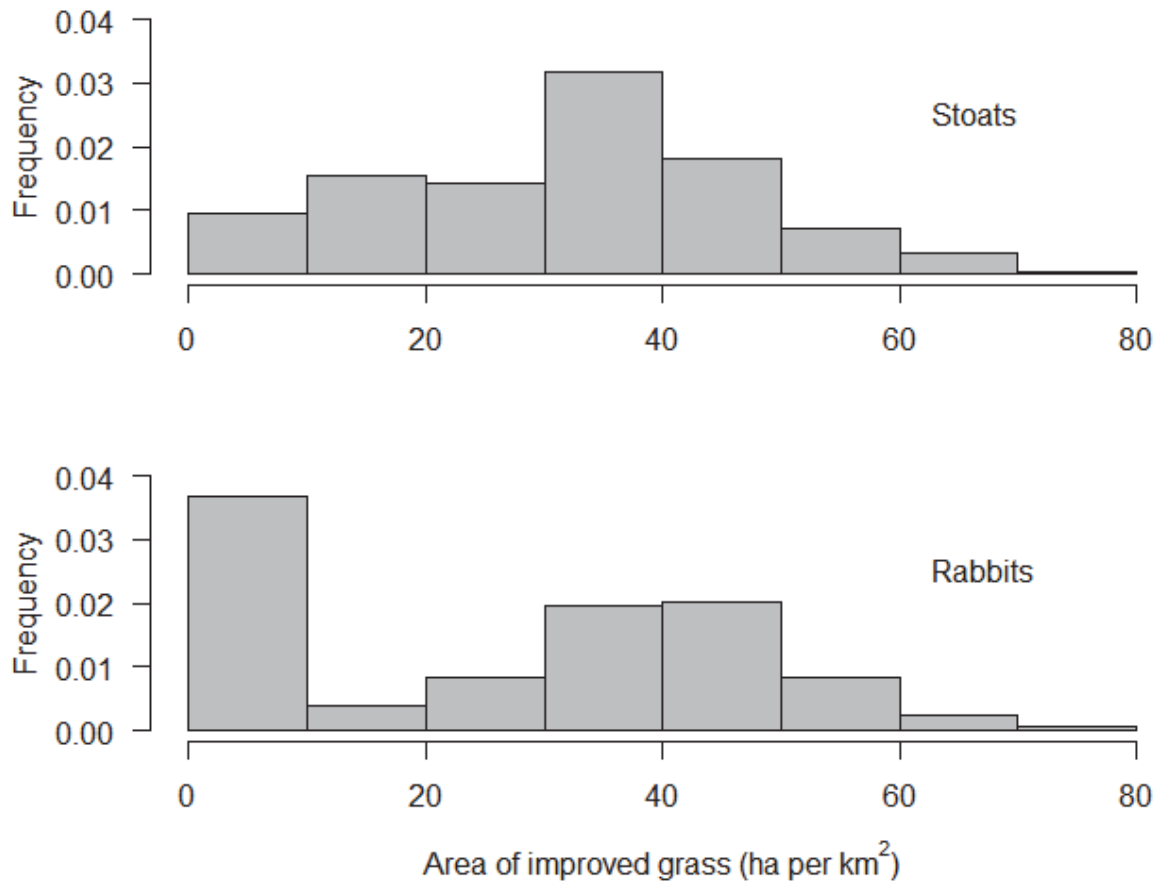


Figure 19. Frequency of stoat and rabbit records occurring within increasing areas of improved grassland (ha km⁻²)

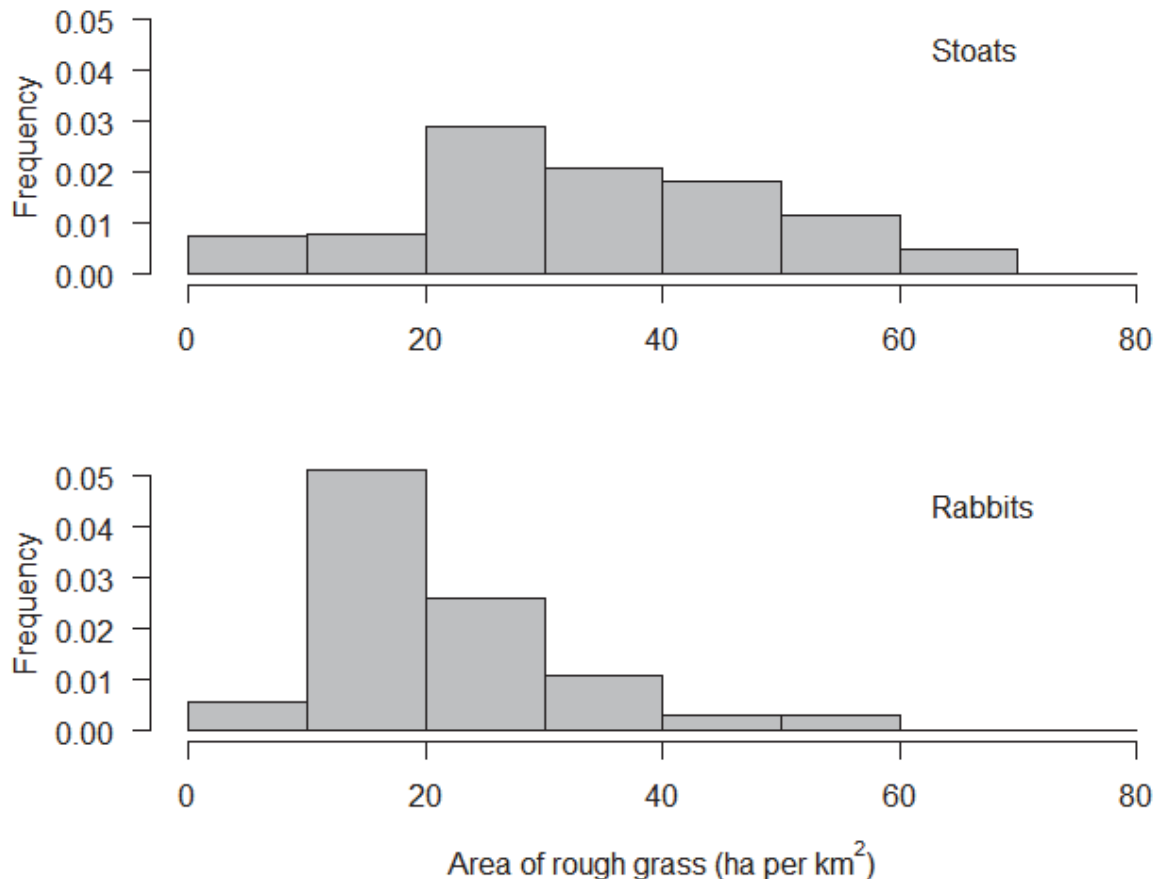


Figure 20. Frequency of stoat and rabbit records occurring within increasing areas of rough grassland (ha km⁻²)

3.5 Assess the degree or risk that introduced stoats pose to the island ecology of Orkney, with an emphasis on vulnerable prey species such as Orkney vole

In order to assess the degree of risk posed by introduced stoats to the island ecology of Orkney we have listed three potential scenarios accompanied by our opinions on the likelihood of each scenario occurring in Orkney.

1. Vole and stoat populations establish novel inter-annual fluctuations that may be cyclic

In this scenario, predation of voles by stoats shifts Orkney vole population dynamics from the relative stability that has hitherto prevailed into a novel, fluctuating, potentially cyclical, dynamic. We posit this would arise because of reciprocal feedback between vole and stoat abundance. Under this scenario stoat predation contributes to depletion of voles to the point that stoats eventually experience starvation, their numbers decline and eventually rebuild when vole numbers have recovered after a period with low predation. The cyclical process typically repeats itself every 3-5 years in similar systems where mustelids and their rodent prey are tightly linked to each other. Thus changes in the impact of stoats results from the combined impact of their functional and numerical responses to changing vole abundance. The amplitudes of both vole and stoat fluctuations is hard to predict as it would depend upon the availability of alternative prey for the stoat, e.g. rabbits, rats, birds, and the threshold at which prey switching is induced, neither of which is quantified in Orkney.

Effect on other wildlife: The declining and low phases of any emerging vole cycle could extend to 2 years out of 4 and would have a negative impact on vole-eating raptors because of a) reduced vole availability and b) a functional response by food-limited stoats switching to alternative prey. Short eared owls are likely to suffer most from reduced prey availability throughout the year, in years of vole scarcity. For hen harriers a reduced number of voles in spring could affect the breeding condition of females, and hence overall productivity. In a cyclically fluctuating system, short-eared owls would be expected only to breed in peak vole years, rather than in most years as is presently the case in Orkney. However, hen harriers are less likely to breed when voles are scarce, thus instances of stoat predation on the chicks of this species will be relatively rare compared to good breeding years. Years of declining and low vole abundance could result in an increased contribution of all other ground-nesting bird species to stoat diets. However, we consider the direct impact of such prey-switching by stoats to be of secondary importance to bird of prey populations, relative to the impact of low vole availability. Any impact of stoats on waders will be direct through augmented nest predation when voles become scarce. How pervasive such an impact will be depends on how rapidly stoat mortality increases when vole availability is low. Again, this will vary in relation to the availability of alternative prey, primarily rabbits.

In high phases of a vole cycle, there may alternatively or additionally be increased negative impacts from stoat predation. This is because of the likely rapid and very marked numerical response of stoats, via increased rates of fertility. The species' unusual trait of delayed implantation means female stoats can greatly increase litter size when prey is abundant. Increased fertility of female stoats and the subsequent increase in stoat juveniles leads to increased predation of all stoat prey species, including rare species which are taken opportunistically. This is what happens in New Zealand, when beech mast events lead to increased mouse abundance, increased stoat fertility and greatly increased rates of predation on native birds (O'Donnell *et al.*, 1996b).

Likelihood:

We consider that the likelihood of emergence of a novel cyclic fluctuation in vole populations is low because of the abundance of alternative prey for stoats on Orkney, high mobility of stoats (they will move around to find food) and absence of top predators that would impose a mortality cost to stoat mobility.

However, should such a dynamic emerge, the likelihood that it would give rise to major detrimental direct and indirect effects on harriers, owls and other ground nesting birds is very high.

2. Vole populations become trapped in a predator-pit, whereby vole populations are permanently reduced to lower average densities, with or without fluctuations

In this scenario, predation of voles by stoats, in addition to existing predation from birds and other predators e.g. feral cats, causes the vole population to decline at a higher rate than it can grow, despite their relatively high reproductive rates. Any occasional or localised increase in abundance is negated by increased predation by stoats arising from their numerical and functional responses because Orkney voles are a sought after and profitable prey. Reductions in vole populations do not negatively affect stoat populations due to the abundance of alternative prey, principally rabbits, to which they switch their attention when vole depletion makes them unprofitable. Voles thus remain perennially at much lower density than current levels.

Effect on other wildlife: All vole predators would suffer from reduced prey supply, leading initially to increased competition among vole predators, including raptors, as vole populations remain low. In the initial phases of this prolonged reduction, there might also be general reductions in the abundance of alternative prey e.g. rabbits, rats, ground nesting

birds, waders and for the scarcer species, this reduction might be prolonged. Rabbits and rats, especially given the rat population is sustained by exogenous farm-derived and coastal subsidies (E. Meek, pers. comm.), are likely to sustain stoats in the long term, regardless of the state of the vole population.

Likelihood:

We consider the likelihood of a permanent reduction in vole abundance to be high because of the range of alternative prey available to stoats, their intrinsic high mobility, and the absence of top predators that would impose a mortality cost to stoat mobility. In addition, the unique evolutionary history of Orkney voles over the last 5100 years post-colonisation, has taken place in an environment devoid of terrestrial predators and was included not only a larger size but crucially a more than 50 % reduction in litter size relative to mainland Europe common vole ancestor (Gorman and Reynolds 2008) will contribute to a greater vulnerability of this species to predation.

We also consider the likelihood of such a reduction having a major detrimental effect on harriers, owls and other ground nesting birds to be high.

3. The impact of stoats on vole abundance is localised and/or seasonal

In this scenario, the growth rates of large populations of voles in contiguous areas of optimal habitat continually exceed rates of stoat predation and so the vole population is not strongly impacted and reduction in density is moderate and the dynamics remain stable. However, in suboptimal habitat or areas of limited extent, stoat predation overtakes vole productivity and thus causes localised population declines and extinctions. In turn, this could cause localised reductions in the effective density of stoats. However, stoats are a highly mobile and adaptable species and there is likely to be a high proportion of non-territorial, transient individuals and so stoats may disperse to areas where voles remain or alternative prey is available. The range of stoats is unlikely to be constrained by any extrinsic factors, such as predation, particularly because there are no foxes on Orkney.

Alternatively, or in conjunction with localised effects, predation of voles by stoats may be seasonal. It is possible that stoats could prey on voles for the majority of the year when ground nesting birds are absent but switch to alternative prey, for example rabbit kits or wader eggs and chicks, when seasonally available. Predation on vole populations will be dependent on season and/or density but insufficient severely to deplete populations. This could lead to a moderate reduction in abundance because vole reproduction will be sufficiently great to allow numbers to recover during the breeding season.

Effect on other wildlife: There may be localised competition for voles and consequent increased predation of alternative prey by all vole predators.

Likelihood:

We view this as the least plausible outcome. Stoats will eat voles year round, but they are just as likely to eat them when they are breeding. In fact, female stoats are more likely to retain a preference for voles over rabbits as there is a sex-related difference in diet and prey (McDonald *et al.*, 2000).

Should this be the outcome for vole populations, we consider this is likely to represent a smaller impact on harriers, owls and ground-nesting birds, compared to Scenarios 1 and 2.

Scenario	Are vole populations fluctuating periodically	Are stoat populations fluctuating periodically?	Are voles dominant or preferred prey species for stoats?	Frequency at which alternative prey is taken	Response by stoats	Stoat population is limited by...	Impact on vole-eating raptors	Other receptors (alternative prey)
1. Voles and stoat populations are cyclic	Yes	Yes	Dominant	Occasionally	Numerical and functional	Episodic starvation, breeding failure	Reduced productivity during years of low vole abundance	Rabbits, waders
2. Vole populations are in a predator pit	No	No	Preferred	Regularly	Functional	Availability of alternative prey	Continuous reduction in productivity (low vole abundance at all times)	Rabbits, waders,
3. Only localised and/or seasonal impact on vole populations	No	No	Preferred	Regularly	Functional	Intrinsic (social) limitation	Some direct predation on nests within stoat territories, localised competition for voles	Rabbits, waders,

4. DISCUSSION

4.1 Review of relevant evidence regarding the predator/prey relationship between hen harriers and short-eared owls and the Orkney vole

We found no evidence of cyclic patterns in vole abundance in Orkney. There was evidence of some inter-annual variability, but the amplitude of such variation and the frequency of deviations from a long term average appear more limited than in most other *Microtus arvalis* populations (Tkadlec & Stenseth, 2001). In the absence of sufficient long term data on vole abundance, we had to base our inferences of vole dynamics on three types of data, which, while imperfect, gave a consistent message. They include fragmentary vole surveys conducted using broadly, but not completely similar methods, in different habitats and by different organisations. Whilst we were able to assemble a partial time series by standardising each survey so as to allow comparison between temporal fragments and seek patterns of variation in vole abundance, such imprecise data were of limited value when examining relationships between voles and hen harriers and short-eared owls.

Data on harriers were more consistent across years, but in earlier years (pre-2000s) tended to focus on successful nests (E. Meek pers comm.). Given there is a large amount of polygyny in harriers on Orkney, variation in the frequency of polygynous females amongst the sample of nests monitored would affect the patterns of variation in productivity. This is because all but the primary females in such situations tended to have low breeding success because they do not benefit from male help during chick rearing (Balfour & Cadbury, 1979). Imprecise vole data and the unknown prevalence of secondary females whose broods often fail in annual samples of hen harrier nests monitored may have contributed to the lack of any evident relationship between vole abundance and clutch size. Indeed, hen harriers in Orkney are known to feed on Orkney voles, with a greatest contribution in spring (Picozzi, 1980; Reynolds, 1992; Amar, 2001) and hen harrier clutch size co-varies with field vole density elsewhere in Scotland (e.g. Langholm, Redpath *et al.* 2002; Figure 10). We did detect a positive correlation between the proportion of successful harrier nests and vole abundance despite the smaller contribution that voles make to diet during chick rearing. Thus a greater proportion of harriers successfully fledged chicks in years when voles were abundant, supporting the idea that voles are important to harrier breeding biology on these islands.

Despite the overwhelming dominance of Orkney voles in short-eared owl diet in Orkney (Reynolds & Gorman, 1999), we found no evidence of any relationships between owl abundance / breeding parameters and vole abundance. The lack of any relationship was perhaps unsurprising given the paucity of data collected in a standardised manner and the very limited variation in both short-eared owl and vole data that would preclude the detection of any association. Given the association between irruptions of short-eared owls and their vole prey evident elsewhere (Village, 1977), we would expect owl numbers and breeding success to fluctuate with vole abundance, should vole numbers become less stable than they are at present.

4.2 Review (and map) the history of colonisation of Orkney by stoats from trapping records, sightings etc.

We have mapped the observed history and apparent colonisation of Orkney by stoats and presented the results in several forms. The number of sightings reported to SNH has increased exponentially since the initial records in 2010, as has the area of the distribution of these sightings. This pattern fits loosely with classical theories of range expansion whereby the distance gained by a species increases each year (Shigesada *et al.*, 1995). We can predict with confidence that the observed rapid expansion in apparent range will run its course and that the whole of Orkney Mainland will shortly be occupied by stoats, if this is not already the case.

In general, it appears that East Mainland and the south of West Mainland has been almost completely colonised by stoats and the population is now spreading into the north of West Mainland. However, we urge considerable caution in making assumptions about the distribution of stoats on Orkney based on sightings data or the maps we produced from them. On the basis of evidence so far and the lack of a systematic assessment, it is impossible to differentiate observer effort from the true distribution of stoats in Orkney. It is highly likely that the true abundance and distribution of stoats has increased over time but the awareness of the public has also fluctuated with an initial increase that probably led to more people reporting sightings. Conversely, there is a risk of observer fatigue, whereby stoats become a common occurrence and people stop reporting their sightings. This could lead to an artificial plateau in the number of sightings being reported and a false sense of stoat distribution if ad hoc sightings are relied upon to track the stoat invasion.

The possible recording of a stoat sighting on Westray is concerning but is so far the only record in outlying islands. Stoats are capable swimmers and can cross open cold water with strong currents for greater than 1.5 km (King *et al.*, 2014; Veale *et al.*, 2012). Many of the islands around the mainland are therefore within reach and so are at risk of invasion by stoats. The importance of stoat reproductive tactics is clear here, in that a single female carrying fertile blastocysts in delay is capable of colonising a new island, by itself.

We have demonstrated a seasonal difference in the number and distribution of stoat sightings. Most reports were made in the summer months (June – August) and fewest in winter (December – February). Several factors could contribute to this. Firstly, in the summer, following the breeding season, there are likely to be juvenile stoats around which significantly increases the visible stoat population. Stoats are opportunistic hunters and are active at all times of the day and night, therefore the long daylight hours in summer create more of an opportunity for stoats to be seen by people. Conversely, short winter days reduce the chance for stoats to be observed at random. Orkney is a popular holiday destination in summer, which leads to an increase in the human population. In turn, this increases the number of observers that could potentially report a stoat sighting. In the north of West Mainland there are several sightings that have only been recorded in spring (Figure 5). This could indicate areas that are only frequented by transient males when searching for mates. In order to make any formal conclusion on this we would have to know that the areas had been covered by observers who had not seen stoats during the other seasons. We anticipated that records of stoats in summer might indicate areas of breeding habitat but instead found that summer records were widely distributed throughout the island making it difficult to distinguish potentially favoured habitats. Interestingly, no records of stoats were reported in summer in the area covering Burray and north of South Ronaldsay but this could be a consequence of observer coverage.

The high proportion of stoat sightings located near roads is likely to have been influenced by the distribution of potential observers. However, as stoats tend to avoid open areas and prefer using the cover of ditches and stone walls to travel (McDonald & King, 2008), it is also possible that some of their preferred habitat is genuinely associated with the road network in Orkney. Further detailed analyses of the distribution of habitat, would be required to answer this but is beyond the scope of this project and of limited value given the stoat data collected were collected entirely opportunistically without any sampling design.

4.3 Review the evidence for population cycling in Orkney vole populations and how this might influence the introduced stoat population

Overall, we have concluded that Orkney vole populations did not have a history of cyclic patterns before the stoat introduction and appear to have sustained exceptionally stable densities when compared to other *Microtus* species which are either irregularly or cyclically irruptive (e.g. Taitt & Krebs, 1983; Lambin *et al.*, 2000; Takdlec & Stenseth, 2001; Lambin *et*

al., 2006). The rare estimates of abundance through capture recapture methodologies furthermore suggest they exist at exceptionally high density (circa 200-500 voles/ha in some habitats) (Reynolds, 1992). In the absence of any consistent surveys on the dynamics of Orkney voles, this conclusion is based on a range of somewhat tenuous, but highly consistent strands of evidence. We formed a view on the prevailing vole dynamics from the sparse data that was available from vole surveys alone and supplemented this with data on the breeding activity of vole-eating raptors. Taken together, these lines of evidence suggest that there have been some infrequent fluctuations in Orkney vole abundance but we do not discern any regular patterns in the abundance of Orkney voles. This implies that Orkney voles have been providing a relatively steady supply of food to protected raptors, including at critical times in their life cycles.

If, as we expect, the introduction of stoats in the Orkney ecosystem results in changes in vole dynamics, such changes are likely to result in a significant deterioration in the condition of species that are the designated features of Special Protection Areas.

We collated a range of historical vole surveys performed by different individuals and organisations in different areas with somewhat variable methodologies and no discernible sampling design. We attempted to make these heterogeneous data comparable by scaling them to common values. While such data would have been sufficient to detect population cycles, had they been present, great care should be exercised when making further inference on vole dynamics. Even though there was a broad agreement between the vole and the raptor data, there were also some worrying discrepancies. For instance, there is no evidence in the raptor data that would suggest that Orkney voles are in long term decline as suggested by Figure 11. There is no evidence in the vole data of the high vole abundance reported by highly experienced local naturalists in the summers following the two hard winters of 2009/10 and 2010/11, and the absence of usable vole abundance data in 2013 precludes linking sudden decrease in both the percentage of successful hen harrier nests and number of pairs of short-eared owls in 2013 to a decline in vole abundance that could have followed high abundance through the process of over-compensation (Barraquand *et al.*, 2015). Given the central role of Orkney voles in the local ecology, and the uncertainty on the impact of factors such as land use, predation by avian and introduced mammalian predators, it is worrying that data on vole abundance should be so sparse and of variable quality and spatial coverage.

An indirect line of evidence we used was clutch size in hen harriers as a proxy for female breeding condition which is influenced by vole abundance. From 2003 – 2014, mean clutch size each year showed little variation. This coincided with a habitat improvement scheme (Orkney hen harrier scheme) aimed at increasing the area of rough grassland across Orkney in an attempt to increase the abundance and availability of voles. Low prey availability reflecting habitat loss has been linked to poor breeding success in hen harriers in Orkney since the 1970s (Amar *et al.*, 2005). We found that the percentage of successful nests in a year was significantly, positively correlated with vole population growth rate from the previous to current year, but found no correlation with clutch size. In contrast, we hypothesised that clutch size was more likely to be related to vole population growth or abundance since, as a prey species, voles were not the preferred food during the chick-rearing period (Picozzi, 1980; Reynolds, 1992) but were important in the pre-laying and incubation stage (Amar *et al.*, 2005). Our analyses did not account for the timing of nest failure and so this could have happened at any time from incubation to fledging. We did not measure success in terms of number of fledglings because there was a high level of uncertainty and missing data. Using the measure of success or failure gave us the maximum dataset to work with. Perhaps population growth rate in voles was also correlated with abundance of alternative prey for hen harriers. We did not have access to information on the mating status of female hen harriers, yet we know this influences their fledging success hence we treat any inference from hen harrier nest success with caution.

We hypothesised that the breeding success of short-eared owls would strongly reflect any fluctuations in vole abundance because their diets tend to have a high proportion of voles and low prey diversity (Reynolds, 1992). We found that breeding data for short-eared owls were not as comprehensive as for hen harriers and that the outcomes of breeding attempts were largely unrecorded. We therefore based our analyses on the number of pairs that were recorded around the breeding season. There was a significant increase in the number of owl pairs recorded through time but, knowing that survey effort had increased (ORSG pers. Comm.), it was difficult to determine what influence an increase in survey effort had on this relationship. We attempted to use a sub-sample of the data where effort was more constant (the area covered by Stuart Williams and Brian Ribbands) but unfortunately the dataset was too small to reach any meaningful conclusions. Nevertheless, using all the available data we concluded that there were no discernible patterns in the number of owl pairs each year and hence it is highly unlikely that vole populations showed any cyclicity or even marked irregular irruptions. This second line of evidence thus supported our initial inference that Orkney voles have had stable dynamics in the absence of stoats, and that this may have contributed to the high density of productive raptors in the area.

4.4 Review the evidence of rabbit populations on Mainland Orkney and assess how this might influence the likely prey to be taken by stoats, such as Orkney vole and ground nesting waders

From the ad hoc records that were gleaned from various sources, we have concluded that rabbits are found throughout Mainland Orkney. By taking the distribution of stoat records in our maps as a conservative estimate of stoat distribution, it seems reasonable to assume that stoats are now distributed throughout most if not all of Mainland Orkney. The recorded sightings of both rabbits and stoats overlap with areas protected for assemblages of breeding birds.

Thus it can be considered highly likely, on the basis that stoats are opportunistic predators, that direct predation of ground nesting waders by stoats will occur in those protected areas.

Our analyses of the habitats in which stoats and rabbits are seen, remain very basic but support the assumption that rabbits are generally not found in areas with a lot of rough grassland and prefer improved grassland such as agricultural pastures (Cowan, 2008). Assuming Orkney voles are primarily found in areas of rough grassland (Reynolds, 1992), and rabbits are not, it could be suggested that predation events of rabbits and voles by stoats will not coincide. However, stoats are very mobile (they frequently travel over 1 km in a day (Sandell, 1986) and Orkney is not a big island, meaning that stoats are likely to transit a variety of habitats both within their own territories and ranges and through dispersal movements. Predation of rabbits, voles and birds is probable but the extent to which rabbits might facilitate stoat predation on other species and the potential impact on each prey type will be discussed in the next section.

4.5 Assess the degree or risk that introduced stoats pose to the island ecology of Orkney, with an emphasis on vulnerable prey species such as Orkney vole

Although all 3 scenarios we have presented are plausible, our opinion is that scenario 2: "Vole populations become trapped in a predator-pit, whereby vole populations are permanently reduced to lower average densities, with or without fluctuations" is the most likely outcome of a long-term impact of stoats on Orkney. This opinion is based on both the results of this study and our own background knowledge of the subject. However, there are certain caveats to these conclusions. Our analyses of the limited available sightings data have highlighted an exponential spread of stoat sightings within a five year period across Mainland Orkney and connected islands.

Our maps of stoat records are only a very conservative estimate of the distribution of stoats on Orkney and we estimate that in reality the majority of Mainland and connected islands will be occupied by stoats now, or in the very near future.

We have concluded that Orkney vole populations are relatively stable and are effectively sustaining breeding populations of hen harriers and short-eared owls. However, we deem it unlikely that the status quo will remain as the stoat population continues to increase. In addition, we suggest that, apart from food depletion there are no other factors at present that will limit the growth of the stoat population. Thus we expect that stoats will reach high densities in the forthcoming years. Only then would the consequences of food limitation captured by the ecological scenarios we outline above lead to divergent outcomes, i.e. decline or oscillations in vole and stoat numbers.

Our conclusions come with the caveat that there is considerable uncertainty associated with the specific mechanisms by which impacts will play out, not least because the available data on which we based our analyses were inadequate for any quantitative evaluation of the likely outcomes. Our only precedent for the situation that now arises in Orkney is the introduction of stoats to New Zealand, in which native and non-native prey communities differ markedly. However, our opinion is that there is a high likelihood for stoats to have a negative impact on the ecology of the Orkney Islands. We deem the most damaging scenario, namely ongoing marked reductions in vole density with abundant stoats preying on a diverse range of prey, as the most probable.

We consider it is highly likely that the introduction of stoats will profoundly change the ecology of Orkney and its value for birds of prey and the SPAs that have been designated for protecting these species.

We advise that averting the damaging changes to Orkney ecology caused by stoats requires rapid and decisive intervention. Even though much of Orkney mainland is now invaded, there is still scope for further spatial expansion and, more damaging, further increase in abundance in stoats. Thus delaying action would only cause escalating costs. In addition, islands such as Rousay and even Hoy are likely to eventually be invaded by stoats, whether through stoats swimming or accidental transport by humans through ferry traffic, such that there is a risk of a bad situation becoming worse.

All scenarios we considered on the likely impact of the stoat introduction are mediated by changes in Orkney vole abundance. In this respect, it was particularly disappointing to us that earlier studies of Orkney voles had been discontinued, and not re-instated when stoats were first detected in Orkney circa 2010.

We strongly recommend implementation of regular monitoring of key components of the ecosystem in Orkney using recognised methods. This monitoring should occur alongside, rather than ahead of, any management that is conducted for stoats because advance monitoring will not now significantly reduce the uncertainty associated with our risk assessments.

Rather, we strongly recommend that a formal adaptive management framework (e.g. Runge *et al.*, 2011) should be adopted to support and guide management. This would deliver a clear protocol for “learning while doing” and targeted monitoring of key components of the system being instigated. Such a programme would provide ongoing improvements in understanding of the system being managed and of the effectiveness of management action in delivering the desired outcome. Adaptive management involves formalising the hypothetical scenarios we outlined (and possibly others) into models and the likely response of the Orkney ecosystem to the removal of stoats and later updating the degree of support for each model with data gathered during any attempts to manage stoats on Orkney. Key to

the process of reducing the uncertainty is to identify the key components of the system that need to be monitored. In this instance, they include a) vole distribution, b) stoat demography in response to culling, and c) proxies of predation levels on ground nesting birds, including through more systematic visits of hen harrier nests at the egg stage. Indices of feral cat and hedgehogs could also be included as both species are relatively novel predators for Orkney voles. Much could also be learned from adaptive management of stoats in New Zealand (Edge *et al.*, 2011; McMurtie *et al.*, 2011).

The scenarios we outline make contrasting predictions on the rate of decline of voles in different parts of the island. Thus, any vole monitoring scheme should include both rough grassland locations that are adjacent to large expenses of habitat, such as seen in the periphery of moorland areas, as well as a sample or more isolated patches of rough grassland such as those prevalent along waterways, lochs and roadsides embedded within grazed farmland areas. We recommend that the Vole Sign Index methodology (VSI) described and calibrated in Lambin *et al.* (2000) is implemented as it provides rapid yet reliable assessment of vole density in a patch in approximately 20 minutes through the quantification of the presence/absence of signs of recent vole feeding signs (green grass clippings with un-oxidised bite marks) in 25 cm x 25 cm quadrats sampled at approximately 25 m intervals. Given the good road access in Orkney, we estimate that 2 person-days in spring, or 4 person-days if surveys are done in spring and autumn might suffice to survey 30-40 locations and hence provide a good characterisation of vole dynamics.

Stoats are highly mobile, potentially highly fecund and populations are likely to show a degree of resilience to culling attempts. Substantial culling efforts on grouse moors only have localised impact and any attempt to eradicate stoats would have to be operated on a large scale. Deploying large numbers of lethal traps in a manner that reduces by-catch of unintended species would yield data on capture rates in different habitats and season. Such information could be carefully recorded and could readily be supplemented with information on the age structure of the stoat population that can readily and cost effectively be collected by examination of canines (McDonald & Harris, 2002). Progress towards the goal of eradication could also be measured through the reduction of the number of matriline which could be obtained through genotyping if tissue samples are systematically collected from the outset of any removal effort. Variation in diet and predation by stoats in relation to prey availability and management could be readily investigated using stomach contents collected from culled animals (McDonald *et al.*, 2000).

One objective of managing stoat numbers is to prevent any rise on predation on ground nesting birds, including birds of prey whose populations are the basis for the designation of SPAs in Orkney. One measure of the success of any stoat control would be the prevalence of predation on ground nesting birds, eggs and broods. We suggest that proxies for predation risk by stoats, and other predators should be quantified through the deployment of dummy eggs in different habitat using standard protocols (Major & Kendal, 1996).

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