ECOLOGY AND CONSERVATION OF BREEDING LAPWINGS IN UPLAND GRASSLAND SYSTEMS:
EFFECTS OF AGRICULTURAL MANAGEMENT AND SOIL PROPERTIES

Heather M. McCallum

September 2012

A thesis submitted for the degree of Doctor of Philosophy in the

School of Natural Sciences: Biological and Environmental Sciences

University of Stirling

Abstract

Agriculture is the principal land use throughout Europe and agricultural intensification has been implicated in large reductions in biodiversity, with the negative effects on birds particularly well documented. The lapwing (*Vanellus vanellus*) is one such species where changes in farming practices has reduced the suitability and quality of breeding habitat, leading to a drop in population size that has been so severe as to warrant its addition to the Red List of Birds of Conservation Concern in the UK. Lowland areas, where agricultural intensification has generally been most pronounced, have been worst affected, however, more recently declines in marginal upland areas, previously considered refuges for breeding wader populations, have been identified.

An upland livestock farm in Stirlingshire that uses an in-bye system of fodder crop management and has unusually high densities of breeding lapwings provides a basis for this project to test causal hypotheses for the decline of upland lapwing populations and to identify potential conservation management solutions. Specifically this farm plants a forage brassica in an in-bye field for two consecutive years, followed by reseeding with grass and seven, out of sixteen, in-bye fields have undergone this regime at the study site since 1997. Fields that had undergone fodder crop management supported almost 60% more lapwings than comparable fields that had not previously been planted with the fodder crop. Lapwing density was highest in the year after the fodder crop was planted, once it had been grazed, which results in a high percentage of bare ground, likely to be attractive to nesting lapwings. Lapwing densities remained above that which occurred in fields that had not undergone fodder crop management for a further four years after the field had been returned to grass. The effect of management on lapwing food resources and nesting structure was tested through a field experiment; liming increased the abundance of *Allolobophora chlorotica,* an earthworm species that was associated with chick foraging location at the study site, suggesting that lapwings may benefit from liming conducted as part of fodder crop management.

The relationship between lapwings and soil pH is further explored across 89 sites on mainland Scotland, using soil property data to improve the predictive power of habitat association models, something which has not previously been done for any farmland bird. Adding soil and topographical data to habitat models, based on established relationships between breeding lapwings and their habitat, improved model fit by almost 60%, indicating that soil properties influence the distribution of this species. The density of breeding lapwings was highest at higher altitude sites, but only when the soil was relatively less peaty and less acidic, providing further support for the hypothesis that agricultural liming benefits lapwings.

In addition to assessing the conservation benefit of fodder crop management, the economic costs are also considered. Fodder crop management provides a source of livestock fodder in the autumn and winter during a period when forage demands outstrip grass growth, and ultimately improves the grazing quality of the grass that is replaced; this system currently operates outside of any agri-environment scheme (AES). However, at the study site, planting of the fodder crop and grass is delayed to avoid agriculture operations during the breeding season, which reduces yield and hence profitability. An initial estimate of £200 ha^{-1} is suggested as an incentive to encourage wider adoption of fodder crop management in a “lapwing friendly” manner, although further work is required to determine if this payment level is appropriate and the current method of AES implementation may limit the suitability of fodder crop management as an AES.

The results indicate that agricultural liming could benefit breeding lapwings in pasture fields where soil pH falls below pH 5.2, by increasing earthworm abundance. Where soil pH is below pH 5.2, liming should provide a cost effective mechanism for farmers to improve grass yields. Regular soil testing and liming in response to low pH, within improved or semi-improved grassland fields, where management activities such as use of nitrogen fertiliser can contribute to soil acidification, should be advocated to farmers in marginal areas as a mechanism for improving grass productivity whilst potentially benefitting breeding lapwing and other species where earthworms contribute significantly to their diet.

Declaration

I declare that this thesis has been composed by myself and embodies the results of my own research. Where work was carried out in collaboration with others, I have acknowledged the nature and extent of their work.

…………………………………………………………………….

Heather M. McCallum

Acknowledgements

This research was funded by the University of Stirling and the Royal Society for the Protection of Birds. I would like to thank my supervisors for their support, advice, encouragement, and above all their genuine interest in the project for the past four years. I had a large supervisory team, with three supervisors at the University: Kirsty Park, Dave Goulson and Nick Hanley, and four key members of staff at RSPB who have been involved in a supervisory role for all or part of the project: Jerry Wilson, Mark O'Brien, Rob Sheldon and Dave Beaumont. I am particularly grateful to Kirsty and Jerry for the wealth of feedback they have provided on earlier drafts and for statistical advice, to OB for teaching me how to find lapwing nests, providing me with his lapwing data for chapter 4 and even responding to emails for help after relocating to Fiji, to Rob for digging numerous soil cores at the field trial and making it look easy, and for being as good as he claimed to be at finding lapwing chicks, and to Dave B for coming up with the project idea, the funding and for talking me into doing a PhD in the first place!

This PhD could not have taken place without the support of Alistair Robb, the farmer at Townhead Farm. I am extremely grateful to him for allowing me to spend so much time on his farm, helping organise setting up the field experiment and sorting out extra lime when there was a mix up with this in the final year, providing information on his management and for caring about the birds that use his farm.

I would also like to thank Willie Owen, Muirpark Farm and Andrew Morton, Lochend Farm for allowing me access to their farms to carry out wader surveys and collect soil cores. Thank you to the staff and volunteers at RSPB's Geltsdale reserve for putting in some trial management for me and carrying out feeding observations. Additionally thanks to staff at the RSPB's reserve on The Oa, Islay for setting up additional trial management.

For help with field work I am particularly grateful to Gail Robertson, who gave up so much of her time voluntarily to assist during my 2nd field season - I'm so pleased that she is now doing her own PhD! I would also like to thank Madeleine Murtagh for assistance during the 3rd field season and both Laura Kubasiewicz and Elisa Fuentes-Montemayor for providing additional help. I would like to thank the technical staff at Stirling University for their support, in particular Helen Ewing for showing me how the soil lab operates, Willie Thomson for fixing the yagi-antennae and James Weir for making the ground "bumpometer".

I would not have been able to undertake the radio-tracking work without training in ringing and attaching tags from Jen Smart (RSPB), with additional training in radio-tracking from Claire Smith (RSPB) and training in ringing from Rob Campbell – thanks all. Thank you also to Malcolm Ausden (RSPB) for training in earthworm identification. I would also like to thank John Vipond (SAC) for discussing fodder crop management and Amy Corrigan (RSPB) for information on agricultural policy.

Thank you to Alessandro Gimona and Laura Poggio of the James Hutton Institute for providing soil property data for Chapter 4. In addition the data unit at RSPB extracted topographical data from GIS which was used in this chapter.

I have made some fantastic friends during the course of my PhD and could not have got through this without them. I've enjoyed numerous much needed coffee breaks with Lynne, Nicky, Dani and Rachael, who have all been great office mates! Thanks as well to Kirsty's research group for interesting discussions on my and their research, in particular thanks to Jeroen Minderman for knowing a lot about stats and R and being happy to answer lots of questions.

Thank you also to the support and encouragement from my family and for passing on the determination genes necessary for getting me this far!

Finally I could not have completed this PhD without Ewan's support, his excel wizardry saved me so much time and stress, he's put up with me working very long hours particularly during field work and write-up, been able to cope with the "emotional rollercoaster" of doing a PhD, calmed me down on many occasions and even dug a few soil cores in the first year!

Contents

Chapter 1 General introduction

1.1 Agriculture and declines in biodiversity

Agriculture is the principal land use throughout Europe and accounts for approximately 70% of land in the UK (DEFRA 2012). The Common Agricultural Policy (CAP), which was introduced shortly after World War II, has been instrumental in driving agricultural intensification by paying farmers subsidies for production, leading to artificially high prices and vast quantities of surplus food (Krebs *et al*. 1999). With its dominance in the landscape, agriculture is an important habitat for many species and over half of all European biodiversity is dependent on farmland (Kleijn 2012). Agricultural intensification has been implicated in widespread d declines in biodiversity, with negative effects of agricultural processes on birds particularly well documented (Krebs *et al.* 1999, Stoate *et al.* 2001, Robinson & Sutherland 2002, Newton 2004).

Intensification has resulted in simplification of the farmed landscape and a significant loss in habitat heterogeneity (Chamberlain *et al*. 2000, Wilson, Evans & Grice 2009). Changes which have contributed to this include increased field sizes, removal of hedgerows and field margins and a decline in mixed farming systems, with livestock farming now occurring predominantly in the west of the UK and arable mainly in the east. Faster growing varieties of crops and grass, along with increased use of fertilisers, herbicides and pesticides have also contributed to large increases in production, with the result that there is less space and reduced habitat quality for many species (Vickery *et al*. 2001, Newton 2004). Further changes include large scale land drainage for conversion to arable land or increased grass productivity, increased stocking densities facilitated by increased grass production and a change from spring to autumn sowing of arable crops.

1.2 The lapwing

The Northern Lapwing (*Vanellus vanellus*, from now on referred to as lapwing) is “one of the losers: everything that could go wrong has gone wrong: field drainage, over-grazing, silage production, autumn sowing.....” (Marren 2002, p145).

1.2.1 Declines and conservation status

The global population of lapwings is estimated to be between 5 and 10 million individuals and this very large population size coupled with the broad distribution of lapwings within the Palearctic, mean that this species falls within the Least Concern category on the IUCN Red List, despite recent declines in numbers (BirdLife International 2012a). Between 50% and 74% of the world’s lapwings breed in Europe, and recent population declines here have led to lapwings being considered of unfavourable conservation status in Europe (SPEC 2; Birdlife International 2004). Within Europe, population declines have been particularly severe in Russia, the Netherlands and the UK (Birdlife International 2004) and lapwings were added to the Red List of Birds of Conservation Concern in the UK in 2009 (Eaton *et al*. 2009). Declines in breeding lapwings have been linked to agricultural intensification and, in the UK, declines have been most severe in lowland areas, where agricultural intensification has been most pronounced. Worryingly, recent declines in marginal upland areas, previously considered refuges for breeding wader populations, have been identified (Taylor & Grant 2004, Henderson *et al.* 2004).

1.2.2 Breeding ecology and negative effects of agricultural intensification

Like most other species of wader, lapwings nest on the ground (Mullarney *et al*. 1999), typically laying a clutch of four eggs within a simple scrape (Klomp 1954). If the clutch is lost during the incubation period then the female will often lay a replacement clutch, however, only one brood of chicks will be raised in a breeding season and if the chicks are lost, any further attempt at breeding that year is unlikely (Klomp 1951, Beintema & Muskens 1987, Parish, Thomson & Coulson 1997).

Lapwings nest in both arable and pasture fields, though the choice of nest site is restricted to areas with short vegetation or bare ground, which enables good visibility around the nest to see approaching predators (Klomp 1954, Whittingham & Evans 2004, Shrubb 2007). Early detection of predators is important as these will be mobbed, or chased off by lapwings to defend their nests (Elliot 1985). Nest defence is communal and nest failure due to predation is higher in smaller colonies (Berg, Lindberg & Kallebrink 1992). Nest sites with open views are selected often in relatively flat, large fields, tending to avoid potential perches for avian predators and field boundaries that restrict the visible area (Small 2002, Wallander, Isaksson & Lenberg 2006). In addition to these anti-predation mechanisms, lapwings select nest sites which offer some degree of camouflage to the eggs and the incubating bird such as, tussocky vegetation, areas of variable sward height, areas with a mixture of vegetation and bare ground and damp areas with dull green- brown sward (Galbraith 1989b, Baines 1990, Shrubb 2007).

In general, incubation starts once all four eggs have been laid, in order that they will hatch around the same time. The incubation period is variable and was found to be anything between 21 and 28 days, with a mean of 25 days at a site in central Scotland (Galbraith 1988a). Lapwing chicks are precocial and can feed themselves within a few hours of hatching (Cramp & Simmons 1983). The adults’ role is threefold and involves leading them to suitable foraging areas, brooding them at night and periodically during the day, until they are around two weeks old, and protecting them against predators (Shrubb 2007). Whilst both arable and pasture fields are suitable for nesting, chicks hatched in arable habitats will be led to more suitable foraging areas such as grazed pasture, damp areas or grassy field margins (Galbraith 1988b, Sheldon *et al.* 2004). Chicks hatched within pasture fields may stay within the vicinity of the nest area until fledging but conversely they can also be moved over large distances (Cramp & Simmons 1983, Shrubb 2007).

Chicks fledge around 35 days after hatching and they are still dependent on their parents until around 6 or 7 days after they can fly.

Within arable fields the change from spring to autumn sowing has reduced the availability of preferred nesting habitat, with autumn sown crops too tall and dense by spring to be used (Sheldon *et al*. 2004). The intensity of agricultural operations in spring has increased, leading to high rates of nest destruction in fields that are otherwise suitable for nesting (Wilson, Evans & Grice 2009). Faster growing varieties of crops and high fertiliser application rates mean that spring sown crops quickly become too tall to be used, shortening the period that a field is suitable for nesting and thus reducing the opportunity to replace clutches lost to agricultural operations.

Land drainage in grassland areas, which is often accompanied by increased fertiliser use and reseeding with faster growing varieties, has led to taller more uniform swards, reducing the suitability of pasture for nesting (Klomp 1954, Milsom *et al.* 2000, Vickery *et al.* 2001). Increased grass production has facilitated increased stocking densities resulting in high rates of nest destruction by trampling and high rates of nest abandonment by adults (Beintema & Muskens 1987, Pakanen, Luukkonen & Koivula 2011).

The suitability of arable fields for nesting depends on the proximity of chick rearing habitat such as damp grassland and chicks that need to travel greater distances between the nest site and brood rearing habitat are less likely to survive (Galbraith 1988). As such, large blocks of arable land are rarely used by lapwings and the decline in mixed farming systems has led to a reduction in the availability of arable nesting habitat that is close enough to chick rearing habitats to be used or if it is used then chicks need to be moved over far larger distances reducing their chances of survival (Stoate *et al*. 2001, Shrubb 2007, Wilson, Evans & Grice 2009).

1.2.3 Food resources

Lapwings are strongly associated with wet habitats and rely on wet features or moist soil to supply their invertebrate prey (Berg 1993, McKeever 2003, Eglington *et al.* 2008, Eglington *et al.* 2010, Rhymer *et al.* 2010). Adults and chicks feed on a wide range of invertebrates including beetles, flies, moths, ants, spiders, woodlice and earthworms (Cramp & Simmons 1983). Lapwings are visual hunters that generally take their prey from the ground surface, and they have often been observed foot trembling whilst hunting which is likely used to make hidden prey move or bring earthworms up to the soil surface.

Whilst lapwings have an eclectic diet, a number of studies have identified earthworms as an important prey resource, likely due to their relatively high calorific value coupled with their high water content (Hogstedt 1974, Galbraith 1989a, Baines 1990, Beintema *et al.* 1991, Sheldon 2002, Watkins 2007). Both adults and chicks take earthworms, although younger chicks may not be capable of catching earthworms due to their small bill length. Beintema *et al.* (1991) suggested that older chicks need to consume more earthworms in order to meet their increasing energy demands as they approach fledging and they identified an increase in the number of earthworms consumed with increasing chick age, despite decreasing availability of earthworms as the breeding season progressed. Providing further support for Beintema *et al.'s* theory, Watkins (2007) discovered that chicks older than 12 days foraged in relatively earthworm rich areas within fields, whereas the opposite was true for younger chicks. Furthermore, positive relationships have been identified between the number of earthworm chaetae within chick faecal samples, chick age, growth rates and body condition, indicating an increase in earthworms consumed as chicks age and increasing weight gain with increasing numbers of earthworms consumed (Sheldon 2002).

The pre-breeding / early breeding season is a particularly energetically demanding period for adult lapwings (Galbraith 1989). Territorial males expend considerable energy on display flights, reducing the amount of time available for foraging, whilst females put significant resources into producing eggs. During this period, lapwings forage within fields that have relatively high prey biomass (Galbraith 1989) and select earthworm rich patches within fields (Watkins 2007). Female body condition is an important determinant of egg size, which in turn influences chick weight and subsequently chick condition and survival, illustrating the importance of females consuming adequate food resources prior to egg laying (Galbraith 1988a, Blomqvist, Johansson & Gotmark 1997). The length of the pre-laying period is highly negatively correlated with the abundance of earthworms, indicating that lapwings can obtain adequate body condition for egg laying faster in areas that are particularly earthworm rich (Hogstedt 1974).

Widespread land drainage is likely to have significantly reduced the abundance and availability of invertebrate prey for lapwings (Baines 1990, Taylor & Grant 2004, Wilson, Evans & Grice 2009). Higher yielding grass is also likely to have reduced the detectability of prey species within these taller, more uniform swards (Devereux *et al.*2004).

1.2.4 Agri-environment schemes

Since 1992 the EU has provided funding through agri-environment schemes (AES) for famers to adopt “environmentally friendly” farming practices (Stoate *et al.* 2001, Donald *et al.* 2006). To date, the majority of AES targeted at breeding waders, including lapwings, have involved compensatory payments for a reduction in land productivity brought about, for example, by reducing livestock densities during the breeding season or raising the water table (Kleijn *et al.* 2001, Ausden & Hirons 2002, Kleijn & Zuijlen 2004, Ottvall & Smith 2006, Wilson, Vickery & Pendlebury 2007, Verhulst, Kleijn & Berendse 2007, O’Brien & Wilson 2011). So far the success of AES in increasing lapwing populations has been mixed.

Dutch AES, involving the restriction of agricultural operations on meadows during the wader breeding season, stop nests from being destroyed by activities such as mowing. Reducing nest destruction rates should have resulted in improved lapwing productivity in farms that are managed under AES, however, breeding populations have not increased in comparison to those on conventionally managed farms (Kleijn *et al.* 2001, Kleijn & Zuijlen 2004, Verhulst, Kleijn & Berendse 2007). In the UK, populations of breeding waders on land managed under AES have fared better than those on conventionally managed farms (Wilson *et al*. 2007, O'Brien and Wilson 2011). However the cost effectiveness of different options has been variable (Ausden & Hirons 2002, Wilson, Vickery & Pendlebury 2007), and the current area of land managed under AES is estimated to fall well short of that required to reverse on-going population declines (O'Brien & Wilson 2011).

1.3 Linking soil pH, earthworms and lapwings

One aspect of agriculture change which has not received much attention in relation to farmland bird declines is soil pH. Soil pH is reduced by agricultural processes such as cropping and the use of nitrogenous fertilisers, but also reduces naturally through leaching of calcium out of the soil and has been reduced further in some areas by anthropogenic atmospheric acid deposition (Rowell & Wild 1985, Gasser 1985, Johnston *et al.* 1986). Natural leaching of calcium out of the soil is faster in areas with higher rainfall. Furthermore, the effect that both natural leaching and acid deposition will have on soil pH is dependent on the buffering capacity of the underlying geology, and in Scotland much of the underlying geology has poor buffering capacity against the effects of acidification (Langan & Wilson 1992, Hornung *et al.* 1997).

The effects of soil acidification can be counteracted through agricultural liming which involves the application of calcium oxide (quicklime), calcium carbonate (including limestone and chalk), calcium hydroxide (slaked lime) or magnesium or dolomitic limestone, all known as lime, to the land to raise soil pH (MAFF 1969, Goulding, McGrath & Johnston 1989). Failure to apply sufficient lime to maintain soil pH at around pH 6 for grass and pH 6.5 for crops results in lower yields, lower nutrient uptake by grass or crops, and inefficient use of nitrogenous fertilisers (Agricultural Lime Association No Date).

The effect that agricultural liming has on soil pH means that it could affect the abundance of earthworms, which have been identified as an important prey resource for breeding lapwings (Section 1.3). Earthworms are sensitive to soil pH and very few earthworms occur in soils below pH 4.3 (Edwards & Bohlen 1996). Earthworms can be broadly divided into three distinct ecological groups; epigeic earthworms dwell at the surface, whilst endogeic species live in or just below the root mat and anecic species form deep vertical burrows, and are capable of descending at least one metre below the soil surface, coming up to the surface only periodically to obtain food material such as dead leaves (Edwards & Bohlen 1996). Due to their distribution within the soil, endogeic and epigeic species are available to foraging lapwings for more of the time than anecic species, which are only available when they have come to the soil surface and are out of reach when they are within their burrows. As lime is applied as a surface dressing, its effects on soil pH is most pronounced in the top portion of the soil and it therefore seems likely that lime has a greater effect on endogeic and epigeic than anecic earthworm species. Indeed reported increases in earthworm abundance following liming are mainly for epigeic species (Deleport & Tillier 1999, Bishop 2003, Potthof *et al*. 2008), although smaller increases in both endogeic and anecic species were found by Potthof *et al*. (2008), and Bishop (2003) also identified an increase in one endogeic species. Positive effects of liming on earthworms indicate that the practice of agricultural liming may be of benefit to lapwings and in fact Brandsma (2004) identified an increase in field use by both lapwings and black-tailed godwits (*Limosa limosa*) following increases in earthworm abundance that occurred after liming.

1.4 The history of lime use in Great Britain

Lime has been used as a fertiliser in the UK for at least 2000 years (Gardner & Gardner 1957), but with the advent of inorganic fertilisers in the 1850s, which provided far greater increases in yield at lower cost, lime use began to decline (Johnston & Whinham 1980). In the 1930s, the UK government, concerned by the prospect of war and declining soil fertility introduced a Lime Subsidy for farmers (MAFF 1969). The quantity of agricultural lime purchased annually in the UK increased from around half a million tonnes prior to the introduction of the subsidy to a peak of around seven million tonnes in the late 1950s and early 1960s (Figure 1-1). The quantity of agricultural lime sold annually started to drop again in 1965. Whilst The Ministry of Agriculture, Forestry and Fisheries (MAFF) attributed this drop to the fact that large doses of lime applied in the earlier part of the subsidy period had increased soil pH enough that only smaller doses of lime were now required to maintain soil fertility, there was some evidence to suggest that the level of liming occurring in the 1970s was not sufficient to maintain soil pH at optimum levels (The Agricultural Lime Producers' Council 1977, Church & Skinner 1986). The quantity of lime sold for agricultural purposes in the UK continued to decline to just below two million tonnes in 1999 and has remained around that level since. Current agricultural lime purchases are similar to that which occurred at the start of the lime subsidy period in 1939 and are less than a third of that purchased during the peak period.

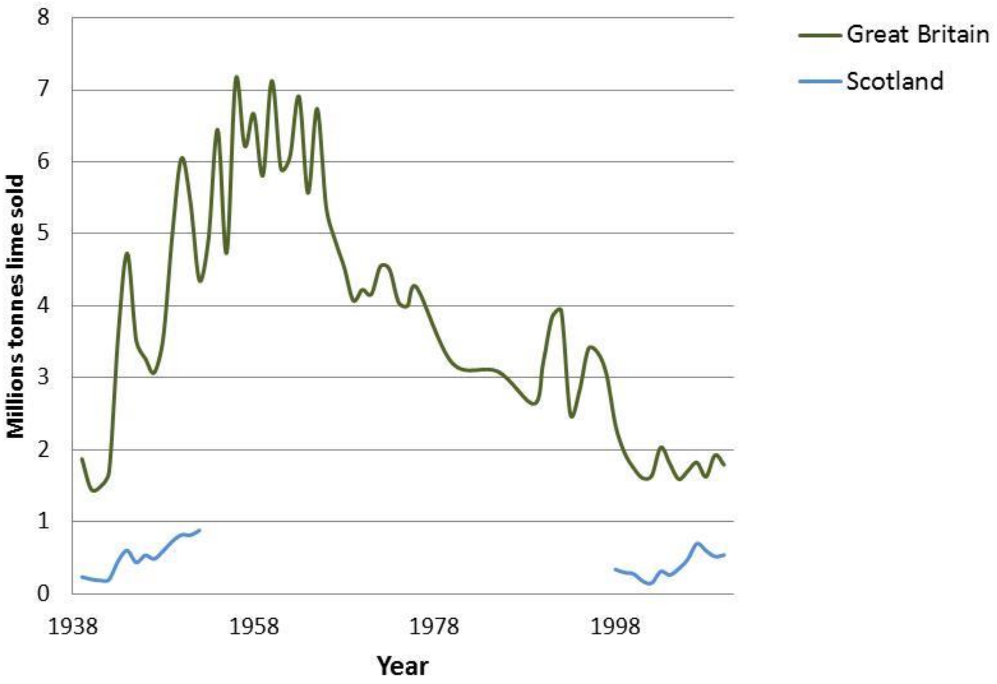


Figure 1-1 The quantity of lime sold in Great Britain and Scotland for agricultural purposes, annually since 1938: data sources: Great Britain 1939 – 1976, The Lime Producers Council (1977), Great Britain 1980 – 1989, Wilkinson (1998), Great Britain 1990 – 2010, Hillier *et al*. (2003), Idoice, Bide & Brown (2012), Scotland 1939 – 1952, Gardener & Gardener 1957, Scotland 1998 – 2010, Scottish Government (2012).

The percentage of land limed in Great Britain rose slightly from the late 1960s until the mid-1970s (Figure 1-2; Chalmers 2001). This increase occurred at a time when agricultural lime sales were declining and this apparent disparity in the two measurements results from a decline in application rates during this period (Chalmers, Kershaw & Leech 1990). The percentage of agricultural land receiving lime inputs remained fairly steady from the mid-1970s until the end of the 1980s, during a period of fluctuating lime sales. There was a peak in the percentage of land that received lime in 1998 and since then the percentage of land limed annually has returned to roughly the same as that which occurred in the 1980s, with around 6% of all agricultural land limed annually corresponding with reasonably stable lime sales during this period. The percentage of arable land limed annually was higher than the percentage of grassland limed annually in all years, however, the difference has increased since 1969.

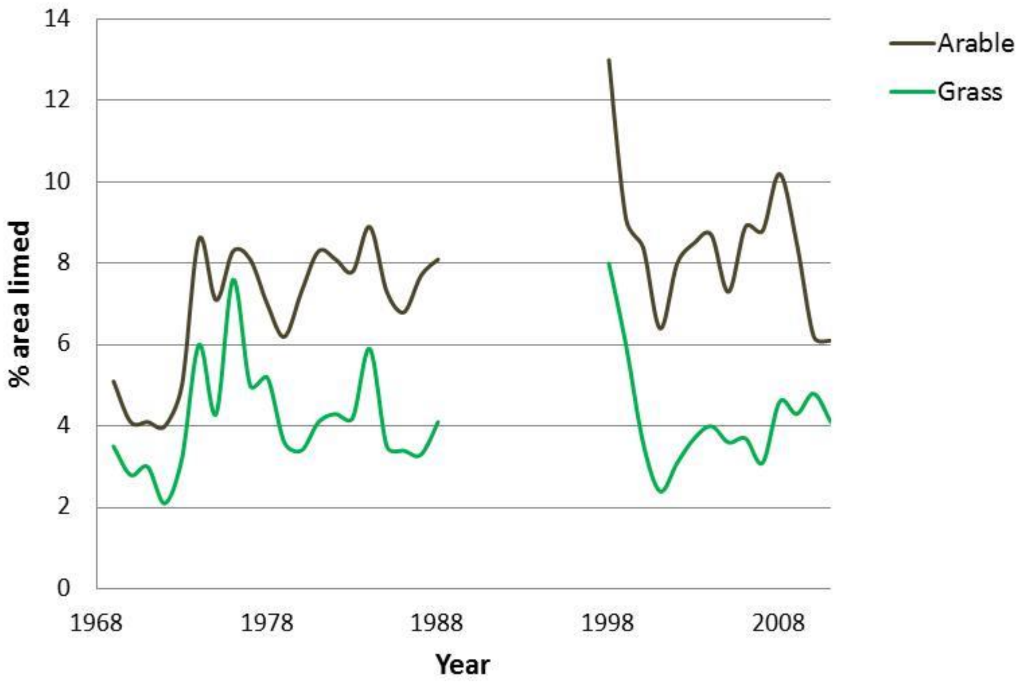
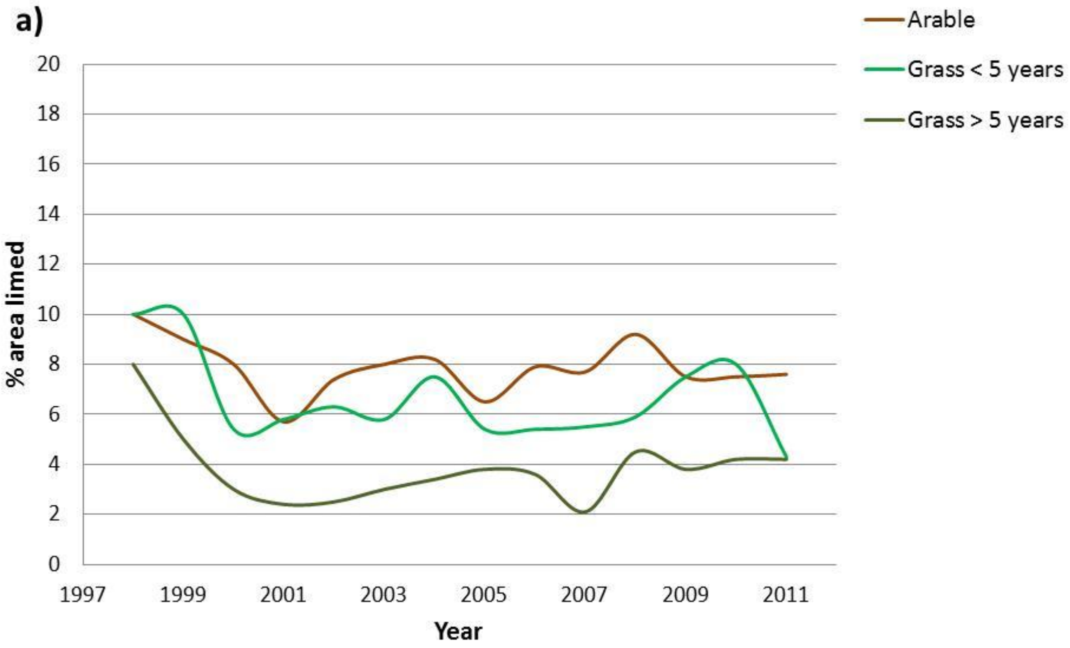


Figure 1-2 Percentage of agricultural land (arable and all grass) in Great Britain that received lime inputs from 1969 to present (no data found for 1989 – 1997). Data sources: 1969 – 1989, Chalmers, Kershaw & Leech (1990) and 1998 – 2011, DEFRA (1999 – 2012).

In England and Wales the percentage of arable land and the percentage of temporary grass (grass that has been sown within the last five years) limed annually are fairly similar and have remained at around 7% since 2000 (Figure 1-3a). The percentage of permanent grassland limed annually in England and Wales is only around half as much as for temporary grassland. In Scotland there is a much larger disparity in the percentages of arable land and grassland that are limed, with around 14% of all arable land limed annually since 1998, whereas only 4% of all grassland was limed annually during the same period. As in England and Wales the percentage of temporary grassland that is limed is higher than the percentage of permanent grassland. The percentage of arable land limed annually in Scotland is almost twice as high as in England and Wales, whereas the percentage of grassland limed is similar.



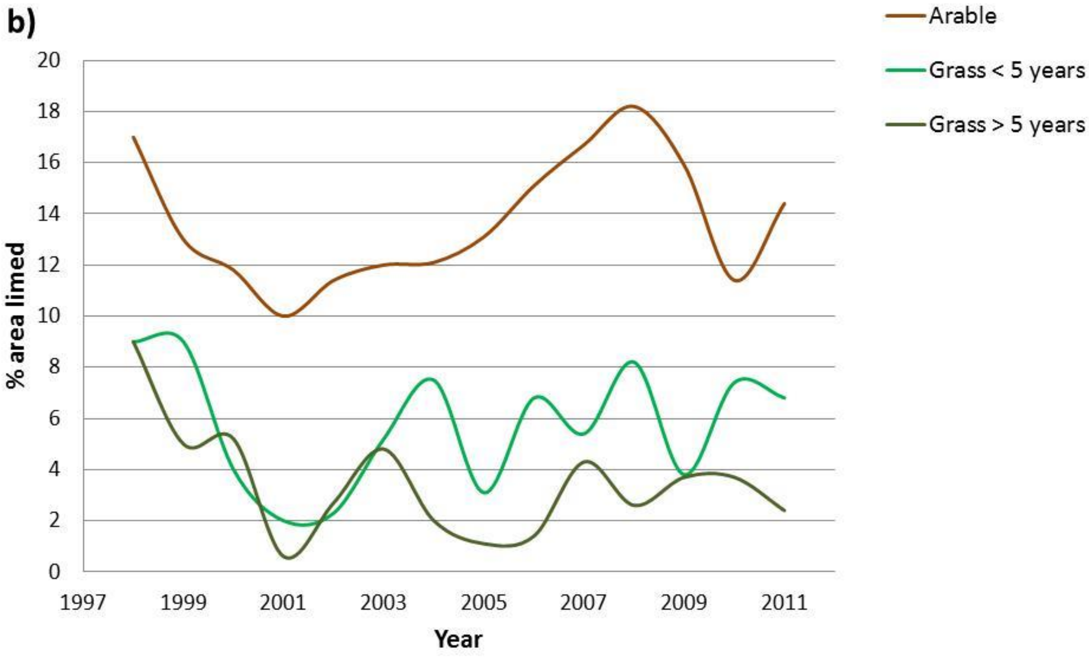


Figure 1-3 Percentage of arable and grassland (separated into grass under 5 years = temporary grass and grass > 5 years = permanent grass) limed between 1998 and 2011 in a) England and Wales, b) Scotland. Data source: DEFRA (1999 – 2012).

Differences in liming patterns between arable and grassland reflect higher soil pH requirements of arable crops than grass (Agricultural Lime Association No date), but may also indicate under-liming of grassland. Under-liming in arable areas can result in crop failure, whereas low grass yields resulting from low soil pH may not be obvious, suggesting that there is a higher probability of grassland being under-limed (Church & Skinner 1986). The Representative Soil Sampling Scheme of England and Wales (RSSS) confirmed under-liming of grassland between 1978 and 1998, with a decline in soil pH in permanent grass detected, contrasting with an increase in soil pH on arable land (Skinner, Church & Kershaw 1992, Skinner & Todd 1998, Webb *et al*. 2001). Spatial analysis of the RSSS data reveals strong regional trends in pH with low soil pH and declines in pH in Wales, the West Country and Northern England, areas that are dominated by livestock farms (Figure 1-4; Baxter *et al.* 2006). A higher percentage of arable land is limed annually in Scotland in comparison to England and Wales (Figure 1-3), implying that Scottish soils have higher lime requirements and this is indeed the case with soil pH on average lower in Scotland, than in England (Figure 1-5; Emmett *et al*. 2010).

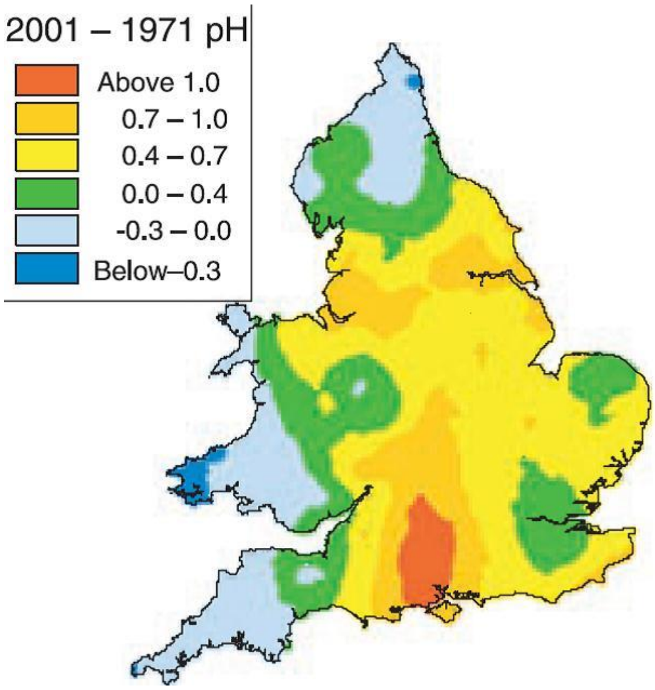


Figure 1-4 Change in soil pH between 1971 and 2001 detected by the Representative Soil Sampling Scheme of England and Wales (RSSS), with declines in pH over this period indicated by blue colouration. Figure from Baxter *et al.* (2006).

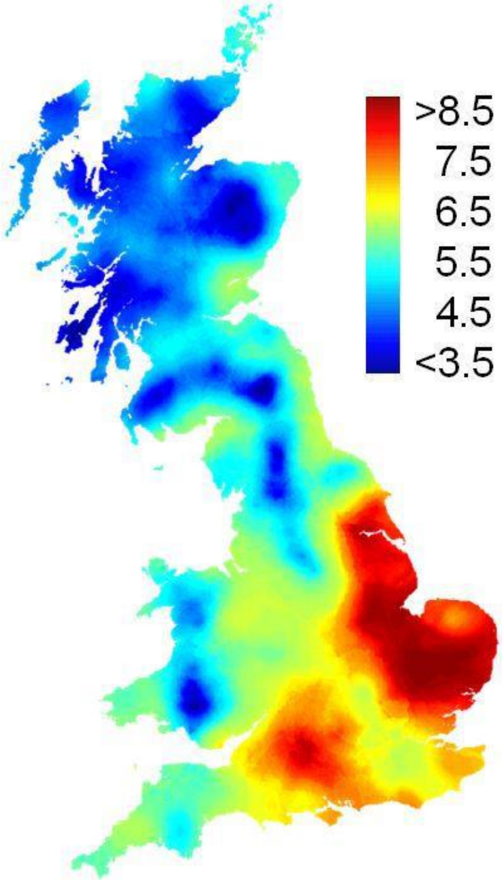


Figure 1-5 Soil pH results in the UK, as found by the 2007 countryside survey, figure from Emmett *et al*. (2010).

In contrast to the results of the RSSS the Countryside Survey identified an increase in soil pH in grassland areas as well as in arable areas between 1978 and 2007 and this was attributed to a decrease in acid deposition during this period (Emmett *et al.* 2010). Increases in soil pH were higher in England than in Scotland and in Scotland soil pH increases were generally confined to the period between 1978 and 1998, with no further significant increases detected between 1998 and 2007.

In conclusion there has been a decline in lime use in Great Britain since a peak period in the 1960s. Arable land is much more likely to be limed than grassland, in particular permanent grassland, and the RSSS indicates that permanent grassland has been under-limed, which may have had negative consequences for earthworm abundance. However, a decline in acid precipitation means that there has been an overall increase in soil pH (across all land uses) between 1978 and 2007, although this survey did not look specifically at agricultural permanent grasslands. Furthermore, changes in soil pH (and lime use) have not been examined in relation to altitude and it is likely that soil acidification will be faster in upland areas due to higher leaching rates associated with higher rainfall.

1.5 Research objectives

In contrast to the many negative effects that agriculture is known to have on breeding lapwings, the principal objective of this thesis is to identify the driver(s) of the unusually high lapwing densities, which occur at an upland livestock farm near to Stirling (Townhead Farm), that appear to be linked to an in-bye management system employed here. The management system at the study site involves planting a forage brassica (tyfon *Brassica campestris* x *B.rapa*) for two consecutive years, in a field that was previously permanent pasture, prior to reseeding the field with grass. This process ultimately improves grass productivity (EBLEX 2008), as well as providing fodder for fattening of lambs over the winter (Koch *et al.* 1987). The ground is limed for up to three years in the lead up to reseeding in order that the optimum soil pH for grass growth is obtained. This process has been implemented on seven in-bye fields at the study site since 1997 and will be referred to as fodder crop management throughout this thesis.

There are a number of mechanisms by which the farm management may be benefitting breeding lapwings, these are:-

1. Tyfon is grazed over the autumn / winter creating an open vegetation structure in the spring, with a high percentage of bare ground, which is likely to be “attractive” to nesting lapwings

2. Liming potentially increases earthworm abundance and as such food resources for lapwings
3. There are many naturally wet areas on the farm which have not been drained and these are likely to be important particularly during the chick rearing period
4. Both fox and crow control are carried out at the farm and in the surrounding area.

This thesis will specifically address the following questions:-

Are lapwing densities at the study site related to fodder crop management and what habitat features are important for the lapwing population? (Chapter 2)

How does fodder crop management affect factors important for breeding lapwings: vegetation structure and food resources? (Chapter 3)

Can soil properties improve habitat models for breeding lapwings? (Chapter 4)

Is fodder crop management economically viable and how does it compare to other in-bye management strategies? (Chapter 5)

Finding out what is driving the unusually high densities of breeding lapwings at Townhead Farm could have conservation benefits for a species that has undergone severe declines, by informing future conservation management practices. Exploring the relationship between breeding lapwings and soil properties may suggest areas where management should be targeted and provide new ideas for conservation management to benefit breeding lapwings and potentially other species. Furthermore, assessing the economic viability of the management system at Townhead, will inform whether management recommendations from this thesis are likely to require agri-environment funding or if they can be promoted without the need for a financial incentive.

Chapter 2 Lapwing habitat use at a high density site in upland Scotland

2.1 Abstract

The lapwing has suffered significant declines in breeding populations across much of its range in Europe. Declines have been linked to several aspects of agricultural intensification including land drainage, increased fertiliser use and increased stocking densities. In contrast to the many negative effects that increasing agricultural productivity has had on breeding lapwing populations, this study explores the relationship between an economically viable farm management system and breeding lapwings at a high density site in upland Scotland. Management involved planting of a fodder crop for two consecutive years followed by reseeding with grass, with seven in-bye fields at the farm undergoing this management since 1997. Breeding density was significantly higher in fields that had undergone fodder crop management than those that had not, whilst controlling for other field habitat parameters of importance to breeding lapwings. Density of breeding lapwings was highest in the first year after the fodder crop was planted, but remained elevated above levels in fields that had not undergone fodder crop management for approximately four years after reseeding with grass. Sparse rush patches, which were more prevalent in grass fields that had undergone fodder crop management, likely as a result of the management process, appeared to be used preferentially for both nesting and chick rearing. Lapwing chick foraging location was associated with high soil moisture and relatively high abundance of *Allolobophora chlorotica*, an acid intolerant earthworm that may have benefitted from liming carried out as part of fodder crop management. Implementing fodder crop management at other sites may have conservation benefits for a species that has undergone severe declines; however, management must be targeted at sites that have adequate densities of wet features if it is to be successful.

2.2 Introduction

Agriculture is the predominant land use across much of Europe and agricultural intensification has resulted in widespread declines in many species that use farmland (Krebs *et al.* 1999, Stoate *et al.* 2001, Robinson & Sutherland 2002). Declines in farmland birds have been particularly well documented (Chamberlain *et al.* 2000, Newton 2004). Agricultural land is the primary habitat used by breeding lapwings (*Vanellus vanellus*; Shrubb 2007) and the severity of population declines in this species led to its addition to the Red List of Birds of Conservation Concern in 2009 (Eaton *et al.* 2009). The lapwing is also a UK Biodiversity Action Plan priority species (http://jncc.defra.gov.uk/page-5163, accessed 17 November 2011).

Declines in breeding lapwing abundance have been related to agricultural intensification, which has brought about many changes in land management practices that have had negative effects on the suitability of farmland as breeding habitat for lapwings (Hudson *et al.* 1994, Sheldon *et al.* 2004, Wilson, Evans & Grice 2009). Drainage of land to improve its agricultural productivity has been particularly detrimental for lapwings (Taylor & Grant 2004), which like other wading birds are reliant on wet habitats (Berg 1993, Eglington *et al.* 2008, Rhymer *et al.* 2010). Drying out of soils leads to a reduction in the abundance and availability of soil and surface invertebrates including earthworms (Edwards & Bohlen 1996, McKeever 2003), which have been identified as a particularly important prey item (Galbraith 1989a, Beintema *et al.* 1991, Sheldon 2002).

The combination of land drainage and increased use of inorganic fertilisers on grasslands has resulted in taller, denser and more uniform swards which are harder for lapwings to detect their prey in (Vickery *et al.* 2001, Devereux *et al.* 2004). Since lapwings select nest sites with short sward or bare ground, taller swards also reduce nest site availability (Klomp 1954, Milsom *et al.* 2000, O’Brien 2001, Shrubb 2007). Increased grass production means that pastures can support greater stocking density and this can result in high rates of nest destruction by trampling or increased likelihood of nest abandonment by incubating adults (Beintema & Muskens 1987, Pakanen, Luukkonen & Koivula 2011).

Another feature of agricultural intensification has been the loss of mixed farming systems with the majority of arable land now occurring in the south and east of the UK and grassland farms more prevalent in the west (Newton 2004, Wilson, Evans & Grice 2009). Mixed farming systems are particularly beneficial for lapwings as arable land, especially spring tillage, is a preferred nesting habitat (Sheldon *et al.* 2004, Shrubb 2007) and in mixed farms this occurs in close proximity to suitable chick rearing habitat, in the form of pasture (Galbraith 1988, Galbraith 1989b).

Since 1992 the EU has provided funding through agri-environment schemes (AES) for farmers to adopt more “environmentally friendly” management practices. To date, AES in the UK for breeding waders have focussed on compensatory payments for a reduction in land productivity brought about, for example, by reducing livestock densities during the breeding season or raising the water table (Ausden & Hirons 2002, Wilson, Vickery & Pendlebury 2007, O’Brien &Wilson 2011). So far AES for breeding waders have had limited success and have not been sufficient to halt population declines in lapwings or other breeding wader species (Ausden & Hirons 2002, Kleijn & Van Zuijlen 2004, Verhulst, Kleijn & Berendse 2007, O’Brien & Wilson 2011).

In contrast to the well documented negative effects of agricultural intensification on breeding lapwings, an upland livestock farm in Stirlingshire, Scotland has unusually high densities of breeding lapwings which appear to be linked to an economically viable management system at the farm, which operates outside of any AES. This system involves planting of a forage brassica (tyfon, *Brassica campestris* x *B.rapa*) for two consecutive years, prior to reseeding with grass; from now on this process will be referred to as fodder crop management. Fodder crop management ultimately improves grass productivity and fields are selected based on the agricultural quality of the grassland, with fields with swards containing a relatively low percentage of perennial rye-grass (*Lolium perenne*) and thus lower agriculturally productive grassland, chosen by the farmer.

Management may be influencing the lapwing population at the site by grazing of tyfon creating an “attractive” vegetation structure for nesting lapwing in the spring, with a high percentage of bare ground. Liming which is carried out as part of the fodder crop management process may have increased earthworm abundance through raising soil pH. Finally naturally wet areas that have not been drained and are left unmanaged are likely to provide important habitat for lapwings particularly during the chick rearing stage.

This study tests the hypothesis that high densities of lapwings at this farm are related to the fodder crop management process, specifically addressing the following questions:-

Comparisons between fields

1. Is the density of breeding lapwings related to land management history, specifically in regards to fodder crop management?

Comparisons within fields

2. Are lapwing nests associated with habitat patches within fields, such as wet unmanaged patches?
3. Is lapwing chick foraging location associated with within field habitat characteristics such as earthworm density that may relate to field management history?

2.3 Methods

2.3.1 Study site

This study took place at Townhead Farm, Stirlingshire, Scotland, which is a 315 ha upland (140 – 320 m altitude) livestock farm supporting approximately 1200 black-faced sheep and 50 limousin cross cattle (Figure 2-1). The study site is part of the Clyde plateau volcanic formation, with underlying geology of basalt and spilite laid down during the Carboniferous period (Geology Roam, available from EDINA Digimap Ordnance Survey Service, http://digimap.edina.ac.uk/geologyroam/mapper, accessed 7 April 2013). The soil derives from basaltic rocks and mainly constitutes brown forest soils (http://sifss.hutton.ac.uk/SSKIB_Stats.php, accessed 7 April 2013).

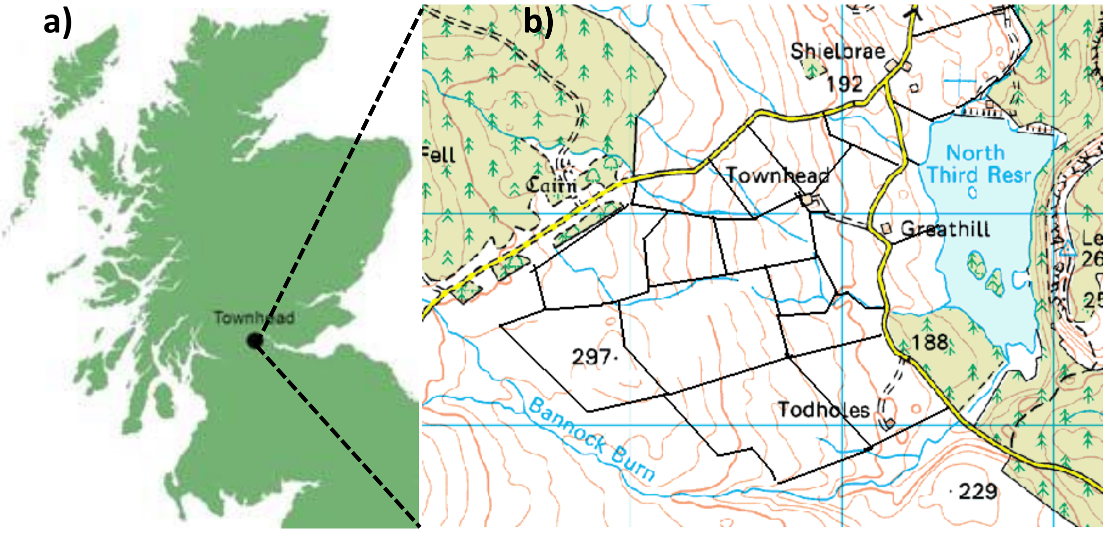


Figure 2-1 a) The location of the study site (Townhead Farm) in Scotland b) Ordnance Survey map of the study site showing topography of the site.

The farm comprises 120 ha of in-bye land (140 – 270 m altitude) and 195 ha of out-bye (175 – 320 m altitude, Figure 2-2, Figure 2-3). With in-bye defined as the enclosed fields used for either arable or grass production, close into the farm house, which occur below the moorland wall, whereas the out-bye is outside the moorland wall and is used for rough grazing only (http://www.scotland.gov.uk/Topics/farmingrural/SRDP/RuralPriorities/Options/BrackenManage ment/DefinitionsofLandTypes, accessed 9 March 2013). At the study site, management intensity on the in-bye fields is greater than on the out-bye fields, with out-bye fields limed less frequently than in-bye fields or not at all, and inorganic fertilisers and farmyard manure applied only to in-bye fields. The out-bye fields are generally much larger than the in-bye fields and have a less productive sward grading from acid grassland to moorland. In-bye fields are more productive than out-bye fields, resulting in lower livestock densities on the out-bye.

Figure 2-2 a) In-bye fields at the study site, have a more agriculturally productive sward (indicated by brighter green colour) than b) out-bye fields at the study site.

Fodder crop management has been used on the in-bye since 1997 and to date seven fields have undergone this management regime (Figure 2-3). Tyfon, which is a variety of stubble turnip, is planted in late June or early July, and is then grazed by livestock over the autumn and winter (Figure 2-4, Table 2-1). These fields remain out of production until tyfon is planted again a year after it was first grown. Following two consecutive years of tyfon the field is reseeded with grass (perennial rye-grass and clover *Trifolium repens* seed mix) in June or July of the next year. All fields that have undergone this process at the farm have remained as grass since reseeding.

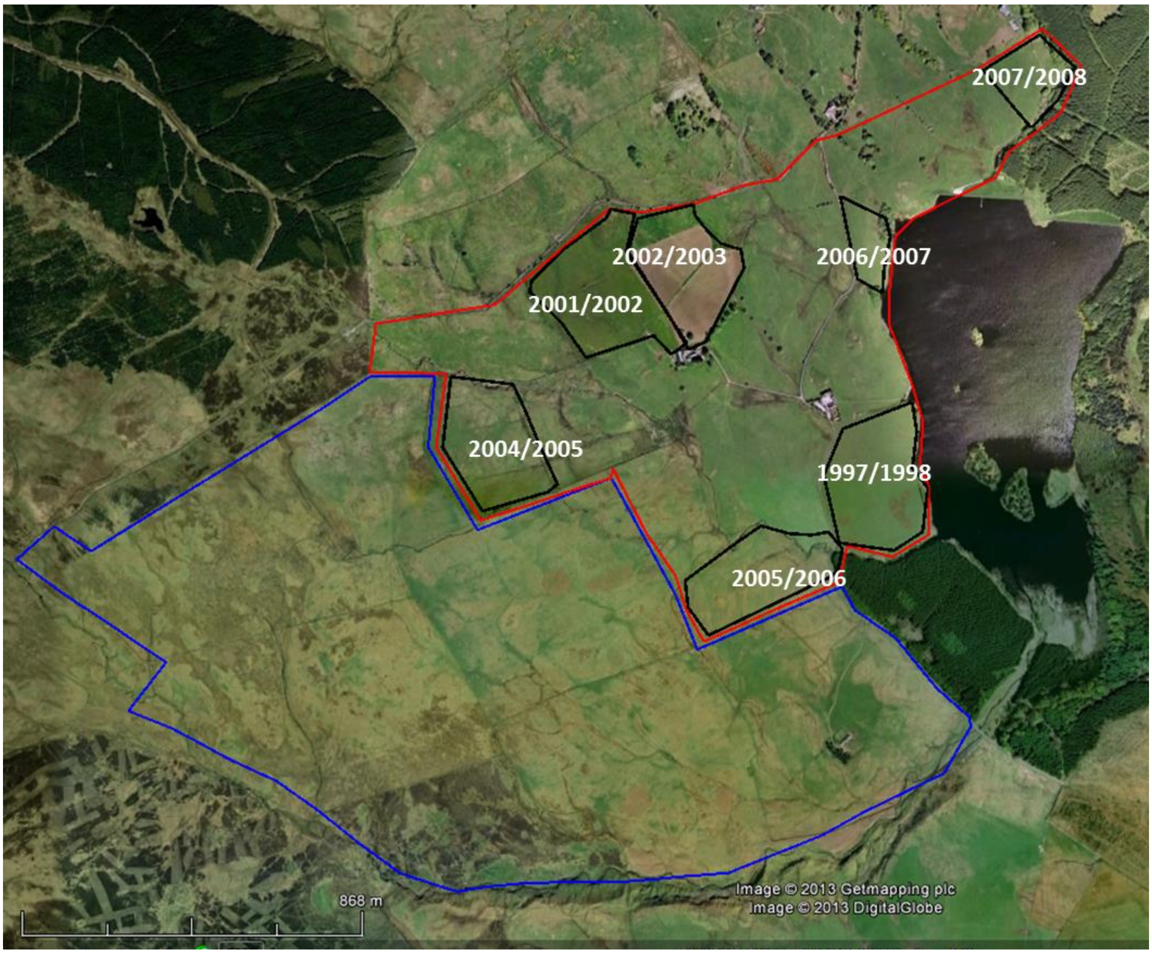


Figure 2-3 Google Earth image of the study site. The out-bye is outlined in blue with the in-bye outlined in red. Fields that have undergone fodder crop management are outlined in black, with the years in which the fodder crop was planted shown for these fields. This image is from 2004 and the brown field indicates that this field had been tilled ready for grass reseeding but that the field that was planted with tyfon in 2004 had not yet been tilled.

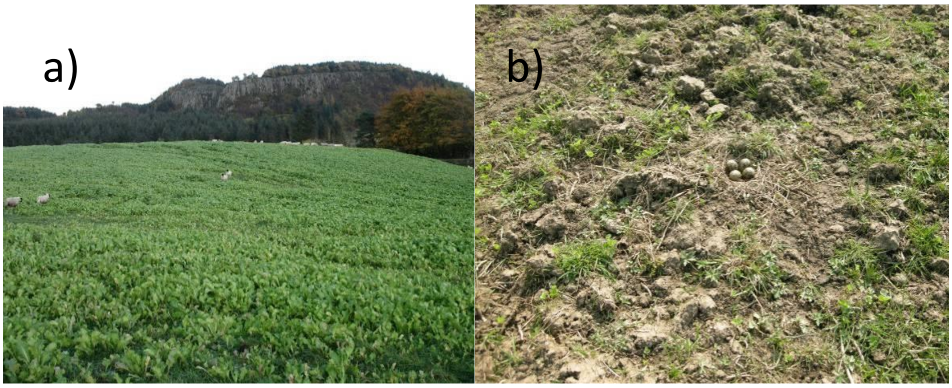


Figure 2-4 a) Sheep grazing tyfon crop in autumn. b) In the spring following autumn / winter grazing, tyfon field has a high percentage of bare ground, with a lapwing nest on the grazed field.

Table 2-1 Timings of fodder crop management process in comparison to lapwing use at the study site.

Farm management	**Late June / July**	**Autumn / winter**	**March**
Year 1	Tyfon planted	Tyfon grazed	Most of crop has been grazed
Year 2	Tyfon planted	Tyfon grazed	Most of crop has been grazed
Year 3	Grass planted	Grazing excluded for grass growth	Grass grazed
Lapwing activity	Leave for wintering grounds	At wintering grounds	Arrival for breeding

Fields selected for fodder crop management are on average further from the farmhouse than those that have not been, indicating that proximity to the farmhouse did not influence selection (Table 2-2). Whilst fields that were selected formerly for fodder crop management were of a similar size to the majority of in-bye fields, the latter two fields that were chosen are relatively small and these were likely selected to reduce the cost of management. Fields selected for fodder crop management have a relatively low density of wet features suggesting that fields with high densities of streams and ditches were avoided due to increased difficulty in manoeuvring the machinery used to carry out fodder crop management.

Table 2-2 Characteristics of in-bye fields that have undergone fodder crop management at the study site compared to in-bye fields that have not. Data presented are means ± standard error.

	Undergone fodder crop management	Not undergone fodder crop management
Distance from farm house (m)	334 ± 81	513 ± 150
Field Area (ha)	6.64 ± 1.08	8.65 ± 0.58
Altitude (m)	202 ± 9	201 ± 12
Slope	5.6 ± 0.4	5.0 ± 0.3
Density of streams and ditches (length/area)	60 ± 16	86 ± 28
Extent of field enclosure	0.17 ± 0.03	0.10 ± 0.03

Prior to growing tyfon, soil pH is tested. Lime (5 tonnes ha^{-1} $annum^{-1}$) is applied in up to three consecutive years with the first application at the time that tyfon is first planted. The objective of liming is to raise soil pH to 5.8 to coincide with grass reseeding. Fertiliser (NPK, 2:1:1, 250 kg ha^{-1}) is applied at the same time as tyfon or grass is planted. Some fields have also had super triple phosphate applied. In-bye fields that have not undergone fodder crop management have not been reseeded since at least 1997. Reseeded grass fields (i.e. those that have undergone fodder crop management) receive inorganic fertiliser (NPK, 2:1:1, 250 kg ha^{-1}) annually, whereas non reseeded in-bye fields receive this fertiliser less frequently. In-bye fields that have not undergone fodder crop management are limed a maximum of once every five years.

Lapwings arrive at the farm from the beginning of March and leave at the end of the breeding season, around the end of June / early July. The timing of operations at the farm is such that planting of tyfon or grass occurs either at the end or after the breeding season so lapwing use will only be affected in the year after management has occurred (Table 2-1).

2.3.2 Comparisons between fields

Lapwing density and field management history

Lapwing surveys

Lapwing surveys were carried out with varying numbers of repeated visits and by a number of different observers in 2003 and from 2006 to 2011 (Table 2-3). Surveys followed the O'Brien and Smith (1992) method, and were carried out on a field-by-field basis. Survey visits were conducted on foot, walking to within 100 m of all points of each field and scanning ahead (up to 400 m) with binoculars from appropriate vantage points. The position and behaviour of all lapwings were marked on a 1:10000 Ordnance Survey map using standard British Trust of Ornithology (BTO) codes. Lapwings were assigned to the first field in which they were noted, or if in display flight, the field at the centre of their display.

Table 2-3 Wader survey visits carried out at the study site, initials denote surveyor: HMcC = Heather McCallum, M'OB = Mark O'Brien, DB = David Beaumont, JW= Jeremy Wilson, SD = Sarah Davis, DBr = Daniel Brown, AF = Adam Fraser, LB = Laura Black. Date for visits 2-4 followed O'Brien & Smith (1992), dates for visits 1 and 5 followed Bolton *et al.* (2011).

	Visit 1	**Visit 2**	**Visit 3**	**Visit 4**	**Visit 5**
	15 Mar - 17 Apr	18 - 30 Apr	1 - 21 May	22 May - 18 Jun	19 Jun - 8 Jul
2011	HMcC	HMcC	HMcC	HMcC	HMcC
2010	HMcC	HMcC	HMcC, DBr, AF	HMcC	HMcC
2009	HMcC	HMcC	HMcC	HMcC	HMcC
2008		HMcC, MO'B	HMcC, DB, SD	HMcC, MO'B, DB	
2007			MO'B, DB		
2006			MO'B, DB, JW		
2003			LB	LB	LB

Visits 1 -4 were conducted within 1-4 hours of dawn or dusk and visit 5 took place between 0700 and 1330. Consecutive visits were at least 18 days apart. In 2003, 2006, 2007 and 2008, survey visits were carried out in one morning or one evening. Between 2009 and 2011, it was necessary to split each survey visit into two sessions, surveying approximately half of the farm in each session. When possible split visits were done on consecutive days, however weather conditions did not always allow this (surveys not carried out in continuous or heavy rain, low visibility or when wind speeds were above Beaufort Force 4). All split visits were conducted within the space of a week. Annual totals of lapwing pairs were calculated on a field by field basis by halving the number of individuals (excluding flocks not exhibiting breeding behaviour) recorded on visit 2 or 3, selecting the visit where the maximum number of lapwings was recorded across the whole farm (Barrett & Barrett 1984).

Measurement of field characteristics that influence the suitability of a field for breeding lapwings

Data on field characteristics likely to influence the suitability of a field for breeding lapwings were measured using ArcGIS 9.2 (ESRI inc 2006). The length of streams and ditches and field boundaries were obtained from the OS Mastermap Topography Layer (EDINA Digimap Ordnance Survey Service). This data was used to calculate the density of streams and ditches per hectare by dividing the total length of these within each field by field area, giving an indication of field wetness. Field slope was extracted from the OS digital terrain map (EDINA Digimap Ordnance Survey Service). The proportion of the field perimeter with enclosed boundaries (either trees or buildings) was calculated by measuring the length of perimeter made up of trees or buildings and dividing this by total field perimeter.

2.3.3 Comparisons within fields

Defining habitat patch types within fields

To assess lapwing habitat use within fields, defined habitat patches within in-bye pasture fields were mapped using a GPS (Garmin Etrex Vista HCx) in 2010.

Two types of habitat patch were identified and plotted onto a GIS:

- Naturally wet areas, characterised by a high percentage of jointed rush (*Juncus articulatus*), which were left uncultivated and un-drained by the farmer, from now on referred to as unmanaged wet patches (Figure 2-5a & b)
- Distinct patches of sparse rush (mainly soft rush *J. effusus* but in some patches also jointed rush) with rush accounting for approximately 5% of the sward within a sparse rush patch (Figure 2-5c & d)

Areas outside of these two habitat patches were mainly grass (Figure 2-5a, b & c).

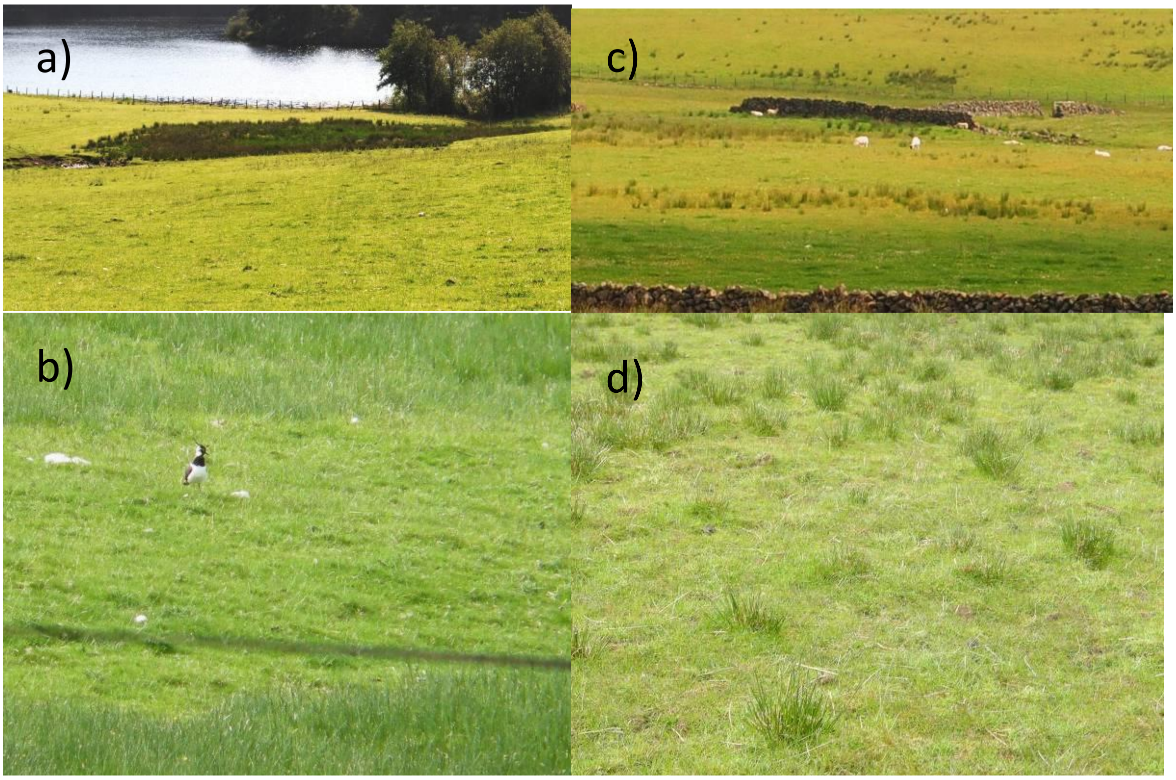


Figure 2-5 Habitat types on the in-bye at the study site: a) unmanaged wet patch, outside of patch is mainly grass b) lapwing between two unmanaged wet patches on mainly grass area c) sparse rush patches within mainly grass d) close up of a sparse rush patch.

Nesting habitat use

Locating nests

Nests were located by looking for incubating adult lapwings with binoculars or a spotting scope in 2009, 2010 and 2011. Detailed descriptions of nest locations were made in order to find the nests on the ground and confirm that they were still active on subsequent visits. Nest location was marked using a GPS on the first visit to the nest and locations were transferred to the habitat GIS. The habitat category for each nest location was extracted from the GIS after first converting the habitat data to raster format (cell size 0.4 m x 0.4 m). Habitat type of each nest was defined as the habitat that wholly contained the nest.

Chick foraging location

Radio-tagging chicks to estimate chick foraging location

A total of 19 lapwing chicks (10 in 2010, 9 in 2011) from separate broods were fitted with Pip3Ag376 backpack mounted radio-tags (Biotrack Ltd, Dorset, UK). All chicks within a brood were ringed using BTO metal rings. Coloured insulating tape was used on the ring to provide each brood with a temporary unique colour marker. Radio-tagged chicks were re-caught at approximately weekly intervals in order that tags that were beginning to come loose could be re-glued.

Chick locations were estimated using triangulation by taking the bearing of the strongest signal from the chick's radio-tag (using a Sika receiver and three-element flexible Yagi antennae – Biotrack Ltd, Dorset, UK) from a minimum of three locations in succession (White & Garrot 1990, Kenward 2001). Estimated chick locations and the associated error ellipses (50% confidence) were calculated using Lenth's maximum likelihood estimator (White & Garrot 1990), using Location of a Signal 4.0.3.7 (Ecological Software Solutions LLC 2010). Error ellipses incorporated antennae error, which was established from a number of test triangulations carried out at the study site (standard deviation 11.5). Chicks were located with triangulation around every one to three days.

This work was carried out under SNH (9797) and BTO licences (C/5642).

Direct observations of chicks

In addition to triangulated locations, some radio-tagged chicks were sighted using direction of the strongest signal to guide where to look for the chick. Fields were also searched visually (with a spotting scope) for non radio-tagged chicks, using clues from adult behaviour to concentrate on areas in which chicks were likely to be located. Visual searches for chicks were carried out no more than once per day for each field. It was difficult to see chicks in unmanaged wet patches due to taller vegetation in these areas; however, it was sometimes possible to ascertain that chicks were using this habitat based purely on adult behaviour.

For all directly observed chicks, chick habitat use was assigned to the first habitat type that the chick was observed in on that day. GPS locations were only obtained for directly observed chicks if earthworm sampling was carried out for that observation (see below).

Earthworm sampling

To avoid repeated disturbance of chicks, earthworm sampling was conducted at a maximum frequency of once per week per field for one chick location. Chick locations were either estimated from triangulation and located using GPS, or directly observed, in which case a waymark (GPS) was made at the time of earthworm collection (Table 2-4). At each chick location four soil cores (10cm depth, 10.5cm diameter) were collected and these were paired with four random soil cores which were taken from four separate random locations within the same field as the chick was located. Random points were generated using the Sampling Tool extension (Finnen & Menza 2007) within ArcGIS and were located in the field using GPS. For each soil core two soil moisture measurements were taken within 15cm of the soil core location using a soil moisture metre (HH2 moisture metre, SM200 moisture sensor, Delta-T Devices, Cambridge, England).

Table 2-4 Number of chick locations where earthworms were sampled within each field type, showing method used to locate chick.

	In-bye			
	With history of fodder crop management	With no history of fodder crop management	Out-bye	Total
Estimated from triangulation	8	10	4	22
Direct observation of tagged chick	5	1	3	9
Direct observation of unmarked chick	3	4	1	8
Total	16	15	8	39

Soil cores were hand sorted in the laboratory to determine soil invertebrate abundance (Edwards & Bohlen 1996). To avoid double counting of broken earthworms only earthworms with heads were counted. Earthworms were identified to species level (Sims & Gerard 1985), with the exception of juvenile earthworms of *Lumbricus* species or *Aporrectodea caliginosa / Aporrectodea rosea*, which were assigned to one of these two groups based on colour, prostomium shape and spacing of chaetae.

Assessing chick habitat use at foraging locations

To complement the earthworm data, habitat was assessed within the GIS for all chick and random locations that earthworms were collected from. The mean error ellipse area for triangulated locations was 4764 ± 1067 m^2 which exceeded the mean area of unmanaged wet patches and sparse rush patches (3155 ± 516 m^2), thus making a high rate of habitat mis-classification likely if habitat type was simply assigned to triangulated locations (Rettie & McLoughlin 1999). Instead my approach here, to estimate chick habitat selection, was to compare the distance of chick locations to the scarcer habitat patch types (unmanaged wet patches, sparse rush patches and stream/ditches) with the distance of the paired random locations to these patches. Distances to habitat features were measured using the Spatial Analyst tool.

2.3.4 Analysis

All statistical analyses were performed with R version 2.12.1 (R Development Core Team 2010). GLMMs where the response variable was a count were implemented with Poisson errors and log link, using the lme4 package (Bates & Maechler 2010). Log_e field area was used as an offset in all of the Poisson models and these models were checked for overdispersion by comparing the residual deviance with the residual degrees of freedom. Pseudo r^2 (from now on referred to as r^2) was calculated by correlating the predicted values with the observed data and squaring this (Zuur *et al.* 2009).

Binomial GLMMs were conducted with the MASS package (Venables & Ripley 2002), using logit link. Model fit was assessed by comparing the predicted probabilities calculated from the model with the observed data within a confusion matrix, using the mean of the fitted values as the threshold level above which a location was assigned as a chick rather than random location (Fielding & Bell 1997).

Minimum adequate models were obtained using stepwise backwards selection, retaining all explanatory variables that were significant at the 5% level.

Comparisons between fields

Three generalised linear mixed effects models (GLMMs) were implemented to test the relationship between lapwing field use and field management history:

1. Do fields with a prior history of fodder crop management have higher lapwing densities?

If a field had been planted with tyfon, it was included in the “fodder crop” treatment group for all lapwing surveys after this occurred. As tyfon was only grown in in-bye fields, out-bye fields were excluded from the analysis. Field characteristics thought likely to influence the suitability of a field for breeding lapwings were also included.

The model took the form:

Lapwing pairs =
(Count)

Factor: **Prior history of fodder crop management (Y/N)**

Covariates: Length of streams and ditches + slope + proportion enclosed boundaries

Random (grouping) factors: Field ID and Year

Offset: Log_e field area

2. Is lapwing brood use related to a prior history of fodder crop management?

The model above was repeated replacing the response variable of lapwing pairs with the number of alarm-calling adult lapwings used as an indicator of the number of broods in a field. Including an interaction between visit number and prior history of fodder crop management (Y/N) enabled movement of broods between fields with a prior history of fodder crop management and those without over the course of the breeding season to be detected. This model only included data from 2009 - 2011 and took the form:

Alarm-calling lapwings = per visit (Count)	*Factors*: **Prior history of fodder crop management (Y/N)*Visit Number** + Year *Covariates*: Length of streams and ditches + slope + proportion enclosed boundaries Random (grouping) factor: Field ID Offset: Log_e field area

Year was included as a fixed factor rather than a random factor as data used in this model (alarm-calling lapwings) was only available for three years, too few a number to be treated effectively as a random factor (Bolker *et al.* 2009, Crawley 2002).

3. Is the density of breeding lapwings related to the number of years since fodder crop management?

This model only included fields that had been planted with tyfon in one or more years prior to the lapwing survey. Fields assigned as one year after tyfon was last planted, had been planted with tyfon in the year preceding the survey and this had been grazed prior to lapwing use, but the field had not yet been reseeded with grass (this occurred immediately after the breeding season). This included fields that had been planted with tyfon in either one or two consecutive years preceding the lapwing survey. In the survey year following reseeding with grass, a field was assigned the value of two years after tyfon was last planted, and this value was incremented annually thereafter. The number of years since tyfon was last planted was $\log_{10}$ transformed prior to inclusion in the model; this improved model fit. As in the previous models, factors already identified as important for breeding lapwing were included. The model took the form:

Lapwing pairs = (Count)	*Covariates*: **Number of years since tyfon last planted** + Length of streams and ditches + slope + proportion enclosed boundaries
	Random (grouping) factors: Field ID and Year
	Offset: Log_e field area

Comparisons within fields

Nesting habitat use

The number of observed nests per habitat type (unmanaged wet patches, sparse rush patches and short grass) was compared to the number of expected nests within that habitat type using a Chi-square test. Data were summed across all years. The expected number of nests was calculated separately for each field by multiplying the total number of nests found by the proportion of each habitat category within that field. Numbers of observed and expected nests were summed across all in-bye fields.

Chick foraging location

Binomial GLMMs were used to identify factors that influenced chick foraging location, using all chick and random locations where earthworm sampling took place. Mean earthworm abundance was used for the four soil cores collected at a chick location, however, as each paired random core was collected from a separate location, data from the four paired locations were included individually. As the distances to sparse rush and unmanaged wet patches were only available for in-bye fields two separate models were implemented, the first using locations from both in-bye and out-bye fields and the second using just those within the in-bye. The models took the form:

Location status = (**chick or random**)	Covariates: Number of earthworms + Soil moisture + Distance to stream/ditch (In-bye only model: + Distance to sparse rush patch + Distance to unmanaged wet patch) Random factor: Sample pair nested within chick identity

Prior to implementing the GLMMs, all covariates were tested for collinearity.

The inverse of the area of the error ellipse was included as a case weight (Crawley 2007) within the GLMMs, with weights calculated using the formula:

$(1/\mathrm{Area}_i) / \Sigma\ (1/\ \mathrm{Area})$

where Area_i is the area of the 50% confidence ellipse for the individual triangulated chick location, and Σ (1/ Area) is the sum of 1/Area for all triangulated chick locations. Direct observations of chick locations and random locations were given a case weight of 1.

Earthworm species composition at chick and random locations indicated that the green morph of the *Allolobophora chlorotica* species was particularly prevalent at chick locations. As such the models were repeated replacing the total number of earthworms with *A. chlorotica* abundance only.

Further analysis (Chi-square test, as per nest habitat selection) was conducted using all direct observations of chicks on in-bye fields (including 41 observations where earthworm samples were not collected, and therefore not included in the above models and a further 13 that were), to determine if chicks used habitat patches or the areas outside of them more than would be expected based on availability.

2.4 Results

2.4.1 Comparisons between fields

Lapwing density and field management history

Lapwing density across the whole study site was 0.22 ± 0.4 pairs ha^{-1} for the seven years of the study, where 0.22 is the mean density across the study site and 0.4 is the standard error. This equates to a five year mean of 59 ± 7 pairs of lapwings breeding on the study site between 2007 and 2011 (2003 and 2006 data excluded as only part of the study site was surveyed in these years). Across the in-bye mean lapwing density was 0.37 ± 0.07 pairs ha^{-1}. Density of lapwings was substantially lower on the out-bye with a mean of 0.09 ± 0.01 pairs ha^{-1}. In-bye with a prior history of fodder crop management had the highest density of breeding pairs of lapwings: 0.47 ± 0.12 pairs ha^{-1}, with in-bye which had not undergone fodder crop management having a mean density of 0.26 ± 0.06 pairs ha^{-1} (Figure 2-6).

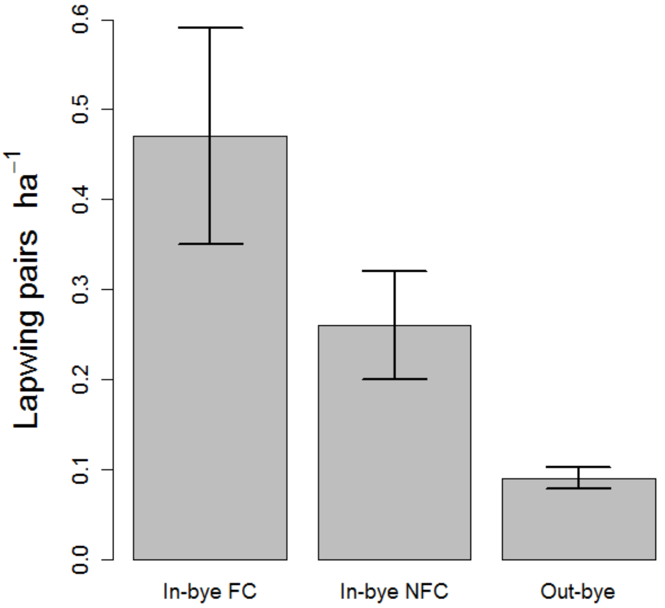
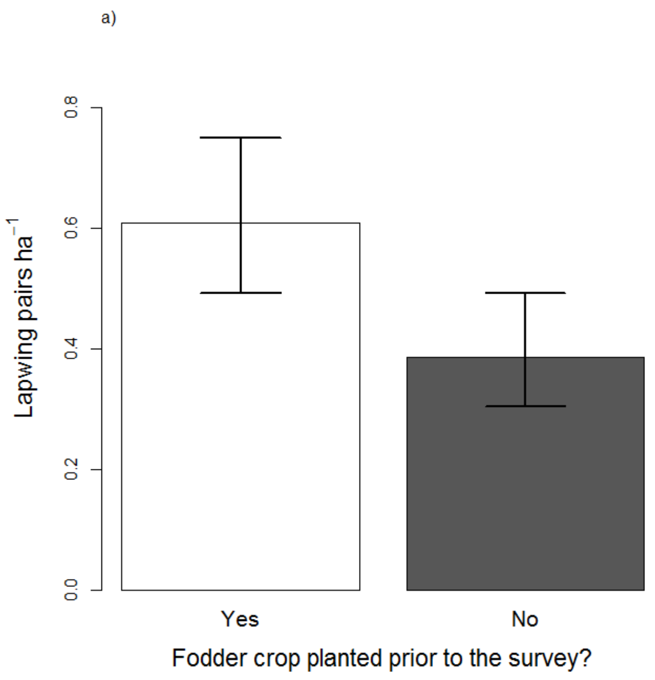


Figure 2-6 Density of breeding pairs of lapwings in the three field types at the study site across the seven years of the study, showing mean ± standard error. Field types are; In-bye FC = in-bye fields with a history of fodder crop management, In-bye NFC = in-bye fields which had not undergone fodder crop management and Out-bye = all out-bye fields.

The density of lapwing pairs was on average, 57% higher in fields with a past history of fodder crop management than those without, whilst controlling for other habitat and topographical variables (Table 2-5, Figure 2-7a). Lapwing density was also higher in less enclosed fields and fields with more wet features, but was not related to how a steep a field was. The r^2 for this model was 0.57.

Table 2-5 Statistical summary for GLMMs assessing the relationship between lapwings and field management history i.e. whether or not an in-bye field had undergone fodder crop management. Comparison of models using lapwing pairs and alarm calling lapwings, as an indicator of brood use, as the response variable. Models also included the density of wet features, field enclosure and slope as explanatory variables as these have previously been shown to influence field use by lapwings. Parameters statistically significant at the 5% level are in bold, parameters not statistically significant at the 5% level were removed from the model.

	Lapwing pairs (n = 105, across 17 fields and 7 years)				**Alarm-calling lapwings (n = 144, across 16 fields)**			
% of variability accounted for by random effect field	1%				<1%			
% of variability accounted for by random effect year	11%				NA			
	DF	Parameter estimate ± SE	z-value	p-value	DF	Parameter estimate ± SE	z-value	p-value
Fodder crop prior to survey (yes compared to no)	**1**	**0.45 ± 0.15**	**3.00**	**0.003**	**1**	**-1.62 ± 0.75**	**-2.2**	**0.031**
Length water ha^{-1}	**1**	**0.003 ± 0.001**	**2.31**	**0.021**	**1**	**0.0008 ± 0.0001**	**4.5**	**0.021**
Proportion field enclosed	**1**	**-0.51 ± 0.96**	**-5.22**	**< 0.001**	**1**	**-0.55 ± 1.28**	**-4.3**	**< 0.001**
Slope	1	-0.12 ± 0.08	-1.65	0.10	1	0.056 ± 0.10	0.56	0.57
Fodder crop prior to survey (yes compared to no) * **Visit N**o (visit 4 compared to visit 3)		-	-	-	**1**	**1.92 ± 0.78**	**2.47**	**0.013**
Fodder crop prior to survey (yes compared to no) * **Visit N**o (visit 5 compared to visit 3)		-	-	-	**1**	**2.24 ± 0.82**	**2.74**	**0.006**
Fodder crop prior to survey (yes compared to no) * **Visit N**o (visit 5 compared to visit 4)		-	-	-	NA	0.32 ± 0.39	0.84	0.40
Visit 4 (compared to visit 3)		-	-	-	**1**	**1.22 ± 0.28**	**4.27**	**< 0.001**
Visit 5 (compared to visit 3)		-	-	-	1	0.06 ± 0.35	0.17	0.86
Visit 5 (compared to visit 4)		-	-	-	**NA**	**-1.16 ± 0.9**	**-4.2**	**<0.001**
Year					2		chi-sq=1.6	0.49



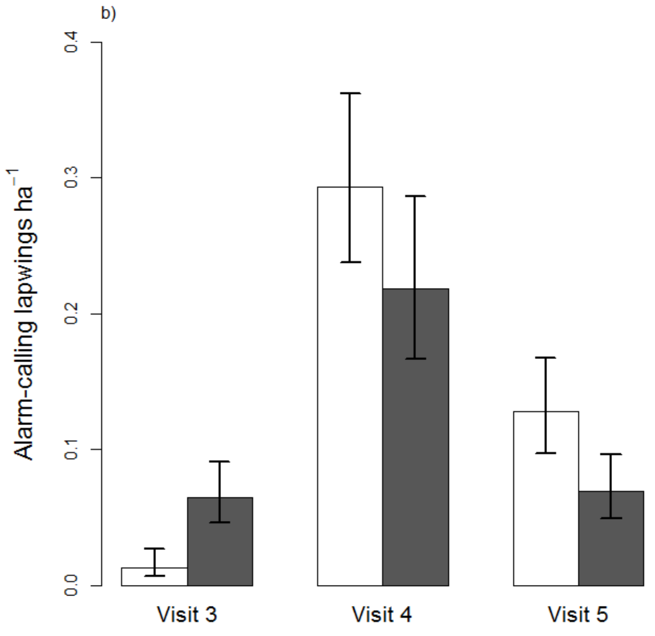


Figure 2-7 a) Density of lapwing pairs in fields with a prior history of fodder crop management compared to those without, b) Density of alarm-calling lapwings across visits 3 – 5 comparing fields with a prior history of fodder crop management (white) to those without (grey). Both graphs are for fields with the mean level of enclosure and density of wet features within the data set, and show predicted values from the model estimate ± standard error.

Higher densities of alarm-calling adult lapwings occurred on in-bye fields with no prior history of fodder crop management at the start of the chick rearing period (visit 3), whereas later on (visits 4 and 5), alarm-calling adult lapwings were more prevalent in fields with a prior history of fodder crop management (Table 2-5, Figure 2-7b). As with the first model, the density of alarm-calling adult lapwings was greater in fields with a higher density of streams and ditches and in less enclosed fields, and was unrelated to field slope. The r^2 for this model was 0.62.

The density of lapwing pairs was highest the year after the fodder crop was last planted and declined steeply thereafter (i.e. once the field had been returned to grass, Table 2-6, Figure 2-8). Densities of lapwings levelled off to around the same as occurred on in-bye fields that had not previously been planted with fodder crop, around five to eight years after the fodder crop was last planted. As with the previous models, lapwing density was lower in more enclosed fields and was not related to field slope. However, unlike the previous models, lapwing density was not significantly related to the density of streams and ditches in a field. The r^2 for this model was 0.81.

Table 2-6 Statistical summary for GLMM assessing the relationship between lapwing density and number of years since a field was last planted with fodder crop (log10 transformed to improve model fit). Models also included the density of wet features, field enclosure and slope as explanatory variables as these have previously been shown to influence field use by lapwings. Parameters statistically significant at the 5% level are in bold, parameters not statistically significant at the 5% level were removed from the model.

	Lapwing pairs (n=40, across 8 fields and 7 years)			
% of variability accounted for by random effect field	<1%			
% of variability accounted for by random effect year	<1%			
	DF	Parameter estimate ± SE	z- value	p-value
No. years since fodder crop last planted ($\log_{10}$ transformed)	**1**	**-1.28 ± 0.29**	**-5.3**	**< 0.001**
Proportion perimeter enclosed	**1**	**-6.47 ± 1.33**	**-5.0**	**< 0.001**
Length water ha^{-1}	1	0.0036 ± 0.003	1.1	0.28
Slope	1	-0.12 ± 0.11	-1.12	0.26

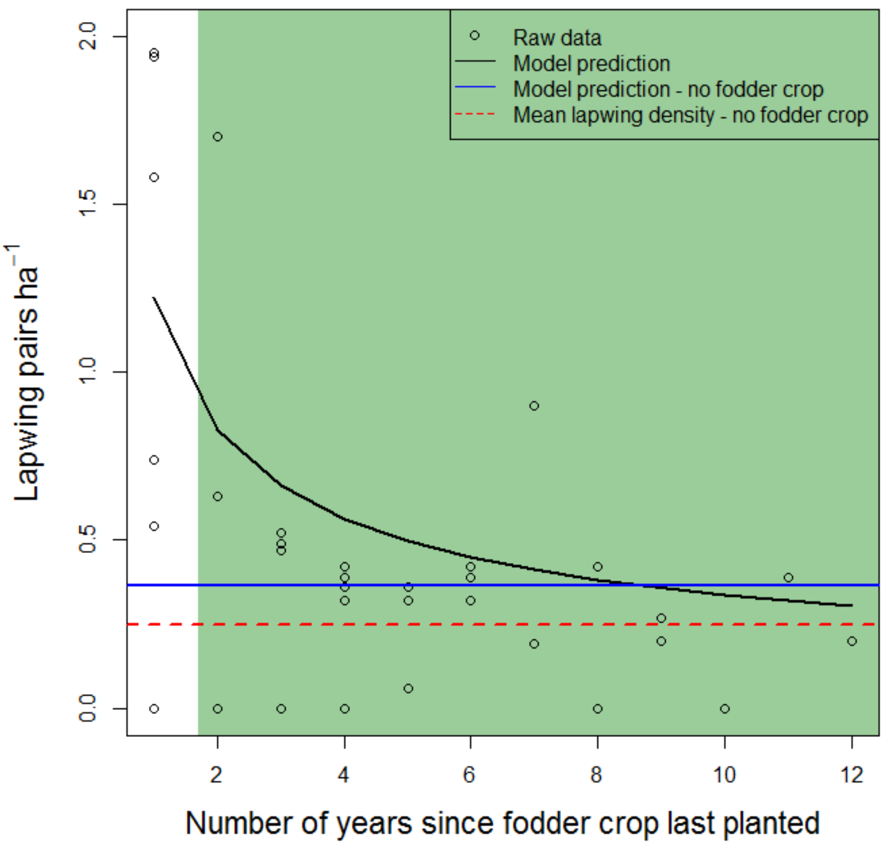


Figure 2-8 Predicted change in lapwing density with increasing number of years since tyfon was last planted (for a field with mean enclosed boundaries within the data set). The green shaded area indicates that the field was in grass at this stage (i.e. reseeded with grass after the end of the breeding season the 1st year after tyfon was last planted). The blue line represents the predicted lapwing density from fields with no prior history of fodder crop management, generated from the previous model (for a field with the mean enclosure of boundaries and mean density of wet features within the data set). Raw data for fields with a prior history of fodder crop management are shown with open circles, with the mean lapwing density (raw data) for fields with no prior history of fodder crop management shown with the red dotted line.

2.4.2 Comparisons within fields

Nesting habitat use

On the in-bye 75 nests were monitored across three years (2009 – 2011). More nests were found in sparse rush patches and slightly more in unmanaged wet patches than would be predicted based on the availability of these habitat types across the in-bye ($\chi^2 = 26.1$, df = 2, $p < 0.001$, Table 2-7).

Table 2-7 Number of observed and expected (in brackets) lapwing nests in different habitat types within the in-bye and the areas of these habitat types at the study site.

	Observed no. nests (Expected no. nests)				**Area (ha)**			
	Short grass	**Sparse rush patches**	**Unmanaged wet patches**	**Total**	**Short grass**	**Sparse rush patches**	**Unmanaged wet patches**	**Total**
In-bye fields with history of fodder crop management	11 (22)	18 (7)	1 (1)	30	24.11	7.78	3.00	34.89
In-bye fields with no history of fodder crop management	24 (30)	3 (1)	18 (14)	45	36.59	1.46	13.97	52.02
All in-bye fields	35 (52)	21 (8)	19 (15)	75	60.70	9.24	16.97	86.91

Chick foraging location

A total of 261 earthworms were found across 39 chick foraging locations that occurred across 13 fields at the study site (Figure 2-9). Earthworm abundance was lower at the paired random locations with 185 earthworms found in total. The most abundant earthworm species group across both chick and random locations was *A. caliginosa* / *A. rosea* comprising around 55% of all earthworms. The second most abundant species was *A. chlorotica* accounting for 20% of all earthworms, however, *A. chlorotica* accounted for a higher percentage of earthworms at chick foraging locations (26%) than at random locations (15%). The third most abundant species group of earthworms was the *Lumbricus* species group comprising 12% of all earthworms across chick and random locations.

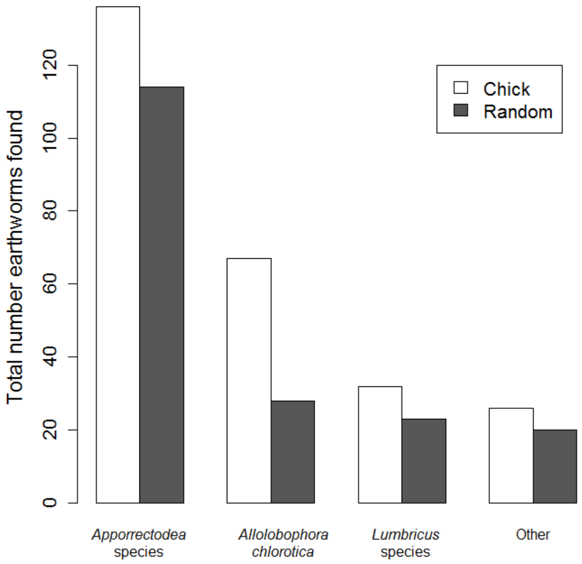
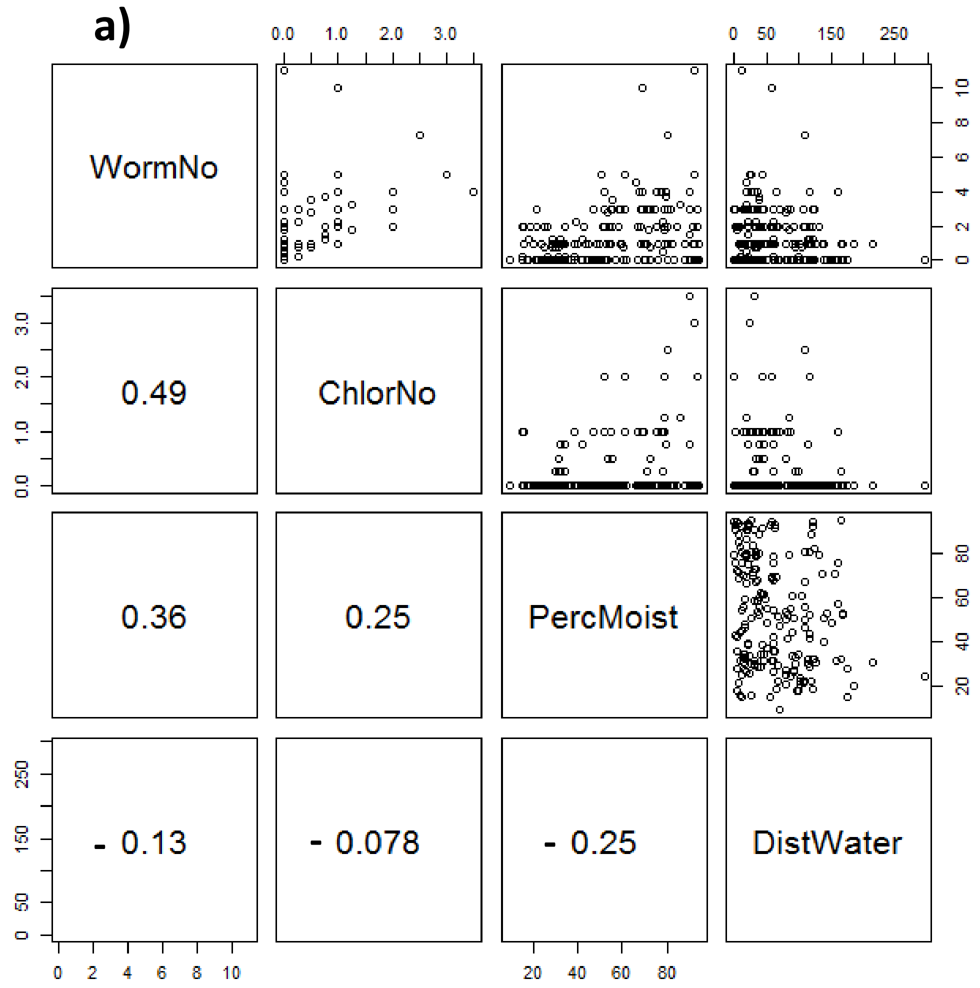


Figure 2-9 Total number of earthworms found at 39 chick locations and all paired random locations.

Habitat characteristics associated with chick foraging location were assessed for chicks located within any field at the study site and then using only locations that occurred within in-bye fields, allowing for inclusion of distance of chicks to habitat patches that were only mapped for in-bye fields. The highest correlation between covariates was 0.42; this was for the distance of locations within in-bye fields to unmanaged wet patches and to streams or ditches (Figure 2-10). The second highest correlation between covariates was for total earthworm abundance and soil moisture content and this was 0.36 when all locations were used and 0.39 when only locations within in-bye fields were used. The abundance of *A. chlorotica* was also positively correlated with soil moisture, although this correlation was lower than for total earthworm abundance (0.25 when all locations were included and 0.28 when only in-bye fields were included). Total earthworm abundance and *A. chlorotica* abundance were not included within the same models.



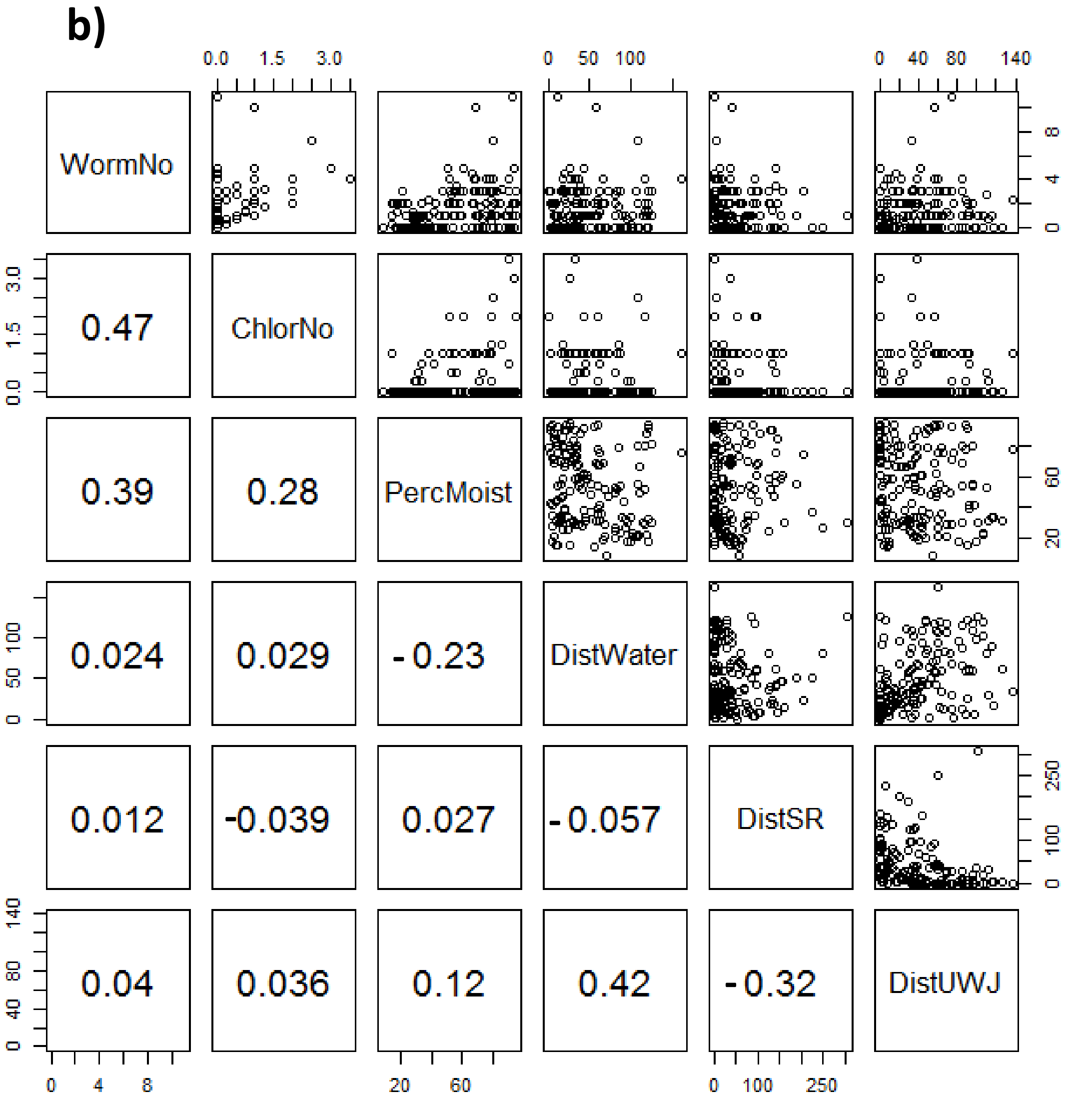


Figure 2-10 Correlations between habitat characteristics measured at chick and random locations for a) locations within all fields b) locations within in-bye fields only. WormNo = total earthworm abundance per soil core, ChlorNo = abundance of *A. chlorotica* per soil core, PercMoist = volumetric soil moisture content as a percentage, DistWater = distance to nearest stream or ditch (m), DistSR = distance to nearest sparse rush patch, DistUWJ = distance to nearest unmanaged wet patch.

Chick foraging location was not associated with total earthworm abundance, and this was the case when locations from both in-bye and out-bye fields were included in the model as well as when locations only from in-bye fields were included (Table 2-8). When total earthworm abundance was replaced with *A. chlorotica* abundance, chick foraging location was associated with relatively higher density of this species of earthworm (Figure 2-11), and again this was the case whether all fields or only in-bye fields were considered. Chick foraging location was associated with areas with relatively high soil moisture content within a field and this was the case for all models.

Distances to spares rush patches, unmanaged wet patches and streams or ditches were not associated with chick foraging location. Adding *A. chlorotica* abundance to the model did not increase the number of correct predictions of chick foraging or random locations, in comparison to the model where only soil moisture remained as a significant predictor of chick foraging location.

As 18 out of 31 chick foraging locations within the in-bye were estimated from triangulation and could not be directly assigned to one of the three habitat types (sparse rush patches, unmanaged wet patches and short grass areas outside these patches), an additional chi-square analysis of all direct observations of chicks within the in-bye was conducted to determine whether chicks were particularly associated with any of these three habitat types. This analysis involved 54 direct observations of chicks, including 13 that were used in the above analysis of chick foraging locations. Chicks were observed in sparse rush patches and unmanaged wet patches more frequently than would be expected based on the availability of these habitat patches ($\chi^2 = 99.4$, df = 2, $p < 0.001$, Table 2-9). 44% of chicks were observed within sparse rush patches, despite this habitat type accounting for just 13% of the available habitat. 39% of chicks were observed within the unmanaged wet patches and this habitat type accounted for 15% of the available area.

Table 2-8 Results of binomial GLMMs testing whether habitat charachteristics could be used to predict when a location was used for chick foraging or if it was a random location a) model outputs, with parameters that were retained as statistically signficant in the final model in bold, b) confusion matrices showing the number of correctly predicted chick locations, correctly predicted random locations as well as the false positives, false negatives and overall error rate.

a)	**All fields**							
	n = 195 (for 39 sample pairs, consisting of 1 chick location and 4 paired random locations, for 22 chicks)							
% of variability accounted for by random effect chick identity	<1%				<1%			
% of variability accounted for by random effect actual / random sample pair nested within chick identity	<1%				<1%			
	Total earthworm abundance				***A. chlorotica* abundance**			
	DF	Parameter estimate ± SE	t-value	p-value	DF	Parameter estimate ± SE	t-value	p-value
Earthworm abundance (total or *A. chlorotica*)	1	0.15 ± 0.11	1.33	0.18	**1**	**0.68 ± 0.30**	**2.24**	**0.026**
Soil moisture	**1**	**0.03 ± 0.01**	**2.74**	**0.007**	**1**	**0.02 ± 0.01**	**2.20**	**0.029**
Distance to stream or ditch	1	0.003 ± 0.004	0.77	0.44	1	0.004 ± 0.005	0.75	0.45
	In-bye fields only							
	n = 155 (for 31 sample pairs, consisting of 1 chick location and 4 paired random locations, for 18 chicks)							
% of variability accounted for by random effect chick identity	<1%				<1%			
% of variability accounted for by random effect actual / random sample pair nested within chick identity	<1%				<1%			
	Total earthworm abundance				***A. chlorotica* abundance**			
	DF	Parameter estimate ± SE	t-value	p-value	DF	Parameter estimate ± SE	t-value	p-value
Earthworm abundance (total or *A. chlorotica*)	1	0.13 ± 0.13	1.01	0.31	**1**	**0.63 ± 0.32**	**1.98**	**0.050**
Soil moisture	**1**	**0.04 ± 0.01**	**2.98**	**0.003**	**1**	**0.03 ± 0.01**	**2.48**	**0.015**
Distance to stream or ditch	1	0.005 ± 0.007	0.74	0.46	1	0.005 ± 0.008	0.64	0.53
Distance to unmanaged wet patch	1	0.01 ± 0.008	1.4	0.16	1	0.012 ± 0.008	1.37	0.17
Distance to sparse rush patch	1	-0.0007 ± 0.006	-0.10	0.92	1	0.0002 ± 0.007	0.03	0.98

b)	**Models using total earthworm abundance**		**Models using *A.chlorotica* abundance**	
	All fields	**In-bye only**	**All fields**	**In-bye only**
Chick location predicted correctly	17	14	16	13
Random location predicted correctly	95	78	98	78
Chick location predicted when real location = random location(false positive)	61	46	58	46
Random location predicted when real location = chick (false negative)	17	17	23	18
Overall error rate	43%	41%	42%	41%

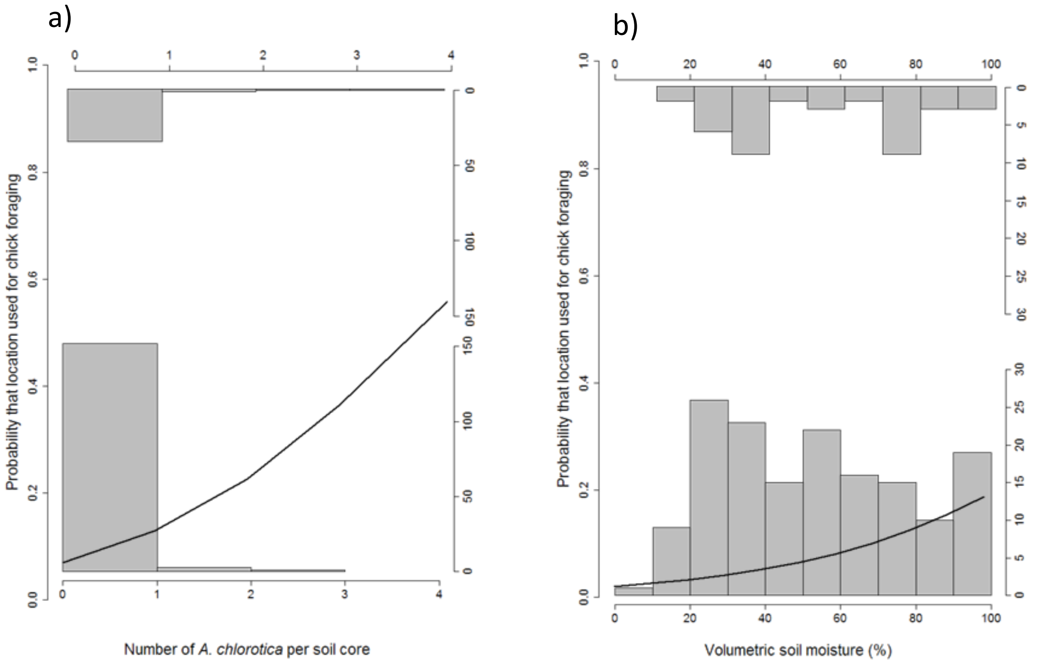


Figure 2-11 Predicted probability that a location was a chick foraging location with increasing a) abundance of *A. chlorotica* and b) soil moisture, with histograms of data distribution for chick locations (top; mean of four cores taken from the same location) and random locations (bottom; four separate cores taken from four random locations).

Table 2-9 Number of observed and expected (in brackets) chick observations in different habitat types within the in-bye.

	Observed no. chicks (Expected no. chicks)			
	Short grass	**Sparse rush patches**	**Unmanaged wet patches**	**Total**
In-bye fields with history of fodder crop management	5 (19)	21 (6)	0 (1)	26
In-bye fields with no history of fodder crop management	4 (20)	3 (1)	21 (7)	28
All in-bye fields	9 (39)	24 (7)	21 (8)	54

2.5 Discussion

2.5.1 Comparisons between fields

Lapwing density and field management history

Fields that had previously been planted with tyfon supported almost 60% (95% CI: 17 – 111%) more breeding lapwing pairs than in-bye fields that had not previously been planted with tyfon, whilst controlling for other habitat parameters that influence a field's suitability for breeding lapwings. Lapwing densities were highest the first year after tyfon was planted once the fodder crop had been grazed but prior to the field being returned to grass. The ground surface created by grazing of tyfon potentially disguises eggs, which are harder to see on brown earth than green pasture, and provides clearer views of approaching predators (Berg *et al.* 2002), from which lapwings actively defend their nests (Elliot 1985, Green, Hirons & Kirby 1990). At the study site, tyfon fields have unmanaged wet patches within or adjacent to them and are in close proximity to pasture fields, resulting in "attractive" nesting habitat within close proximity to suitable chick rearing habitat, as in the case of mixed farming systems (Galbraith 1988), this likely accounts for the very high lapwing densities seen in the first year after tyfon was planted.

The density of breeding pairs of lapwing declined steeply once the tyfon field was reseeded with grass, however, it remained above that in fields with no prior history of fodder crop management for approximately four years (mean density of lapwings in unenclosed fields during the first four years after reseeding with grass = 0.69 pairs ha^{-1}). This contrasts with previous research, suggesting that declines in breeding lapwing density on in-bye pasture resulted from agricultural improvements which included reseeding and use of inorganic fertiliser (Baines 1988, Taylor & Grant 2004), both of which are part of fodder crop management at the study site. In Northern England, densities of breeding lapwing were considerably lower on improved in-bye pasture in comparison to unimproved in-bye pasture (0.14 vs 0.54 pairs ha^{-1}; Baines 1988); the current study found lapwing density over five times higher than that found by Baines (1988) on improved grassland in the first year after reseeding. Potential reasons for this difference include a lesser extent of land drainage, lower application rates of inorganic fertiliser, lower stocking densities and differences in the use of lime at the study site in comparison to Baines' study area.

The fact that fields with a prior history of fodder crop management have a higher density of breeding lapwing pairs than fields which have not undergone this process for a number of years after reseeding suggests that some other part of fodder crop management, in addition to an initial attractive vegetation structure for nesting lapwing, benefits breeding lapwings at the study site. Further to this, in the latter part of the brood rearing period, lapwing broods used fields with a prior history of fodder crop management more frequently than those without, and of fields with a prior history of fodder crop management, broods exclusively used fields that had been reseeded with grass at least two years previously, during the three year period that was considered. Lapwing broods used fields without a prior history of fodder crop management more frequently at the start of the brood rearing period indicating that a mosaic of fields with different land management histories may provide the optimum habitat for breeding lapwings. The higher density of broods in fields which had undergone fodder crop management, later on in the brood rearing period, is in accordance with Galbraith (1988), who found that lapwing broods moved from nesting sites on unimproved to improved upland rough grazing, where improvement consisted of liming.

In addition to the relationship between lapwing density and fodder crop management at the study site, lapwing density was higher in fields with a higher density of streams and ditches and less enclosed field boundaries. These relationships are consistent with previous research on lapwing habitat preferences (Milsom *et al.* 2000, Whittingham, Percival & Brown 2000, O'Brien 2001, Small 2002, Eglington *et al.* 2008), highlighting the fact that any management strategy attempting to increase numbers of breeding lapwings, must be targeted at fields that are otherwise suitable for breeding lapwings.

2.5.2 Comparisons within fields

To test how fodder crop management may be influencing lapwings once the field has been returned to grass, habitat use within fields was assessed. Sparse rush patches were more prevalent in fields that had undergone fodder crop management, with unmanaged wet patches accounting for a higher percentage within fields that had not undergone this management. This is likely due to the fodder crop management process, with areas with standing water or saturated soil at the time of ploughing and planting left to comply with Good Agricultural and Environmental Condition 9 (GAEC), as required under the Common Agricultural Policy (CAP) to receive farming subsidies (http://www.scotland.gov.uk/Publications/2005/12/0990918/09207, accessed 7 September 2012), resulting in unmanaged wet patches within fields that had undergone fodder crop management. Areas that were dominated by jointed rush but where the soil was not so wet would have been converted to tyfon and it is likely that these areas have since developed sparse rush patches due to high soil moisture content, indicating that the fodder crop process resulted in the conversion of patches that were classified as unmanaged wet patches (i.e. dominated by a high percentage of jointed rush) into sparse rush patches; this has been inferred from Google Earth satellite imagery.

Lapwing chicks are precocial and adults lead their chicks away from the nest site to suitable foraging areas within a few days of hatching, meaning that habitat requirements can differ for nesting and chick rearing (Galbraith 1988, Blomqvist & Johannson 1995, Berg *et al.* 1992, Berg 1993, Berg *et al.* 2002); as such both nesting and chick rearing habitat use were considered.

Nesting habitat use

Across the in-bye, lapwings nested relatively more frequently in comparison to habitat availability within sparse rush patches, than the other two habitats (unmanaged wet patches and short grass outside the two patches). Unmanaged wet patches were also used more frequently than predicted based on area, with most nests in these patches within fields with no prior history of fodder crop management . Nest locations imply that sparse rush patches are preferred over both short grass and unmanaged wet patches for nesting, with the creation of sparse rush patches linked to fodder crop management. However, it is important to note that the unmanaged wet patches were the hardest habitat type in which to observe incubating lapwings, so the proportion of nests within these patches may have been underestimated, meaning that they may have been just as important for nesting lapwings as sparse rush patches at the study site.

Relatively high use of sparse rush patches by nesting lapwings supports findings by Picozzi, Catt & Cummins (1996), that lapwing preferentially nest in rush pasture fields. In contrast to this, O'Brien (2001) found that lapwings avoid soft rush when selecting nest sites and this was attributed to the adverse effect that tall rush tussocks have on the ability of lapwings to see approaching predators. Grazing by sheep at the study site is successful in removing the majority of rush growth over the winter, meaning that rush tussocks consist of just one season's growth and may therefore be smaller, shorter and occur in sparser patches than those avoided in O'Brien's study. Soft rush grows in wet conditions and can be used as an indicator of soil wetness (O'Brien 2001) meaning that sparse rush patches likely occurred in naturally wetter areas within fields. Grass growth within sparse rush patches is potentially less vigorous than in drier parts of the field, and this appears to be the case at this site (*pers. obs*.). Slower grass growth within sparse rush patches may mean that grass within these patches is shorter and more open in structure than outside of these patches and this would be of benefit to nesting lapwing. In addition to shorter grass sward, the duller colour of the grass within sparse rush patches is likely to provide a greater degree of camouflage for nests than the bright green vegetation in surrounding areas with heterogeneity of sward height created by the rush tussocks likely to further disguise nests (Galbraith 1989b, Baines 1990).

The presence of dull heterogeneous sparse rush patches within bright green fields that have been improved by fodder crop management could go some way towards explaining the difference in the density of breeding lapwings found on improved in-bye pasture in the North of England (Baines 1988 – see section 2.5.1) in comparison to this study. Baines (1989, 1990) found significantly lower nest survival on improved compared to unimproved pasture, due to higher rates of nest predation on improved pasture. It is possible that sparse rush patches provide areas of sward within improved fields that bear greater resemblance to that found in unimproved pasture by Baines (1988, 1989, 1990), and the development of these patches is likely facilitated by less extensive land drainage at the study site, than potentially occurred on the improved grassland within Baines' study area.

Chick foraging location

Chick foraging location was associated with relatively high within field soil moisture and relatively high abundance of *A. chlorotica.* An increase in volumetric soil moisture content from 30% to 80%, resulted in a threefold increase in the probability of a foraging chick using a location and a location was more than five times as likely to be a chick foraging location when *A. chlorotica* increased from 0 m^{-2} to 350 m^{-2}. Total earthworm abundance, the distance of locations to unmanaged wet patches, sparse rush patches and streams or ditches did not predict chick foraging location.

The importance of wet areas for foraging lapwing chicks is well established and this is associated with improved foraging success resulting from poorer vegetation growth, in addition to higher invertebrate prey abundance (Milsom *et al.* 2002, Devereux *et al.* 2004, Eglington *et al.*2008, Eglington *et al.* 2010). Earthworms can be a major component of a lapwing chick's diet, particularly for older chicks (Beintema *et al.* 1991, Sheldon 2002) and older chicks (>12 days) have previously been shown to forage in relatively earthworm rich areas within fields (Watkins 2007). In this study, whilst total earthworm abundance was not a significant predictor of chick foraging location (although chick age was not taken into consideration), the abundance of one species of earthworm, *A. chlorotica* was.

A. chlorotica is generally found within the top 6cm of soil and is often located just below the soil surface within the roots (Gerard 1967, Sims & Gerard 1985, personal observation). One of the main ecological niches that lapwing chicks exploit for food resources is just below the soil surface

(Benteima *et al.* 1991), suggesting that *A. chlorotica* is more readily available to foraging lapwing chicks than earthworm species with lower vertical distributions in the soil. *A. chlorotica* is an acid-intolerant species (Satchell 1955, Edwards & Bohlen 1996), and liming carried out as part of the farm management at the study site may have increased the abundance of this. Further to this, Bishop (2003) found over twice as many *A. chlorotica* in limed compared to un-limed soil.

Model discrimination between chick foraging locations and random locations was quite poor and this probably ensued from the suitability of some random locations for chick foraging. The number of correct predictions was similar for all four models (i.e. those that included all fields compared to just in-bye fields, and those that included *A. chlorotica* abundance in place of total earthworm abundance which was eliminated from the minimum adequate model), indicating that model fit was not improved by the addition of *A. chlorotica* abundance, potentially resulting from the positive correlation between this species of earthworm and soil moisture. However, increasing abundance of *A. chlorotica* had a larger effect than soil moisture on the probability that a location would be a chick location rather than a random location.

Whilst distance to unmanaged wet patches and sparse rush patches did not predict chick foraging locations, direct observations of chick habitat use indicated that these patches were preferentially used by chicks in comparison to the short grass outside of these patches, suggesting that these patches are important for both nesting and chick rearing. Chicks mainly used sparse rush patches within fields with a prior history of fodder crop management, with unmanaged wet patches used most frequently in fields without a prior history of fodder crop management. Whilst lapwing broods were generally seen within sparse rush or unmanaged wet patches at the study site, adult birds were often observed standing next to the habitat patch (i.e. in the short grass) that chicks were using rather than within the patch (pers obs), and this may have helped them to detect predators more quickly (Berg *et al.* 2002). The behaviour of adult birds implies that the size of habitat patches may impact on their suitability for brood rearing and the density of broods that could be supported.

Conclusions

High densities of breeding lapwings at an upland farm in Scotland are associated with fodder crop management, a farming system that currently operates outside of AES. The density of breeding lapwings was almost 60% higher on fields that had undergone fodder crop management than those that had not, indicating that high lapwing densities are primarily driven by fodder crop management rather than solely the result of predator control that occurs at the farm and in the surrounding area. Breeding densities were highest in the first year after tyfon was planted, and this likely arose from grazing of the fodder crop over winter creating an "attractive" nesting surface the following spring. Lapwing densities remained above that in fields which had not undergone fodder crop management for approximately four years after the field had been reseeded with grass. Elevated densities of lapwings in reseeded fields may be related to sparse rush patches, which appeared to be preferred both for nesting and chick rearing and accounted for a greater area in fields that had a history of fodder crop management. Furthermore, chick foraging location was related to the abundance of *A. chlorotica*, an acid intolerant earthworm that may have increased in numbers as a result of liming that is integral to fodder crop management at the study site.

The association between chick foraging location and high soil moisture, coupled with positive relationships between the density of lapwing pairs and lapwing broods with streams and ditches at the farm, highlights the importance of targeting lapwing management at sites which are sufficiently wet to support breeding lapwings. A mosaic of different habitat types, created by a mix of fields with different management histories may provide the optimum conditions for breeding lapwings.

Chapter 3 The effect of fodder crops and liming on factors important for breeding lapwings: vegetation structure and food resources

3.1 Abstract

Changes in agricultural management have led to reductions in the quality and availability of nesting habitat and food resources for breeding lapwings, contributing to severe declines in this species. This study researched an in-bye management system (fodder crop management) employed at an upland livestock farm in Scotland that has unusually high densities of breeding lapwings. Management involves a combination of different activities, including planting of a fodder crop and liming, and the purpose of this research was to tease out the individual effects of these on key resources for breeding lapwings. The effect of management on vegetation structure and food resources for breeding lapwings was assessed at two spatial scales; firstly by experimental manipulation at the plot scale, and secondly across several fields with different management histories. Fodder crop management creates a patchy vegetation structure and high variability in ground micro-topography, likely to be attractive to nesting lapwings, in the year after the fodder crop has been planted, following over-winter grazing. Liming involved in fodder crop management increases soil pH and this appears to benefit *Allolobophora chlorotica*, an earthworm species previously identified to be associated with chick foraging location at the study site. Total earthworm abundance peaked at around pH 5.2, suggesting that liming could increase earthworm abundance in soils that are more acidic than this. Tillage, involved in fodder crop management reduced earthworm abundance indicating that liming of permanent pasture could result in greater food resources for breeding lapwings than fodder crop management.

3.2 Introduction

Many populations of breeding farmland birds have been adversely affected by large scale agricultural intensification which has occurred throughout much of Europe (Chamberlain *et al*. 2000, Newton 2004, Wilson, Evans & Grice 2009). Farmland is an important breeding habitat for lapwings (*Vanellus vanellus*) and agricultural processes that have reduced the availability or quality of nesting habitat or food availability have contributed to substantial declines in breeding populations of this species (Hudson *et al*. 1994, Sheldon *et al*. 2004, Taylor & Grant 2004).

Declines in breeding lapwing populations have been attributed to low productivity, with many populations failing to produce the minimum number of fledglings per nest estimated to be required to sustain a population, based on survival rates (Peach, Thomson & Coulson 1994, Catchpole *et al*. 1999). Low productivity results from poor nesting success, low chick survival or a combination of these. Lapwings preferentially nest in areas with bare ground or short sward, with arable fields in particular spring tillage often used (Berg, Lindberg & Kallebrink 1992, Sheldon *et al*. 2004). Nest success can be higher on tilled ground than grassland, possibly because increased crypticity of eggs on bare ground reduces predation rates (Chamberlain & Crick 2003, Shrubb 2007). The suitability of arable fields for nesting depends on the proximity of chick rearing habitat such as damp grassland, and the decline in mixed farming systems has had negative consequences for lapwings (Galbraith 1988b, Stoate *et al*. 2001).

Food resources for both the adult and the chick contribute to productivity levels. Adult lapwings that are in better body condition produce larger eggs, resulting in larger chicks that are more likely to survive, whilst chicks will only survive to fledging if they have sufficient food resources to reach their energetic requirements (Galbraith 1988b, Blomqvist, Johansson & Gotmark 1997, Beintema & Muskens 1991). Lapwings eat a range of prey including beetles, earwigs, ants and spiders (Shrubb 2007), however, both earthworms and tipulid larvae have been identified as particularly important due to their high calorific value (Galbraith 1989a, Baines 1990, Beintema *et al*. 1991, Sheldon 2002).

Earthworm abundance is reduced by tillage with repeated deep ploughing resulting in particularly large reductions (Edwards & Lofty 1982a). In contrast, earthworm populations can be increased by fertiliser use, with increases most pronounced for organic fertiliser due to the extra food that is directly provided for earthworms, and inorganic fertiliser perhaps indirectly increasing food resources through the extra plant material that is produced (Edwards & Lofty 1982b, Watkins 2007). However, the use of inorganic nitrogen contributes to soil acidification (Gasser 1985, Rowell & Wild 1985), which may have reduced earthworm abundance due to their sensitivity to low soil pH (Edwards & Bohlen 1996). Agricultural liming is used to counteract soil acidification, which can result from a number of sources including inorganic fertilisers, with any excess nitrogen not incorporated into plants requiring 3.6 kg active liming material to counteract 1 kg (Gasser 1985). Adding lime raises soil pH and has previously been shown to increase earthworm abundance (Deleporte & Tillier 1999, Bishop 2008). There has been a general decline in agricultural lime use since the 1960s (Wilkinson 1998) and this may have led to a reduction in earthworms and consequently food resources for breeding lapwings.

This study investigated a land management system currently employed at an upland livestock farm that is associated with high densities of breeding lapwings (Chapter 2). Land management involves cultivation of a forage brassica, which is planted for two years, followed by reseeding with grass in the third year. The ground is enriched with lime for up to three consecutive years (dependent on soil pH) in the run up to grass reseeding. From now on this process will be referred to as fodder crop management.

The overall objective of this study was to assess the effects of fodder crop management on factors important for breeding lapwings by testing:

1. Whether fodder crop management results in a patchy vegetation structure in the spring following grazing of the crop, which is likely to be attractive to breeding lapwings.
2. Whether liming, carried out as part of fodder crop management has increased soil pH, and earthworm abundance.

These hypotheses were tested at two spatial scales; firstly, by experimental manipulation at the plot scale within a single pasture field, and secondly at the field scale by correlating earthworm abundance with soil properties across several fields with differing management histories.

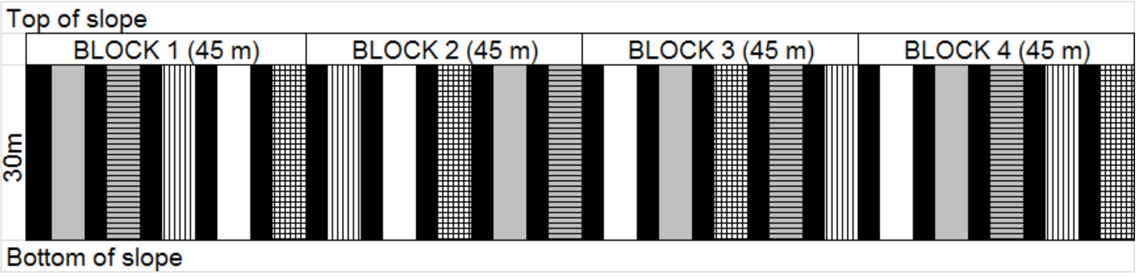
3.3 Methods

3.3.1 Field experiment

Set-up

The field experiment was established in July 2008 in a pasture field at the study site (grid reference: NS 709869, altitude: 320 m), which had not been reseeded, limed or fertilised for at least 10 years prior to the start of the study. The field experiment consisted of five different treatments repeated four times within a randomised blocked design (Figure 3-1, Figure 3-2). The experiment was set up in the top corner of the field, which was sloping and plots were orientated side by side on the slope. Individual plots were 6 m wide and 30 m long, with 3 m buffer strips between the plots. Plot width was dictated by the size of the farm machinery used to carry out the treatments and the length was selected to provide a similar area of plot as that used in the NERC soil biodiversity programme (Usher *et al*. 2006), whilst avoiding the steepest part of the field. The treatments were: control, till, lime, grass/fodder rape (GFR) and tyfon these were selected to break down fodder crop management into components and assess which parts of the management process affected vegetation structure, soil properties and soil invertebrates. Agricultural management was conducted annually with first management in 2008, and final management in 2010.

Tillage consisted of disking followed by power harrowing and occurred on the till, grass and tyfon treatments. Lime was applied at approximately 5 tonnes ha^{-1} and fertiliser (NPK, 2:1:1) at 250 kg ha^{-1}, as these were the application rates used at the main study site. Lime and fertiliser were applied to the lime, GFR and tyfon treatments. In 2008 the GFR treatment was seeded with mixed grass seed at 15 kg ha^{-1} and the tyfon treatment was seeded with tyfon at 2 kg ha^{-1}. Treatments were repeated in June 2009, however, in 2009 tillage consisted of disking only and the GFR treatment was seeded with fodder rape (6 kg ha^{-1}) instead of grass. In August 2010 treatments were repeated for a final year, however, to replicate as closely as possible the management that is carried out at the study farm, the till, GFR and tyfon treatment were all reseeded with grass (15 kg ha^{-1}). In 2010, one of the control plots and one of the till plots were accidently limed.



		Tilled (all yrs)	Limed (all yrs)	Fertilised (all yrs)	Seed 2008	Seed 2009	Seed 2010
1. Control	□	x	x	x	x	x	x
2. Till	▥	✓	x	x	x	x	Grass
3. Lime	▦	x	✓	✓	x	x	x
4. GFR (Grass / fodder rape)	▤	✓	✓	✓	Grass	Fodder Rape	Grass
5. Tyfon	▒	✓	✓	✓	Tyfon	Tyfon	Grass
Buffer strip	■	-	-	-	-	-	-

Figure 3-1 Design of field experiment to assess the effect of management on vegetation structure, soil properties and soil invertebrates. Plots were organised in a randomised block design, with each of 5 treatments occurring once within each block. Plots were 6 m wide and 30 m long and separated by a 3 m buffer strip. The treatments were control, till, lime, grass / fodder rape and tyfon. The treatments were separated into 3 management activities:- tillage, addition of lime and fertiliser and seeding. Management occurred in summer 2008, 2009 and 2010.

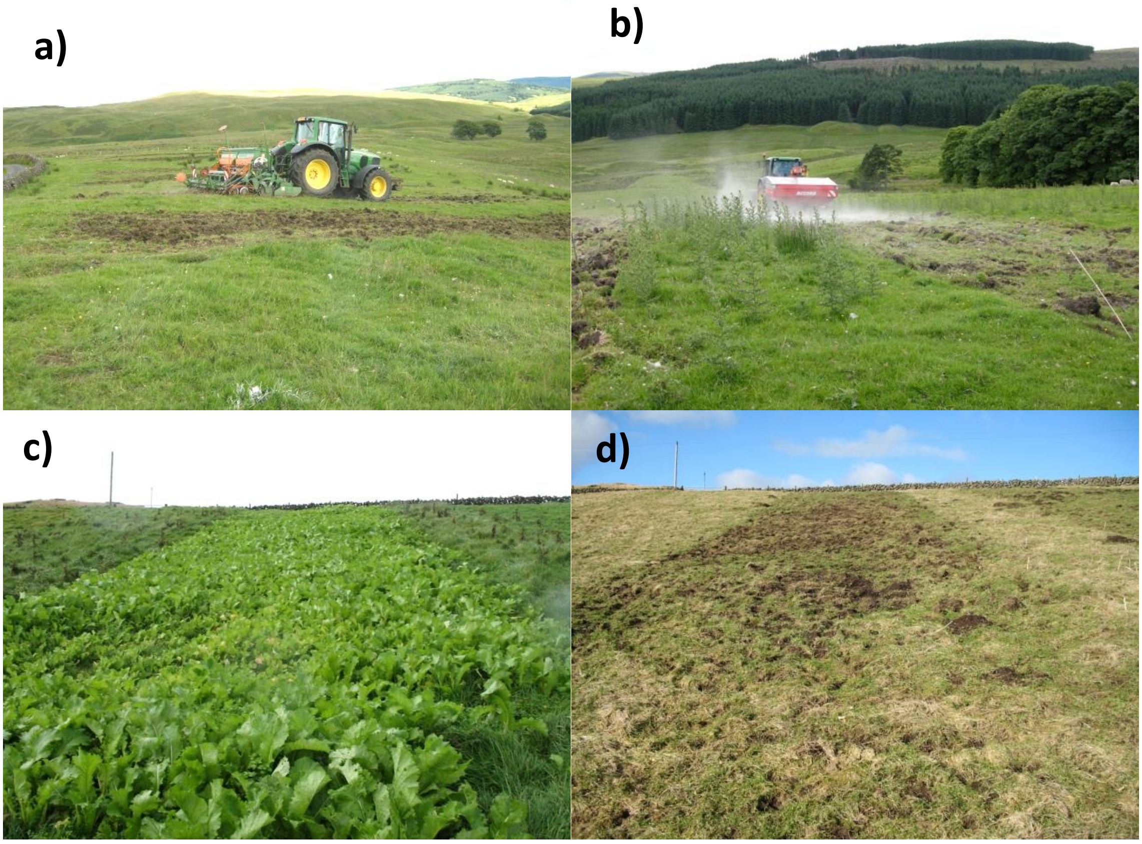


Figure 3-2 The agricultural experiment a) tillage was the first stage in setting up the different treatments with 3 out of 5 treatment types involving tillage b) the second stage in setting up the treatments was liming c) the fodder crop prior to grazing, in the tyfon treatment d) the tyfon treatment following grazing.

Livestock were excluded from the field in which the trial was set up between June and November. The remainder of the year the field was grazed with a combination of black faced sheep and limousin cross cattle. As the field experiment was not fenced off from the rest of the field it was not possible to control grazing densities.

Data collection

Within each plot six random sampling points were generated using pairs of random numbers. Plots were stratified ensuring that two random points were located within the top 10 m, two in the middle 10 m, with the final two points in the bottom 10 m. Sample points were located on each field visit by pacing from a marker cane in the top right hand corner of each plot. The same sampling locations were used to assess vegetation structure, soil properties and soil invertebrates. Data collection was carried out in the spring following management, i.e. in spring

2009, 2010 and 2011 (Table 3-1). Data collection occurred during the first half of April, coinciding with the period when lapwings are setting up breeding territories in the study area.

Table 3-1 Timing of agricultural operations and data collection at the agricultural experiment.

Date	**Activity**
July 2008	Experiment established
April 2009	First set of field data collected
June 2009	Treatments repeated, grass treatment planted with fodder rape at this time
April 2010	Second set of field data collected
August 2010	Final management conducted, tyfon, till and GFR planted with grass at this time
April 2011	Final set of field data collected

The percentage cover of bare ground was estimated by eye, within a 50 x 50cm quadrat. Vegetation height was measured (with a 30cm ruler) at the corners and the centre of the quadrat.

In 2010 and 2011 ground micro-topography (bumpiness) was measured. This was accomplished using a 50cm length of wood that was supported 10cm above ground level at either end and pushing a peg marked in 1cm gradations through six equally spaced holes in the length of wood, until reaching the ground (Figure 3-3; Sheldon 2002). The distance between the wood and the ground surface at each hole was recorded and the standard deviation of distances was used as an index of variability in ground micro-topography.

Figure 3-3 Measuring variation in ground micro-topography at the agricultural experiment.

Soil cores (with 10cm depth and 10.5cm diameter) were collected to assess soil pH and soil organic matter. Two soil moisture measurements were taken in the field within 15cm of each soil core. In 2009 this was done with a theta probe (ML2, Delta-T Devices, Cambridge, England) and in

2010 and 2011 with a soil moisture metre (HH2 moisture metre, SM200 moisture sensor, Delta-T Devices, Cambridge, England).

Soil was air dried for a minimum of two weeks and then sieved to < 2 mm prior to carrying out soil analysis. Soil pH was measured using a digital pH meter (pH209, Hanna Instruments, Woonsocket, Rhode Island, USA), which was calibrated using buffers of pH 7 and pH 4. Soil pH was tested on 10 g of air dried, sieved soil, mixed with 25 ml distilled water, once the solution had been left to settle for a minimum of 10 minutes. A correction offset of 0.18 was added to the soil pH results obtained in 2009 and a correction offset of 0.24 was subtracted from the 2010 results due to inconsistencies in pH measurements obtained in the three years of the study (Appendix A).

Soil organic matter was calculated as the percentage of weight lost by burning sieved soil in a furnace at 425^{o}C overnight (i.e weight loss on ignition). The soil was prepared by drying at 105^{o}C for a minimum of four hours and then weighed both before and after burning.

Soil invertebrates were sampled using the same cores used to assess soil properties, with soil cores hand sorted in the laboratory within four days of collection (Edwards & Bohlen 1996, Laidlaw 2008). To avoid double counting of broken earthworms, only earthworms with heads were counted. All earthworms, bits of earthworms and tipulid larvae were immersed in 70% industrial methylated spirits (IMS) for two minutes, to encourage evacuation of the stomach contents (Watkins 2007) and remove loose soil, blotted dry and then weighed on a three point balance. Earthworms were identified to species level (Sims & Gerard 1985), with the exception of juvenile earthworms of either *Lumbricus* species or *Apporrectodea caliginosa / Apporrectodea rosea*, which were assigned to one of these two groups based on colour, prostomium shape and spacing of chaetae. In 2009, earthworms were stored in 70% IMS prior to identification, with identification in 2010 and 2011 taking place at the time of hand sorting of the soil.

Analysis

To test the effect that agricultural management had on factors important for breeding lapwings a number of linear mixed effects models (LMMs) and generalised linear mixed effects models (GLMMs) were implemented on the field experiment data(Table 3-2). Models took the structure:-

Response variable = **Treatment * Year** + Plot nested within Block (random factors)

Year was included as a factor in all models. All models included plot, nested within block as random factors to account for non-independence of samples collected from within the same plot and potential differences as a result of position within the trial set up.

In addition to these models the effect of treatment on soil invertebrates was re-analysed by splitting up the treatments into the two main management components that each treatment was composed of i.e. tillage and liming / fertilising. These models took the form:-

Response variable = **Lime/Fertiliser + Tillage** + Year + Plot nested within Block (random factors)

Table 3-2 Summary of statistical analysis conducted for the field experiment data, to assess the effect of management on vegetation structure, soil properties and soil invertebrates.

	Unit of response variable	**Model Error Structure**	**Link**
Soil pH	Soil core	Gaussian	Identity
Soil organic matter	Soil core	Binomial	Logit
% Bare ground	Quadrat	Binomial	Logit
Vegetation height	Quadrat	Gaussian	Identity
Ground micro-topography (standard deviation of measurements)	One set measurements from wood block	Gaussian	Identity
Total earthworm abundance	Soil core	Poisson	Log
Tipulid larvae abundance	Soil core	Poisson	Log
*Allolobophora chlorotica** abundance	Soil core	Poisson	Log

* earthworm species that was associated with chick foraging location, Chapter 2

3.3.2 Between-field correlative study

Study area

The majority of samples for the field scale correlation were collected at Townhead Farm, Stirlingshire, Scotland, where fodder crop management has been used on 7 out of 16 in-bye fields since 1997 (Chapter 2). Samples were collected from in-bye fields that had undergone fodder crop management, in-bye fields that had not undergone fodder crop management and out-bye fields in 2009 and 2010 (Table 3-3). In 2010, samples were also collected from two additional livestock farms within the vicinity of Townhead; Muirpark and Lochend (4 miles between farms; Figure 3-4).

Table 3-3 Number of fields where soil cores were collected from in 2009 and 2010, showing the number of fields at the three different farms and the three field types at Townhead Farm.

Farm	**Field Type**	**2009**	**2010**
Townhead	In-bye with a prior history of fodder crop management	6	3 (2 of these repeats of fields sampled in 2009)
Townhead	In-bye with no prior history of fodder crop management	4	2
Townhead	Out-bye	1	2 (1 of these repeat of field sampled in 2009)
Muirpark	In-bye	0	2
Lochend	In-bye	0	2

Figure 3-4 The three farms involved in the study, showing differences in habitat between the farms and between the in-bye and out-bye fields at Townhead Farm a) Townhead Farm in-bye, b) Townhead Farm, out-bye, c) Muirpark Farm, in-bye d) Lochend Farm, in-bye.

Data collection

To measure soil properties and the abundance of soil invertebrates, soil cores (10cm depth x 10.5 cm diameter) were collected from nine random locations within each field, which were located using a GPS (Garmin Etrex Vista HCx). For fields with high variability in soil invertebrate abundance between the samples, up to an additional five samples were collected. Random locations were generated within fields using the Sampling Tool (Finnen & Menza 2007) extension in ArcGIS 9.2 (Esri inc. 2006) stratifying sampling by field quarter (at least two samples were collected from each quarter) and ensuring that all sampling points were a minimum of 10 m from the field edge. Soil coring was conducted in the latter half of April into the beginning of May and soil moisture, soil pH, soil organic matter and soil invertebrate abundance and biomass, were assessed in the same manner as for the field experiment (Section 3.4.1). As with the field experiment, a correction offset of 0.18 was added to the soil pH results obtained in 2009 and a correction offset of 0.24 was subtracted from the 2010 pH results (Appendix A).

Analysis

Were soil pH and organic matter related to a history of fodder crop management?

The fodder crop management process only occurs on in-bye fields at Townhead Farm, therefore to ensure as fair a comparison as possible between fields that had undergone fodder crop management and those that had not, only in-bye fields at Townhead were included in these analyses. A GLMM and LMM were conducted to assess the relationship between soil pH and soil organic matter with the fodder crop management process, taking the form: -

Response variable = **History of fodder crop management (Y/N)** + Year (factor) + Field (random factor).

The response variable was analysed at the soil core level.

A further two models were conducted using data only from fields with a prior history of fodder crop management. The first of these tested the relationship between soil pH and the number of years since a field was last limed as part of fodder crop management while the second tested the relationship between soil organic matter and the last time that a field was ploughed as part of fodder crop management, these models took the form :-

Response variable = **Number of years since lime / plough** + Year (factor) + Field (random factor)

Was soil invertebrate abundance related to a field history of fodder crop management?

Using only data from in-bye fields at Townhead a further three GLMMs were conducted to assess the relationship of total earthworm abundance, *A. chlorotica* abundance and tipulid larvae abundance with the fodder crop management process. These models took the form:-

Response variable = **History of fodder crop management (Y/N)** + Year (factor) + Field (random factor).

Was soil invertebrate abundance related to soil properties?

A final three GLMMs were implemented to assess the relationship between soil invertebrates and soil properties. These models used data from all soil cores collected as part of the between-field correlative study (i.e from all three farms and all field types) and took the form:-

Response variable =	Covariates: Soil pH + Soil organic matter + Soil moisture + Soil pH^2 + Soil organic matter^2 + Soil moisture^2
	Factors: Farm + Year
	Random factor: Field

The three response variables were total earthworm abundance, abundance of *A. chlototica*, and presence of tipulid larvae in the soil core. Prior to analysis soil pH, soil organic matter and soil moisture were checked for collinearity.

Statistical analyses

All statistical analyses were performed with R version 2.15.0 (R Development Core Team 2012). All LMMs and GLMMs were conducted using glmmPQL from the MASS package (Venables & Ripley 2002). Covariates were standardised by centring (subtracting the mean value of the variable found within the dataset from all input variable values), then scaling (dividing the centred input values by the standard deviation of the variable within the dataset), prior to analysis (Schielzeth 2010). Models where the response variable was a count were implemented with Poisson errors and log link and were automatically corrected for over-dispersion. Models where the response variable was a percentage or presence/absence were implemented with binomial error structure and logit link. For all other models Gaussian error structure and identity link, were specified. Model residuals were checked graphically for normality and homogeneity of variance (Zuur, Ieno & Smith 2007). With the exception of the presence / absence models, model fit was assessed by calculating pseudo r^2 (from now on referred to as r^2), the square of the correlation between the predicted values and the observed data (Zuur et al. 2009). Minimum adequate models were obtained using stepwise backwards selection, retaining all explanatory variables that were significant at the 5% level. For the field experiment data, the significance of differences between treatments was assessed using Tukey contrasts with the multcomp package (Hothorn, Bretz & Westfall 2008), unless treatment was involved in a significant interaction.

3.4 Results

3.4.1 Field experiment

Management effects on vegetation structure and ground micro-topography

The percentage of bare ground was significantly higher in the till and tyfon treatments than in the control or lime treatments in all three years (Table 3-4, Figure 3-5). There was also significnatly more bare ground within the GFR treatment in all three years than in the control, however, this treatment only had significantly more bare ground than the lime/fertiliser treatment in 2010 and 2011. Bare ground increased across all treatments that had been tilled (tilled, GFR and tyfon) across the length of the study, even once these treatments had been returned to grass in 2011. The percentage of bare ground was similar in both the control and lime/fertiliser treatment in all years. The r^2 for this model was 0.53.

Table 3-4 Statistical summary for GLMM assessing the effect of management treatment and year on percentage of bare ground, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

	% Bare ground (n = 360, 6 samples per year in 20 plots, within 4 blocks, for 3 years)			
% of variability accounted for by random effect plot (nested within block)		<1%		
% of variability accounted for by random effect block		<1%		
Reference levels are control for treatment and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	**4**	**-**	**F = 49.7**	**<0.001**
GFR		**2.12 ± 0.77**	**t = 2.75**	**0.016**
Lime		1.33 ± 0.82	t = 1.62	0.13
Till		**3.15 ± 0.74**	**t = 4.24**	**0.001**
Tyfon		**3.52 ± 0.74**	**z = 4.76**	**<0.001**
Year	**2**	**-**	**F = 22.5**	**<0.001**
2010		0.61 ± 0.90	t = 0.68	0.49
2011		0.49 ± 0.92	t = 0.54	0.59
Treatment*Year	**8**	**-**	**F = 2.5**	**0.012**
GFR, 2010		0.92 ± 0.95	t = 0.97	0.33
Lime, 2010		-1.45 ± 1.13	t = -1.28	0.20
Till, 2010		-0.14 ± 0.93	t = -0.15	0.88
Tyfon, 2010		-0.055 ± 0.93	t = -0.06	0.95
GFR, 2011		1.39 ± 0.97	t = 1.44	0.15
Lime, 2011		-0.59 ± 1.07	t = -0.55	0.58
Till, 2011		0.45 ± 0.95	t = 0.48	0.63
GFR, 2011		0.10 ± 0.94	t = 0.11	0.91

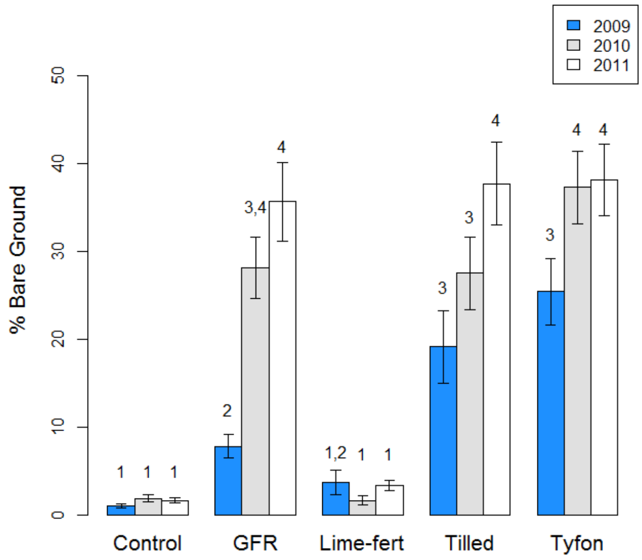


Figure 3-5 Percentage bare ground within the five different treatments across the three years at the field experiment. Bars show mean of raw data ± standard error. Bars with the same number are not significantly different from each other, i.e. treatments and years that do not share a number are significantly different.

Vegetation was shorter than 5cm in all treatments in all three years of the study although there were significant differences between treatment types and between years (Table 3-5, Figure 3-6). Vegetation was shorter in the till, GFR and tyfon treatments than the control or lime treatments in all three years of the study. For all treatments vegetation was shortest in 2009 and tallest in 2010. The r^2 for this model was 0.57.

Table 3-5 Statistical summary for LMM assessing the effect of management treatment and year on percentage on vegetation height, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

		Vegetation Height (n = 360, 6 samples per year in 20 plots, within 4 blocks, for 3 years)		
% of variability accounted for by random effect plot (nested within block)		1%		
% of variability accounted for by random effect block		6%		
Reference levels are control for treatment and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	**4**	**-**	**F = 28**	**<0.001**
GFR		**-1.03 ± 0.20**	**t = -5.06**	**<0.001**
Lime		-0.32 ± 0.20	t = -1.56	0.14
Till		**-0.86 ± 0.20**	**t = -4.25**	**<0.001**
Tyfon		**-1.03 ± 0.20**	**z =-5.08**	**<0.001**
Year	**2**	**-**	**F = 120**	**<0.001**
2010		**1.63 ± 0.19**	**t = 8.43**	**<0.001**
2011		0.25 ± 0.19	t = 1.26	0.21
Treatment*Year	**8**	**-**	**F = 4.5**	**<0.001**
GFR, 2010		**-0.56 ± 0.27**	**t = -2.0**	**0.04**
Lime, 2010		-1.0 ± 0.27	t = -0.36	0.71
Till, 2010		-0.21 ± 0.27	t = -0.75	0.45
Tyfon, 2010		**-0.63 ± 0.27**	**t = -2.59**	**0.02**
GFR, 2011		**0.77 ± 0.27**	**t = 2.81**	**0.005**
Lime, 2011		0.33 ± 27	t = 1.23	0.22
Till, 2011		0.16 ± 0.27	t = 0.59	0.55
GFR, 2011		**0.58 ± 0.27**	**t = 2.12**	**0.035**

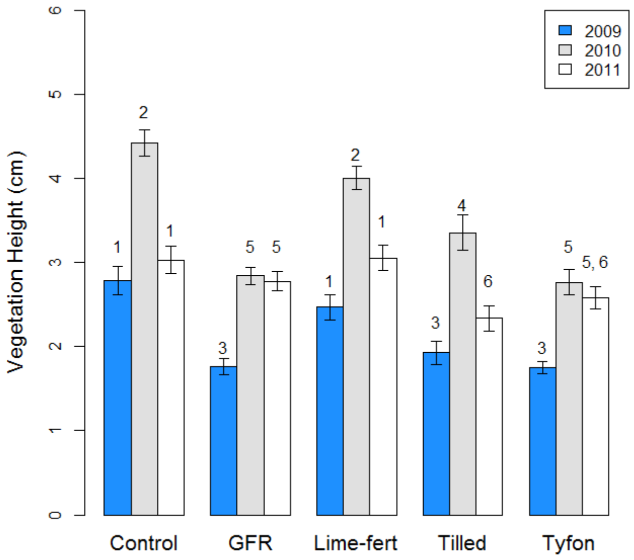


Figure 3-6 Vegetation height within the five different treatments across the three years at the field experiment, for a description of treatments see Figure 3.1. Bars show mean of raw data ± standard error. Bars with the same number are not significantly different from each other, i.e. treatments and years that do not share a number are significantly different.

Variation in ground micro-topography was greater for the tyfon treatment in 2010 (i.e. prior to reseeding with grass) than all other treatments in 2010 and than all treatments in 2011 (Table 3-6, Figure 3-7). In 2010, the till and GFR treatments had signficantly greater variation in ground micro-topography than the control or lime treatments in 2010 and than all treatments in 2011. In 2011, once the till, GFR and tyfon treatments had been reseeded with grass, variation in ground microtopography was similar in all treatments. The r^2 for this model was 0.50.

Table 3-6 Statistical summary for LMM assessing the effect of management treatment and year on percentage on variability in ground micro-topography, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

		Variation in ground microtopography (n = 240, 6 samples per year in 20 plots, within 4 blocks, for 2 years)		
% of variability accounted for by random effect plot (nested within block)		3%		
% of variability accounted for by random effect block		<1%		
Reference levels are control for treatment and 2010 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	**4**	**-**	**F = 17.14**	**<0.001**
GFR		**1.10 ± 0.19**	**t = 5.77**	**<0.001**
Lime		0.11± 0.19	t = 0.57	0.58
Till		**1.17 ± 0.19**	**t = 6.13**	**<0.001**
Tyfon		**1.60 ± 0.19**	**t = 8.39**	**<0.001**
Year	**1**	**-**	**F = 74.7**	**<0.001**
2011		-0.09 ± 0.18	t = -0.53	0.60
Treatment*Year	**4**	**-**	**F = 10.5**	**<0.001**
GFR, 2011		**-0.89± 0.25**	**t = -3.6**	**<0.001**
Lime, 2011		0.019 ± 25	t = 0.08	0.94
Till, 2011		**-0.81 ± 0.25**	**t = -3.25**	**0.001**
GFR, 2011		**-1.25 ± 0.24**	**t = -5.03**	**<0.001**

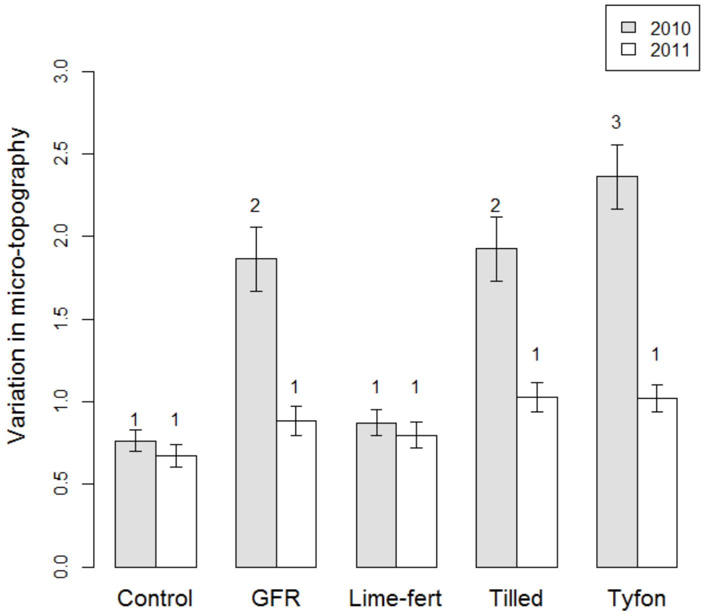


Figure 3-7 Variability in ground micro-topography within the five different treatments across the three years at the field experiment, for a description of treatments see Figure 3.1. Bars show mean of raw data ± standard error. Bars with the same number are not significantly different from each other, i.e. treatments and years that do not share a number are significantly different.

Management effects on soil properties

Soil pH increased significantly in all treatments (including the control) over the three years of the trial, however, the increase in pH was significantly greater in the treatments that had been limed than those that had not, i.e. the lime, GFR and tyfon treatments as opposed to the control and till treatments (increase of approximately 0.8 pH units in limed treatments, in comparison to 0.5 in un-limed treatments (Table 3-7, Figure 3-8). In the first year of testing, pH was around 0.5 pH units higher in the limed and tilled treatments than those that had not received lime and was around 0.3 pH units higher than the treatments that had been limed but not tilled (i.e GFR and tyfon treatments had significantly higher pH than the lime treatment in the year after the first lime application). By the final year the difference in pH between limed and tilled treatments in comparison to un-limed treatments had increased to around 0.8 pH units, with the limed and untilled treatment around 0.7 pH units higher than the un-limed treatments. The r^2 for this model was 0.63.

Soil organic matter was not related to treatment or year (Table 3-8, Figure 3-9).

Table 3-7 Statistical summary for LMM assessing the effect of management treatment and year on soil pH, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

	pH (n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)			
% of variability accounted for by random effect plot (nested within block)		1%		
% of variability accounted for by random effect block		3%		
Reference levels are control for treatment and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	**4**	**-**	**F = 57**	**<0.001**
GFR		**0.53 ± 0.12**	**t = 4.5**	**<0.001**
Lime		**0.32 ± 0.11**	**t = 2.8**	**0.015**
Till		0.13 ± 0.11	t = 1.1	0.27
Tyfon		**0.54 ± 0.11**	**t = 4.7**	**<0.001**
Year	**2**	**-**	**F = 110**	**<0.001**
2010		**0.32 ± 0.11**	**t = 3.0**	**0.003**
2011		**0.47 ± 0.10**	**t = 2.1**	**<0.001**
Treatment*Year	**8**	**-**	**F = 2.27**	**0.022**
GFR, 2010		0.15± 0.15	t = 0.99	0.32
Lime, 2010		0.13± 0.15	t = 0.87	0.39
Till, 2010		-0.16± 0.14	t = -1.1	0.27
Tyfon, 2010		0.15± 0.15	t = 1.0	0.31
GFR, 2011		**0.31 ± 0.15**	**t = 2.1**	**0.036**
Lime, 2011		**0.43 ± 0.15**	**t = 3.0**	**0.003**
Till, 2011		-0.003± 0.14	t = -0.02	0.98
GFR, 2011		**0.31 ± 0.015**	**t = 2.09**	**0.037**

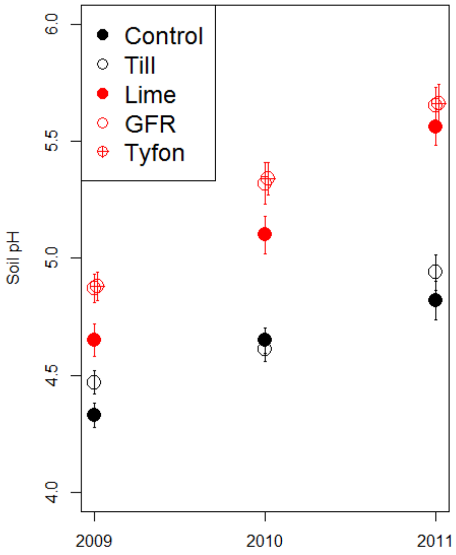


Figure 3-8 Soil pH in the five different treatments across the three years of the study at the field experiment, for a summary of treatments see Figure 3.1. Treatments which received lime are shown in red, with non-limed treatments black. Points show the mean of the raw data ± standard error. Non-limed treatments are not statistically different from each other. Soil pH increased significantly in all treatments across years but increases in limed treatments were greater than in non-limed treatments (Table 3-7).

Table 3-8 Statistical summary for GLMM assessing the effect of management treatment and year on percentage loss on ignition, which was used to assess soil organic matter, for a description of treatments see Figure 3.1. No parameters were significant at the 5% level.

	% loss on ignition(n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)			
% of variability accounted for by random effect plot (nested within block)		1%		
% of variability accounted for by random effect block		2%		
Reference levels are control for treatment and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	4	-	F = 0.4	0.78
GFR		-0.26± 0.29	t = -0.90	0.38
Lime		-0.08 ± 0.29	t = -0.29	0.77
Till		-0.34 ± 0.28	t = -0.12	0.25
Tyfon		-0.34± 0.29	t = -1.17	0.26
Year	2	-	F = 2.8	0.06
2010		-0.02 ± 0.15	t = -0.76	0.45
2011		-0.11 ± 0.22	t = -0.10	0.92
Treatment*Year	8	-	F = 0.44	0.90
GFR, 2010		-0.11± 0.22	t = -0.47	0.64
Lime, 2010		0.10± 0.22	t = 0.44	0.66
Till, 2010		0.15± 0.22	t = 0.67	0.5
Tyfon, 2010		0.21± 0.23	t = 0.93	0.35
GFR, 2011		0.07 ± 0.22	t = 0.32	0.75
Lime, 2011		0.33 ± 0.22	t = 0.38	0.71
Till, 2011		0.22 ± 0.22	t = 0.99	0.32
GFR, 2011		0.27 ± 0.23	t = 1.20	0.23

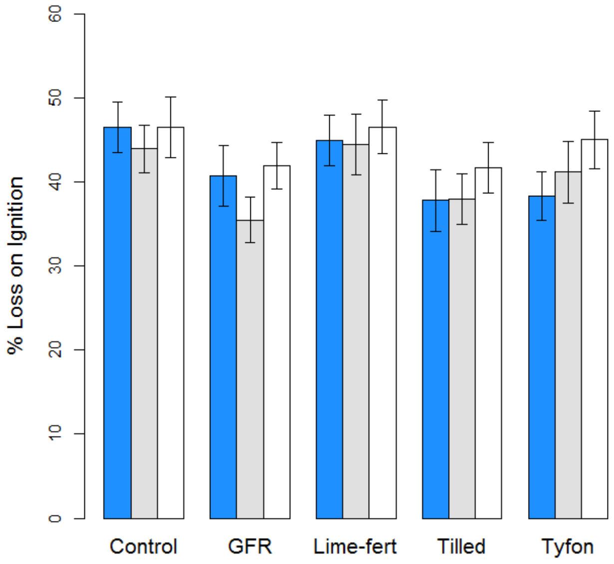


Figure 3-9 % loss on ignition, used to assess soil organic matter, within the five different treatments across the three years at the field experiment, for a description of treatments see Figure 3.1. Bars show mean of raw data ± standard error. Differences are not statistically significant (Table 3-8).

Management effects on soil invertebrates

Across the three years of the experiment 1543 worms were collected (Table 3-9). *Apporectodea caliginosa / rosea* occurred most frequently accounting for 66% of all earthworms. *Allolobophora chlorotica* accounted for 6% of all earthworms found.

Table 3-9 Earthworm species found at the field experiment, summed across treatments. Earthworm abundance was assessed in 2009, 2010 and 2011.

Species	**Ecological group**	**2009**	**2010**	**2011**	**Total**
Aporrectodea caliginosa / rosea	Endogeic	321 (66%)	402 (63%)	294 (70%)	**1017 (66%)**
Allolobophora chlorotica	Endogeic	17 (3%)	45 (7%)	37 (9%)	**99 (6%)**
Octolasion cyaneum	Endogeic	1 (0.2%)	1 (0.3%)	0	**2 (0.1%)**
Dendrobaena octaedra	Epigeic	0	2 (1%)	1 (0.2%)	**3 (0.2%)**
Dendrodilius rubidus	Epigeic	5 (1%)	8 (1%)	4 (1%)	**17 (1%)**
Eiseniella tetraedra	Epigeic	0	7 (1%)	0	**7 (0.5%)**
Lumbricus castaneus / rubellus	Epigeic	85 (17%)	82 (13%)	49 (12%)	**216 (14%)**
Satchellius mammalis	Epigeic	20 (4%)	41 (6%)	12 (3%)	**73 (5%)**
Aporrectodea longa	Anecic	5 (1%)	23 (4%)	18 (4%)	**46 (3%)**
Lumbricus terrestris	Anecic	0	0	1 (0.2%)	**1 (0.06%)**
Unidentified	-	35	24	3	**62**
Total	**-**	**489**	**635**	**419**	**1543**

Total earthworm abundance was higher in the lime treatment than in the till, GFR or tyfon treatments, with approximately 60% more earthworms in the lime treatment than the three treatments that had been tilled (Table 3-10, Figure 3-10). Approximately 30% more earthworms were found in the control treatment than the GFR or tyfon treatments. Earthworm abundance was highest in 2010 across all treatments. The r^2 for this model was 0.21.

When management treatments were split into the two main components (lime/fertiliser and tillage), tillage was shown to decrease earthworm abundance (Table 3-11, Figure 3-11). Lime had no effect on earthworm abundance. The r^2 for this model was also 0.21.

Table 3-10 Statistical summary for GLMM assessing the effect of management treatment and year on total earthworm abundance, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

	Total earthworm abundance (n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)			
% of variability accounted for by random effect plot (nested within block)		<1%		
% of variability accounted for by random effect block		2%		
Reference levels are control for treatment and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	**4**	**-**	**F = 7.44**	**0.002**
GFR		**-0.43 ± 0.13**	**t = -3.4**	**0.005**
Lime		0.14± 0.11	t = 1.3	0.22
Till		-0.23± 0.12	t = -1.9	0.07
Tyfon		**-0.31 ± 0.12**	**t = -2.5**	**0.024**
Year	**2**	-	**F = 12.13**	**<0.001**
2010		**0.25 ± 0.08**	**t = 2.9**	**0.004**
2011		-0.17 ± 0.09	t = -1.8	0.07
Treatment*Year	8	-	F = 0.88	0.53

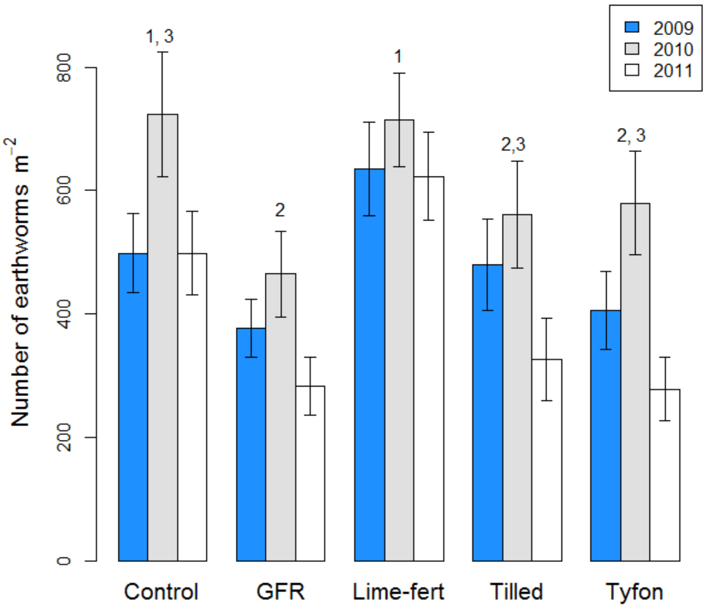


Figure 3-10 Earthworm abundance within the 5 different treatments across the three years at the field experiment. Bars show mean of raw data ± standard error. Treatments with the same number above the bars are not significantly different from each other, i.e. treatments that do not share a number are significantly different. Significantly more earthworms were found in 2010 than in either 2009 or 2010, this did not differ between treatments (Table 3-10).

Table 3-11 Statistical summary for GLMM assessing the effect of management treatment, split into lime and fertiliser, and tillage, and year on total earthworm abundance, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

	Total earthworm abundance (n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)			
% of variability accounted for by random effect plot (nested within block)		<1%		
% of variability accounted for by random effect block		1%		
Reference levels are not limed, not tilled and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Lime	1	0.55 ± 0.27	t = 2.00	0.064
Till	**1**	**-0.39 ± 0.08**	**t = -4.5**	**<0.001**
Year	**2**	**-**	**F = 12.2**	**<0.001**
2010		**0.25 ± 0.08**	**t = 2.9**	**0.004**
2011		**-0.17 ± 0.09**	t = -1.84	0.07

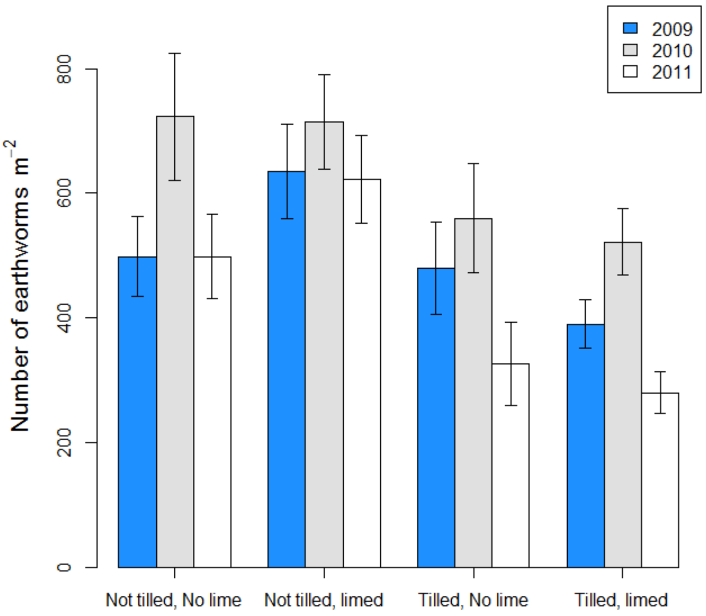


Figure 3-11 Earthworm abundance (mean of raw data ± standard error) with treatments split into the components of lime and tillage. Tilled treatments had significantly fewer earthworms than those that had not been tilled and earthworm abundance was highest in all treatments in 2010 (Table 3-11).

A. chlorotica was most prevalent in the lime treatment in 2009 and 2011, but was most prevalent in the control in 2010, which had the fewest of this earthworm in 2009 and 2010 (Table 3-12, Figure 3-12). Differences in abundance of *A. chlorotica* between treatments were not statistically significant. There were significantly fewer *A. chlorotica* across treatments in 2009 than in either 2010 or 2011. The r^2 for the final model (containing year only) was 0.10.

When *A. chlorotica* was looked at in relation to tillage and liming, higher numbers were found in treatments that had been limed, although this was only significant at the 10% level and was not significant if tillage was removed from the model (Table 3-13, Figure 3-13). The r^2 for the model containing lime and tillage as well as year was lower than the model that contained year only at 0.08.

Table 3-12 Statistical summary for GLMM assessing the effect of management treatment and year on the abundance of *A. chlorotica*, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

		***A. chlorotica* abundance (n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)**		
% of variability accounted for by random effect plot (nested within block)		15%		
% of variability accounted for by random effect block		<1%		
Reference levels are control for treatment and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	4	-	F = 1.7	0.21
GFR		0.07 ± 0.42	t = 0.18	0.86
Lime		0.68 ± 0.34	t = 1.80	0.095
Till		-0.21 ± 0.44	t = -0.48	0.64
Tyfon		-0.01 ± 0.31	t = 0.83	0.42
Year	**2**	**-**	**F = 4.3**	**0.014**
2010		**0.88 ± 0.30**	**t = 2.9**	**0.003**
2011		**0.69 ± 0.31**	**t = 2.2**	**0.03**
Treatment*Year	8	-	F = 1.2	0.29

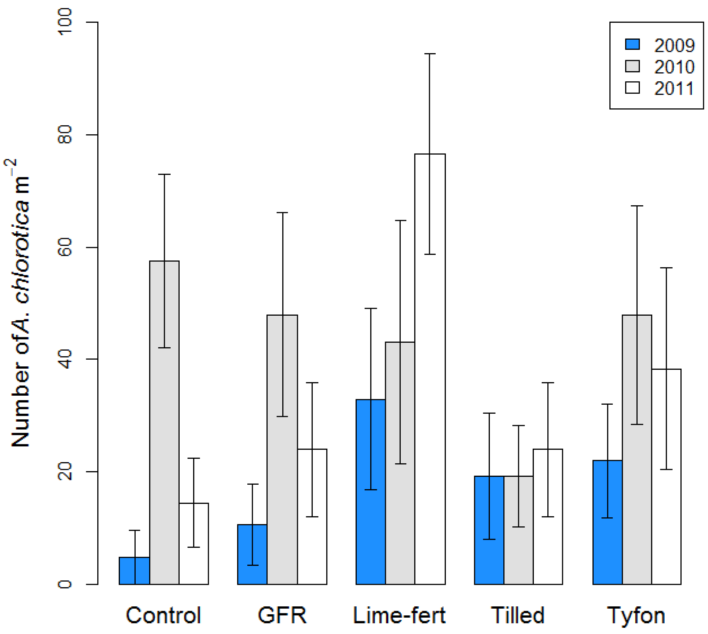


Figure 3-12 *A. chlorotica* abundance within the 5 different treatments across the three years at the field experiment. Bars show mean of raw data ± standard error. Differences between treatments were not significant. Significantly more *A. chlorotica* were found in 2010 and 2011 than in 2009, this did not differ between treatments (Table 3-12).

Table 3-13 Statistical summary for GLMM assessing the effect of management treatment, split into lime and fertiliser, and tillage, and year on *A. chlorotica* abundance, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

		***A. chlorotica* abundance (n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)**		
% of variability accounted for by random effect plot (nested within block)		15%		
% of variability accounted for by random effect block		<1%		
Reference levels are not limed, not tilled and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Lime	1	0.55 ± 0.27	t = 2.00	0.064
Till	1	-0.39 ± 0.26	t = -1.5	0.15
Year	**2**	**-**	**F = 4.3**	**0.014**
2010		**0.88 ± 0.30**	**t = 2.9**	**0.003**
2011		**0.69 ± 0.31**	**t = 2.2**	**0.03**

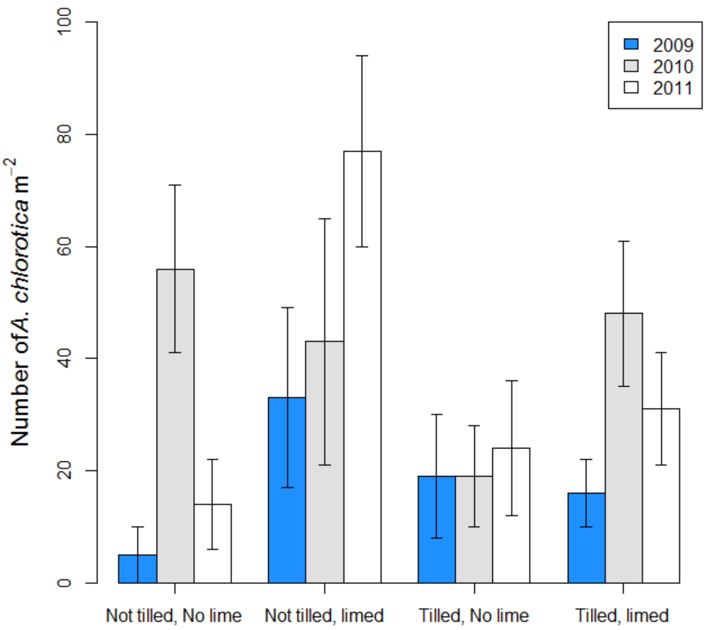


Figure 3-13 *A. chlorotica* abundance (mean of raw data ± standard error) with treatments split into the components of lime and tillage. Significantly fewer *A. chlorotica* were found in 2009 than in 2010 or 2011 (Table 3-13).

Tipulid larvae were significantly more abundant in the lime treatment than in the control, till or tyfon treatments (in 2008:- around 200 tipulid m^{-2} compared to around 80 tipulid m^{-2}) and close to significantly more than in the GFR treatment (around 100 tipulid m^{-2}; Table 3-14, Figure 3-14). Tipulid larvae abundance declined across all treatments over the course of the study and was significantly lower in 2011 than in 2009 or 2010. The r^2 for this model was 0.17.

Splitting the treatments into components revealed that tipulid larvae occurred at higher densities in the treatments that had been limed and fertilised than those that had not, whilst tillage was associated with lower densities of tipulid larvae (Table 3-15, Figure 3-15). The r^2 for this model was also 0.17.

Table 3-14 Statistical summary for GLMM assessing the effect of management treatment and year on the abundance of tipulid larvae, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

		Total tipulid larvae abundance (n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)		
% of variability accounted for by random effect plot (nested within block)		<1%		
% of variability accounted for by random effect block		2%		
Reference levels are control for treatment and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Treatment	**4**	**-**	**F = 6.4**	**0.005**
GFR		0.29 ± 0.29	t = 1.0	0.32
Lime		**0.86± 0.26**	**t = 3.3**	**0.005**
Till		-0.39 ± 0.33	t = -1.2	0.27
Tyfon		-0.01 ± 0.31	t = -0.03	0.97
Year	**2**	**-**	**F = 18.2**	**<0.001**
2010		-0.33 ± 0.18	t = 1.8	0.07
2011		**-2.13 ± 0.35**	**t = -6.0**	**<0.001**
Treatment*Year	8	-	F = 0.84	0.57

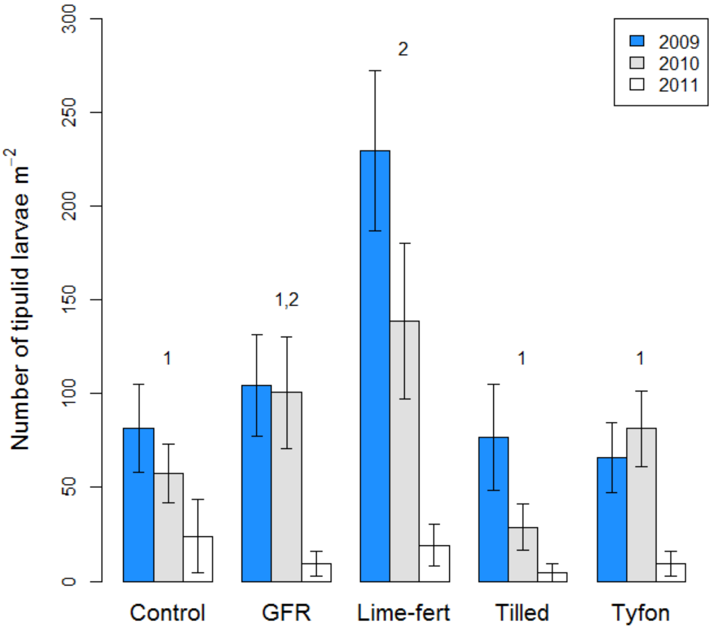


Figure 3-14 Tipulid larvae abundance within the 5 different treatments across the three years at the field experiment. Bars show mean of raw data ± standard error. Treatments with the same number above the bars are not significantly different from each other, i.e. treatments that do not share a number are significantly different. Significantly fewer tipulid larvae were found in 2011 than in either 2009 or 2010, this did not differ between treatments (Table 3-14).

Table 3-15 Statistical summary for GLMM assessing the effect of management treatment, split into lime and fertiliser, and tillage, and year on tipulid larvae abundance, for a description of treatments see Figure 3.1. Parameters statistically significant at the 5% level are in bold.

	Tipulid larvae abundance (n = 352, 6 samples per year in 20 plots, within 4 blocks, for 3 years, 8 samples missing from 2009)			
% of variability accounted for by random effect plot (nested within block)		<1%		
% of variability accounted for by random effect block		3%		
Reference levels are not limed, not tilled and 2009 for year	DF	Parameter estimate ± SE	Statistic	p-value
Lime	**1**	**0.73 ± 0.20**	**t = 3.7**	**0.002**
Till	**1**	**-0.62 ± 0.18**	**t = -3.5**	**0.003**
Year	**2**	**-**	**F = 18.22**	**<0.001**
2010		-0.33 ± 0.18	t = -1.81	0.07
2011		**-2.13 ± 0.35**	**t = -6.02**	**<0.001**

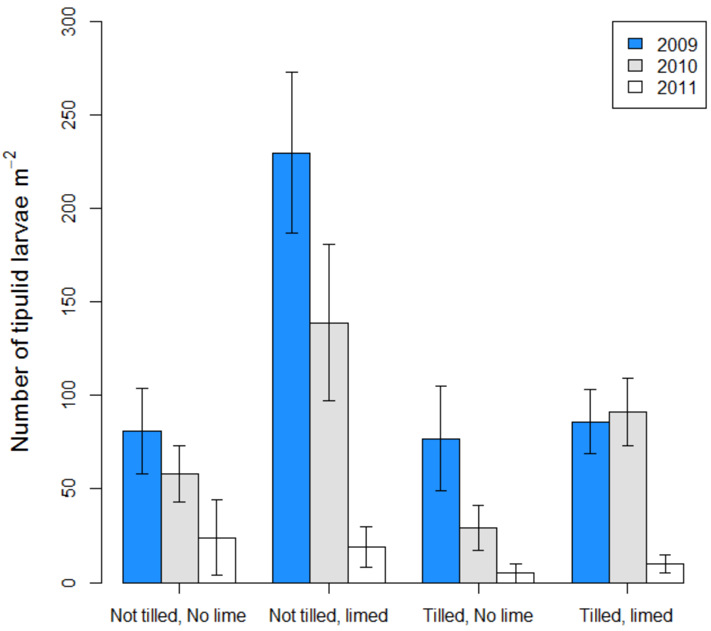


Figure 3-15 Tipulid larvae abundance (mean of raw data ± standard error) with treatments split into the components of lime and tillage. Significantly fewer tipulid larvae were found in 2011 than in 2009 or 2010, with significantly more tipulids in treatments that had been limed and fertilised and significantly fewer tipulids in treatments that had been tilled (Table 3-15).

3.4.2 Between-field correlative study

Soil pH was highest and soil organic matter lowest at Townhead for in-bye fields with a prior history of fodder crop management (Table 3-16). The out-bye fields at Townhead had the lowest soil pH. Muirpark also had low soil pH and the highest soil organic matter.

Table 3-16 Mean ± standard error of field soil pH and field soil organic matter, from the three farms involved in the study and the three field types at Townhead.

Farm	Field Type	No. of fields	**Mean soil pH**	**Mean soil organic matter**
Townhead	In-bye with a prior history of fodder crop management	7	5.2 ± 0.07	21 ± 3%
Townhead	In-bye with no prior history of fodder crop management	6	5.0± 0.05	30 ± 2%
Townhead	Out-bye	2	4.4 ± 0.22	33 ± 3%
Muirpark	In-bye	2	4.4 ± 0.003	37 ± 1%
Lochend	In-bye	2	5.1 ± 0.16	26 ± 5%

Across all samples the correlation between soil pH and soil organic matter was -0.47. The correlation between pH and soil organic matter was lower for in-bye fields at Townhead with no prior history of fodder crop management at -0.22, and lowest at Townhead for the fields with a prior history of fodder crop management at -0.13 (Figure 3-16).

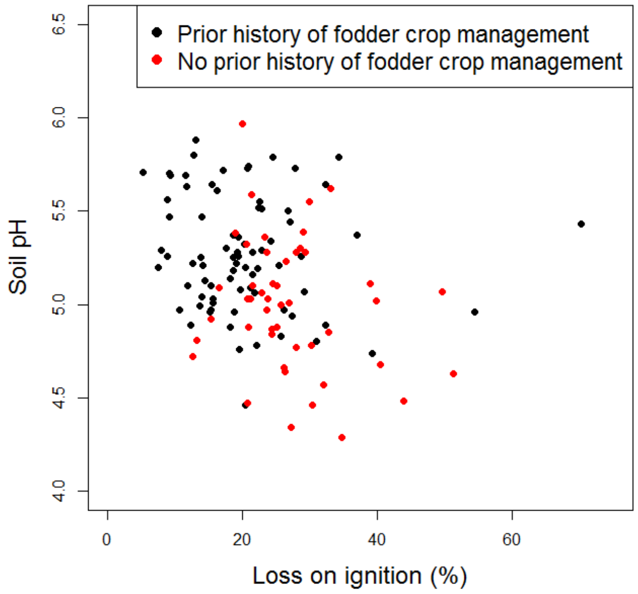


Figure 3-16 Soil pH compared to soil organic matter (% loss on ignition) for in-bye field at Townhead Farm, the correlation between fields which have not previously undergone fodder crop management was stronger than that for fields which had undergone fodder crop management.

Relationship between soil properties and field management history

In in-bye fields at Townhead, soil pH was on average 0.2 pH units higher in fields that had undergone fodder crop management than those that had not (Table 3-17). Soil pH declined with increasing number of years since a field was last limed as part of fodder crop management, but remained above that found in fields that had not undergone fodder crop management for at least 7 years after liming (Figure 3-17a). The percentage of soil organic matter was lower in fields that had a history of fodder crop management compared to those that had not, although this result was only significant at the 10% level (Figure 3-17b).

Table 3-17 Statistical summary for GLMMs testing the relationship between soil properties and fodder crop management on in-bye fields at Townhead Farm. Model A compared in-bye fields which had undergone fodder crop management with those that had not. Model B examined the relationship between the length of time since liming or ploughing was last carried out as part of fodder crop management and soil properties, and only included fields that had undergone fodder crop management.

	Soil pH							
	n	No. of fields	Variability accounted for by fields	DF	Parameter estimate ± SE	t-value	p-value	r^2
Model A								
Fodder crop prior to survey (yes/no)	115	13	11%	1	0.22 ± 0.08	2.65	0.02	0.29
Model B								
Number of years since lime	68	7	8%	1	-0.13 ± 0.045	-2.86	0.006	0.28

	Soil organic matter							
	n	No. of fields	Variability accounted for by fields	DF	Parameter estimate ± SE	t-value	p-value	r^2
Model A								
Fodder crop prior to survey (yes/no)	115	13	3%	1	-0.41 ± 0.18	-2.15	0.054	0.44
Model B								
Number of years since plough	68	7	3%	1	0.03 ± 0.04	0.69	0.49	NA

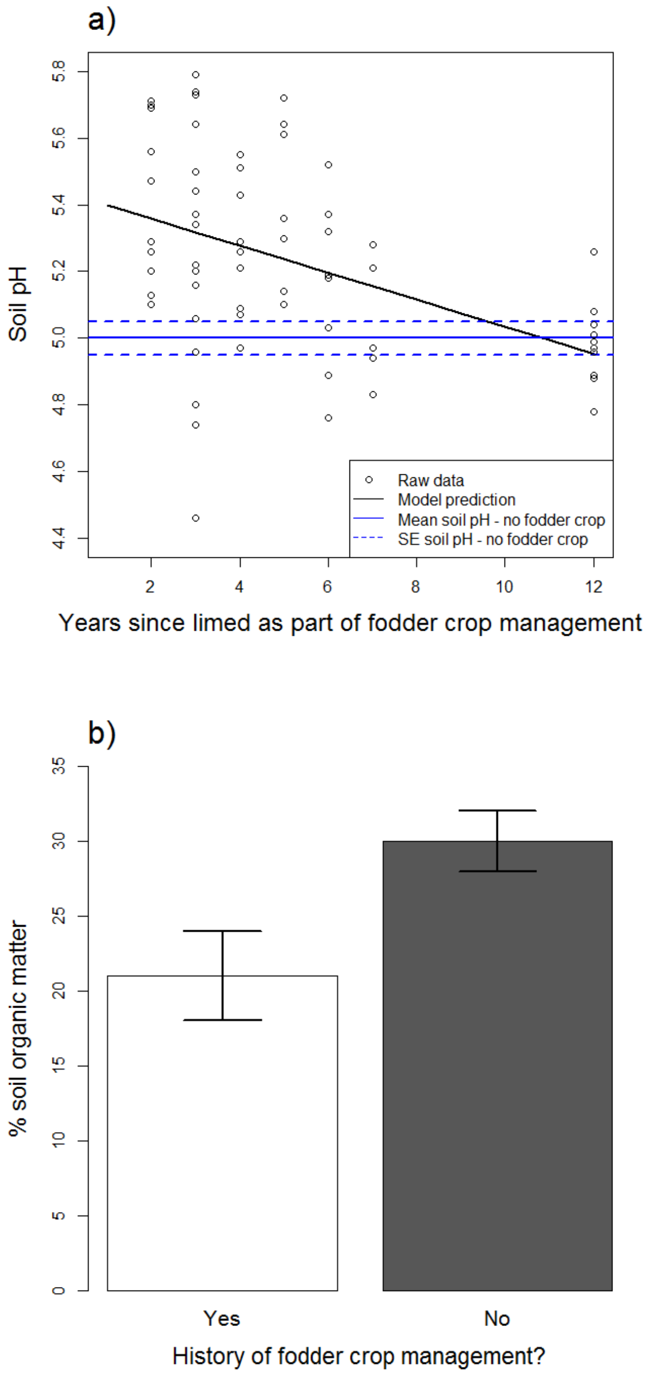


Figure 3-17 The relationship between soil properties and fodder crop management a) predicted decline in soil pH with number of years since a field was last limed as part of fodder crop management (black line), compared to mean ± standard error soil pH for in-bye fields that have not undergone fodder crop management (blue), open circles show raw data for fields with a prior history of fodder crop management. b) % soil organic matter (mean ± standard error) for fields with a prior history of fodder crop management compared to those without a prior history of fodder crop management, difference is borderline significant (Table 3-17).

Relationship between soil invertebrates and field management history

Total earthworm abundance was 75% higher in fields with a prior history of fodder crop management than those without, however, high variability between fields and samples meant that this relationship was only significant at the 10% level, p = 0.066; Figure 3-18). Neither *A. chlorotica* abundance nor tipulid larvae presence differed significantly between in-bye fields at Townhead with a prior history of fodder crop management and those without.

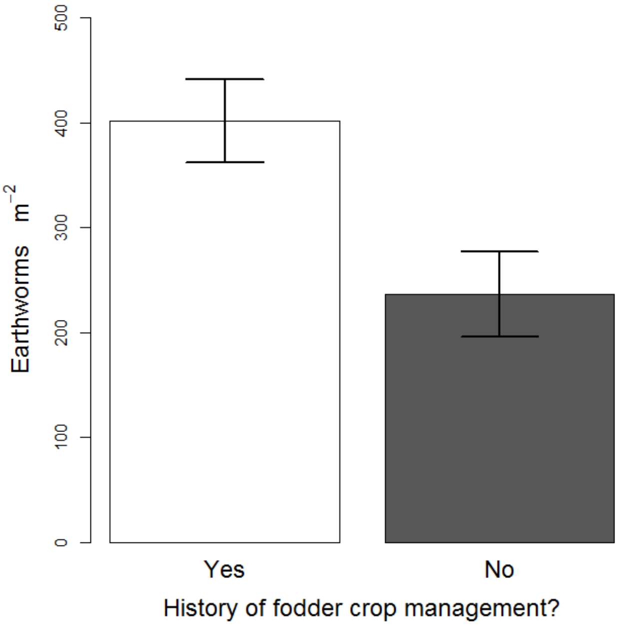


Figure 3-18 Earthworm abundance (mean ± standard error) in fields that had undergone fodder crop management in comparison to in-bye fields with no prior history of fodder crop management.

Relationship between soil invertebrates and soil properties

Across the three farms and the two years of the study, 516 earthworms were collected (Table 3-18). 75% of earthworms collected were *A. caliginosa / rosea*, and 9% were *A. chlorotica*.

Table 3-18 All earthworms found during the field correlative study, showing species composition and ecological groups of earthworms.

Species	Ecological group	2009	2010	Total
Aporrectodea caliginosa / rosea	Endogeic	193 (71%)	192 (78%)	**385 (75%)**
Allolobophora chlorotica	Endogeic	39 (14%)	10 (4%)	**49 (9%)**
Octolasion cyaneum	Endogeic	1 (0.4%)	0	**1 (0.2%)**
Dendrobaena octaedra	Epigeic	2 (1%)	1 (0.4%)	**3 (0.6%)**
Dendrodilius rubidus	Epigeic	5 (2%)	0	**5 (1%)**
Eiseniella tetraedra	Epigeic	1 (0.4%)	2 (0.8%)	**3 (0.6%)**
Lumbricus castaneus / rubellus	Epigeic	24 (9%)	18 (7%)	**42 (8%)**
Aporrectodea longa	Anecic	3 (1%)	12 (5%)	**15 (3%)**
Unidentified	-	2	11	**13**
Total	**-**	**270**	**246**	**516**

Total earthworm abundance had a quadratic relationship with soil pH, and decreased with increasing soil organic matter (Table 3-19, Figure 3-19a). Earthworm abundance peaked around pH 5.2 at just over 300 earthworms m^{-2} (for the mean soil organic matter content found within the dataset: 26%).

A. chlorotica abundance also had a quadratic relationship with soil pH (Figure 3-19b), but was not influenced by soil organic matter and was positively related to soil moisture. Similarly to total earthworm abundance *A. chlorotica* peaked at around pH 5.25, this time at a much lower density of around 40 earthworms m^{-2} (at the mean soil moisture content for the data). The r^2 for both the total earthworm abundance and the *A. chlorotica* models was 0.36.

The presence of tipulid larvae within a soil core was not significantly related to any of the soil properties. Tipulids occurred more often at higher percentages of soil organic matter, but this relationship was only significant at the 10% level (parameter estimate = 0.31 ± 0.17, p = 0.071).

Table 3-19 Statistical summary for GLMMs testing the relationship between soil invertebrate abundance and soil properties. Parameters significant at the 5% level are shown in bold. Non-significant terms were removed from the models using backward selection.

	Total Earthworm Abundance **n = 192, across 19 fields**				***A. chlorotica* Abundance** **n = 192, across 19 fields**				**Tipulid larvae presence** **n = 192, across 19 fields**			
% variability accounted for by random factor field	4%				47%				24%			
	DF	Parameter estimate ± SE	Statistic	p-value	DF	Parameter estimate ± SE	Statistic	p-value	DF	Parameter estimate ± SE	Statistic	p-value
Soil pH	**1**	**0.29 ± 0.11**	**t = 2.64**	**0.0089**	**1**	**1.56 ± 0.49**	**t = 3.16**	**0.0019**	1	0.24 ± 0.22	t = 1.09	0.27
Soil organic matter	**1**	**-0.45 ± 0.12**	**t = -3.88**	**0.0001**	1	-0.39 ± 0.27	t = -1.43	0.16	1	0.31 ± 0.17	t = 1.81	0.071
Soil moisture	1	0.054 ± 0.087	t = 0.63	0.53	**1**	**0.53 ± 0.26**	**t = 2.07**	**0.0396**	1	0.089 ± 0.26	t = 0.34	0.73
Soil pH^2	**1**	**-0.27 ± 0.09**	**t = -3.10**	**0.0023**	**1**	**-1.24 ± 0.41**	**t = -3.01**	**0.003**	1	-0.22 ± 0.18	t = -1.20	0.23
Soil organic matter^2	1	0.057 ± 0.055	t = 1.02	0.31	1	-0.23± 0.24	t = -0.98	0.42	1	0.13 ± 0.11	t = 1.19	0.23
Soil moisture^2	1	-0.047 ± 0.054	t = -0.87	0.34	1	-0.15 ± 0.19	t = -0.08	0.42	1	0.041 ± 0.16	t = 0.26	0.79
Farm	2	-	F = 0.06	0.94	2	-	F = 0	1	2	-	F = 2.7	0.097
Year	1	-	F = 0.02	0.88	1	-	F = 0.11	0.74	1	-	F = 2.3	0.21

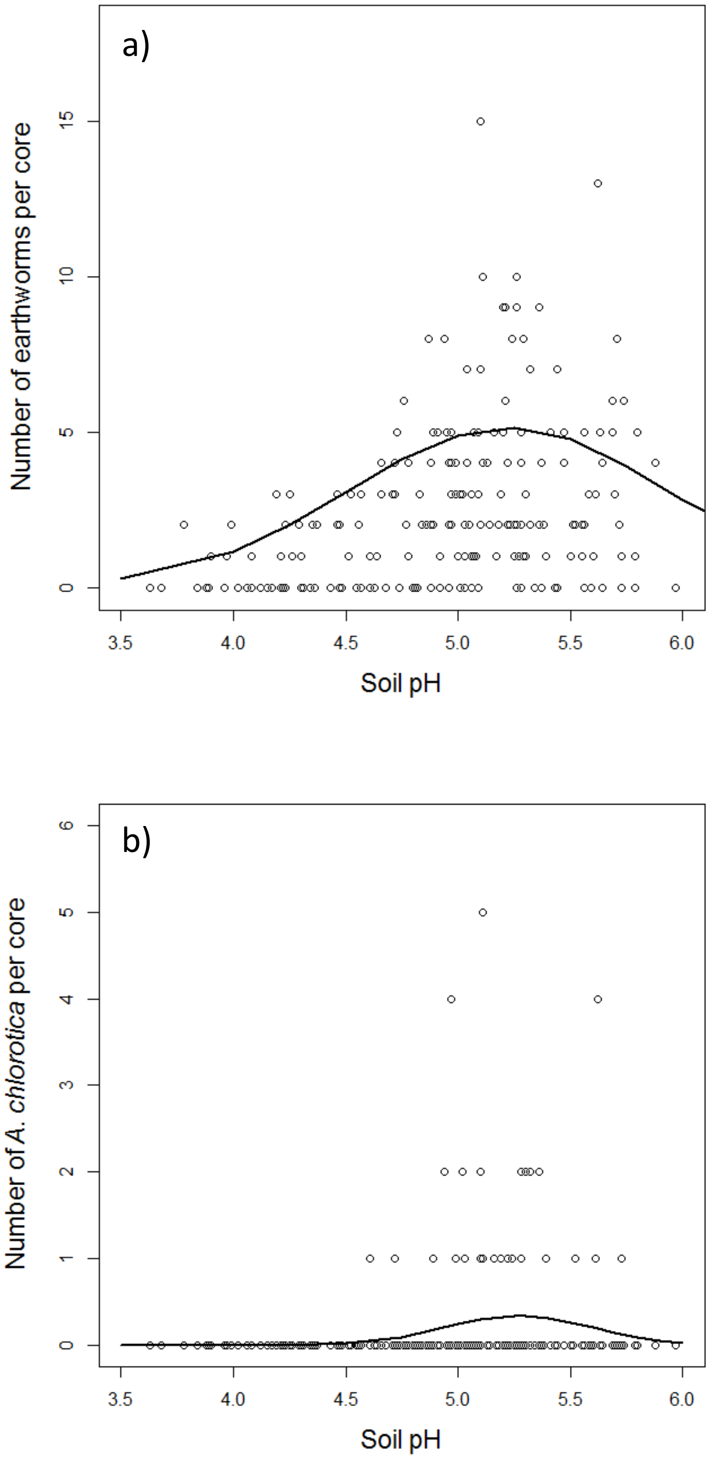


Figure 3-19 Relationship between earthworm abundance and soil pH, showing the predicted earthworm abundance with varying soil pH from GLMMs (Table 3-19) for a) total earthworm abundance and b) *A. chlorotica* abundance. The raw data is represented by open circles.

3.5 Discussion

Management effects on vegetation structure and ground micro-topography

All treatments involving tillage had significantly more bare ground in spring than those that were not, providing a patchy vegetation structure which has previously been identified as “attractive” to nesting lapwings (Klomp 1954, Sheldon 2002, Shrubb 2007). A high percentage of bare ground is likely to further benefit lapwings by improving detectability of their invertebrate prey (Devereux *et al*. 2004).

Additional experimental management conducted at RSPB’s Geltsdale reserve in Cumbria, involving cultivation of vollenda, an organic alternative to tyfon, also resulted in a high percentage of bare ground following grazing, and four lapwing nests were initiated in the vollenda plot during two breeding seasons, in an area of the reserve not previously used by lapwings (*pers. com.* Ian Ryding, RSPB Geltsdale). This provides further support for the likely “attractiveness” of the vegetation structure created by grazing of stubble turnips. Feeding observations at Geltsdale suggested that prey detectability was higher in the vollenda plot as lapwings were observed foraging more frequently in the vollenda plot than in the adjacent grassland area, despite higher earthworm abundance in the grassland area in the first year after management (Appendix B).

In the first year of the field experiment at the principal study site, the GFR treatment was sown with grass resulting in substantially less bare ground than either the tilled or tyfon treatments; therefore vegetation structure created by tyfon is likely to be preferable to that created by reseeding. In the second year, the GFR treatment was sown with fodder rape and this led to a similar percentage of bare ground as the tyfon treatment. In the final year all tilled treatments were reseeded with grass and unexpectedly the percentage of bare ground increased. This likely relates to poor establishment of grass across the plots and is in contrast to the pattern in the newly reseeded fields at the main study site (*pers. ob*s.).

In addition to higher percentages of bare ground in the tilled treatments, these treatments all had shorter vegetation than either the control or lime treatments. However, as vegetation was shorter than 5cm in all treatments it is unlikely that this would be of relevance to nesting lapwings, as all treatments had sward height short enough to be used by breeding lapwings (Milsom *et al*. 2000). Short sward was likely due to grazing pressure, and creation of short sward at this time for breeding lapwings, needs to be balanced with risks of nest trampling (Pakanen, Luukkonen & Koivula 2011) to create the optimum habitat conditions.

Variation in ground micro-topography was highest in the tyfon treatment prior to reseeding with grass, potentially enhancing the level of camouflage for nests created by the high percentage of bare ground. Both the tilled treatments and fodder rape had higher variability in ground micro-topography than either the control or lime treatments although they were not as variable as the tyfon treatment, suggesting that the grazing of the turnip bulb (not present in fodder rape) creates additional variation over and above that generated by the tillage process. Whilst tyfon and fodder rape provided similar levels of bare ground, the additional variability in micro-topography for the tyfon treatment suggest that some varieties of fodder crop may provide better habitat for lapwings than others.

Management effects on soil properties

Liming carried out as part of the field experiment resulted in higher soil pH in all treatments that were limed (lime, GFR and tyfon treatments) compared to those that had not been limed (control and till treatments) and there was an additive effect of liming over the three years of the study. However, soil pH of un-limed treatments also increased during the three years, although this increase was smaller than for the limed treatments. It is likely that the increase in pH within un-limed treatments arose from contamination of these with lime, as has been noted in previous trials involving liming (Bishop 2008), with accidental liming of one of the control plots and one of the till plots exacerbating the effects of contamination. There are a number of ways that contamination may have occurred including, difficulties constraining lime application to a six metre wide plot using machinery that was designed to spread lime over a far larger area, transfer of lime between treatments by livestock that were present in the field during the time of the second lime application and leaching of lime between plots despite the three metre buffer strip between plots.

Soil pH increased more quickly in the treatments that were tilled in addition to receiving lime. Tillage meant that lime could be incorporated into the soil faster than when lime was applied directly onto the grass surface, thus speeding up the time between initial application and an increase in soil pH (Conyers *et al*. 2003).

Soil pH was not tested prior to the first lime application, however, the design of the trial was such that soil pH should not have differed between treatment types prior to treatment occurring. Overall, liming carried out within the trial (three applications at a rate of 5 t ha^{-1}) resulted in an increase in soil pH of at least 1.3 pH units (maximum starting pH of 4.5 up to final pH of approximately 5.7), resulting in soil pH considerably closer to that recommended for growing grass (pH 5.3-5.5 for organic soils; SAC 2010) following the three lime applications. The effect that liming has on soil pH varies with soil type, initial soil pH, fertiliser use and crop being grown (Goulding & Blake 1998). Despite this, the effect of liming on soil pH in this study is not dissimilar to that previously reported; approximately 1.4 pH units following an application of 17.3 t ha^{-1} (Bolton 1977), approximately 1 pH unit following an application of 12 t ha^{-1} (Stevens & Laughlin 1996) and around 0.9 pH units following an application of around 8 t ha^{-1} (Bailey 1997).

Lime is applied for up to three consecutive years as part of fodder crop management and overall soil pH was approximately 0.2 pH units higher in fields that had undergone fodder crop management than in-bye fields that had not. Fields included within the fodder crop management group had most recently been limed between one and twelve years prior to soil pH being tested and soil pH declined with number of years since the field had last been limed. It was estimated that fields that had been limed as part of fodder crop management in the year prior to pH testing would have had soil pH of around 0.4 units higher than fields that had not undergone fodder crop management. This difference is far smaller than that obtained by three consecutive years of liming at the field experiment, which may be due to liming of in-bye fields within the last ten years that has occurred outside of fodder crop management. The results suggest that soil pH achieved by liming as part of fodder crop management was lower than recommended for grass growth for mineral soils (pH 6, SAC 2010), but within the threshold for organic soils (pH 5.2 - 5.5; SAC, 2010). Using a threshold of 20% organic matter, three out of seven fields would be considered mineral soils.

Soil pH in fields that had undergone fodder crop management declined to a level similar to that found in fields that had not undergone this process around 8 to 12 years following the most recent lime application. On average the annual decline in soil pH was 0.04 pH units, which is smaller than the decline reported by Bolton (1977) of around 0.08 pH units and by Stevens & Laughlin (1996) of around 0.06 pH units. The differences between these three studies may result from variation in initial soil pH, management post liming including fertiliser use and crop type, as well as soil properties such as texture, organic matter content and pH buffering capacity (Chambers & Garwood 1998). Furthermore, the post liming decline in soil pH in this study was measured in a number of fields that had been limed a variable number of years prior to testing soil pH rather than by testing soil pH in the same field for a number of years after liming.

The decline in soil pH following liming and the difference in pH between fields that had undergone fodder crop management and those that had not, were both smaller than the correction offset that was applied to pH measurements (Appendix A). The inconsistency in pH results, necessitating the use of the correction offset, casts some doubt on the absolute pH values obtained from this study, making comparisons between soil pH obtained from fodder crop management and that recommended for grass growth somewhat ambiguous; however, as model fit for soil pH at the field experiment was quite high ($r^2 = 0.62$), it seems reasonable to assume that differences in pH detected between treatments are reliable.

Soil organic matter was around 7% lower in fields that had undergone the fodder crop management process than in those that had not. Whilst this difference may have resulted from a reduction in organic matter associated with tillage (Ball, Cheshire & Robertson 1996), no effect of treatment on organic matter was detected in the field experiment. This implies that fields with relatively low soil organic matter were selected for fodder crop management, suggesting that soil pH may also have been relatively high in fields selected for fodder crop management prior to implementation of this process and that the difference in soil pH detected between the two management histories may not just be due to management differences.

Management effects on soil invertebrates

Fodder crop management in the field experiment did not increase earthworm abundance in comparison to the other treatments and both the control and the lime treatment had significantly more earthworms than the tyfon treatment. The main influence on total earthworm abundance appears to have been tillage, with significantly fewer earthworms in all tilled treatments than the lime treatment, and two out of three tilled treatments having significantly lower earthworm abundance than the control. A further analysis replacing treatment with two of the main components of agricultural management used in the treatments, i.e. lime/fertiliser and tillage, confirmed the negative effect of tillage and the lack of effect of lime and fertiliser on total earthworm abundance. Reduced tillage, as carried out here in the form of disking and power harrowing, is less detrimental to earthworm abundance than conventional deep ploughing. However, the benefits of reduced tillage are largely confined to anecic (deep burrowing) species

(Edwards & Lofty 1982a, Capowiez *et al*. 2009), which accounted for just 3% of earthworms sampled at the trial, explaining why even reduced tillage implemented as part of fodder crop management reduced earthworm abundance. The low percentage of anecic earthworms encountered likely results from the sampling methods employed (only the top 10cm of soil sampled), reflecting lower availability of this ecological group of earthworms to foraging lapwings.

In contrast to the negative impact of tillage in the field experiment, total earthworm abundance was 75% higher in fields that had undergone fodder crop management compared to those that had not, although high variability within and between fields meant that this was only significant at the 10% level. It is possible that the greater length of time between tillage and sampling for the majority of fields in comparison to the field experiment allowed for recovery of earthworm populations. In addition it may be that the small area of the plots meant that earthworms were able to move out of less favourable conditions in tilled plots, resulting from loss of the insulating vegetation layer (Edwards & Bohlen 1996) more easily than when a whole field was tilled.

Higher earthworm abundance in fields that had undergone fodder crop management might be related to the slightly higher soil pH in these fields. Peak earthworm abundance occurred at around pH 5.2, corresponding with the overall predicted pH of fields that had undergone fodder crop management (pH 5.22). However, the slightly lower soil organic matter in these fields, indicates that they were also less peaty thus providing more favourable conditions for earthworms (Edwards & Bohlen 1996). The selection of fields for fodder crop management with relatively low organic matter, suggests that soil pH may also have been relatively higher in these fields initially and that differences in soil conditions between the two field types are not entirely the result of differences in management.

Whilst lime and fertiliser did not increase total earthworm abundance in the field experiment, it did increase abundance of *A. chlorotica*, although the difference between limed and un-limed treatments was only significant at the 10% level. Furthermore, the abundance of this species increased in over the period of the trial potentially arising from increases in soil pH in all treatments bringing about more favourable conditions (i.e less acidic) for this species (Satchell 1955). Model fit was very poor, likely as a result of small numbers of this earthworm species and a high number of zeros in the dataset and further complicated by accidental liming of two plots that were not meant to receive lime in the final year.

The abundance of *A. chlorotica* peaked at around pH 5.25, similar to total earthworms; however, the range of soil pH over which this species occurred was considerably narrower. The model predicted that *A. chlorotica* would occur at densities above 10 m^{-2} between pH 4.75 and pH 5.8, i.e. towards the upper end of the soil pH scale encountered. Whilst peak numbers of *A. chlorotica* occurred below the optimum pH for grass growth, final soil pH in the field experiment was around 5.7 with abundance of this species highest in the final year indicating that increasing pH above 5.25 did not have a detrimental effect and that liming sufficiently for good grass growth should result in soil pH conditions suitable for this species.

Similarly to *A. chlorotica*, the abundance of tipulid larvae at the field experiment was highest for the lime treatment and tipulid larvae appeared to benefit from application of lime and fertiliser, whilst tillage reduced abundance. Tipulid larvae declined in all treatments between the first and third year of the trial, suggesting that lime and fertiliser did not increase tipulid larvae abundance through increasing soil pH, which occurred over the course of the experiment. It therefore seems likely that tipulids responded positively to the fertiliser part of this treatment rather than the lime. Alternatively it may be that grazing animals spent more time on the plots that had been limed and fertilised resulting in higher dunging in these plots creating more favourable conditions for tipulid larvae. The lack of relationship between tipulid presence and soil pH in the field scale correlation adds support to this theory and corroborates the findings of McCracken, Foster & Kelly (1995).

Overall, liming carried out as part of the fodder crop management has likely created more favourable soil pH conditions for earthworms, with peak earthworm abundance occurring at higher soil pH than occurred in fields that had not undergone fodder crop management. Raising soil pH is of particular benefit to *A. chlorotica*, which has previously been identified as associated with chick foraging location (Chapter 2). Lapwings also feed on tipulid larvae and these may have responded to inorganic fertiliser which is used more frequently on fields that have undergone fodder crop management than those that have not, at the main study site. However, tillage carried out as part of fodder crop management appears to have a short term negative effect on the soil invertebrate prey of lapwing.

Conclusions

Fodder crop management creates a patchy vegetation structure in the year after tyfon is planted following overwinter grazing of the crop, likely to be attractive to nesting lapwings. The patchy vegetation structure was similar for both tyfon and fodder rape indicating that the specific type of fodder crop is unlikely to be of great importance to a lapwing; however, variability in ground micro-topography was higher for tyfon than fodder rape suggesting that fodder crops with turnip bulbs could create more favourable conditions for breeding lapwings than those without.

Liming is a critical process in fodder crop management which raises soil pH and soil pH remains above that found in fields which have not undergone fodder crop management for at least seven years following liming, resulting in more favourable soil pH conditions for earthworms. Unlike total earthworm abundance, *A. chlorotica* responded positively to liming carried out in the field experiment and peak abundance occurred at slightly higher soil pH than total earthworm abundance, suggesting that this species, has particularly benefitted from fodder crop management.

Tillage required for planting of tyfon negatively impacts on earthworm abundance and it is likely that liming permanent grass would result in higher earthworm abundance than carrying out fodder crop management.

3.6 Appendix A – Soil pH Correction Offset

Soil was sampled and tested for pH from two fields at Townhead in both 2009 and 2010 without any liming, fertilising or tillage occurring in-between the two sampling periods. Soil was sampled at the same GPS locations in both years. For 13 out of the 17 samples that were taken in both years, pH was higher in 2010 despite the likelihood that pH should have declined slightly in these fields during this period based on the management. A GLM was implemented on these data, taking the form:-

Soil pH = Year + Sample ID

Although soil pH is on a logarithmic scale the model residuals did not change with increasing soil pH, indicating that it was valid to model the difference in pH and add a correction offset to the measured pH results without transforming the data first (Figure 3-20).

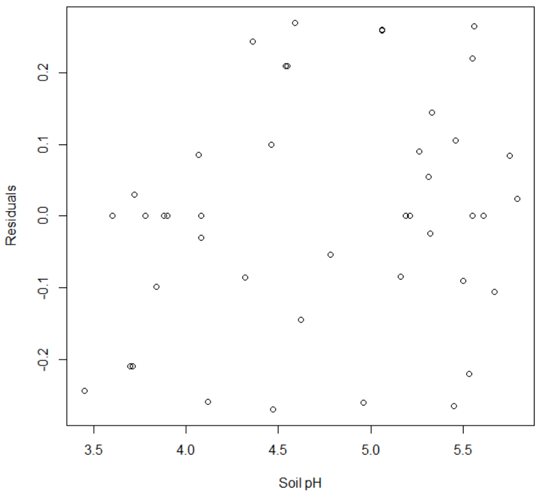


Figure 3-20 Model residuals from the GLM testing the effect of year of measurement on soil pH.

Soil pH was 0.42 units higher in 2010 than in 2009 (parameter estimate = 0.42 ± 0.09, p = 0.0002). Unfortunately soil samples collected in 2009 had been tested for all soil properties then disposed of prior to collecting and testing in 2010 so it was not possible to retest the 2009 samples at this time. It seems likely that the difference in pH arose from a difference in pH buffers used in the two years.

The field experiment involved measuring pH on samples in 2009, 2010 and 2011. Some samples collected in 2010 were kept and re-tested for pH in 2011. A significant difference occurred between the pH of samples collected in 2010 and tested in 2010, compared to the retest pH of these samples in 2011, this time the measurements made in 2010 were 0.24 pH units higher than when the samples were retested in 2011 (parameter estimate = 0.24 ± 0.07, p = 0.004).

As the 2011 data were close to equidistant between the 2009 and 2010 data, it was decided that it would be most appropriate to add a correction offset to the 2009 data of 0.18 (i.e. 0.42 – 0.24) and to subtract a correction offset of 0.24 from the 2010 results, so that data from all three years were on a comparable level to that obtained in 2011. Graphic comparison of the raw soil pH data from the field experiment before and after conversion, illustrates that a substantial increase in pH between 2009 and 2010 in the unconverted data was likely to be an artefact of inconsistency in pH levels obtained with different pH buffers (Figure 3-21). Converting the data meant that the increase in pH form 2009 to 2011 was approximately equal in the two years and this seems more plausible given the management treatments.

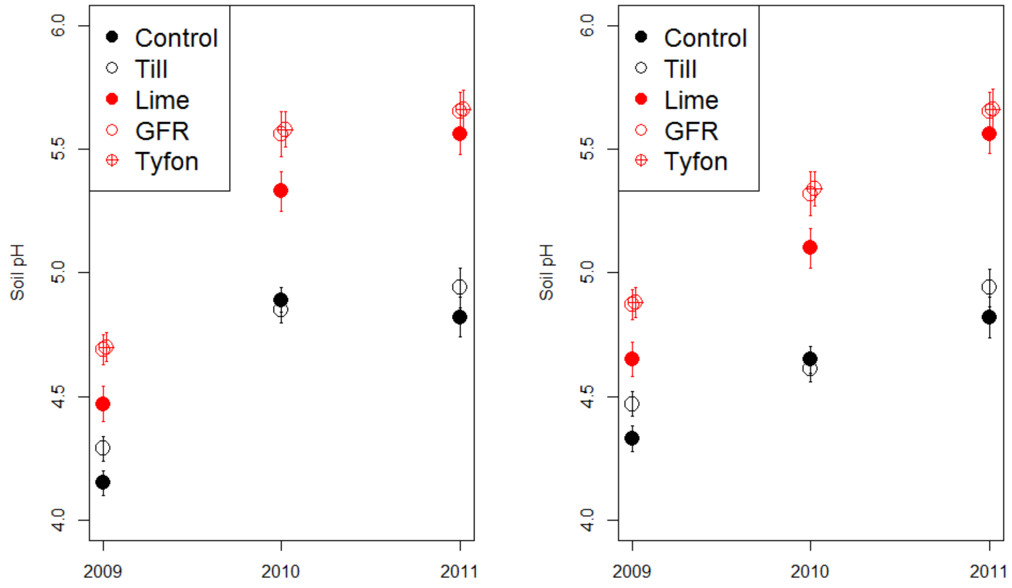


Figure 3-21 Soil pH across treatments and years a) without correcting soil pH data, b) after correcting soil pH data.

3.7 Appendix B – Trial management at RSPB Geltsdale

In 2009 RSPB Geltsdale planted approximately 1 ha of stubble turnips, to provide an additional trial site for this study. Geltsdale is an organic farm and tyfon seeds are not available organically (seeds are pre-treated with fungicide), therefore the reserve used vollenda, which is an organically available variety of stubble turnip instead. Prior to vollenda being planted I collected a number of soil cores to determine both soil pH and earthworm abundance. At this stage the area to be planted had already been deep ploughed and was found to have lower soil pH (mean pH 5) and earthworm abundance (mean 1 earthworm per core) than the adjacent grassland area (mean pH 5.8, mean 5 earthworms per core) that had provisionally been set aside for the control. Vollenda was sown across the whole area that had been deep ploughed and lime was applied to this at an application rate determined by the soil pH results, with the result that there was no proper control for this trial. Further to this there was no replication of the treatment.

Samples were collected in spring 2010 from the area that had been planted with vollenda and limed in the previous year and also from the grassland area for comparison. Staff and volunteers carried out observations of birds feeding on the vollenda area and the adjacent grassland area. Following the breeding season the plot was planted with more vollenda, no additional lime was applied as soil pH had been raised sufficiently by the large dose of lime applied in 2009. Field data were collected in spring 2011 as per spring 2010. The timing of agricultural operations and field work are summarised in Table 3-20. Results are summarised in Table 3-21.

Table 3-20 Time of agricultural operations and field work at RSPB Geltsdale.

Month	Activity
pre May 2009	Plot deep ploughed
May 2009	Samples collected
June 2009	Plot planted with vollenda and limed
April 2010	Samples collected
April and May 2010	Feeding observations (reserve staff and volunteers)
July 2010	Vollenda sown for 2nd year
April 2011	Samples collected
April and May 2010	Feeding observations (reserve staff and volunteers)

Table 3-21 Summary of results from Geltsdale, showing soil pH, numbers of earthworms per core, % bare ground and number of lapwings foraging per observation session. Results show mean ± standard error. Observation sessions were either 1 or 2 hours long. In 2010 7 observation sessions were carried out with a further 10 in 2011.

	Soil pH		Earthworm abundance		*A. chlorotica* abundance		% bare ground		Number lapwings foraging per session	
	Vollenda	Grass	Vollenda	Grass	Vollenda	Grass	Vollenda	Grass	Vollenda	Grass
2009	5.0 ± 0.03	5.8 ± 0.11	0.9 ± 0.3	4.4 ± 1.0	1.5 ± 1.0	0.5 ± 0.3	94 ± 3%	0 ± 0%	-	-
2010	-	-	1 ± 0.3	3.9 ± 1.1	0.3 ± 0.3	0.7 ± 0.3	33 ± 5%	0 ± 0%	3.9 ± 0.8	0.14 ± 0.13
2011	5.6 ± 0.12	5.1 ± 0.05	8 ± 1.9	4 ± 0.8	4 ± 1.1	1 ± 0.4	30 ± 11%	0 ± 0%	3 ± 1	0.75 ± 0.4

Chapter 4 Can soil properties improve habitat association models for breeding lapwings?

4.1 Abstract

Habitat associations of farmland birds have been a long-term focus for research, yet remarkably few studies have considered potential relationships with soil properties. The link between breeding lapwing and soil moisture is well established, but the dependence of lapwings' invertebrate prey on additional soil properties suggests that these could also be influential determinants of lapwing distribution. This study tested the relationship between breeding lapwings and soil and topographical variables, after controlling for other habitat effects, at 89 sites across mainland Scotland. Field scale models were used to identify influential habitat factors, which were then converted to the site scale allowing for inclusion of soil data available only at a broader scale. High collinearity between soil and topographical variables required the use of principal components in place of the raw variables. The addition of soil and topography variables improved model fit by close to 60%, in comparison to only including habitat variables identified as influencing breeding lapwings by previous research. Lapwing density was highest at sites at higher altitudes but only those that had relatively less peaty, less acidic soil. The results suggest that lapwings may be vulnerable to soil acidification at higher altitudes, but could benefit from the use of soil amendments to counteract acidification.

4.2 Introduction

Agriculture is the principal land use in the UK accounting for around 70% of the area (DEFRA 2012). Given the dominance of agriculture in the British landscape it is perhaps unsurprising that significant numbers of over 100 species of bird use farmland for breeding, over-wintering or both and that habitat use of farmland birds is such an active area of scientific research (Wilson, Evans & Grice 2009).

Considering the volume of work that has been published on habitat associations of farmland birds it is remarkable how few studies have explored the relationship between farmland birds and soil properties. A Web of Science search using the terms “farmland”, “bird” and “habitat” returned over 1100 publications since the year 2000, replacing habitat with different soil properties significantly reduced the number of publications: “soil moisture” resulted in seven papers (Devereux *et al.* 2004, Verhulst, Kleijn & Berendse 2007, Vanderhoff & Eason 2008, Olsson & Rogers 2009, Rhymer *et al*. 2010, Paula, Traba & Morales 2011, Berndt & Norbert 2012), “soil” and “organic matter” just three publications (Hazelden & Boorman 2001, Gilroy *et al.* 2008, Gilroy *et al.* 2010), whilst only one publication (Owen & Marrs 2000) was found for “soil pH” and none for “soil depth”. The lack of research into associations between farmland birds and soil properties is particularly surprising when the dependence of agricultural activity on soil quality and the effect that agricultural processes can have on soil properties are considered (Webb *et al.* 2001, White 2006).

Over 90% of the UK population of lapwings (*Vanellus vanellus*) breed on agricultural land and much is known about the breeding habitat requirements of this species (Shrubb 2007). Lapwings nest on both arable and grassland fields, although the suitability of arable sites depends on the distance to suitable chick rearing habitat in the form of pasture or damp areas (Berg *et al.* 1992, Galbraith 1988b, Sheldon *et al.* 2004). The lapwing lays its eggs in a scrape (nest) in areas with short vegetation or bare ground and this is thought to aid detectability of approaching predators from which they actively defend their nests (Klomp 1954, Whittingham & Evans 2004). Nest sites with open views are selected often in relatively flat, large fields, tending to avoid potential perches for avian predators and field boundaries that restrict the area that can be seen (Small 2002, Wallander, Isaksson & Lenberg 2006, Shrubb 2007).

Lapwings are strongly associated with wet habitats, relying on wet features and moist soil to supply their invertebrate prey (Berg 1993, McKeever 2003, Eglington *et al.* 2008, Eglington *et al.* 2010, Rhymer *et al.* 2010). Earthworms are a particularly important prey resource, taken by both adults and chicks (Galbraith 1989a, Baines 1990, Beintema *et al*. 1991, Sheldon 2002). Lapwing distribution during territory establishment has previously been shown to relate to earthworm abundance (Hogstedt 1974), while earthworm abundance is dependent on soil properties including moisture, organic matter and pH (Edwards & Bohlen 1996, Curry 2004), suggesting that lapwing distribution may ultimately be determined by soil properties.

Whilst the relationship between lapwings and soil moisture is well known, possible associations of lapwings with other soil properties have largely been overlooked. This study tested whether soil variables (pH, organic matter and depth) could predict the density of breeding lapwings at a site, after controlling for established relationships between breeding lapwings and their habitat. Identification of relationships between breeding lapwings and soil properties could aid the identification of areas where conservation efforts should be focussed and may suggest new conservation measures for a species that has undergone severe population declines (Eaton *et al*. 2009).

4.3 Methods

This study used pre-existing data collected in 2005 by the RSPB on breeding lapwings and field habitat characteristics. The RSPB study tested the response of breeding waders to agri-environment scheme management at 59 “key” and 60 “random” sites (O’Brien & Wilson 2011), which were selected from a larger sample of sites that were surveyed in 1992 to estimate breeding wader populations in Scotland (O’Brien 1996). Key sites were identified by ornithologists as areas (potentially across a number of neighbouring farms) that supported high densities of breeding lapwing, oystercatcher (*Haematopus ostralegus*), redshank (*Tringo totanus*), curlew (*Numenius arquata*) or snipe (*Gallinago gallinago*) and these were paired with random 1 km squares. All sites selected had Land Capability for Agriculture between class 1 and 5.3, as defined by the Macaulay Land Capability for Agricultural (LCU) Classification in Scotland, which ranks land based on its potential for agricultural activity using information on soil and climate (http://www.macaulay.ac.uk/explorescotland/lca.html, accessed 14 April 2013). The lowest ranked land, class 6 and 7, which equate to the Scottish Uplands were excluded from site selection.

The RSPB study involved 30 sites from Orkney which were excluded for the purpose of this study, leaving a total of 89 sites on mainland Scotland (Figure 4-1). Soil property data for the 89 sites were obtained from the James Hutton Institute (formerly the Macaulay Land Use Institute). Some additional information on field habitat characteristics was obtained using GIS as part of this study (Table 4-1).

Figure 4-1 Sites surveyed for breeding lapwings by the RSPB across mainland Scotland in 2005.

Table 4-1 Data sources used in this study, showing who collected the data and the year that the data was collected.

Variable	Data source
Lapwing abundance per field	RSPB, 2005
Field habitat characteristics; vegetation height, % rush, % flooding, land use, field area)	RSPB, 2005
Field habitat characteristics (altitude, slope)	Data provided by the RSPB data unit for the purpose of this study
Field habitat characteristics (field boundaries, habitat adjacent to field of interest)	Data collected as part of this study
Soil properties (soil organic matter, soil pH and soil depth)	James Hutton Institute, 1978-1988

Lapwing surveys

Surveys were conducted following O'Brien and Smith (1992), and involved three survey visits between 15th April and 21st of June 2005, with all visits to the same site separated by at least one week. Surveys were carried out within three hours of dawn or dusk on a field by field basis covering all fields within a site on each visit. These were conducted on foot walking to within 100 m of all points of the site and scanning ahead up to 400 m, with binoculars, for waders. The number of lapwing pairs was calculated by dividing the number of lapwings recorded in a field (excluding those in flocks) on one of the first two visits, selecting the visit where the maximum number of lapwings was recorded across the whole site (Barrett & Barrett 1984).

Habitat data

At the time of the lapwing surveys, vegetation height, percentage flooding, percentage rush cover and land use were recorded for each field. Vegetation height was recorded on the first two visits taking 10 measurements per field per visit, with heights divided into eight categories (Table 4-2). For each field the mean vegetation height category was calculated from all measurements taken on the first two visits. Percentage flooding and soft rush (*Juncus effusus*, from now on referred to as rush) cover were estimated by eye on all three visits and the mean of these was taken for each field. Land use was recorded for each field and this was divided into three categories; arable, grass (including improved and semi-improved grass) and semi-natural (such as moorland, mire or rough grazing). Areas of woodland and scrub which are unsuitable for breeding lapwing were excluded.

Table 4-2 Categories that measured vegetation heights, within fields were divided into based.

Category	1	2	3	4	5	6	7	8
Vegetation height (cm)	< 5	5 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	>60

Field areas were extracted from Ordnance Survey Digital Data layers. The proportion of the field perimeter that was adjacent to semi-natural habitat was also extracted from the GIS, as this can influence field use by lapwings (Small 2002). The extent of field enclosure was calculated by measuring the length of field boundaries consisting of trees, hedges, buildings or scrub (using Google Earth) and dividing this by the total length of the field perimeter. All GIS manipulations were conducted with ArcGIS 9.2 (Esri inc 2006).

Topographical data

Field altitude and slope were obtained from the Ordnance Survey Digital Terrain map with 50 m resolution, taking the mean level of all points within a field.

Soil data

Data on soil properties (soil organic matter, soil pH and soil depth) were obtained from the James Hutton Institute (formerly the Macaulay Land Use Institute). The soil property data were derived from the Scottish Soil Survey which took place between 1978 and 1988 (Lilly *et al.* 2010). Soil organic matter, soil pH and soil depth were measured for soil profiles collected on a 10 km grid across Scotland. The soil property data were interpolated from the sampling points (Poggio *et al.* 2010), and the mean value for each wader site was extracted from the interpolated data within a GIS framework.

4.3.1 Analysis

Lapwing, habitat and topographical data were collected on the field scale, however, the soil data were collected on a 10 km grid, meaning that it was more appropriate to analyse the data on the site scale rather than the field scale. Preliminary analysis of factors important for breeding lapwings at the field scale was conducted to inform the choice of habitat variables to include in site scale models, and to guide the combination of habitat variables collected at the field scale to create appropriate site scale variables.

Factors affecting breeding lapwings at the field scale

Generalised linear mixed effects models (GLMMs) were used to test which factors affected a) whether a field was used by breeding lapwings (presence / absence) and b) the density of breeding lapwings within a field (only including fields where breeding lapwing were present). Prior to implementing the GLMMs, covariates were tested for collinearity but as none exceeded Pearson's correlation coefficient of 0.5 (Zuur, Ieno & Smith 2007), all covariates were included in the models (Table 4-3). The field scale models took the form:-

Lapwings =

a) Presence / absence
b) Count

Covariates
Vegetation height + % flooding + % rush cover + (% rush cover)^2 + field area + proportion field boundary with semi-natural habitat + extent field enclosed + altitude + (altitude)^2 + slope

Factor
Land use (grass, arable or semi-natural)

Random factor (grouping variable)
Site

Table 4-3 Pearson's correlation coefficients for habitat variables collected at the field scale.

	Vegetation height category	% Flooding	% Rush cover	Field area	Extent field enclosed	Proportion field boundary with semi-natural habitat	Altitude
Slope	-0.01	-0.02	-0.05	-0.06	0.11	0.08	-0.06
Altitude	0.13	0.15	0.16	0.09	0.01	0.24	
Proportion field boundary with semi-natural habitat	0.16	0.41	0.23	0.14	-0.09		
Extent field enclosed	0.08	-0.07	-0.08	-0.07			
Field area	0.06	0.14	0.07				
% Rush cover	0.46	0.49					
% Flooding	0.31						

Factors affecting breeding lapwings at the site scale

Site scale analysis was implemented in two stages. The first stage tested the effect of habitat variables identified by previous research as important for breeding lapwings, such as the extent of rush cover and field enclosure; this model only included variables that remained in either of the field scale minimum adequate models. In the second stage, soil and topographical variables were added to the minimum adequate model that was obtained from the first stage.

Covariates collected on the field scale were combined to create site scale variables by taking the mean value for all fields within a site. Land use within fields were combined to create a farm type variable based on the proportion of land within a site that was classed as grassland, arable or semi-natural (Table 4-4). However, the farm type variable was not included within further analysis as several of the covariates of interest varied significantly between the different farm types (tested with Analysis of Variance), meaning that these explanatory variables would be confounded with farm type. Lapwing count was summed across all fields within a site.

Table 4-4 Farm types calculated by percentage of each land use at the site.

Farm type	No. of farms	% arable	% grass	% semi-natural
Arable	4	>80		
Grass	36		>80	
Semi-natural	17			>80
Mixed	27	>20	>20	
Grass / semi-natural	17	<20	>20	>20

Factors affecting breeding lapwings at the site scale: Stage 1 habitat variables identified to be influential by previous research

Prior to modelling the effect of habitat variables identified as influential to breeding lapwings by previous research, covariates were tested for correlation. A high correlation between percentage flooding and percentage rush cover (Table 4-5) led to the implementation of a principal components analysis (PCA) on these two variables; the two principal components ("wet 1" and "wet 2") generated from this were included in the subsequent model in place of these variables. As the sole aim of the PCA was to remove problems associated with high collinearity, all principal components were included within the model, thus eliminating the risk of reducing explanatory power by only including principal components with large eigenvalues (Graham 2003). The effect of habitat variables previously identified as influencing lapwing density was tested using a generalised linear model (GLM) with the form:

Lapwings =	Covariates:
(count)	Vegetation height + extent field enclosed + field area + wet 1 + wet 2

Table 4-5 Pearson's correlation coefficients for site scale variables identified as influencing lapwing distribution by previous research. Correlations above 0.5 are shown in bold.

	Field area	Extent field enclosed	% rush cover	% flooding
Vegetation height	-0.02	0.21	0.32	0.24
% Flooding	0.33	-0.26	**0.65**	
% Rush cover	0.20	-0.25		
Extent field enclosed	-0.31			
Field area				

Factors affecting breeding lapwings at the site scale: Stage 2 adding soil and topographical variables

The second stage of the modelling involved adding soil and topographical variables to the minimum adequate model from the first stage; prior to this, correlations between the variables retained from the first stage of the modelling and the additional variables were tested. A number of high correlations (three above 0.5, with a further two involving the same set of variables between 0.4 and 0.5) were found between soil organic matter, soil pH, altitude and slope (Table 4-6a). A PCA was carried out on these four variables and the principal components ("soil 1", "soil 2", "soil 3" and "soil 4") generated from these were added to the model in place of the variables, thus reducing the highest correlation between covariates from 0.74 to 0.38 (Table 4-6a & b). The only other variable to be added at this stage (soil depth) was not included in the PCA as it did not exhibit high collinearity (>0.5) with any of the other soil or topographical variables. A further GLM was then implemented to test how much variability in lapwing density could be explained by soil and topography variables, in addition to established habitat relationships:

Lapwings = Covariates:
(count) Retained covariates from stage 1 + soil 1 + soil 2 soil 3 + soil 4 + soil depth

Table 4-6 a) Correlations between covariates retained from the site scale stage 1 model and the soil and topographical variables to be added in stage 2 (correlations above 0.5 in bold). b) Correlations between covariates included in the stage 2 model, ie soil / topography pcs in place of altitude, slope, soil organic matter and soil pH.

a)	Soil depth	Soil pH	Soil organic matter	Slope	Altitude	Flood / rush PC1
Vegetation height	-0.08	0.26	-0.18	-0.05	0.12	0.38
Flood / rush PC1	0.06	-0.24	0.16	0	0.38	
Altitude	0.12	**-0.55**	0.43	**0.55**		
Slope	-0.05	-0.45	0.30			
Soil organic matter	0.31	**-0.74**				
Soil pH	-0.16					

b)	Soil depth	Soil / top PC1	Soil / top PC2	Soil / top PC3	Soil / top PC4	Flood / rush PC1
Vegetation height	-0.08	0.12	-0.22	-0.27	0.17	0.38
Flood / rush PC1	0.06	-0.25	0.04	-0.38	-0.09	
Soil / top PC1	-0.11	0	0	0		
Soil / top PC2	0.38	0	0			
Soil / top PC3	-0.10	0				
Soil / top PC4	0.11					

Statistical analyses

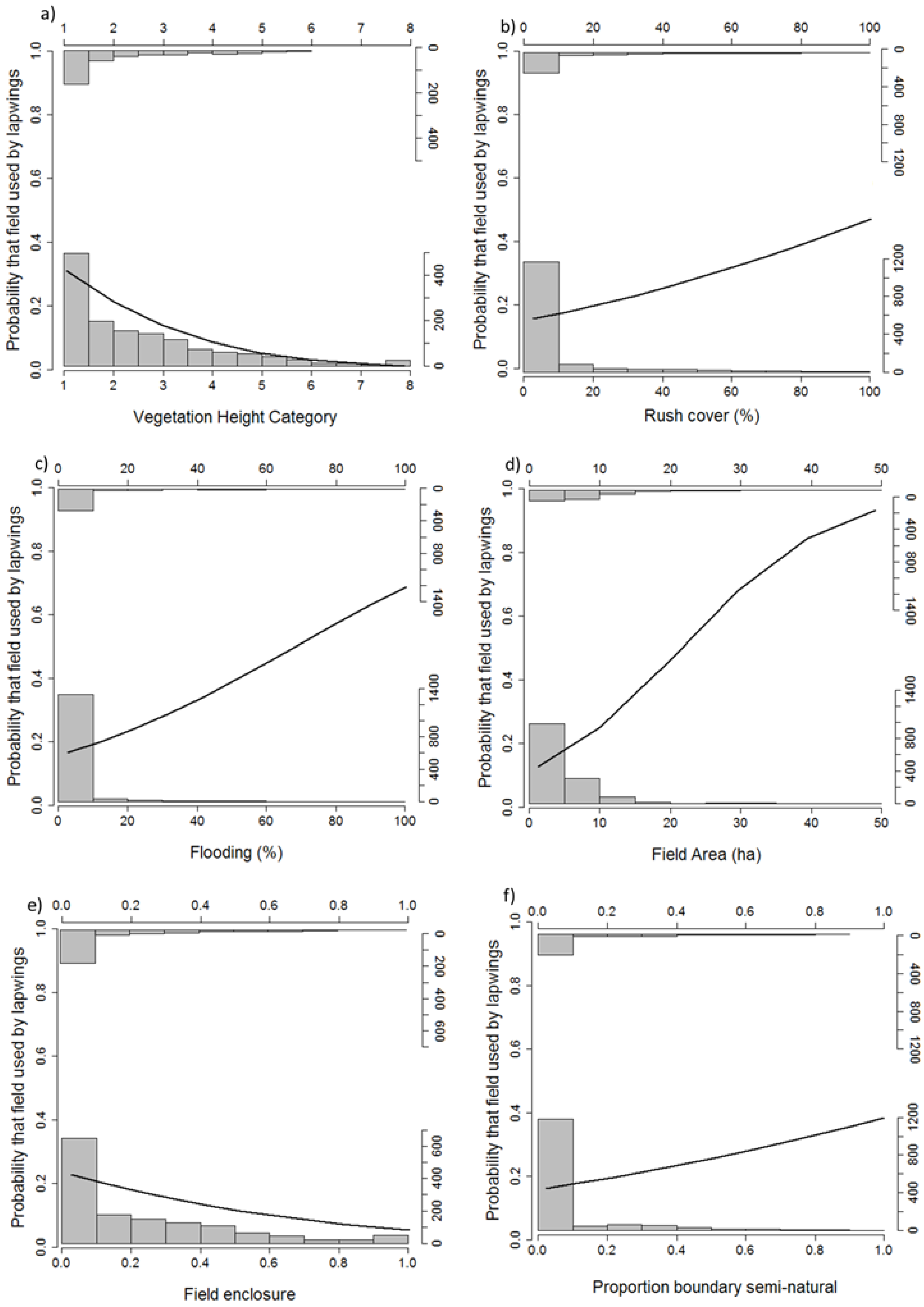
All statistical analyses were implemented in R version 2.15.0 (R Development Core Team 2012) using standardised variables. Variables were standardised by centring (subtracting the mean value of the variable found within the dataset from all input variable values), then scaling (dividing the centred input values by the standard deviation of the variable within the dataset; Schielzeth 2010). All GLMMs were performed with the lme4 package (Bates, Maechlar & Bolker 2011). The presence / absence model was specified with a binomial error distribution and logit link, with the lapwing count models specified with Poisson error distribution, log link and log of field or site size as an offset. For Poisson models the residual deviance was compared to the residual degrees of freedom to test for over-dispersion. There was no over-dispersion in the Poisson GLMM, however, all of the GLMs were over-dispersed and therefore the standard errors and respective p-values were corrected using quasi-likelihood (Crawley 2007, Zuur *et al.* 2009). Minimum adequate models were obtained by backwards selection removing all variables that were not statistically significant at the 5% level. Model residuals were tested for spatial autocorrelation using Moran's I test within the APE package (Paradis, Claude & Stimmer 2004) and visualised using correlograms with the ncf package (Bjornstad 2012).

Model fit was assessed for the presence / absence model by comparison of the predicted probabilities calculated from the model with the observed data within a confusion matrix, using 0.5 as the threshold level above which a field would be predicted to be used by breeding lapwings (Fielding & Bell 1997). For the Poisson models, model fit was assessed by comparing Akaike's Information Criterion (AIC) of the final model and null models to give a measure of deviance explained by the model, whilst taking into account the number of parameters within the model (Burnham & Anderson 2002). AIC was calculated using the formula: AIC = -2log likelihood + 2K, where K = the number of parameters estimated within the model (including the intercept). For the models where over-dispersion was observed QAIC was used in place of AIC and was calculated as: QAIC = AIC/dispersion parameter. The dispersion parameter was taken from the global model (i.e. the model with the most parameters in it), and used in all QAIC calculations, and was included as a parameter in calculating K. For the models with a small sample size in relation to the number of parameters in the model $QAIC_c$ was used and calculated as: $QAIC_c = (QAIC + 2K (K+1)) / (n – K – 1)$, where K = the number of parameters and n = sample size. The deviance explained within the model was then calculated as:- deviance explained = 1 – ($QAIC_c$ maximum model / $QAIC_c$ null model) (Cameron & Trivedi 1998).

4.4 Results

Factors affecting breeding lapwings at the field scale

The probability that a field would be used by breeding lapwings was highest for fields with the following characteristics; short vegetation, high percentage of flooding and rush cover, large size, low enclosure on flat ground at higher altitudes, adjoining semi-natural habitat and under arable crops rather than grass or semi-natural habitat (Figure 4-2, Table 4-7). All of these effects were additive. The random effect, Site, accounted for 58% of the variability in the data. The model predicted just 119 out of the 307 fields used by breeding lapwing correctly, i.e. only 38% correct. However, the model was far better at predicting which fields would not be used by lapwings with 1360 out of 1414 fields not used by breeding lapwings predicted correctly, i.e. 96% correct.


a)
Probability that field used by lapwings
Vegetation Height Category
b)
Probability that field used by lapwings
Rush cover (%)
c)
Probability that field used by lapwings
Flooding (%)
d)
Probability that field used by lapwings
Field Area (ha)
e)
Probability that field used by lapwings
Field enclosure
f)
Probability that field used by lapwings
Proportion boundary semi-natural

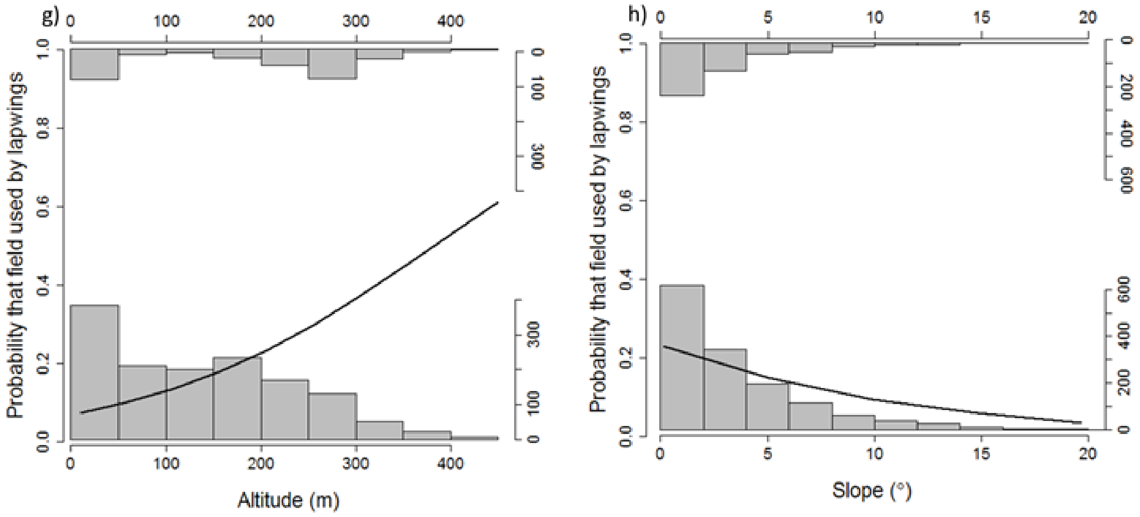


Figure 4-2 Predicted probability that a field would be used by lapwings with increasing a) vegetation height b) rush cover, c) flooding, d) field area, e) field enclosure, f) proportion of boundary onto semi-natural habitat, g) altitude, h) slope. The histograms depict the data distribution for fields within the dataset. The histogram at the top represents field characteristics of all fields where lapwings were present and the bottom histogram shows the data for fields where lapwings were absent.

In the 307 fields (across 65 sites) where lapwings were present, density was also higher in fields with shorter vegetation and higher percentages of flooding and rush cover (Table 4-7). However, lapwing density was lower in bigger fields and in fields next to semi-natural habitats. A quadratic relationship between lapwing density and altitude meant that the highest lapwing densities occurred at mid-altitudes within the dataset, around 200 m. Lapwing density was not related to how enclosed or flat the field was or field land use. The random effect, Site, accounted for 7% of the variability in the data and the proportion of deviance explained by the fixed effects was 0.23.

Table 4-7 Statistical summary for GLMMs, assessing factors associated with lapwing distribution at the field scale. Comparison of results for models examining lapwing presence / absence and lapwing density. Parameters statistically significant at the 5% level are in bold.

	Lapwing presence / absence n = 1720, across 89 sites				Lapwing density n = 307, across 65 sites			
% of variability accounted for by random effect site	58%				7%			
	DF	Parameter estimate ± SE	Statistic	p-value	DF	Parameter estimate ± SE	Statistic	p-value
Vegetation height category	**1**	**-0.80 ± 0.14**	**z = -5.59**	**<0.0001**	**1**	**-0.16 ± 0.065**	**z = -2.41**	**0.016**
% rush cover	**1**	**0.28 ± 0.11**	**z = 2.65**	**0.008**	**1**	**-0.22 ± 0.072**	**z = -3.07**	**0.0022**
% rush cover^2	1	-0.06 ± 0.05	z = -1.12	0.26	1	-0.06 ± 0.04	z = -1.60	0.11
% flooding	**1**	**0.21 ±0.092**	**z = 2.26**	**0.024**	**1**	**0.27 ± 0.061**	**z = 4.40**	**<0.0001**
Field area	**1**	**0.46 ± 0.075**	**z = 6.17**	**<0.0001**	**1**	**-0.29 ± 0.041**	**z = -6.94**	**<0.0001**
Extent field enclosure	**1**	**-0.42 ± 0.11**	**z = -3.87**	**0.0001**	**1**	-0.027 ± 0.05	z = -0.54	0.59
Proportion of field boundary with semi-natural habitat	**1**	**0.19 ± 0.089**	**z = 2.12**	**0.034**	**1**	**-0.12 ± 0.053**	**z = -2.17**	**0.03**
Altitude	**1**	**0.69 ± 0.16**	**z = 4.34**	**<0.0001**	1	0.040 ± 0.068	**z = 0.59**	**0.55**
Altitude^2	1	0.17 ± 0.13	z = 1.28	0.20	**1**	**-0.18 ± 0.079**	**z = -2.30**	**0.022**
Slope	**1**	**-0.33 ± 0.12**	**z = -2.84**	**0.0045**	1	-0.06 ± 0.06	z = -0.99	0.32
Land use:	**2**	**-**	**Chi sq = 13.18**	**0.0014**	2	-	Chi sq = 2.79	0.25
Grass compared to arable	**NA**	**-0.89 ± 0.25**	**z = -3.62**	**0.0003**	NA	-0.20 ± 0.12	z = -1.59	0.11
Grass compared to semi-natural	NA	0.27 ± 0.33	z = 0.81	0.41	NA	0.093± 0.16	z = 0.29	0.55
Semi-natural compared to arable	**NA**	**-0.16 ± 0.41**	**z = -2.82**	**0.0048**	NA	-0.29 ± 0.20	z = -146	0.14

Factors affecting breeding lapwings at the site scale: Stage 1 habitat variables identified to be influential by previous research

The PCA on percentage rush cover and percentage flooding generated two principal components (wet 1 and wet 2), the first of which accounted for 80% of the variability within the data and was positively correlated with both rush cover and flooding (Table 4-8, Figure 4-3). The second principal component accounted for the remaining 20% of the variability within the data and had a positive relationship with percentage rush cover but a negative relationship with percentage flooding.

Table 4-8 Proportion of variance in the data accounted for by the two wet principal components (representing percentage rush cover and percentage flooding) and loadings (i.e. relationships with the variables that made up the principal components).

	Wet 1	Wet 2
Eigen value	1.60	0.40
Proportion of the variance	0.80	0.20
Cumulative proportion	0.80	1.00
Loadings		
% Flooding	0.707	-0.707
% Rush cover	0.707	0.707

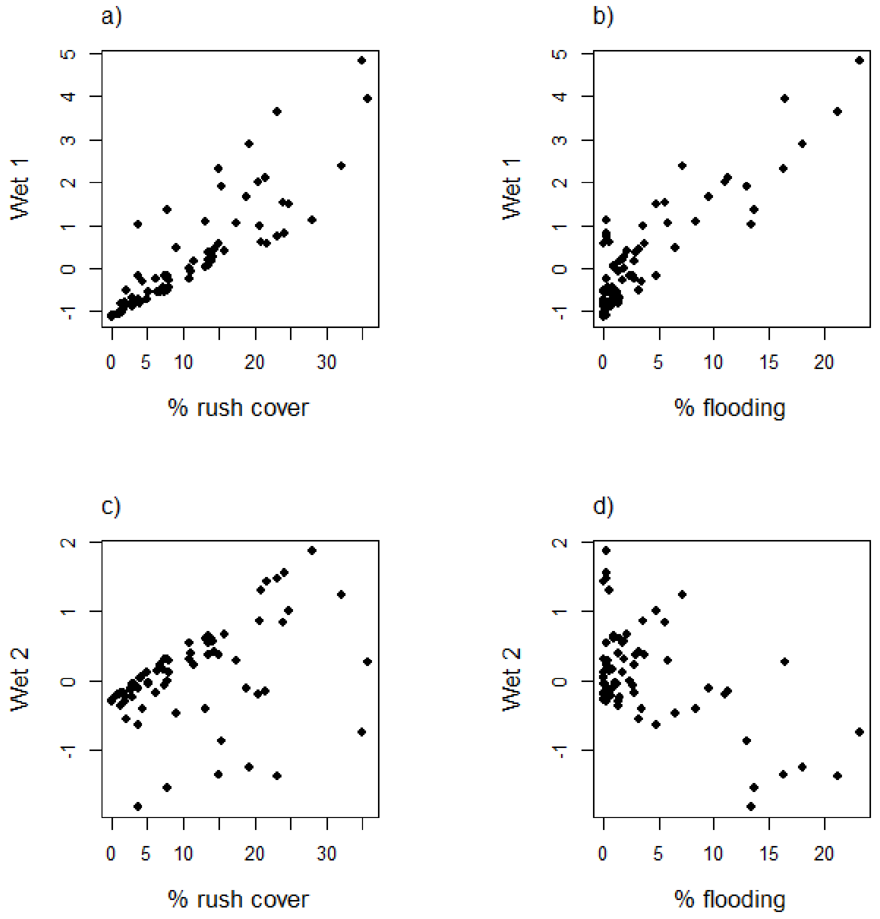


Figure 4-3 Relationship between principal components wet 1 and wet 2 and the two variables that the principal components group – percentage rush cover and % flooding, a) Wet 1 compared to percentage rush cover, b) Wet 1 compared to percentage flooding, c) Wet 2, compared to % rush cover and) Wet 2 compared to % flooding.

At the site scale lapwing density was highest for sites with short vegetation and a high percentage of flooding and rush cover, as described by the Wet 1 principal component (Table 4-10). The proportion of deviance explained by the minimum adequate model was 0.20.

Factors affecting breeding lapwings at the site scale: Stage 2 adding soil and topographical variables

The PCA on altitude, slope, soil organic matter and soil pH generated four principal components (Table 4-9). Soil 1 accounted for 63% of the variability within the data and described the typical relationship found between altitude, slope, soil pH and soil organic matter, such that slope and soil organic matter increased with altitude, whereas soil pH declined (Figure 4-4). Soil 2 accounted for 20% of the variability within the data and increased with soil organic matter but declined with altitude, slope and soil pH (Figure 4-5). Soil 3 accounted for 11% of the variability within the data and was similar to soil 2, except for the relationship with slope, such that soil 3 increased with increasing soil organic matter and slope, but declined with altitude and soil pH. (Figure 4-6). Soil 4 accounted for the remaining 6% of variability within the data and had a positive relationship with all four variables, in particular soil pH, such that as soil 4 increased so did altitude, slope, soil pH and organic matter (Figure 4-7).

Table 4-9 Proportion of variance in the data accounted for and loadings (i.e. relationships with the variables that made up the principal components) for the four soil / topography principal components.

	Soil 1	Soil 2	Soil 3	Soil 4
Eigen value	2.52	0.81	0.43	0.24
Proportion of the variance	0.63	0.20	0.11	0.06
Cumulative proportion	0.63	0.83	0.94	1.00
Loadings				
Altitude	-0.50	-0.36	-0.78	0.10
Slope	-0.44	-0.65	0.60	0.13
Soil organic matter	-0.50	0.58	0.13	0.63
Soil pH	0.55	-0.32	-0.11	0.76

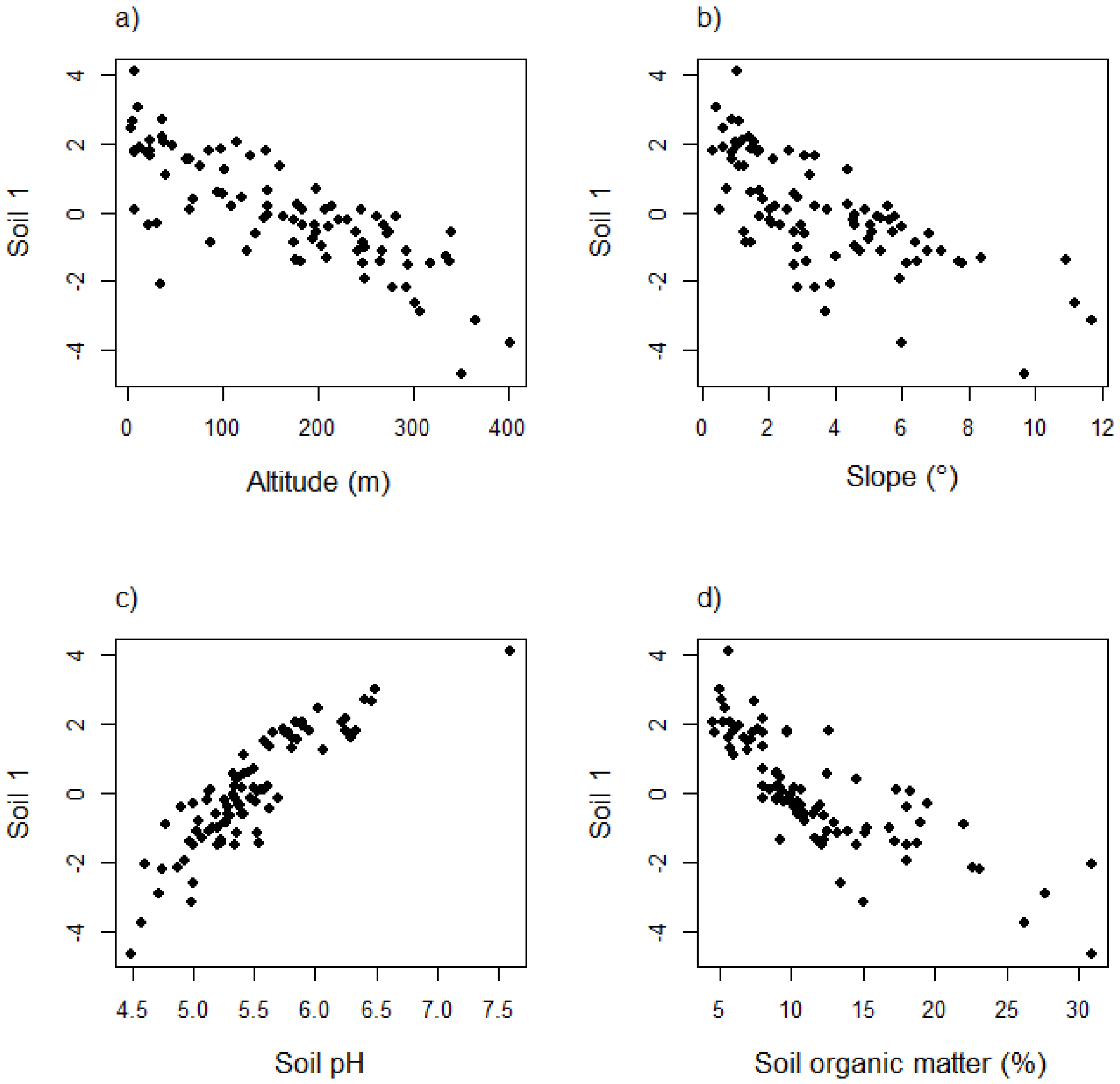


Figure 4-4 Relationship between principal component soil 1 and the four variables that the principal component groups a) Altitude, b) Slope, c) Soil pH and d) Soil organic matter.

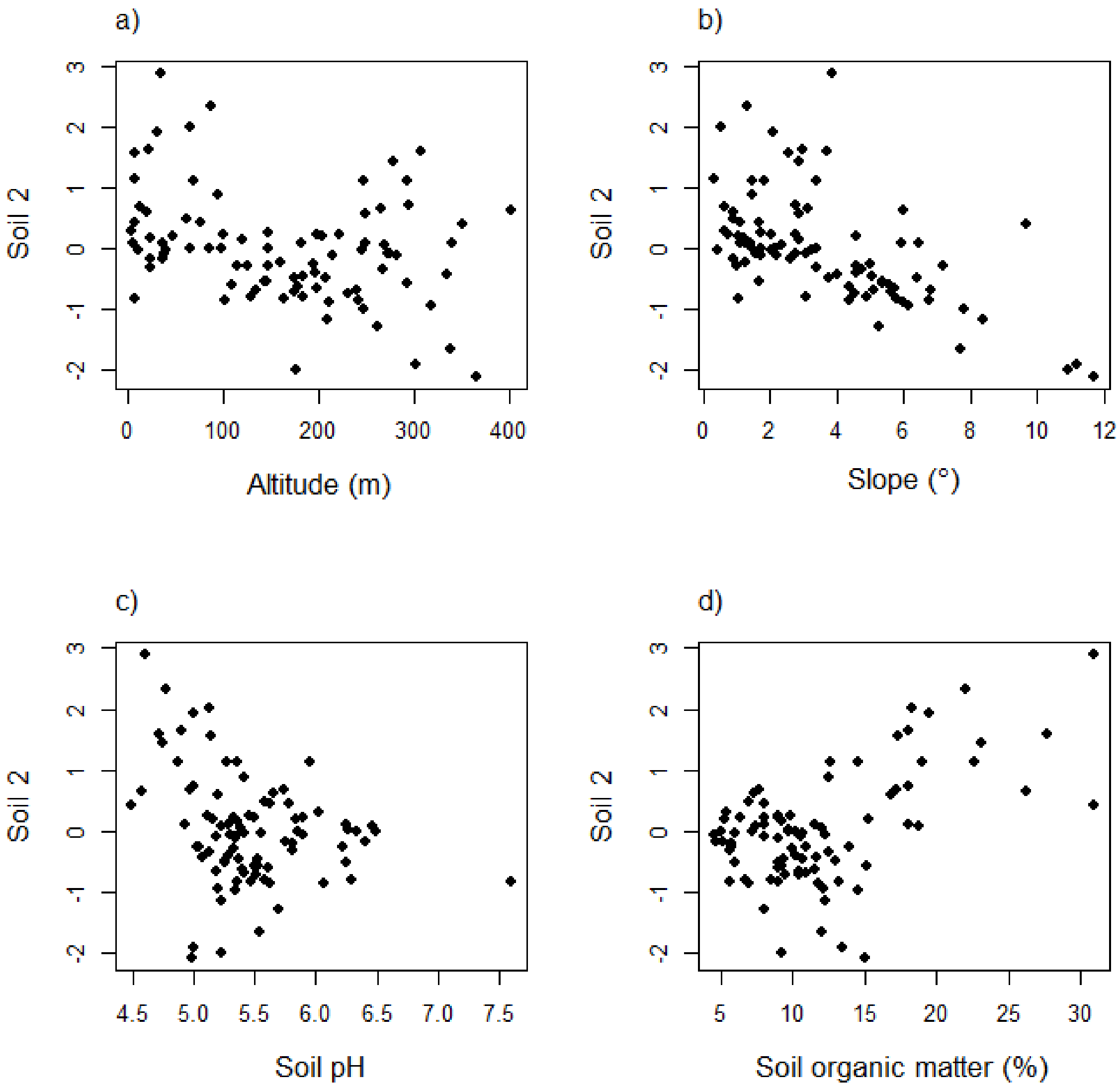


Figure 4-5 Relationship between principal component soil 2 and the four variables that the principal component groups a) Altitude, b) Slope, c) Soil pH and d) Soil organic matter.

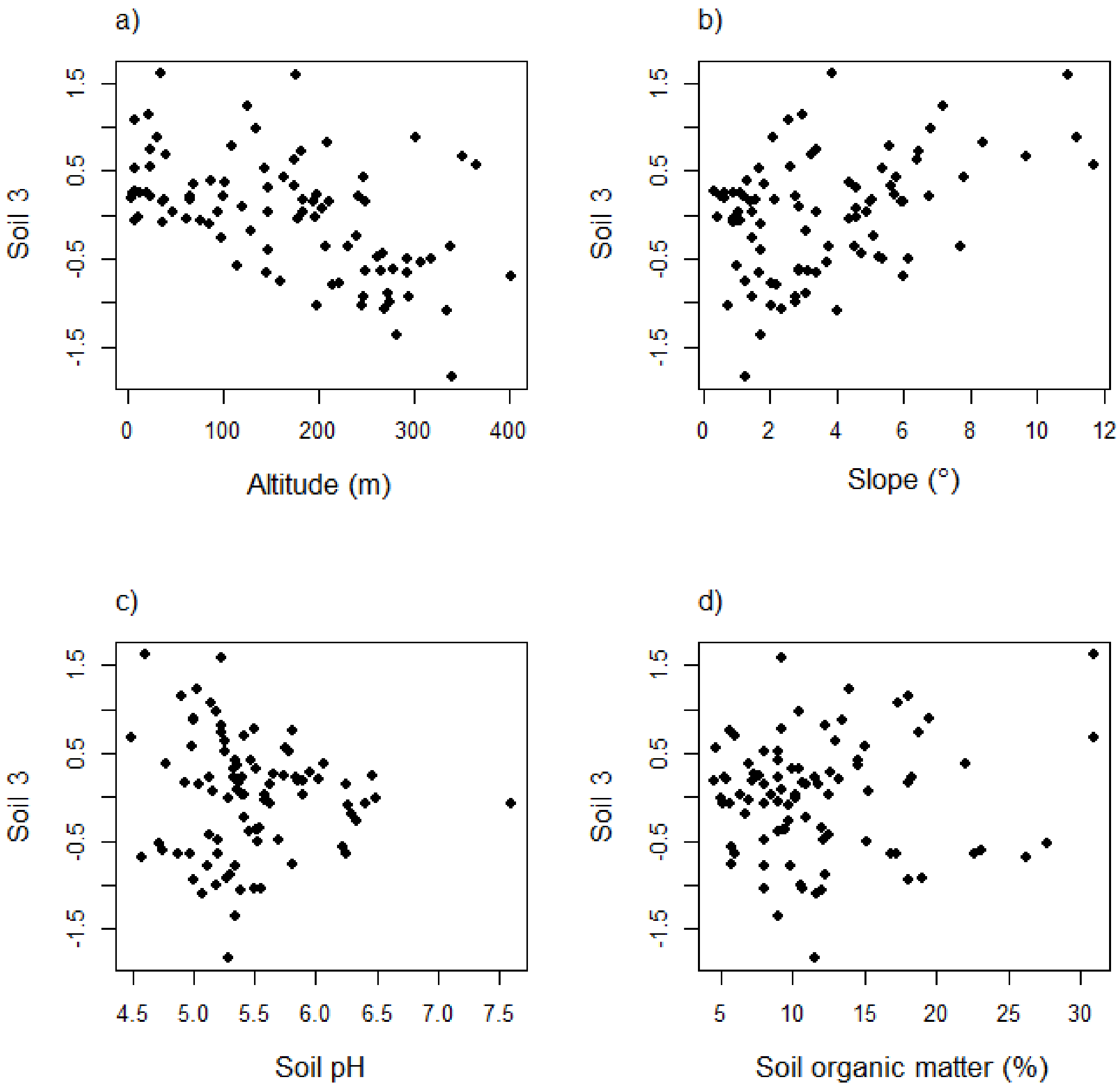


Figure 4-6 Relationship between principal component soil 3 and the four variables that the principal component groups a) Altitude, b) Slope, c) Soil pH and d) Soil organic matter.

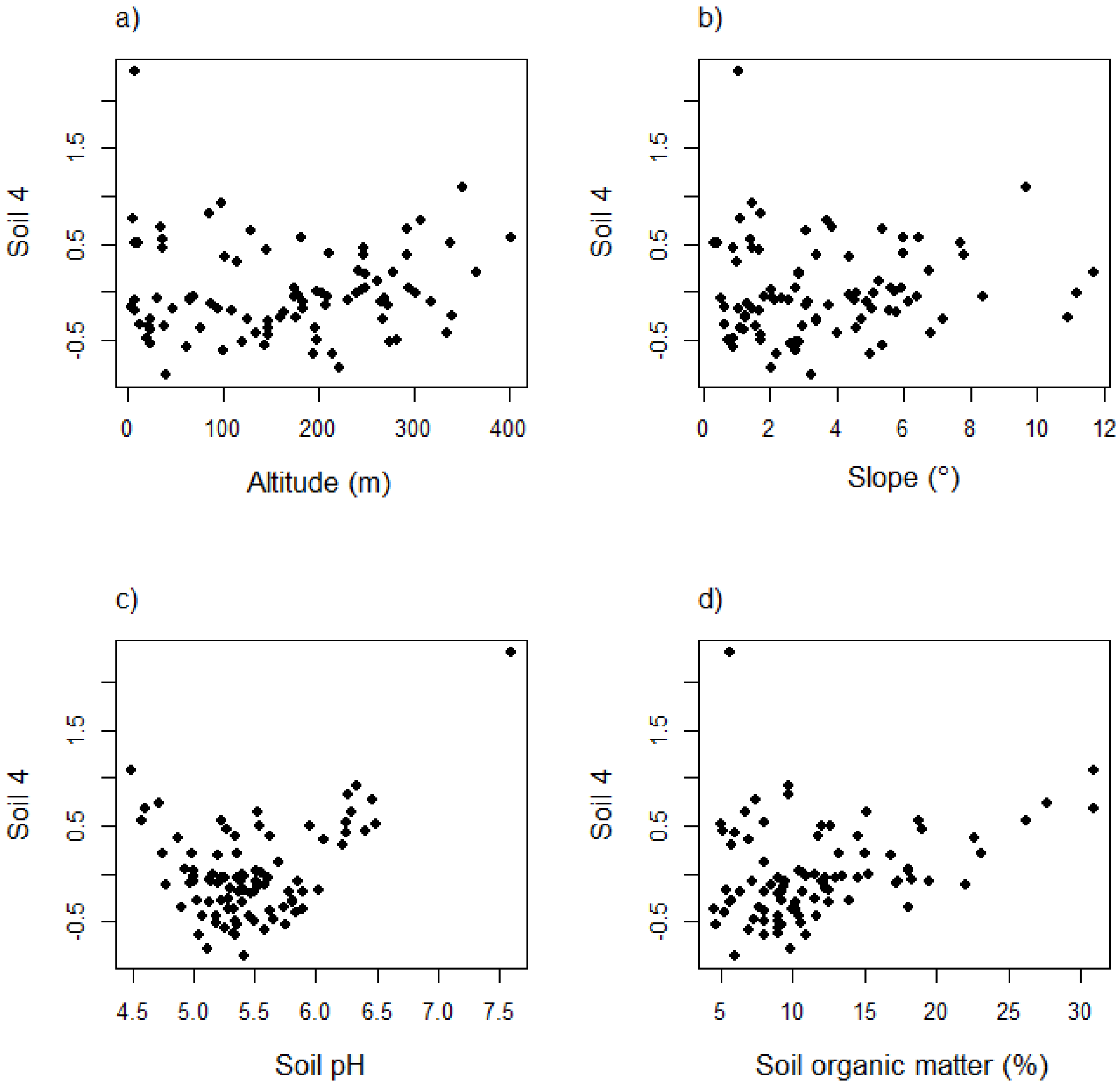


Figure 4-7 Relationship between principal component soil 4 and the four variables that the principal component groups a) Altitude, b) Slope, c) Soil pH and d) Soil organic matter.

As in the first stage of the site scale modelling, lapwing density was highest for sites with short vegetation and high percentages of flooding and rush cover (Table 4-10, Figure 4-8). Lapwing density was also negatively related to soil 2 and soil 3, and positively related to soil depth. The negative relationships between lapwing density and soil 2 and soil 3, equate to higher lapwing densities at higher altitude sites, where the soil had relatively low organic matter and high pH, in comparison to sites without these characteristics. Soil 2 relates to relatively hilly sites with these characteristics, whereas soil 3 describes sites that are flatter. Including soil and topography variables in addition to habitat variables identified as influential by previous research (stage 1) increased the proportion of deviance explained (after accounting for the increase in number of parameters within the model) from 0.20 to 0.31, an increase of almost 60%.

Spatial autocorrelation was not considered to be an issue in any of the models indicated by low Moran's I and from the correlograms.

Table 4-10 Statistical summary for GLMMs, assessing factors associated with lapwing distribution at the site scale. Comparison of results for models examining lapwing distribution in relationship to habitat variables that have been identified by previous research as influencing lapwing distribution (Stage 1), then adding in soil and topography variables to the first stage model (Stage 2). Parameters statistically significant at the 5% level are in bold.

		n = 89 sites				n = 89 sites		
		Stage 1				**Stage 2**		
	DF	Parameter estimate ± SE	t-value	p-value	DF	Parameter estimate ± SE	t-value	p-value
Vegetation height category	**1**	**-0.56 ± 0.15**	**-3.76**	**0.0003**	**1**	**-0.71 ± 0.15**	**-4.74**	**<0.0001**
Extent field enclosed	1	0.014 ± 0.15	0.09	0.93	-	-	-	-
Mean field area	1	0.08 ± 0.11	0.78	0.44	-	-	-	-
Wet 1	**1**	**0.45 ± 0.08**	**0.80**	**<0.0001**	**1**	**0.44 ± 0.08**	**5.47**	**<0.0001**
Wet 2	1	0.05 ± 0.17	0.30	0.76	-	-	-	-
Soil 1	-	-	-	-	1	0.05 ± 0.07	0.70	0.48
Soil 2	**-**	**-**	**-**	**-**	**1**	**-0.48 ± 0.15**	**-3.15**	**0.0027**
Soil 3	**-**	**-**	**-**	**-**	**1**	**-0.55± 0.19**	**-2.62**	**0.0060**
Soil 4	-	-	-	-	1	-0.26 ± 0.26	0.26	0.32
Soil depth	**-**	**-**	**-**	**-**	**1**	**0.29 ± 0.10**	**2.81**	**0.0062**

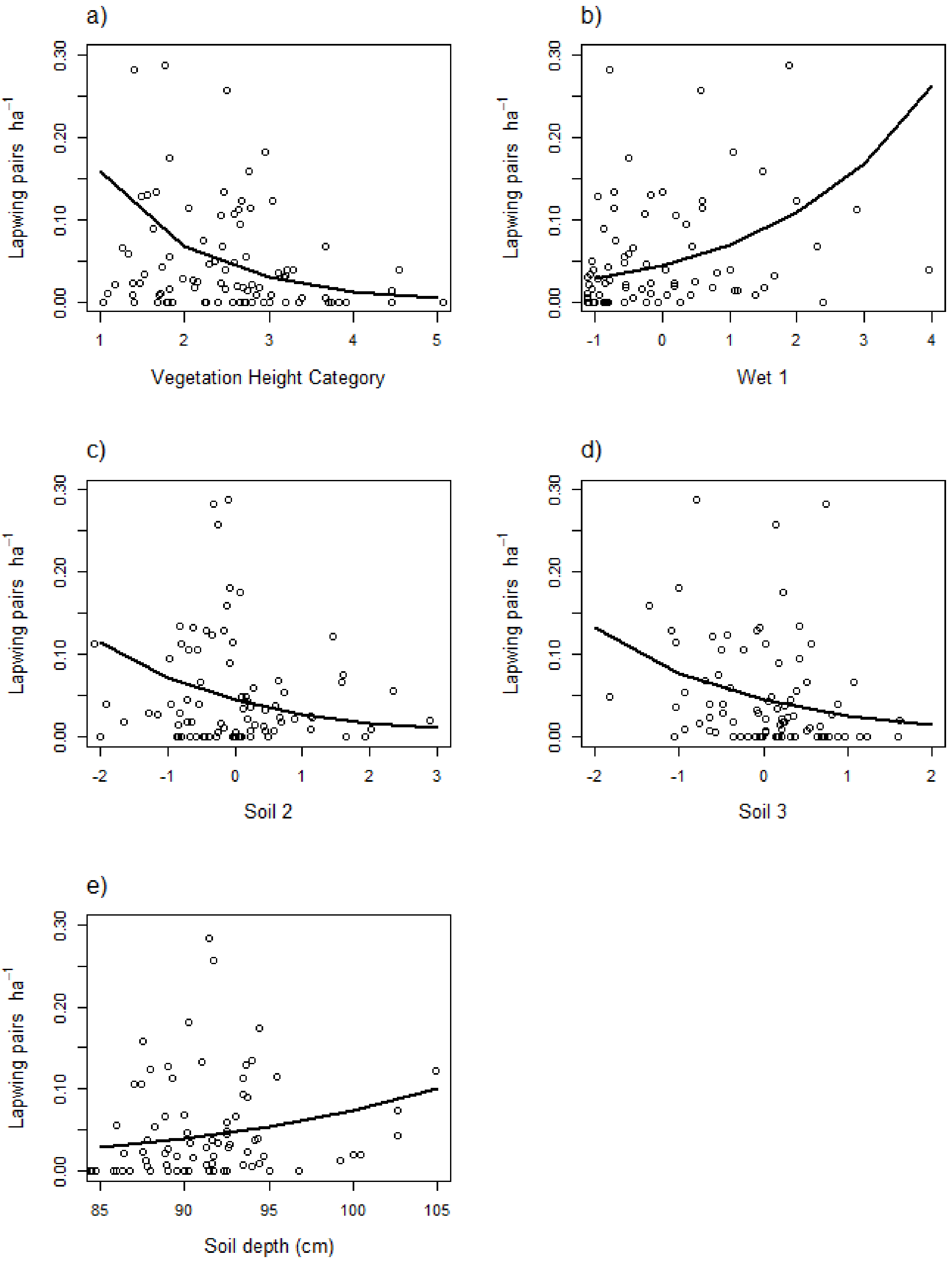


Figure 4-8 Predicted lapwing densities calculated from model estimates (solid line) in comparison to significant predicator variables of lapwing densities across sites. Graphs are for a) vegetation height, b) Wet 1, c) Soil 2, d) Soil 3 and e) soil depth, for each prediction regression line, the other significant variables in the model are held at the mean level found within the dataset. Open circles on each graph show the actual data.

4.5 Discussion

Factors affecting breeding lapwings at the field scale

The results from the field scale models were consistent with established relationships between breeding lapwings and their habitat. Fields with short vegetation were more likely to be used by breeding lapwings and support higher densities (Milsom *et al.* 2000, O'Brien 2001, Shrubb 2007). Lapwings were more likely to use fields with higher percentages of flooding and occurred at higher densities in these fields (Small 2002, Eglington *et al.* 2008 and 2010).

The remaining results contrasted between the two model types, or were significant only in the presence/ absence model. The probability that a field would be used by breeding lapwings increased with increasing percentage rush cover, however, lapwing density declined with increasing levels of rush. O'Brien (2001) and Small (2002), found that whilst field use by lapwings was positively related to the presence of rush, when rush cover exceeded a threshold level (O'Brien – 15 – 40%, Small 10%) lapwing use declined. The contrasting results between the two models is likely related to the threshold rush level, above which a field becomes less suitable for breeding lapwings, however, as no quadratic relationship was found, it was not possible to determine the threshold level within this dataset.

The probability that a field would be used by breeding lapwings was positively related to the proportion of semi-natural habitat next to the field. In contrast, density was negatively related to this, where semi-natural habitats in this study referred to moorland, rough grazing, mires and marshy grassland. This discrepancy again suggests a threshold level above which the amount of semi-natural habitat in the landscape begins to make the area less suitable for breeding lapwings. This is in keeping with lapwing habitat associations reported by Small (2002); lapwings occurred more frequently in areas with less intensive agriculture (i.e with more semi-natural habitat in the area) however, lapwings tended to occupy the more intensively managed fields within the surrounding semi-natural habitat.

Lapwings bred more frequently in bigger, less enclosed fields, whereas lapwing density was higher in smaller fields and unrelated to how enclosed the field was. The lapwing density model recorded no significant effect of field enclosure presumably because the most enclosed fields were not used by lapwings, and so were not included in this model. The contrasting results in terms of field area potentially relate to the lack of enclosure in fields that were used by lapwings; several small unenclosed fields next to each other would provide as open a vista (Milsom *et al.* 2000, Small 2002) as one large enclosed field. Lapwing densities may have been higher in smaller unenclosed fields due to higher heterogeneity within the landscape, potentially with arable fields in close proximity to grassland providing preferred nesting habitat within reach of suitable chick rearing habitat, or allowing for more intensively managed fields within a semi-natural area (Galbraith 1988b, Galbraith 1989b, Small 2002, Sheldon *et al.* 2004).

The field scale models included Site as a random (grouping) effect. The proportion of the variability in the data accounted for by Site in the presence / absence model was close to 60%, suggesting that the biggest determinant of whether a field was used by lapwings was whether or not lapwings were present in other fields in close proximity (i.e. within the same Site). In contrast to this, only 7% of the variability within the density model was accounted for by Site, indicating that high density fields were mainly the result of habitat factors within fields; this has implications for the site scale models.

Factors affecting breeding lapwings at the site scale: Stage 1 habitat variables identified to be influential by previous research

When data were pooled at the site level, the density of breeding lapwings was higher for sites with short vegetation, and higher levels of flooding and rush cover. Averaging rush cover across a site is effectively an index of long-term site wetness (O'Brien 2001), illustrated by the higher levels of collinearity between flooding and rush at the site scale and the strong relationship between wet 1 and lapwings is unsurprising, given the importance of wetness for breeding lapwings (Berg 1993, Rhymer *et al*. 2010).

Converting field scale variables to the site scale inevitably reduced variability within the data and would be expected to results in a loss of explanatory power. However, the proportion of deviance explained by the fixed effects in the field scale density model (0.23), was comparable to the proportion of deviance explained by the site scale model, that included the same variables (0.20), indicating that combining the field scale variables into site scale variables did not adversely affect the model. Furthermore, relationships between lapwing density and habitat parameters at the site scale were consistent with those at the field scale and established lapwing habitat preferences indicating that site scale models, derived from field scale characteristics, can identify factors important in determining species' distribution.

Factors affecting breeding lapwings at the site scale: Stage 2 adding soil and topographical variables

Adding soil and topographical data to the site scale model, improved model fit by close to 60% (from 0.20 to 0.31, whilst accounting for the additional parameters added in the soil model), revealing their importance in determining the distribution of breeding lapwings. The improvement in model fit by adding these variables occurred despite the length of time (17 to 27 years) between soil data collection and the lapwing surveys. The length of time between soil surveys and lapwing surveys may have resulted in changes to some soil properties, with pH potentially affected by agricultural practices such as liming and acid deposition during this period (Kuylenstierna & Chadwick 1991, Baxter, Oliver & Archer 2006, Emmett *et al.* 2010). Soil organic matter and soil depth may also have changed, due to differential rates in soil erosion and deposition (White 2006). Whilst both these processes are natural, erosion can be sped up by human activity, with repeated tillage of agricultural fields potentially doubling the speed of erosion. Further to this, a significant decline in soil carbon occurred in arable soils in the UK between 1978 and 2007, whilst there was no change in grassland soils (Emmett *et al*. 2010).

Lapwing density was highest at higher altitude sites with relatively less peaty (lower soil organic matter) and less acidic soil, both flatter and hillier sites with these characteristics supported higher densities of breeding lapwings than sites without these characteristics. Whilst it would be expected that steeper sites would be less suitable for breeding lapwings (Small 2002) it is likely that flatter fields within the more hilly sites were used more frequently by lapwings than steep fields but that this relationship was obscured at the site scale. Sites with deeper soil supported higher densities of breeding lapwings.

Lapwing density was not related to soil 1 which accounted for over 60% of the variability within the four soil and topography variables, and described the typical relationship that exists between altitude, slope, soil organic matter and soil pH; namely that sites at lower altitudes are generally flatter with less peaty (mineral soils) and less acidic soils, whereas higher altitude sites tend to be more hilly with peaty, acidic soil. This lack of relationship between lapwing density and soil 1 suggests that the majority of sites surveyed did not support high densities of breeding lapwings. This is indeed the case with lapwing density exceeding 16.8 pairs km^{-2}, the threshold density previously identified as defining a key site for this species in Scotland (O’Brien & Bainbridge 2002), at fewer than 10% of sites.

Higher densities of lapwings at sites at higher altitude are likely to be the result of lower agricultural production in these areas due to generally lower agricultural land capability. Lower agricultural productivity means that agricultural practices associated with intensification, which have had detrimental effects on breeding lapwings, (e.g. land drainage; see Chapter 1), are likely to have occurred to a lesser extent or not at all within these areas and this has resulted in marginal farmland becoming particularly important for breeding lapwings (Forrester *et al*. 2007). However, not all sites at higher altitudes supported high densities of breeding lapwings. The soil / topography principal components that explained lapwing distribution were those that indicated a positive effect of higher soil pH and lower soil organic matter on lapwing densities. This suggests that only those marginal sites with relatively less peaty, less acidic soil are capable of supporting high densities of breeding lapwings. A likely contributing factor to the importance of these less peaty, less acidic areas for breeding lapwings is that earthworm abundance is suppressed in peat as a result of acidity, poor quality of the organic material and water logging, with higher earthworm densities in less peaty, less acidic areas (Guild 1951, Satchell 1955, Edwards & Bohlen 1996), providing more food for lapwings (Galbraith 1989a, Beintema *et al.* 1991, Sheldon 2002).

Less peaty less acidic soil is atypical at higher altitudes in Scotland, as a result of relatively high rainfall leading to leaching of calcium, magnesium, potassium and sodium out of the soil and thus acidic soils (White 2006, Aitkenhead *et al*. 2012). This is further exacerbated by the low buffering capacity of much of the underlying geology in Scotland, with outcrops of Cambrian and Dalradian limestone, with infinite pH buffering capacity, restricted to less than 1% of the country (Langan & Wilson 1992, Hurnung *et al.* 1995). Historically the practice of agricultural liming has been used to counteract poor crop (including grass) growth in acidic soils by raising soil pH, however there has been a decline in lime use in Great Britain since the 1960s (see Chapter 1), which is likely to have reduced the area of land suitable for breeding lapwings due to an increase in soil acidity.

Lapwing density was positively related to soil depth, and this may also result from the relationship of earthworms with soil conditions. Anecic earthworms, the ecological group of earthworms that live in deep burrows but feed on the soil surface, cannot build their burrows in shallow soils and require deep soils to persist (Edwards & Bohlen 1996, Curry 2004), therefore deeper soils could potentially support higher densities of earthworms.

Soil depth also influences available water capacity within the soil (Poggio *et al*. 2010) and deeper soils can stay wetter for longer under the same environmental conditions, due to the larger volume of water that is stored (Tromp-van Meerveld & McDonnell 2005). The positive relationship found here between lapwings and soil depth could well be due to the resilience of deeper soils to drying out, with the importance of soil moisture for breeding lapwings well established.

Conclusions

The inclusion of soil and topographical variables significantly improved the site scale habitat association model for breeding lapwings. Lapwings occurred at highest densities at higher altitude sites but only when soils were relatively less peaty and less acidic. Areas where these conditions occur naturally are scarce in Scotland and habitat conditions for breeding lapwing in marginal areas outside of these naturally occurring areas, has potentially declined due to a reduction in agricultural liming (see Chapter 1), contributing to a fall in soil pH in marginal, grassland areas (Kuylenstierna & Chadwick 1991, Baxter, Oliver & Archer 2006). This has significant implications for the conservation of breeding lapwings, which have undergone severe population declines as a result of agricultural intensification, which has been most pronounced in the lowlands and has led to marginal farmland becoming of critical importance for this species.

Chapter 5 The economic costs and benefits of managing upland grassland systems in a “lapwing friendly” manner

5.1 Abstract

To date, agri-environment schemes (AES), targeted at breeding waders, have had limited conservation success and vary widely in their cost-effectiveness. This study assessed the economic costs and benefits of an upland grassland management system (fodder crop management) that is associated with unusually high densities of breeding lapwings and currently operates without the financial benefits of an AES. Fodder crop management involves cultivation of a forage brassica for two consecutive years followed by reseeding with grass. This process provides the farmer with a mechanism for fattening lambs over autumn and winter during a period when livestock feed demands are likely to outstrip grass growth, and ultimately results in grass that will provide a higher yield than that which it replaced for five years. The profitability of fodder crop management was assessed under ten different price scenarios, using data on past costs from 2000 to 2010 and compared to five alternative grassland management strategies. The simple analysis of costs and revenues used here, indicates that fodder crop management is likely to provide similar profit margins to alternative grassland management systems. However, the high set up costs coupled with adaptations that have been put in place to benefit lapwings at the study site mean that a financial incentive may be required to encourage wider adoption of fodder crop management to benefit lapwings. Simple analyses presented here suggest that an incentive be in the region of £200 ha^{-1}, however, further analysis is required to take into account uncertainty in yield estimates and profits obtained from selling lambs.

5.2 Introduction

Agriculture is the principal land use across Europe and in the UK alone over 17 million hectares, equating to around 70% of the land area, were classed as agricultural land in 2011 (DEFRA 2012). With such a vast area of land involved, farming has a fundamental role in the delivery of ecosystem services, in addition to meeting increasing demands for food (Zhang *et al*. 2007, Power 2010). Delivering environmental benefits can conflict with optimising economic gains and since 1992 the EU has provided funding in the form of agri-environment schemes (AES) to encourage the adoption of "environmentally friendly" management practices by compensating for lost income (Donald *et al.* 2006). To date the success of AES in halting declines in biodiversity associated with agricultural intensification has been mixed (Kleijn & Sutherland 2003, Whittingham 2011). Reasons for failure of AES in increasing species abundance include implementation at too small a spatial scale to have a significant impact either on individuals or at the population level (Fuentes-Monteymayor, Goulson & Park 2011, O'Brien & Wilson 2011), lack of appropriate schemes for certain species, taxa or farming systems (Redpath *et al.* 2010, Fuentes-Monteymayor, Goulson & Park 2011) and a lack of flexibility within schemes to adapt to new information or allow land managers to use their own experience to bring about benefits (Gibbons *et al.* 2011, Whitthingham 2011). When schemes are targeted effectively and are able to adapt they can provide the desired conservation benefits (Perkins *et al.* 2011).

Farmland breeding waders have suffered significant population declines and several studies have assessed the effect of AES on these birds (Kleijn *et al.* 2001, Ausden & Hirons 2002, Kleijn & Zuijlen 2004, Ottvall & Smith 2006, Wilson *et al.* 2007, Verhulst, Kleijn & Berendse 2007, O'Brien & Wilson 2011). Dutch AES, involving the restriction of agricultural operations on meadows during the wader breeding season, stop nests from being destroyed by activities such as mowing, and should therefore result in improved productivity; however, breeding populations on land managed under AES have not increased in comparison to those on conventionally managed farms

(Kleijn *et al.* 2001, Kleijn & Zuijlen 2004, Verhulst, Kleijn & Berendse 2007). In the UK, populations of breeding waders on land managed under AES have fared better than those on conventionally managed farms (Wilson *et al*. 2007, O'Brien and Wilson 2011). However, the cost effectiveness of different prescriptions has been variable (Ausden & Hirons 2002, Wilson *et al*. 2007), and the current area of land managed under AES is estimated to fall well short of that required to reverse on-going declines (O'Brien and Wilson 2011).

There is an urgent need to deliver conservation benefits for waders on farmland in a cost-effective manner. Whilst AES have been developed to try and fulfil this requirement, there may be certain management systems which provide both ecological and economic benefits and can therefore be promoted without the need for compensatory payments (see Osgathorpe *et al*. 2011). The aim of this study was to assess whether a system that provides ecological benefits but that was started for economic reasons, and currently operates outside on an AES, really is economically viable.

Fodder crop management is an in-bye management system that is associated with high densities of breeding lapwings (Chapter 2). Fodder crop management was instigated at the study site as a mechanism for improving grassland productivity and to provide forage over the autumn / winter during a period when grass growth is insufficient to meet the forage demands of livestock. If fodder crop management is economically viable then it could be promoted more widely without the need to secure agri-environment funding. Here the profitability of fodder crop management is assessed over a range of past prices and compared to five alternative grassland management strategies that are likely to be used at farms comparable to the study site, specifically addressing the questions:

1) Is fodder crop management profitable?

2) How does the profitability of fodder crop management compare to alternative grassland management systems?

5.3 Methods

5.3.1 Estimating profits from fodder crop management

Fodder crop management has been in operation at the study site since 1997 and has been used in seven in-bye fields to date (Chapter 2). Tyfon (*Brassica campestris* x *B.rapa*, a variety of stubble turnip) is planted, in fields that were previously permanent pasture, in late June or early July and is used to fatten lambs over the autumn and winter. The tyfon field remains out of production until the following June / July when it is planted with tyfon again a year after it was first grown. Following two consecutive years of tyfon the field is reseeded with grass (perennial rye-grass *Lollium perenne* and clover *Trifolium repens* seed mix) in June or July the following year. Soil pH is tested prior to growing tyfon. Lime (5 tonnes ha^{-1} $annum^{-1}$) is applied in up to three consecutive years with the first application at the time that tyfon is first planted. The objective of liming is to raise soil pH to pH 5.8 to coincide with grass reseeding. Fertiliser (NPK, 250 kg ha^{-1}) is applied at the same time as tyfon or grass is planted and continues to be used on an annual basis after reseeding.

At the study site, tyfon is used for fattening lambs that are raised to “store” level (require further fattening before they can be sold for slaughter) on grass fields on the farm. Extra store lambs produced at the farm that cannot be “finished” (fattened, ready for slaughter) on tyfon are sold to be fattened elsewhere prior to slaughter.

Fodder crop management ultimately results in reseeded grassland which is more productive than the old pasture that it replaced for approximately five years (EBLEX 2008). To account for the full period that fodder crop management affects costs and revenues, these were calculated for a system involving one hectare at each stage of the fodder crop management process, i.e. two hectares of tyfon, representing the first two years and five hectares of grass ranging from zero to four years old, representing the five years when new grass is more productive than the permanent pasture it replaced. This would be the equivalent of fodder crop management rotating round the farm (as it does at the study site), with different fields at different stages of the process, and allows for all costs and revenues to be calculated within the same year period.

Profits were estimated using data on past costs and revenues, and compared across prices from 2001 to 2010, which were obtained from the Farm Management Handbook (SAC 2000 – 2009) and the Economic Report on Scottish Agriculture (Scottish Government / Scottish Executive 2001 – 2012). Revenues were calculated from the number of black-faced lambs (the breed produced at the study site) that the system was estimated to produce. Typical yields for tyfon and grass, and the number of lambs that can be fattened on one hectare of tyfon, are published within the agricultural advisory literature produced by the advisory bodies in Scotland (SAC), England (EBLEX) and Wales (Hybru Cig Cymru), and this data was used. The number of lambs that can be produced on grass is not provided directly with the agricultural literature, as such, this was calculated based on ewe feed requirements of 640 kg dry matter (DM) per annum, and lamb food requirements of 214 kg DM during the period from birth in April until the beginning of December (data from SAC 2009), when they would be moved to tyfon. Ewes were assumed to produce on average 1.35 lambs per year, and dry matter utilisation was assumed to be 70% (SAC 2009).

It was assumed that tyfon would be used to fatten store lambs produced on grass within the system. However, the number of lambs that was estimated to be fattened on tyfon exceeded that which would be raised to store level (ready for fattening) on the five grass hectares representing the later stages of fodder crop management. Therefore 7 ha of permanent grassland, equivalent to the in-bye fields at the study site that had not undergone fodder crop management, were added in order that lambs fattened on tyfon could all be raised from birth to slaughter within the system.

Costs were calculated including both establishment and maintenance costs. The cost of establishment consisted of seed, contractor employment (to carry out tillage, sowing, rolling and spreading), fertiliser and lime. Maintenance costs resulted from application of fertiliser to fields that had been reseeded with grass. Permanent grass fields did not receive any inputs and therefore had no costs within this simple analysis.

5.3.2 Estimating profits from alternative management systems

Estimated profit from fodder crop management was compared to five alternative grassland management strategies. The alternative management strategies are considered to occur at livestock farms comparable to the main study farm, and indeed a combination of strategies 1 – 4 operate in in-bye fields at the study farm that have not undergone fodder crop management; these were:-

1) Grass older than five years with no inputs (Grass >5yr)
2) Grass older than five years with inputs of NPK (Grass >5yr - NPK)
3) Grass older than five years with inputs of lime (Grass >5yr - CaO)
4) Grass older than five years with inputs of NPK and lime (Grass >5yr – CaO, NPK)
5) Grass reseeding in the first year, directly replacing grass older than five years with a new seven year ley, receiving inputs of NPK and lime (Reseed – CaO ,NPK)

For a fair comparison with the fodder crop management system outlined above, these management strategies were applied to seven hectares. An additional seven hectares of permanent grassland with no inputs (the same as system 1, Grass >5yr), was added to each system, as was done for fodder crop management. These 7 ha of permanent grassland were not attributed with any costs as there were no inputs added, however, they were estimated to produce 28 store lambs which were included within the revenues of all systems.

In each of the relevant systems, NPK was included for all seven hectares under management. To provide an initial estimate of how sensitive the analysis used was to yield estimates from different management, lime was added to the relevant systems across two different areas, but attributed with the same yields and therefore livestock produced for the two areas:

1) Lime was applied to 1.4 ha of the 7 managed grassland hectares – this is a fifth of the managed grassland area, and equates to the general recommendation that lime should be applied to grassland once in every five years (SAC 2009).
2) Lime was applied to 3 ha of the 7 managed grassland hectares – this is the quantity of lime that was applied for fodder crop management so is likely to provide a fairer comparison between fodder crop management and the alternative grassland management strategies involving liming, due to the yield estimates for each field type.

5.4 Results

5.4.1 The costs and benefits of fodder crop management

Fodder crop management produced 8 tons of dry matter (DM) from 2 hectares of tyfon, 52 t DM from the 5 ha of grass that represented the later stages of fodder crop management and a further 28 t DM from the 7 ha of permanent grassland, that were added to the system, in order that all lambs fattened on tyfon could be produced to store level on grass within the system (Table 5-1). The whole system resulted in 80 finished (fattened) lambs.

Fodder crop management was profitable under all 10 years of cost scenarios, with a mean profit of £1398 for the full 14 ha within this management system (Figure 5-1). The highest profits were obtained under 2005 prices and the lowest under 2002 prices.

Table 5-1 Summary of fodder crop management for the full 14 ha of management accounting for the different stages of this management system and the permanent grass required to produce the number of store lambs that could then be fattened using tyfon. Dry matter yields and estimated number of lambs that could be produced for each stage of fodder crop management are presented. 1 = dry matter yields estimated based on SAC no date A & B, Hybu Cig Cymru 2007, EBLEX 2008 & 2011, 2 = numbers of lambs fattened by tyfon estimated from data in SAC no date A, Hybu Cig Cymru 2007, 3 = number of store lambs calculated based on data in SAC 2009.

Crop	NPK	Lime	Hectares	Total DM yield[1]	Number of lambs[2,3]	Store / fat
Tyfon	✓	✓	2	8	80	Fat
Reseeded grass	✓	✓	1	12	12	Store
Grass 1 year old	✓	x	1	10	10	Store
Grass 2 year old	✓	x	1	10	10	Store
Grass 3 year old	✓	x	1	10	10	Store
Grass 4 year old	✓	x	1	10	10	Store
Grass > 5year old	x	x	7	28	28	Store
Total			14	88	80	Fat

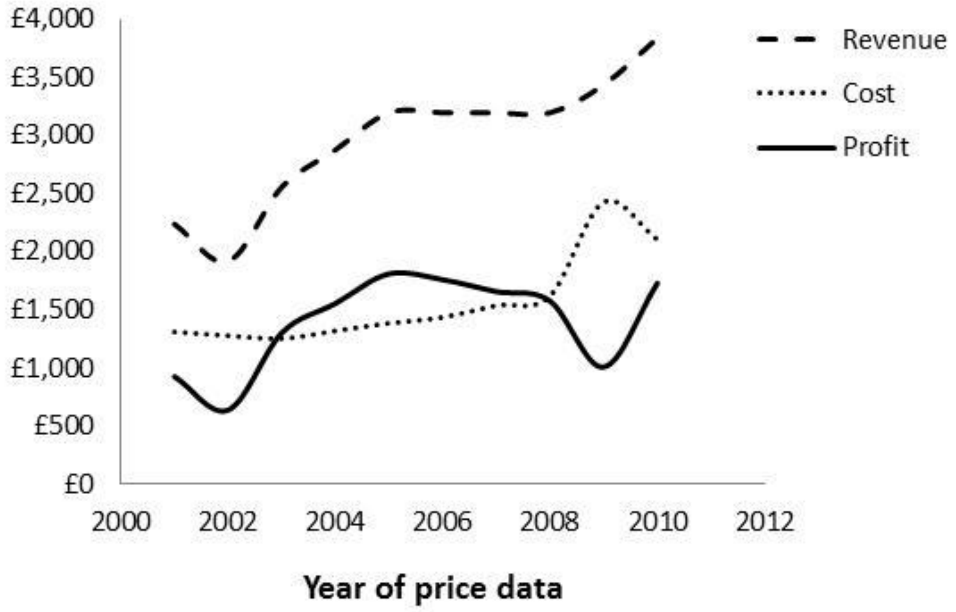


Figure 5-1 Estimated costs, revenue and profit (revenue - cost) associated with fodder crop management based on past costs from SAC 2000 – 2009 and Scottish Government / Scottish Executive 2001 – 2012.

5.4.2 Comparing the costs and benefits of fodder crop management with other management systems

Reseed- CaO, NPK produced the highest yields of the alternative management systems and therefore the highest number of store lambs (Table 5-2). The lowest yields result from the no input system (Grass > 5yr).

Fodder crop management resulted in the highest revenues under all price scenarios, however, costs were also highest for this system (Figure 5-2a, b, Figure 5-3a). Grass > 5 yrs had the lowest revenues and the lowest costs, which were calculated as zero under this simple analysis due to no establishment or input costs.

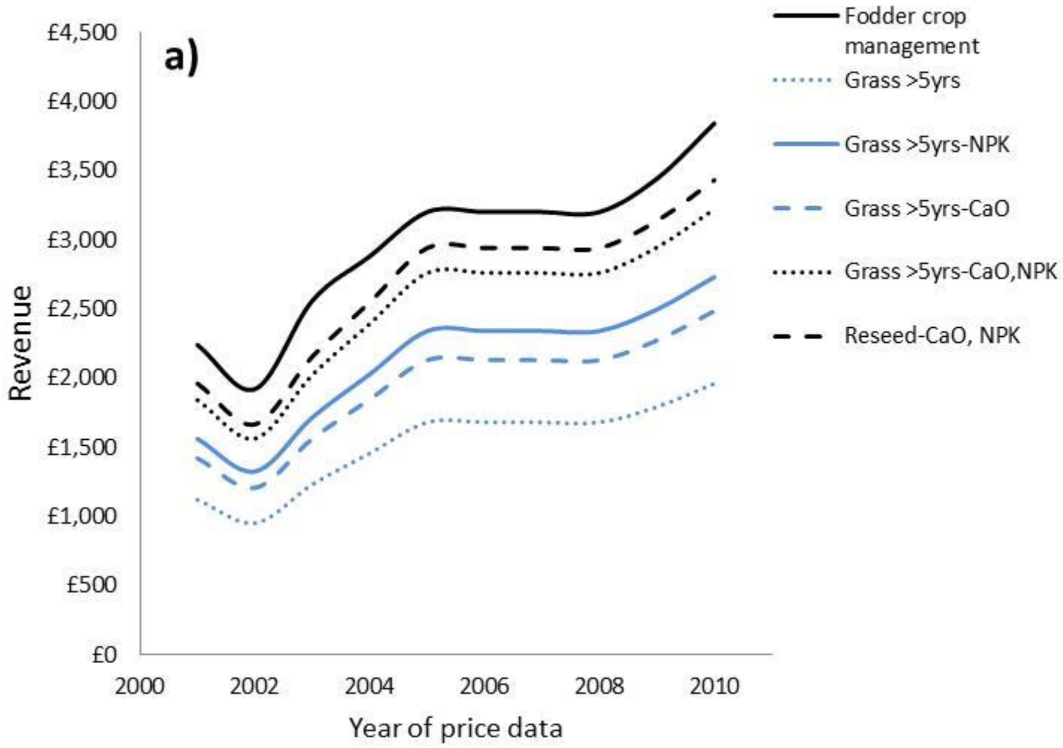
Table 5-2 Dry matter yields and number of lambs (store and fat) produced by fodder crop management and five alternative management strategies.

System	**Fodder crop management**				**Grass > 5 yr**				**Grass > 5 yr - NPK**			
Crop	No. ha	DM yield	No lambs	Store / fat	No. ha	DM yield	No lambs	Store / fat	No. ha	DM yield	No lambs	Store / fat
Tyfon	2	8	80	Fat	-	-	-	-	-	-	-	-
Reseeded grass	1	12	12	Store	-	-	-	-	-	-	-	-
Grass 1 year old	1	10	10	Store	-	-	-	-	-	-	-	-
Grass 2 year old	1	10	10	Store	-	-	-	-	-	-	-	-
Grass 3 year old	1	10	10	Store	-	-	-	-	-	-	-	-
Grass 4 year old	1	10	10	Store	-	-	-	-	-	-	-	-
Grass > 5year old	7	28	28	Store	14	56	56	Store	7	28	28	Store
Grass > 5year old - NPK	-	-	-	-	-	-	-	-	7	49	50	Store
Grass > 5year old- Ca	-	-	-	-	-	-	-	-	-	-	-	-
Grass > 5year old- Ca,NPK	-	-	-	-	-	-	-	-	-	-	-	-
Total	14	88	80	Fat	14	56	56	Store	14	77	78	Store

System	**Grass > 5 yr - Ca**				**Grass > 5yr - Ca, NPK**				**Reseed - Ca, NPK**			
Crop	No. ha	DM yield	No lambs	Store / fat	No. ha	DM yield	No lambs	Store / fat	No. ha	DM yield	No lambs	Store / fat
Tyfon	-	-	-	-	-	-	-	-	-	-	-	-
Reseeded grass	-	-	-	-	-	-	-	-	1	12	12	Store
Grass 1 year old	-	-	-	-	-	-	-	-	1	10	10	Store
Grass 2 year old	-	-	-	-	-	-	-	-	1	10	10	Store
Grass 3 year old	-	-	-	-	-	-	-	-	1	10	10	Store
Grass 4 year old	-	-	-	-	-	-	-	-	1	10	10	Store
Grass > 5year old	7	28	28	Store	7	28	28	Store	7	28	28	Store
Grass > 5year old - NPK	-	-	-	-	-	-	-	-	-	-	-	-
Grass > 5year old- Ca	7	42	43	Store	-	-	-	-	-	-	-	-
Grass > 5year old- Ca,NPK	-	-	-	-	7	63	64	Store	2	18	18	Store
Total	14	70	71	Store	14	91	92	Store	14	98	98	Store

Under lime application area 1 (1.4 ha out of 7 limed), on average Grass > 5yrs, Ca was the most profitable system, with mean profitability of £1667 for the full 14 hectares (Figure 5-2c). Grass > 5yrs, NPK was the least profitable system overall with mean profitability of £1383 and fodder crop management was the second least profitable system with mean profit of £1398, and had the lowest profit based on 2002 prices at just £640. Overall, profitability of fodder crop management was around 80% of the most profitable system.

Under lime application area 2 (3 ha out of 7 limed), Grass > 5yrs is on average the most profitable system, and fodder crop management becomes the second most profitable system (and the most profitable system in four of the ten years considered), with overall profitability around 90% of the most profitable system (Figure 5-3b). With lime applied to this area, Grass >5yrs – CaO, NPK is the least profitable system and Reseed – CaO, NPK the second least.



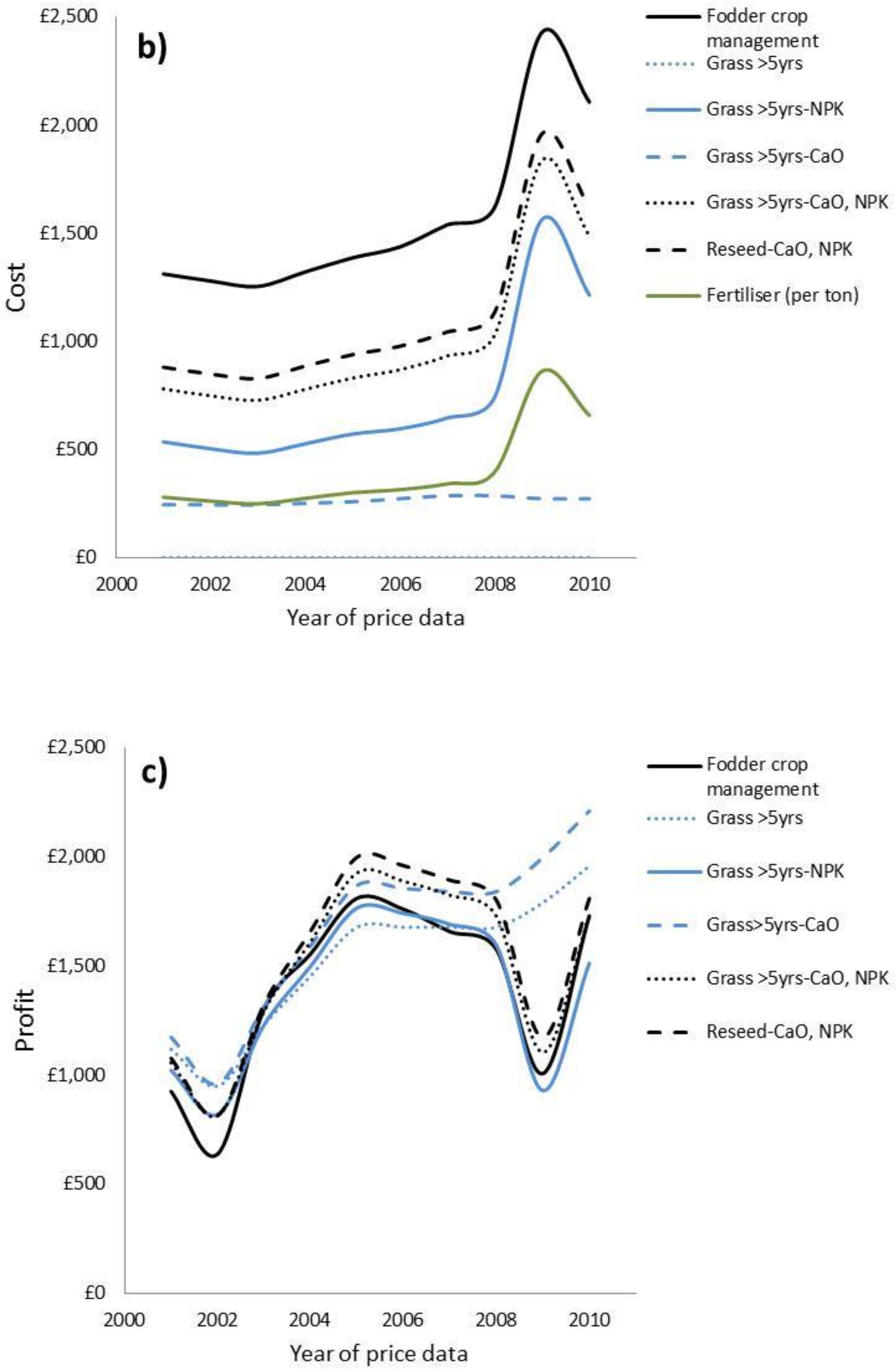


Figure 5-2 Comparison of a) costs, b) revenues and c) profits of fodder crop management to five alternative systems, using lime application area 1 (lime applied to 1.4 ha) for the relevant grassland systems.

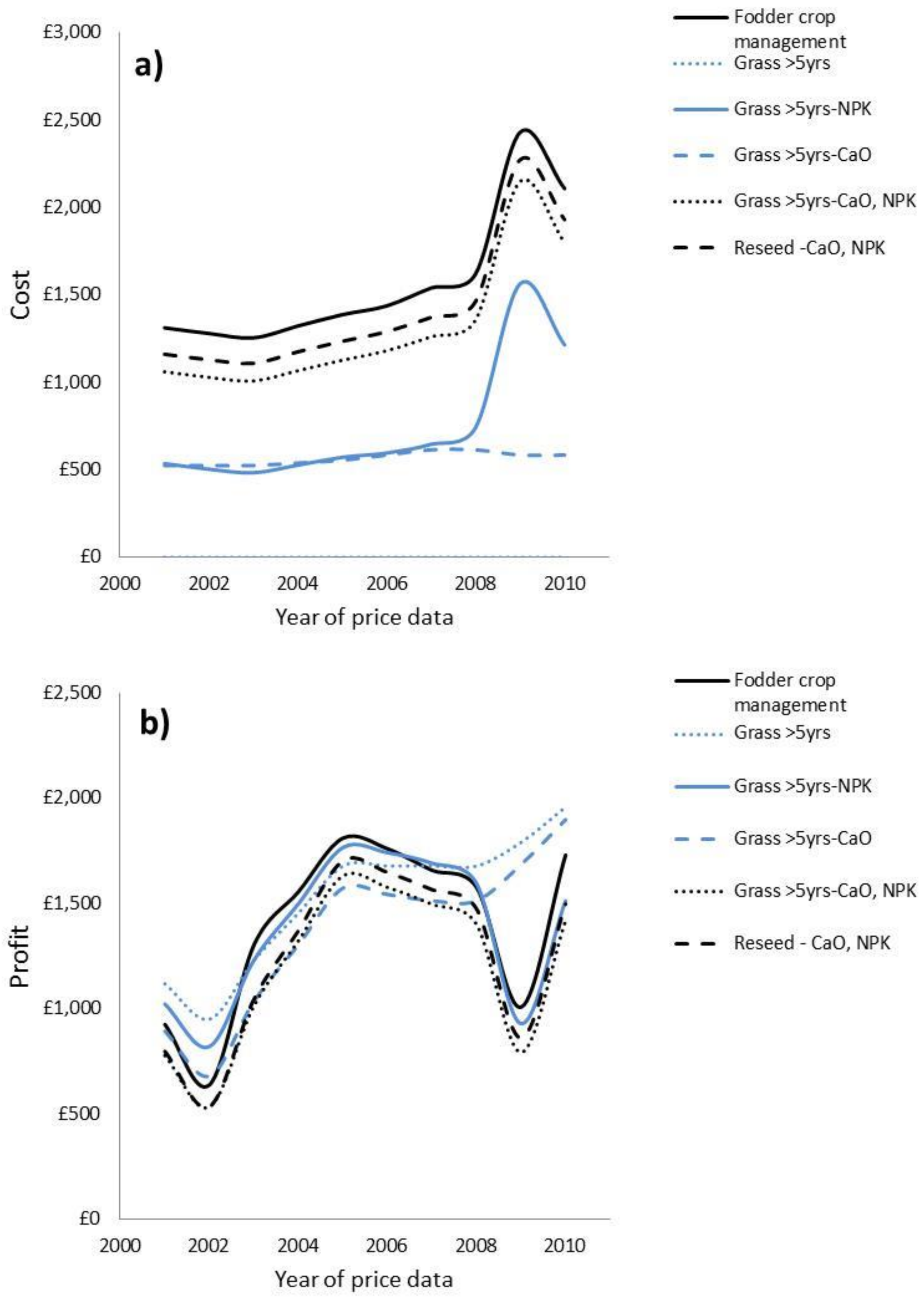


Figure 5-3 Comparison of a) costs, and b) profits of fodder crop management to five alternative systems, using lime application area 2 (lime applied to 3 ha) for the relevant grassland systems.

5.5 Discussion

This simple analysis of costs and revenues indicates that fodder crop management, an in-bye management system associated with high densities of breeding lapwings, is profitable and can achieve higher profits than some alternative in-bye grassland management systems. However, the associated costs of fodder crop management are higher than for all other systems examined and when coupled with low profit margins under some price scenarios, might discourage farmers from adopting this management system. The profitability of fodder crop management in comparison to other systems is dependent on lamb prices remaining sufficiently high to offset the higher set up costs, and also on the area of land that requires to be limed to achieve the estimated yield increases.

Fodder crop management is the only system assessed that provides forage for fattening of lambs and was therefore the only system that resulted in lambs that could be sold directly for slaughter. Whilst the difference between store and fattened lamb prices reported in the farm management handbook is quite small, lamb price is highly variable so the difference between the two prices may also vary throughout the year (Appendix A). Furthermore, use of a fodder crop provides feed at a time of year when livestock demands are likely to outstrip grass production and this provides greater flexibility with when lambs are sold as there is a means of feeding them whilst waiting for prices to become more favourable, essentially allowing the farmer to “play the stock market” (*pers com* John Vipond, SAC). The likely benefits of this were not captured within the simple analysis conducted here.

5.5.1 Sources of uncertainty in profit margins

Whilst calculating set up and maintenance costs of management systems is relatively straightforward, estimating profits associated with grass or fodder crops which are not tradable commodities can be problematic (Doyle & Elliot 1983). It was not possible to use livestock numbers produced from different field types (e.g. tyfon or newly reseeded grass) from the study site, as the farmer leaves gates between fields open, allowing livestock to move freely between fields; this makes it impossible to ascertain the number of livestock that fields with different management histories have produced. As such, the method applied here relied on estimated yields and numbers of livestock that yield could support based on agricultural advisory literature produced in the UK. This literature is designed for all livestock farms, including those in lowland areas which will generally have higher yields than farms at higher altitudes (such as the study site), and there is likely to be year on year and farm by farm variability in yields that are achieved. Further to this, naturally wet areas at the study site, which are of critical importance to lapwings (Chapter 2), will be agriculturally less productive and this was not considered within the analysis. However, although overall yields may not be as high as estimated, the different management systems are expected to provide comparatively similar changes in percentage yield if applied to similar farms. Costs of labour and supplementary feed were not considered which introduces an additional source of error, and these are likely to be higher for systems that support more livestock.

When livestock are fed on fodder crops they require a dry area where they can rest outside of the fodder crop area which is known as a dry lie-back area (Hybu Cig Cymru 2007). At the study site this is provided by leaving gates between tyfon and grass fields open and the areas required for this was not factored into the analysis, potentially raising the cost of fodder crop management. Further uncertainty in estimated number of livestock that could be produced from tyfon arises from the grazing system employed at the farm, which is an extensive system, with continual grazing. Published figures are based on strip grazing with a small lie-back area. This means that utilisation rates of tyfon may be different at the study site to published figures, particularly as tyfon fields are left open to livestock right up until when they are re-planted with tyfon for a second year or planted with grass, so livestock are able to (and do; *pers. obs.*) feed on any weeds that grow over this time.

5.5.2 The cost of agricultural inputs

At the study site, fields that have been reseeded with grass as part of fodder crop management are maintained with annual fertiliser inputs. Fertilisers are widely used to improve grassland yields and around 60% of grassland received nitrogenous fertiliser in Great Britain in 2011 (DEFRA 2012b). Comparison of costs and revenues of grass with and without fertiliser inputs indicates that this is not always economically beneficial, with grassland receiving no inputs more profitable than grass receiving NPK under half the cost scenarios considered. The profitability of fertiliser application depends on both lamb prices and the cost of fertiliser and there has been a decline in the quantity of nitrogen applied to grassland in Great Britain since the early 1990s (AIC 2012). This corresponds with a period of rising fertiliser prices (Scottish Government 2012), in addition to the introduction of the EU Nitrates Directive, which aims to reduce levels of nitrogen pollution (http://ec.europa.eu/environment/pubs/pdf/factsheets/nitrates.pdf, accessed 17 September 2012).

The economics of fertiliser use is reliant on associated yield increases, and the poor economic performance of fertiliser inputs under half the price conditions assessed suggests that the 75% increase in yield used here (based on data in the Farm Management Handbook, SAC 2009) could be on the conservative side. However, this is towards the top end of published yield increases on permanent grazing pastures with the addition of nitrogenous fertilisers; other estimates range from 27% increase at an upland site in Scotland (Barthram *et al*. 2002), to 70% increase across a number of commercial farms in Northern Ireland (Adams 1984) and 73% increase on an upland site in Wales (Fothergill, Davies & Morgan 2001). It is likely that farmers would reduce fertiliser inputs in years when prices are particularly high and the cost of fodder crop management could be reduced by limiting fertiliser inputs once the field had been returned to grass if fertiliser prices were too high at the time to provide an economic advantage. Reducing fertiliser inputs is unlikely to reduce the suitability of fields for breeding lapwings.

Liming is likely to be a critical part of fodder crop management both for crop growth (and therefore numbers of lambs that can be fed) and for breeding lapwings (see Chapters 2 and 3). The use of lime in the purely grassland systems examined here, shows that liming is likely to be more cost effective than applying nitrogenous fertilisers if the application rates used in area 1 (i.e. 1.4 ha out of 7 ha limed = 20%) provide the yield increase attributed to this. However, when the area of lime was increased to match that which occurred under fodder crop management (i.e. 3 ha out of 7 ha limed), but only attributed with the same yield increase as area 1, liming is no longer cost effective. This illustrates the major limitation of this analysis, i.e. that it relies on a number of assumptions in terms of yields that will be produced from each field type and the number of livestock that this can produce. Furthermore, by changing the quantity of lime required to obtain the same yield, it can be seen that the analysis is quite sensitive to the yields involved.

Published yield increases due to liming are highly variable and it is not unreasonable to assume that the effects of lime will vary across different farms and potentially different management systems. Published yield increases from liming range from no consistent effect on Northern Irish pastures (Adams 1984) to almost 90% more sheep supported by Welsh upland pasture that had been limed six years previously in comparison to the non-limed treatment (Fothergill, Davies & Morgan 2001). The variable effect of lime on yield may be a contributory factor in the low percentage of grassland that receives lime within Great Britain (4% in 2011; DEFRA 2012b), in comparison to nitrogenous fertilisers. However, the effect of lime withdrawal is likely to be cumulative with longer periods without lime resulting in progressively lower yields as the soil becomes more acidic, and lime can have a greater effect on yield when applied to soil with lower starting pH (Fystro & Bakken 2005, but see Stevens & Laughlin 1996). The economic benefit of liming is therefore specifically related to soil conditions and regular soil analysis is recommended to inform the need for lime application (SAC 2010).

5.5.3 Potential loss of income due to delaying agricultural operations for lapwings

Stubble turnips, of which tyfon is one variety, can be planted anytime between May and August. However the yield, and hence the number of lambs that can be fed is dependent on sowing date, with later planting resulting in lower yields (SAC 2009) and potentially lower profits. At the study site, planting of tyfon (and grass) is delayed until July (the farmer previously planted tyfon in May) to avoid agricultural operations in fields that are used by lapwings during the breeding season. Delaying the planting of tyfon until July potentially reduces the number of lambs that can be fattened on 1 ha from around 60 to 40 (N.B. the reported number of lambs that can be supported by stubble turnips is highly variable). If this is indeed the case, offering farmers compensation for the reduction in lambs that can be fattened by planting tyfon at a “lapwing friendly” time of year, may encourage them to adopt this management. Based on the mean of the difference in the price of finished and store lambs from 2001 to 2010, and a reduction of 20 lambs that can be fattened by delaying planting, a compensatory payment of around £200 ha^{-1} is potentially required.

Conclusions

This simple analysis of the economic costs and revenues associated with fodder crop management indicates that fodder crop management is a profitable system and can generate higher profits than other systems under certain circumstances. However, delaying planting of tyfon to avoid agricultural operations during the lapwing breeding season, will reduce the yield and hence the number of lambs that can be fattened. This suggests that a compensatory payment may be required to encourage adoption of fodder crop management in a “lapwing friendly” manner and an initial estimate of £200 ha^{-1} was calculated. However, delaying planting until July means that the fodder crop can be grazed between November and January, instead of in August or September (Hybu Cig Cymru 2007) and this potentially increases the value of the crop to the farmer, as the availability of grass is likely to be lower in the winter than at the end of summer. Further to this, the analysis used was sensitive to the yields and the associated number of livestock that were estimated to be produced from each system and it is recommended that further exploration into the actual yields produced by conducting fodder crop management in a “lapwing friendly” manner be carried out prior to determining whether a compensatory payment is required and if so how much this should be.

5.6 Appendix A – Variation in lamb prices

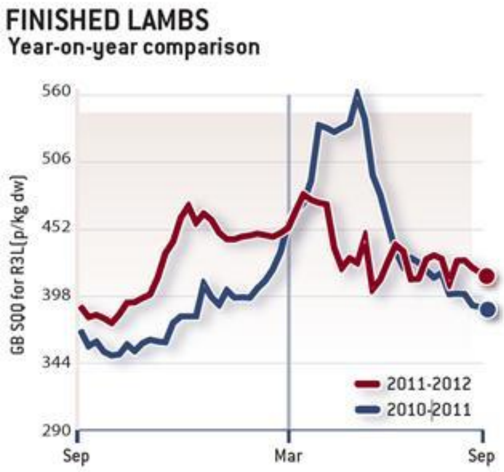


Figure 5-4 Within year variability in lamb price from: http://www.fwi.co.uk/gr/graphs.pdf Accessed 17 September 2012.

Chapter 6 General discussion

Within this thesis I aimed to improve the understanding of breeding lapwings on in-bye grassland to inform future conservation management for a species that is undergoing wide scale declines. Townhead Farm provided an ideal opportunity to conduct farm scale and field scale research into the relationship between the unusual in-bye management system (fodder crop management) and exceptionally high densities of breeding lapwings at the farm. Lapwings are a well-studied species; however, this is the first study to relate lapwing distribution to soil properties, other than moisture. In addition to researching the ecological effects of management, I also explored the potential costs and revenues associated with management and made an initial estimate of a compensatory payment that could be provided as a financial incentive to farmers to encourage adoption of fodder crop management.

6.1 Key findings

6.1.1 Ecology

The density of breeding lapwings at the study site was almost 60% higher on in-bye fields that had undergone fodder crop management compared to those which had not, whilst controlling for other field characteristics that influence lapwings, indicating that the unusually high densities of lapwings at the study site are driven by fodder crop management (Chapter 2). Lapwing densities were highest in the first spring after tyfon is planted (Chapter 2) likely resulting from the high percentage of bare ground and variability in ground micro-topography created by grazing over winter (Chapter 3), providing ideal nesting habitat (Shrubb 2007) and improved detectability of food (Devereux *et al*. 2004). The field experiment was on too small a scale to attract nesting lapwings, so the suitability of the habitat was inferred, based on the vegetation structure, rather than tested directly (Chapter 3). However, experimental management was also conducted at RSPB's Geltsdale reserve in Cumbria, where vollenda, an organic alternative to tyfon was planted and four lapwing nests were initiated in the vollenda plot over two breeding seasons, in an area of the reserve where lapwings had not previously nested (*pers. com.* Ian Ryding, RSPB Geltsdale), adding further support to this hypothesis. Feeding observations at Geltsdale also suggested higher prey detectability within the open vegetation structure created by grazing of stubble turnips over winter, with lapwings observed foraging more frequently in the vollenda plot than in the adjacent grassland area, despite higher earthworm abundance in the grassland area in the first year after management (Chapter 3).

The density of breeding lapwings at the principal study site declined with number of years since a field was last planted with tyfon, however, the density of lapwings remained above that which occurred in fields that had not undergone fodder crop management for approximately four years after the field had been reseeded with grass (Chapter 2). Lapwings exhibit high site fidelity typically returning to the same field year on year to breed (Thomson *et al*. 1994). Consequently, this trend could result from attraction of birds into the field when the nesting structure is good (i.e. when tyfon has been grazed over winter), with the downward curve once the field is returned to grass simply a consequence of survival of site faithful birds. This study did not involve colour ringing so it is not possible to rule this out entirely, but further evidence gathered in chapters 2 and 3 does show that fodder crop management results in better conditions for breeding lapwings which persist when the field is reverted to grassland. Sparse rush patches were used more often than other habitats for both nesting and chick rearing and these patches were more prevalent in fields that had undergone fodder crop management than those that had not, likely resulting from conversion of denser patches of rush to tyfon, with rush re-developing over time in these naturally wet areas, forming sparse rush patches, which are likely to eventually become dense patches again (Chapter 2). Chick foraging location was related to higher densities of

Allolobophora chlorotica (Chapter 2), an acid intolerant earthworm (Satchell 1955, Edwards & Bohlen 1996) whose abundance increased with the application of lime at the field experiment and occurred in soil towards the upper end of the pH scale in the between-field correlative study (Chapter 3). This suggests that this species has benefitted from liming conducted as part of fodder crop management. *A. chlorotica* accounted for just 11% of earthworms found at the study site as part of the between-field correlative study (Chapter 3), whereas 25% of earthworms from chick foraging locations were *A. chlorotica* (Chapter 2), providing further evidence that areas rich in this species of earthworm were selected for brood rearing.

Fields which had undergone fodder crop management had higher soil pH than those that had not, with soil pH declining with number of years since lime was last applied, returning to that which occurred in fields that had not undergone fodder crop management approximately 10 years after the last lime application (Chapter 3). Soil pH was predicted to remain above pH 5.2 (Chapter 3) for the entire period in which a field that had undergone fodder crop management performed better for breeding lapwings than a field that not undergone this process (Chapter 2), and this corresponds with peak total earthworm abundance and peak *A. chlorotica* abundance, which occurred at around pH 5.2 (Chapter 3). Total earthworm abundance was higher in fields that had undergone fodder crop management than those that had not, potentially related to lime use, although there was no effect of lime use on total earthworm abundance at the field experiment (Chapter 3).

The large scale analysis of lapwing distribution in relation to habitat features including soil properties provides further support for the potential benefits of liming in marginal farmland areas; lapwings occurred at higher densities on sites at higher altitudes, though, only where the soil was relatively less peaty and less acidic (Chapter 4). This has important implications given that, more rainfall at higher altitudes, leads to greater leaching rates of calcium, magnesium, potassium and sodium out of the soil and therefore soils that are more acidic (White 2006, Aitkenhead *et al*. 2012). This is further exacerbated by the low buffering capacity of much of the underlying geology in Scotland, with outcrops of Cambrian and Dalradian limestone, with infinite pH buffering capacity, restricted to less than 1% of the country (Langan & Wilson 1992, Hurnung *et al.* 1995). Historically, agricultural lime use may have improved soil conditions for breeding lapwings and their food supplies on underlying geologies of poor buffering capacity, but declines in agricultural lime use since the 1960s (Chapter 1) may have reduced this benefit.

This is the first study to use data on soil pH, soil organic matter and soil depth to explain lapwing distribution. Adding soil and topography data to the model significantly improved model fit, with an improvement of close to 60%, after correcting for the addition of extra parameters (Chapter 4). This is despite the length of time between when soil data were collected and wader surveys were conducted, with approximately 30 years time difference between the two sets of data. When the results of chapters 2, 3 and 4 are considered together, it seems probable that liming of marginal farmland, where soil pH falls below pH 5.2, could improve habitat conditions for breeding lapwings by increasing the abundance of earthworms; soils below this pH are sub-optimal for grass growth so this should be something that farmers would consider doing to improve yields and does not conflict with agricultural objectives.

Chapters 2 and 4 also confirmed established habitat requirements of breeding lapwings, emphasising the importance of targeting conservation measures for this species at fields and sites which are likely to be capable of supporting high lapwing densities. Wet features or areas are crucial, due to higher prey density and accessibility within these areas (Chapter 2, Chapter 4, McKeever 2003, Eglington *et al.* 2008 and 2010, Rhymer *et al.* 2010) and density of *A. chlorotica* increased with increasing soil moisture (Chapter 3). Short vegetation (Chapter 4, Milsom *et al.* 2000, O’Brien 2001, Shrubb 2007) and unenclosed fields are also required (Chapters 2 & 4, Small 2002).

6.1.2 Economics

Fodder crop management was profitable across all ten price conditions that were assessed, and profit margins were comparable to five alternative grassland management strategies (Chapter 5). However, high set up costs involved in fodder crop management and low profitability under some price conditions could put farmers off adopting this management. Furthermore, at the study site, planting of tyfon and grass is delayed until July to avoid agricultural operations during the breeding season, which is likely to reduce the yield that can be obtained and hence the number of lambs that can be fed.

To compensate for the loss in yield that is incurred by delaying planting of tyfon an incentive of around £200 ha^{-1} may be required to encourage farmers to adopt fodder crop management in a “lapwing friendly” manner. This estimate does not incorporate potential benefits to the farmer from planting the crop in July rather than May, as tyfon will be available for grazing in December / January rather than in August / September, providing a source of winter feed, and thus giving the farmer an opportunity to “play the stock market”. Further analysis of the benefits of winter forage in addition to yields obtained under different management conditions is recommended prior to determining if a financial incentive is really necessary and if so how much this should be. However, this simple analysis should provide a useful starting point for a more detailed assessment of the costs of management, and costs of management ought to be considered by any conservationist advising farmers on land management to improve biodiversity.

An advantage of fodder crop management over currently available agri-environment schemes (AES) for breeding waders is that it involves actively farming, rather than a payment received to reduce farming levels, such as excluding livestock from key fields during the breeding season, and this is likely to be more appealing to farmers (*pers com.* Alistair Robb, Townhead Farm).

The analysis indicates that lime use is likely to be cost effective for farmers to maintain adequate soil pH and it is recommended that regular soil testing is advocated to famers that have in-bye grasslands.

6.2 Potential wider effects of management

The diversity of organisms that live within the soil is several orders of magnitude higher than found above ground level and factors influencing this diversity and the distribution of soil biota are relatively poorly understood (Bardgett, Yeates & Anderson 2005). In 1997, NERC initiated the UK's Soil Biodiversity Research programme, to address six key questions relating to the importance of soil biodiversity in soil ecosystem functions (Usher *et al*. 2006). This involved an intensively studied field experiment at an upland grassland site in the Scottish borders (Sourhope). The Sourhope experiment consisted of treatments involving the addition of lime, nitrogenous fertiliser and both of these in relation to a control which had no agricultural inputs.

Earthworms constitute around 75% of the soil faunal biomass within temperate grassland (Bardgett & Cook 1998) and earthworm abundance increased in response to lime application at the Sourhope experimental site (Bishop 2003). Earthworm diversity was not affected by lime application at Sourhope. However, this project found that on average, earthworm diversity was higher in fields that had undergone fodder crop management than those that had not, with a mean of five different species of earthworm found in each field that had undergone fodder crop management, in comparison to four in in-bye fields that had not, and three in out-bye fields. This suggests that lime use may increase species diversity of earthworms in addition to abundance.

At Sourhope, liming increased the abundance of Collembola (springtails), whilst Acari (mites) were relatively unaffected (Cole *et al.* 2006). This contrasts with the application of nitrogen which led to increases in both Collembola and Acari. In contrast to increases in Collembola with lime application, enchytraieids (pot worms) declined; however, species richness within this community was higher in limed compared to control plots. This suggests that there could be an overall increase in species richness of mesofauna, with the use of agricultural liming.

Microbes and fungi make up by far the largest abundance and diversity of organisms within the soil (Bardgett, Yeates & Anderson 2005). Liming at Sourhope, resulted in significant increases in bacterial densities (Bruneau *et al*. 2005), bacterial heterogeneity (in the ammonia-oxidising bacteria; Gray *et al*. 2003) and the abundance of mycorrhizal fungi (Staddon *et al.* 2003). Increased diversity and activity within the archael, bacterial and fungal communities, due to liming, was associated with faster carbon cycling, which may result in reduced carbon storage within the soil and ultimately a decline in soil quality due to agricultural liming (Staddon *et al*. 2003, Griffiths *et al.* 2006, Leake *et al*. 2006). However, Biasi *et al.* (2008) found similar rates of biotic respiration in limed and un-limed soil and that lime derived carbon dioxide (CO_2) emissions were considerably lower than that assumed by the IPCC in their guidelines for calculating greenhouse gas emissions, where all carbon added as lime is assumed to be released as CO_2. Contrary to this, Biasi *et al*. (2008) found that just 1/6th of carbon from lime was released as CO_2 in the field.

In addition to direct impacts of lime involved in fodder crop management on the soil biota, fodder crop management could potentially improve habitat quality for a number of species that predate on soil macrofauna, in addition to lapwings. High densities of other farmland wader species at the principal study site indicate that these may also have benefitted from farm management. The 2007 - 2011 five year mean density of breeding redshank on the in-bye was 3.7 pairs km^{-2}, which qualifies as a key site for redshank (*Tringo totanus*) under the criteria set by O'Brien and Bainbridge (2002) of 3.6 pairs km^{-2}. Whilst the study site falls slightly below the key site density criteria for curlew (*Numenius arquata*) and snipe (*Gallinago gallinago*), the five year mean for curlew density across the whole farm (in-bye and out-bye) was 6.1 pairs km^{-2} with snipe at 3.8

pairs km^{-2}, both of which are higher than 85% of sites involved in the analysis in Chapter 5. Earthworms contribute to the diet of all of these waders so they may well have benefitted from increases in prey resources as a result of liming at the site and these species were all observed foraging on the vollenda plot at Geltsdale (Appendix A). Curlew, snipe and redshank are all birds of conservation concern in the UK with recent declines in curlew of particular concern with this species now considered Near Threatened globally (IUCN Red List; Birdlife International 2012b).

Earthworms are preyed upon by numerous other bird species as well as mammals, including hedgehogs (*Erinaceus europaeus*) and badgers (*Meles meles*), suggesting that increasing earthworm abundance could benefit a suite of species. Further to this, Additional benefits for wintering passerines are likely to be provided by weed seeds within the tyfon crop (Hancock & Wilson 2003).

6.3 Policy implications

The Common Agricultural Policy (CAP) is the primary tool for regulating farming within the European Union. The CAP provides a range of subsidies to farmers to ensure that food production needs are met, and since it was reformed in 1992, incentivises farmers to deliver environmental services and maintain animal welfare standards (http://europa.eu/pol/agr/index_en.htm , accessed 7 September 2012). CAP payments are structured into two pillars, with pillar 1 for direct support payments, currently in the form of the Single Farm Payment (SFP) and pillar 2 providing funding for rural development programmes, with AES funded by pillar 2 (Marsden 2011). Farmers need to maintain their land in Good Agricultural and Environmental Condition (GAEC) and comply with Statutory Management Requirements to qualify for SFP, and this is known as Cross Compliance (http://www.scotland.gov.uk/Publications/2005/12/0990918/09207, accessed 7 September 2012).

6.3.1 Planting fodder crops

Under GAEC farmers must not “carry out any cultivations if water is standing on the surface or the soil is saturated” (GAEC 9, Appropriate Machinery Use; http://www.scotland.gov.uk/Publications/2005/12/0990918/09207#gaec9, accessed 7 September 2012), and areas in this condition at the study site during the time of cultivation were left as unmanaged wet areas. Wet areas are essential to the lapwing population at the study site, and it is possible that farmers will be unwilling to implement fodder crop management in fields with permanently waterlogged areas due to potential difficulties in ensuring that cultivation occurs around these. If insufficient care is taken to avoid these patches this would be a breach of cross compliance and could result in a reduction in SFP received.

The CAP is currently in a period of reform and new proposals were issued by the European Commission (EC) in October 2011, including measures for “greening of the CAP”, under which all farmers would need to comply with a number of “green measures” to receive full direct payments, with “green payments” accounting for 30% of these (Swale 2012). The EC has proposed three “greening measures” and fodder crop management is potentially incompatible with two of these; crop diversification and maintenance of permanent grassland (Article 29, General Rules 1a and b, EC 2011). Under the current proposals farmers would need “to have three different crops on their arable land where the arable land of the farmer covers more than 3 hectares and is not entirely used for grass production (sown or natural), entirely left fallow or entirely cultivated with crops under water for a significant part of the year” (crop diversification; Article 29, General Rules 1a, EC 2011). To date the mean area of fields that have been planted with tyfon at the study site is 6.6 ha and under the current proposal this would mean that any farmer implementing fodder crop management would need to plant two additional crops, which is unlikely to be feasible on livestock farms in marginal areas. In addition, the use of areas currently classed as permanent grassland for growing fodder crops would be severely limited by the proposal for maintenance of permanent grassland; “famers shall be allowed to convert a maximum of 5% of their reference areas under permanent grassland” (Article 31; EC 2011). These proposals have been met by considerable resistance and are in period of consultation (*pers com.* Amy Corrigan, RSPB), however, should these proposals go ahead it may be impossible to get farmers to implement fodder crop management.

6.3.2 Lime use

Application of agricultural lime leads to carbon dioxide emissions from soil (Biasi *et al*. 2008) and this along with quarrying and transport of lime, mean that encouragement of greater use of liming in upland areas could be controversial due to the contribution of liming to greenhouse gas emissions. Furthermore, agricultural lime use is viewed as an agricultural improvement, which could lead to further improvements, with negative consequences for biodiversity. Since lime use is only likely to be of benefit to breeding lapwings on fields where pH has fallen below that recommended for optimal grass growth, liming should only be encouraged in response to the results of soil testing, and soil testing and maintenance of soil pH conditions for grass growth should be promoted, rather than reintroduction of a lime subsidy.

6.3.3 Potential limitations for implementation of fodder crop management as an AES

AES payments are currently provided to compensate for income lost by carrying out (or stopping) a specific management activity, which may mean that paying for fodder crop management could be difficult under this system, as it is profitable. Another potential difficulty is in the way that schemes are implemented; typically an area of land is entered into a scheme for a period of five years with the same payment provided in each year (*pers com.* Amy Corrigan, RSPB). Fodder crop management involves planting tyfon for two years then reseeding with grass in the third year. In order to fit in with the way schemes operate, an AES involving tyfon, may need to provide a compensatory payment for an area planted with tyfon in a “lapwing friendly” manner for two years, then in the subsequent two years pay for a different area to be planted with tyfon in a “lapwing friendly” manner.

6.4 Further research

There are a number of extensions to this work which would provide additional information likely to be beneficial to inform the use of fodder crop management as a conservation tool for breeding lapwings:

1. A survey of livestock farmers in marginal areas to find out how widespread the use of fodder crops is in these situations and to identify if farmers that use fodder crops do so in a “lapwing friendly” manner, such as carrying out operations after the breeding season has finished and leaving wet areas uncultivated.
2. Further research into the economic costs and benefits of fodder crop management in comparison to alternative grassland management systems, looking specifically at the yields and number of livestock that can be produced within an extensive grazing system and testing experimentally the reduction in yield that results from delaying farming operations until after the lapwing breeding season.
3. Additional farm based experiments to determine the vegetation structure produced in spring by a range of different fodder crops, focussing on fodder crops that farmers in marginal areas are currently using.
4. Larger scale trials of fodder crop management which could detect effects on lapwings and an assessment of whether improving food resources results in higher breeding productivity.

5. A continuation of earthworm sampling at the field experiment to identify if total earthworm abundance has a delayed response to liming and to determine how long the negative effects of tillage are apparent.

Further research that would be of interest that is not specifically related to wider implementation of fodder crop management includes:

1. Examination of chick diet to confirm that *A. chlorotica* is consumed preferentially by lapwing chicks; this could potentially be assessed by genetic analysis of faecal samples.
2. Further study into the relationship between earthworms and soil pH extending the upper limit of soil pH tested in this study.
3. Finally, using soil data to improve habitat models for other species of conservation concern could reveal important habitat requirements that have so far been overlooked.

References

Adams, S.N. (1984) Some effects of lime, nitrogen and soluble and insoluble phosphate on the yield and mineral composition of established grassland. *Journal of Agricultural Science, Cambridge*, **102**, 219-226.

Agricultural Lime Association (No date) Agricultural lime: the natural solution.

Agricultural Lime Producers' Council (1977) *Lime in Agriculture*, Agricultural Lime Producers Council, London.

AIC Agricultural Industries Confederation (2012) Fertiliser statistics 2011.

Aitkenhead, M.J. Coull, M.C., Towers, W., Hudson, G. & Black, H.I.J. (2012) Predicting soil chemical composition and other soil parameters from field observations using a neural network. *Computers and Electronics in Agriculture*, **82**, 108-116.

Ausden, M. & Hirons, G.J.M. (2002) Grassland nature reserves for breeding wading birds in England and the implications for the ESA agri-environment scheme. *Biological Conservation*, **106**, 279-291.

Bailey (1997) Some influences of initial sward composition on the responsiveness of Irish grassland to liming. *Irish Journal of Agricultural and Food Research*, **36**, 161-173.

Baines, D. (1988) The effects of improvement of upland, marginal grasslands on the distribution and density of breeding wading birds (Charadriiformes) in Northern England. *Biological Conservation*, **45**, 221-236.

Baines, D. (1989) The effects of improvement of upland marginal grasslands on the breeding success of lapwings *Vanellus* vanellus and other waders. *Ibis*, **131**, 497-506.

Baines, D. (1990) The roles of predation, food and agricultural practice in determining the breeding success of the lapwing (*Vanellus vanellus*) on upland grasslands. *Journal of Animal Ecology*, **59**, 915-929.

Bardgett, R.D. & Cook, R. (1998) Functional aspects of soil animal diversity in agricultural grasslands. *Applied Soil Ecology*, **10**, 263-276.

Bardgett, R.D., Yeates, G.W. & Anderson, J.M. (2005) Patterns and determinants of soil biological diversity, In: *Biological Diversity and Function in Soils*, Edited by Bardgett, R.D*.,* Usher, M. & Hopkins, D. , Cambridge University Press, Cambridge.

Barrett, J. & Barrett, C. (1984) Aspects of censusing breeding lapwings. *Wader Study Group Bulletin*, **42**, 45-47.

Barthram, G.T., Marriott, C.A., Common, T.G. & Bolton, G.R. (2002) The long-term effects on upland sheep production in the UK of a change to extensive management. *Grass and Forage Science*, **57**, 124-136.

Bates, D. & Maechler, M. (2010) *lme4: Linear mixed effects models using SF classes*. R package version 0.999375-37. http://CRAN. R-project.org/package=lme4.

Baxter, S.J., Oliver, M.A. & Archer, J.R. (2006) The Representative Soil Sampling Scheme of England and Wales: the spatial variation of topsoil nutrient status and pH between 1971 and 2001. *Soil Use and Management* **22**, 383-392.

Beintema, A.J. & Müskens, G.J.D.M. (1987) Nesting success of birds breeding in Dutch agricultural grasslands. *Journal of Applied Ecology*, **24**, 743-758.

Beintema, A.J., Thissen, J.B., Tensen, D. & Visser, G.H. (1991) Feeding ecology of charadriiform chicks in agricultural grassland. *Ardea*, **79**, 31-44.

Berg, Å. (1993) Habitat selection by monogamous and polygamous lapwings on farmland - the importance of foraging habitats and suitable nest sites. *Ardea*, **81**, 99-105.

Berg, Å., Lindberg, T. & Källebrink, K.G. (1992) Hatching success of lapwings on farmland: differences between habitats and colonies of different sizes. *Journal of Animal Ecology*, **61**, 469-476.

Berg, Å., Jonsson, M. Lindberg, T. & Källebrink, K.G. (2002) Population dynamics and reproduction of Northern Lapwings *Vanellus vanellus* in a meadow restoration area in central Sweden. *Ibis*, **144**, 131 - 140.

Berndt, A.M. & Norbert, H. (2012) Energy crops as a new bird habitat: utilization of oilseed rape fields by the rare Bluethroat (*Luscinia svecica*). *Biodiversity and Conservation,* **21,** 527-541.

Biasi, C., Lind, S.E., Pekkarinen, N.M., Huttunen, J.T., Shurpali, N.J., Hyvonen, N.P, Repo, M.E., Martikainen, P.J, (2008) Direct experimental evidence for the contribution of lime to CO_2 release from managed peat soil. *Soil Biology & Biochemistry*, **40**, 2660-2669.

BirdLife International (2004) Birds in Europe: population estimates, trends and conservation status Downloaded from http://www.birdlife.org/datazone/userfiles/file/Species/BirdsInEuropeII/BiE2004Sp3153.pdf on 15/08/2012.

BirdLife International (2012a) Species factsheet: *Vanellus vanellus*. Downloaded from http://www.birdlife.org on 15/08/2012.

BirdLife International (2012b) Species factsheet*: Numenius arquata*. Downloaded from http://www.birdlife.org on 08/09/2012.

Bishop, H. 0. (2003) The ecology of earthworms and their impact on carbon distribution and chemical characteristics in soil. School of Biological and Environmental Sciences, University of Stirling.

Bjornstad, O.B. (2012) ncf: spatial nonparametric covariance functions. R package version 1.1-4. http://CRAN. R-project.org/package=ncf.

Blomqvist, D. & Johansson, O.C. (1995) Trade-offs in nest site selection in coastal populations of lapwings *Vanellus vanellus*. *Ibis*, **137**, 550 – 558.

Blomqvist, D., Johansson, O.C.& Gotmark, F. (1997) Parental quality and egg size affect chick survival in a precocial bird, the lapwing *Vanellus vanellus*. *Oecologia*, **110**, 18 – 24.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H & White, J.S.S. (2009) Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology and Evolution*, **24**, 127-135.

Bolton, J. (1977) Changes in soil pH and exchangeable calcium in two liming experiments on contrasting soils over 12 years. *Journal of Agricultural Science, Cambridge*, **89**, 81-86.

Bolton, M., Bamford, R., Blackburn, C., Cromarty, J., Eglington, S., Ratcliffe, N., Sharpe, F., Stanbury, A. & Smart, J. (2011) Assessment of simple survey methods to determine breeding population size and productivity of a plover, the Northern Lapwing *Vanellus vanellus*. Wader *Study Group Bulleti*n, **118**, 141-152.

Brandsma, O. (2004) The importance of fertilisation for the food supply of grassland birds. *Wader Study Group Bulletin* **103**, 17-18.

Bruneau, P.M.C., Davidson, D.A., Grieve, I.C., Young, I.M. & Nunan, N. (2005) The effects of soil horizons and faunal excrement on an upland grassland soil. *FEMS Microbiology Ecology*, **52**, 139-144.

Burnham, K.P. & Anderson, D.R. (2002) *Model Selection and Multimodel Inference: A practical information – Theoretic Approach* 2nd Edition. Springer Science+ Business Media, New York.

Cameron, A.C. & Pravin, K. (1998) *Regression Analysis of Count Data*. Cambridge University Press, Cambridge.

Capowiez, Y., Cadoux, S., Bouchant, P., Ruy, S., Roger-Estrade, J., Richard, G. & Boizard, P. (2009) The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration. *Soil & Tillage Research,* **105,** 209-216.

Catchpole, E.A., Morgan, B.J.T., Freeman, S.N. & Peach, W.J. (1999) Modelling the survival of British Lapwings *Vanellus vanellus* using ring-recovery data and weather covariates. *Bird Study* **46** (suppl) S5-13

Chalmers, A.G. (2001) Lime A review of fertilizer, lime and organic manure use on farm crops in Great Britain from 1983 - 1987. *Soil Use and Management* **17**, 254-262.

Chalmers, A.G., Kershaw, C.D. & Leech, P.K. (1990) Fertiliser use on farm crops in Great Britain: Results from the Survey of Fertiliser Practice, 1969-88. *Outlook on Agriculture* **19**, 269-278.

Chamberlain, D.E. & Crick, D.E. (2003) Temporal and spatial associations in aspects of reproductive performance of lapwings *Vanellus vanellus* in the United Kingdom, 1962-99. *Ardea* **92**, 183 -196.

Chamberlain, D.E., Fuller, R.J., Bunces, R.G.H., Duckworth, J.C. & Shrubb, M. (2000) Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. *Journal of Applied Ecology* **37** 771 -788.

Chambers, B.J. & Garwood, T.W.D. (1998) Lime loss rates from arable and grassland soils. *Journal of Agricultural Science, Cambridge* **131**, 455-464.

Church, B.M. & Skinner, R.J. (1986) The pH and nutrient status of agricultural soils in England and Wales 1969-83. *Journal of Agricultural Science Cambridge*, **107**, 21-28.

Cole, L., Bradford, M.A., Shaw, P.J.A. & Bardgett, R.D. (2006) The abundance, richness and functional role of soil meso and macrofauna in temperate grassland – A case study. *Applied Soil Ecology*, **33**, 186-198.

Conyers, M.K., Heenan, D.P., McGhie, W.J. & Poile, G.P. (2003) Amelioration of acidity with time by limestone under contrasting tillage. *Soil and Tillage Research* **72**, 85-94.

Cramp, S. & Simmons, K.E.L. (1983) *Birds of the Western Palearctic*. Oxford University Press, Oxford.

Crawley, M.J. (2002) *Statistical Computing: An Introduction to Data Analysis Using S-Plus*. John Wiley and Sons, Chichester.

Crawley, M.J. (2007) *The R Book*. John Wiley and Sons, Chichester.

Curry, J.P. (2004) Factors affecting the abundance of earthworms in soils, In: *Earthworm Ecology* 2nd Edition, Edited by Edwards, C.A*.,* CRC Press LLC, Boca Raton, Florida.

DEFRA (1999-2012) The British Survey of Fertiliser Practice: Fertiliser Use on Farm Crops.

DEFRA (2012) Agriculture in the United Kingdom.

DEFRA (2012b) The British survey of fertiliser practice: Fertiliser use on farm crops for crop year 2011.

Deleporte, S. & Tillier, P. (1999) Long-term effects of mineral amendments on soil fauna and humus in an acid beach forest floor. *Forest Ecology and Management*, **118**, 245-252.

Devereux, C.L., McKeever, C.U., Benton, T.G. & Whittingham, M.J (2004) The effect of sward height and drainage on Common Starlings *Srurnus vulgaris* and Northern Lapwing *Vanellus vanellus* foraging in grassland habitats. *Ibis*, **146 (Supp2)**, 115-122.

Donald, P.F., Sanderson F.J., Burfield, I.J. & van Bommel, F.P.J. (2006) Further evidence of continent-wide impacts of agricultural intensification on European farmland birds, 1990-2000. *Agriculture, Ecosystems & Environment*, **116**, 189-196.

Doyle, C.J. & Elliot, J.G. (1983) Putting economic value on increases in grass production. *Grass and Forage Science*, **38**, 169-177.

Eaton, M.A., Balmer, D.E., Cuthbert, R., Grice, P.V., Hall, J., Hearn, R.D., Holt, C.A., Musgrove, A.J., Noble, D.G., Parsons, M., Risely, K., Stroud, D.A., & Wotton, S. (2011) The state of the UK's birds 2011. RSPB, BTO, WWT, CCW, JNCC, NE, NIEH and SNH. Sandy, Bedfordshire.

Eaton, M.A., Brown, A.F., Noble, D.G., Musgrove, A.J., Hearn, R., Aebischer, N.J., Gibbons, D.W., & Gregory, R.D. (2009) Birds of Conservation Concern 3: the population status of birds in the United Kingdon, Channel Islands and the Isle of Man. *British Birds*, **102**, 296-341

EBLEX (2008) Beef and sheep BRP Manual 1: Improving pasture for better returns. www.eblex.org.uk/betterreturns . Funded by DEFRA. EBLEX, Huntingdon.

EBLEX (2011) Beef and sheep BRP Manual 3: Improving soils for better returns. www.eblex.org.uk/betterreturns . Funded by DEFRA. EBLEX, Huntingdon.

EBLEX (2011) Beef and sheep BRP Manual 6: Using brassicas for better returns. www.eblex.org.uk/betterreturns . Funded by DEFRA. EBLEX, Huntingdon.

EC (2011) Proposal for a regulation of the European Parliament and of the Council establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy, 2011/0280 (COD)

Ecological Software Solutions LLC (2010) *Location of a Signal 4.0.3.7.* Hegymagas, Hungary. http://www.ecostats.com/software/loas/loas.htm, accessed May 2010..

EDINA Digimap Ordnance Survey Service. OS MasterMap Topography Layer, http://edina.ac.uk/digimap, accessed August 2010.

Edwards, C.A. and Bohlen, P.J. (1996) *Biology and Ecology of Earthworms* 3rd Edition. Chapman and Hall, London.

Edwards, C.A. & Lofty, J.R. (1982a) The effect of direct drilling and minimal cultivation on earthworm populations. *Journal of Applied Ecology* **37** 723-734.

Edwards, C.A. & Lofty, J.R. (1982b) Nitrogenous fertilizers and earthworm populations in agricultural soils. *Soil Biology and Biochemistry* **14** 515-521.

Eglington, S.M., Gill, J.A., Bolton, M., Smart, M.A., Sutherland, W.J. &Watkinson, A.R. (2008) Restoration of wet features for breeding waders on lowland grassland. *Journal of Applied Ecology* **45** 305-314

Eglington, S.M., Bolton, M., Smart, M.A., Sutherland, W.J. Watkinson, A.R. & Gill, J.A. (2010) Managing water levels on wet grasslands to improve foraging conditions for breeding northern lapwing *Vanellus vanellus*. *Journal of Applied Ecology* **47** 451-458.

Elliot, R.D. (1985) The exclusion of avian predators from aggregations of nesting lapwings (*Vanellus vanellus*). *Animal Behaviour*, **33**, 308-314.

Emmett, B.A., Reynolds, B., Chamberlain, P.M., Rowe, E., Spurgeon, D., Brittain, S.A., Frogbrook, Z., Hughes, S., Lawler, A.J., Poskitt, J., Potter, E., Robinson, D.A., Scott, A., Wood, C. & Woods, C. (2010) Countryside Survey: Soils Report from 2007, CS Technical Report No. 9/07, Centre for Ecology and Hydrology.

ESRI Inc (2006) ArcGis 9.2 http://www.esri.com.

Fielding, A.H. & Bell, J.F. (1997) A review of methods for the assessment of prediction errors in conservation presence / absence models. *Environmental Conservation*, **24**, 38-49.

Finnen, E. & Menza, C. (2007) NOAA's CCMA Biogeography Team's Sampling Tool: A GIS application for ArcGIS. NOAA., Silver Spring, USA. http://arcscripts.esri.com/details.asp?dbid=15080 accessed: February 2009.

Forrester, R.W., Andrews, I.J., McIneny, C.J., Murray, R.D., McGowan, R.Y., Zonfrillo, B., Betts, W.J., Jardine, D.C. & Grundy, D.S. (eds) (2007) *The Birds of Scotland*. The Scottish Ornithologists' Club, Aberlady, UK.

Fothergill, M., Davies, D.A. & Morgan, C.T. (2001) Extensification of grassland use in the Welsh uplands: sheep performance in years 1-6. *Grass and Forage Science*, **56**, 105-117.

Fuentes-Monteymayor, E., Goulson, D. & Park, K.J. (2011) Pipistrelle bats and their prey do not benefit from four widely applied agri-environment management prescriptions. *Biological Conservation*. **144**, 2233-2246.

Fuller, R.J., Ward, E., Hird, D & Brown, A.F. (2002) Declines of ground-nesting birds in two areas of upland farmland in the south Pennines of England. *Bird Study*, **49**, 146-152.

Fystro, G. & Bakken, A.K. (2005) Soil reaction, yields and herbage element content as affected by lime applied on established leys in a multi-site field trial. *Journal of Agricultural Science, Cambridge*, **143**, 407-420.

Galbraith, H. (1988a) Effects of egg size and composition on the size, quality and survival of lapwing *Vanellus vanellus* chicks. *Journal of the Zoological Society of London* **214**: 383-548.

Galbraith, H. (1988b) Effects of agriculture on the breeding ecology of lapwings *Vanellus vanellus*. *Journal of Applied Ecology*, **25**, 487-503.

Galbraith, H. (1989a) The diet of Lapwing *Vanellus vanellus* chicks on Scottish farmland. *Ibis*, **131**, 80-84.

Galbraith, H. (1989b) Arrival and habitat use by lapwings *Vanellus vanellus* in the early breeding season. *Ibis*, **131**, 377-388.

Gasser (1985) Processes causing loss of calcium from agricultural soils. *Soil Use & Management*, **1**, 14-17.

Gerard, B.M. (1967) Factors affecting earthworms in pastures. *Journal of Animal Ecology*. **36**, 235-252.

Gibbons, J.M., Nicholson, E., Milner-Gulland, E.J., & Jones, J.P.G. (2011) Should payments for biodiversity conservation be based on action or results? *Journal of Applied Ecology*. **48**, 1218-1226.
From chapter 5.

Gilroy, J.J., Anderson, G.Q.A, Grice, P.V., Vickery, J.A. Bray, I., Watts, P.N. & Sutherland, W.J. (2008) Could soil degradation contribute to farmland bird declines? Links between soil penetrability and the abundance of Yellow Wagtails *Moticalla flava* in arable fields . *Biological Conservation*, **141**, 3116 - 3126.

Gilroy, J.J., Anderson, G.Q.A, Grice, P.V., Vickery, J.A. & Sutherland, W.J. (2010) Mid-season shifts in the habitat associations of Yellow Wagtails *Moticalla flava* breeding in arable farmland . *Ibis*, **152**, 90 - 104.

Goulding, K.W.T. & Blake, L. (1998) Land use, liming and the mobilization of potentially toxic metals. *Agriculture, Ecosystems and Environment*, **67**, 135-144.

Graham, M.H. (2003) Multicollinearity in ecological multiple regression. *Ecology*, **84**, 2809-2815.

Gray, N.D, Hastings, R.C, Sheppard, S.K., Loughnane, P., Lloyd, D., McCarthy, A.J. & Head, I.M. (2003) Effect of soil improvement treatments on bacterial community structure and soil processes in an upland grassland soil. *FEMS Microbiology Ecology*, **46**, 11-22.

Green, R.E., Hirons, G.J.M. & Kirby, J.S. (1990) The effectiveness of nest defence by black-tailed godwits *Limosa limosa*. *Ardea*, **78**, 405-413.

Gregory, R.D., Noble, D.G. & Custance, J. (2004) The state of play of farmland birds: population trends and conservation status of lowland farmland birds in the United Kingdom. *Ibis*, **146 (Supp2)**, 1–13.

Griffiths, R.I., Bailey, M.J., McNamara, N.P & Whiteley, A.S. (2006) The functions and components of the Sourhope soil microbiota. *Applied Soil Ecology*, **33**, 114-126.

Guild, W.T.M (1951) The distribution and population density of earthworms (Lumbricidae) in Scottish pasture fields. *Journal of Animal Ecology.* **20**, 88-97.

Hancock, M.H. & Wilson, J.D. (2003) Winter habitat associations of seed-eating passerines on Scottish farmland. *Bird Study*, **50**, 116-130.

Hazelden, J., & Boorman, L.A. (2001) Soils and “managed retreat” in South East England. *Soil use and management*. **17**. 150 – 154.

Henderson, I.G., Wilson, A.M., Steele, D. & Vickery, J.A. (2002) Population estimates, trends and habitat associations of breeding lapwing *Vanellus vanellus*, curlew *Numenius arquata* and snipe *Gallinago gallinago* in Northern Ireland in 1999. *Bird Study*, **49**, 17-25.

Henderson I.G., Fuller R.J. , Conway G.J. & Gough S.J (2004) Evidence for declines in populations of grassland associated birds in marginal upland areas of Britain, *Bird Study* **51**, 12-19

Hillier, J.A., Chapman, G.R., Highley, D.E., Gatliff, R.W., Colman, T.B., White, R. & Linley, K.A. (2003) United Kingdom Minerals Yearbook 2002, British Geological Survey, Keyworth, Nottingham.

Högstedt, G. (1974) Length of the pre-laying period in the lapwing *Vanellus vanellus* L. in relation to its food resources. *Ornis Scandinavica*, **5**, 1-4.

Hornung, M., Bull, K.R., Cresser, M., Ullyett, J., Hall, J.R., Langan, S. & Loveland, P.J. (1994) The sensitivity of surface waters of Great Britain to acidification predicted from catchment characteristics. *Enviornmental Pollution*, **87**, 207-214.

Hothorn, T., Bretz, F. & Westfall, P. (2008) Simultaneous inference in general parametric models. *Biometrical Journal*. **50**, 346-363.

Hudson R., Tucker, G.M. & Fuller, R.J. (1994) Lapwing *Vanellus vanellus* populations in relation to agricultural changes: a review. In: The ecology and conservation of lapwings *Vanellus vanellus* edited by Tucker, G.M., Davies, S.M. & Fuller, R.J. pp1 – 33. Peterborough, Joint Nature Conservation Committee, UK Conservation No. 9.

Hybu Cig Cymru (2007) Easier management systems for sheep.

Idoine, N.E., Bide, T. & Brown, T.J. (2012) United Kingdom Minerals Yearbook 2011, British Geological Survey, Keyworth, Nottingham.

Johnston, A.E., Goulding, & Poulton & (1980) *The Use of Lime on Agricultural Soils*, The Fertiliser Society Proceedings number 189.

Johnston, A.E & Whinham, W.N.(1986) Soil acidification during more than 100 years under permanent grassland and woodland at Rothamsted. *Soil Use & Management*, **2**, 3-10.

Kenward, R.E. (2001) *A Manual for Wildlife Radio Tagging.* Academic Press, London.

Kleijn, D. (2012) Do agri-environment schemes contribute to halting the biodiversity decline? Presented at the European Congress of Conservation Biology in Glasgow on 1st September 2012.

Kleijn, D., Berendse, F. Smit, R. & Gillissen, N. (2001) Agri-environment schemes do not effectively protect biodiversity in Dutch agricultural landscapes. *Nature*. **413**, 723-725.

Kleijn, D. & Sutherland, W.J. (2003) How effective are European agri-environment schemes on conserving and promoting biodiversity? *Journal of Applied Ecology*. **40**, 947-970.

Kleijn, D. & Van Zuijlen, G.J.C (2004) The conservation effects of meadow bird agreements on farmland in Zeeland, The Netherlands, in the period 19898 – 1995. *Biological Conservation*. **117**, 443-451.

Klomp, H. (1951) Over de achteruitgang vane de Kievit, *Vanellus vanellsu* (L.), in Nederland en gegevens over het legmechanisme en het eiproductie-vermogen. *Ardea*, **39**, 143-182.

Klomp, H. (1954) De terreinkeus van de Kievit, *Vanellus vanellus* (L.). *Ardea*, **42**, 1-139.

Koch, D.W., Ernst Jr, F.C., Leonard, N.R., Hedberg, R.R., Blenk, T.J & Mitchell, J.R. (1987) Lamb performance on extended-season grazing of tyfon. *Journal of Animal Science*, **64**, 1275-1279.

Krebs, J.R., Wilson, J.D., Bradbury, R.B. & Siriwardena, G.M. (1999) The second silent spring? *Nature*, **400**, 611 – 612.

Kuylenstierna, J.C.I. & Chadwick, M.J. (1991) Increases in soil acidity in North-West Wales between 1957 and 1990. *Ambio*, **20**, 118-119.

Laidlaw, R.A. (2008) Methods for the rapid assessment of earthworm populations and biomass as wader prey in lowland wet grassland. MSc Thesis. University of East Anglia.

Langan, S.J. & Wilson, M.J. (1992) Predicting the regional occurrence of acid surface waters in Scotland using an approach based on geology, soils and land use. *Journal of Hydrology*, **138**, 515-528.

Leake, J.R., Ostle, N.J., Rangel-Castro, I. & Johnson, D. (2006) Carbon fluxes from plants through soil organisms determined by field $^{13}CO_2$ pulse-labelling in an upland grassland. *Applied Soil Ecology*, **33**, 152-175.

Lilly, A., Bell, J.S., Hudson, G., Nolan, A.J. & Towers, W. (compilers) (2010) National Soil Inventory of Scotland 1 (NSIS_1): site location, sampling and profile description protocols (1978 – 1988). *Technical Bulletin, Macaulay Institute.*

MAFF (1969) *Lime and Liming* 6th Edition, Bulletin 35, MAFF, London.

Marren, P. (2002) *Nature Conservation: A Review of the Conservation of Wildlife in Britain 1950-2001.* HarperCollins*Publishers*, London.

Marsden, K. (2011) SPICe Briefing: CAP reform – Legislative proposals. *SPICe The Information Centre, Scottish Government.*

McCracken, D.I., Foster, G.N. & Kelly, A. (1995) Factors affecting the size of leatherjacket (Diptera: Tipulidae) populations in pastures in the west of Scotland. *Applied Soil Ecology*, **2**, 203-213.

McKeever, C. U. (2003) Linking grassland management, invertebrates and Northern Lapwing productivity. PhD Thesis. Institute of Biological Sciences, University of Stirling.

Milsom, T.P., Langton, S.D., Parkin, W.K., Peel, S., Bishop, J.D., Hart, J.D., Moore, N.P. (2000) Habitat models of bird species' distribution: an aid to the management of coastal grazing marshes. *Journal of Applied Ecology*, **37**, 706-727.

Milsom, T.P., Hart, J.D., Parkin, W.K., & Peel, S. (2002) Management of coastal grazing marshes for breeding waders: the importance of surface topography and wetness. *Biological Conservation*, **103**, 199 - 207.

Mullarney K., Svensson, L., Zetterstrom, D. & Grant, P.J. (1999) *Bird Guide: The most complete field guide to the birds of Britain and Europe.* HarperCollins*Publishers*, London.

Newton, I. (2004) The recent declines of farmland bird populations in Britain: an appraisal of causal factors and conservation actions. *Ibis*, **146**, 579-600.

O'Brien, M.G. (1996) The numbers of breeding waders in lowland Scotland. *Scottish Birds*. **18**, 231-241.

O'Brien, M.G. (2001) Factors affecting breeding wader populations on upland enclosed farmland in northern Britain. PhD Thesis. ICAPB, University of Edinburgh.

O’Brien, M.G. (2004) Estimating the number of farmland waders breeding in the UK. International Wader Studies 14, **135 – 139**.

O’Brien M. & Bainbridge, I. (2002) The evaluation of key sites for breeding waders in lowland Scotland. *Biological Conservation*. **103**, 51-63.

O’Brien, M.G. & Smith, K.W. (1992) Changes in the status of waders breeding on wet lowland grasslands in England and Wales between 1982 and 1989. *Bird Study*, **89**, 165-176.

O’Brien, M. & Wilson, J.D. (2011) Population changes of breeding waders on farmland in relation to agri-environment management. *Bird Study*. **58**, 399-408.

Olsson, O. & Rogers, D.J. (2009) Predicting the distribution of a suitable habitat for the white stork in Southern Swedien: identifying priority areas for reintroduction and habitat restoration. *Animal Conservation*, **12**, 62-70.

Osgathorpe, L., Park, K.J., Goulson, D., Acs, S. & Hanley, N. (2011) The trade-off between agriculture and biodiversity in marginal areas: Can crofting and bumblebee conservation be reconciled? *Ecological Economics*. **70**, 1162-1169.

Ottvall, R. & Smith, H.G. (2006) Effects of an agri-environment scheme on wader populations of coastal meadows of southern Sweden. *Agriculture, Ecosystems & Environment*, **113**, 264-271.

Owen, K.M. & Marrs, R.H. (2000) Creation of heathland on former arable land at Minsmere, Suffolk UK: the effects of soil acidification on the establishment of *Calluna* and ruderal species . *Biological Conservation*, **93**, 9-18.

Pakanen, V.M., Luukkonen, A. & Koivula, K. (2011) Nest predation and trampling as management risks in coastal grazed meadows. *Biodiversity and Conservation*, **20**, 2057-2073.

Parish, D.M.B., Thompson, P.S. & Coulson, J.C. (1997) Mating systems in the Lapwing *Vanellus vanellus*. *Ibis*, **139**, 138-143.

Paradis, E., Claude, J. & Strimmer, K. (2004) APE: Analysis of phylogenetics and evolution in R. *Bioinformatics,* **20**, 289-290.

Paulo, D.M., Traba, J & Morales, M.B. (2011) Climate niche constraints in two coexisting steppe birds: the little and the great bustards. *Areola*, **58,** 223 – 238.

Peach, W.J., Thomson, P.S.& Coulson, J.C. (1994) Annual and long-term variation in the survival rates of British lapwings *Vanellus vanellus. The Journal of Animal Ecology,* **63**, 60-70.

Perkins, A.J., Maggs, H.E., Watson, A. & Wilson, J.D. (2011) Adaptive management and targeting of agri-environment schemes does benefit biodiversity: a case study of the corn bunting *Emberiza calandra*. *Journal of Applied Ecology*. **48**, 514-522.

Picozzi, N., Catt, D.C. & Cummins, R.P. (1996) Breeding waders in the Cairngorm Straths ESA in 1995. *Scottish Birds*, **18**, 197-204.

Poggio, L., Gimona, A., Brown, I. & Castellazzi, M. (2010) Soil available water capacity interpolation and spatial uncertainty modelling at multiple geographical extents. *Geoderma*, **160**, 175-188.

Poozesh, V., Castillon, P., Cruz, P. & Bertoni, G. (2010) Re-evaluation of the liming-fertilization interaction in grasslands on poor and acid soil. *Grass and Forage Science*, **65**, 260-272.

Potthoff, M., Asche, N., Stein, B., Muhs, A. & Beese, F. (2008) Earthworm communities in temperate beech wood forest soils affected by liming. *European Journal of Soil Biology*, 44, 247-254.

Power, A.G. (2010) Ecosystem services and agricultural tradeoffs and synergies. *Philosophical Transactions of the Royal Society B*, **365**, 2959-2971.

R Development Core Team (2010) *R: A language and environment for statistical computing*. R foundation for statistical computing, Vienna, Austria. ISBN 3-900051-07-0, http://www.R-project.org/.

Redpath, N., Osgathorpe, L., Park, K.J. & Goulson, D. (2010) Crofting and bumblebee conservation: The impact of land management practices on bumblebee populations in northwest Scotland. *Biological Conservation*. **143**, 492-500.

Rettie, W.J. & McLoughlin, P.D. (1999) Overcoming radiotelemetry bias in habitat-selection studies. *Canadian Journal of Zoology*, **8**, 1175-1184.

Rhymer, C.M., Robinson, R.A., Smart, J. & Whittingham M.J. (2010) Can ecosystem services be integrated with conservation? A case study of breeding waders on grassland. *Ibis*, **142**, 689-712.

Robinson, R.A. & Sutherland, W.J. (2002) Post-war changes in arable farming and biodiversity in Great Britain. *Journal of Applied Ecology*. **39**, 157 – 176.

Rowell, D.I. & Wild, A. (1985) Causes of acidification: a summary. *Soil use and management* **1**, 32-33.

SAC (2000 – 2009) The Farm Management Handbook: The UK reference for farm business management.

SAC (2010) Technical Note TN632: Fertiliser recommendations for grassland.

SAC (No date A) Managing the change to lower input systems with UK sheep breeds.

SAC (No date B) Cattle out-wintering systems.

Satchell (1955) Some aspects of earthworm ecology. In: *Soil Zoology* edited by Kevan, D.K. pp180 – 201. Butterworths Publications Ltd, London.

Schielzeth, H. (2010) Simple means to improve the interpretability of regression coefficients. *Methods in Ecology and Evolution*, **1**, 103-113.

Scottish Government / Scottish Executive (2001 – 2012) Economic Report on Scottish Agriculture.

Sheldon, R.D. (2002) Factors affecting the distribution, abundance and chick survival of the Lapwing (*Vanellus vanellus*). PhD Thesis. Harper Adams University College.

Sheldon, R., Bolton, M., Gillings, S. & Wilson, A. (2004) Conservation management of Lapwing *Vanellus vanellus* on lowland arable farmland in the UK. *Ibis*, **146 (Supp2)**, 41-49.

Shrubb, M. (1990) Effects of agricultural change on nesting lapwings *Vanellus vanellus* in England and Wales. *Bird Study*, **37**, 115 – 127.

Shrubb, M. (2007) *The Lapwing.* T & AD Poyser, London.

Sims, R.W. & Gerard B.M, (1985) *Earthworms, Synopses of the British Fauna No 31.* Brill, Leiden, The Netherlands.

Skinner R.J., Church, B.M. & Kershaw, C.D. (1992) Recent trends in soil pH and nutrient status in England and Wales. *Soil Use and Management* **8**, 16-20.

Skinner R.J., & Todd, A.D. (1998) Twenty-five years of monitoring pH and nutrient status of soils in England and Wales. *Soil Use and Management* **14**, 162-169.

Small C.J. (2002) Waders, habitats and landscape in the Pennine Dales. PhD Thesis. Institute of Environmental and Natural Sciences, University of Lancaster.

Staddon, P.L, Ostle, N., Dawson, L.A. & Fitter, A.H. (2003) The speed of soil carbon throughput in an upland grassland is increased by liming. *Journal of Experimental Botany*, **54**, 1461-1469.

Stevens, R.J. & Laughlin, R.J. (1996) Effects of nitrogen fertilizer on two sward types over a 10-year period. *Journal of Agricultural Science, Cambridge*, **127**, 451-461.

Stoate, C., Boatman, N.D., Borralho, R.J., Carvalho, C.R., Snoo, G.R.D. & Eden, P. (2001) Ecological impacts of arable intensification in Europe. *Journal of Environmental Management*, **63**, 337 – 365.

Swale, V. (2012) Briefing on the proposed CAP “Green Payment”*, RSPB.*

Taylor, I.R. & Grant, M.C. (2004) Long-term trends in the abundance of breeding lapwing *Vanellus vanellus* in relation to land-use change on upland farmland in southern Scotland. *Bird Study*, **51**, 133-142.

Thomson, P.S., Baines, D., Coulson, J.C. & Longrigg, G. (1994) Age at first breeding, philopatry and breeding site-fidelity in the Lapwing *Vanellus vanellus*. *Ibis*, **136**, 474-484.

Tromp-van Meerveld, H.J. & McDonnell (2006) On the interrelations between topography, soil moisture, transpiration rates and species distribution at the hillslope scale. *Advances in Water Resources*, **29**, 293-310.

Vanderhoff E.N.& Eason, P.K. (2008) Influence of environmental variables on foraging by juvenile American Robins. *Journal of Field Ornithology*, **79**, 186-192.

Venables, W.N. & Ripley, B.D. (2002) *Modern Applied Statistics with S*. 4th Edition, Springer, New York.

Verhulst, J., Kleijn, D. & Berendse, F. (2007) Direct and indirect effects of the most widely implemented Dutch agri-environment schemes on breeding waders. *Journal of Applied Ecology*. **44**, 70 – 80.

Vickery, J.A., Tallowin, J.R, Feber, R.E., Asteraki, E.J., Atkinson, P.W., Fuller, R.J. & Brown, V.K. (2001) The management of lowland neutral grasslands in Britain: effects of agricultural practices on birds and their food resources. *Journal of Applied Ecology*. **38**, 647-664.

Wallander, J., Isaksson, D. & Lenberg, T. (2006) Wader nest distribution and predation in relation to man-made structures on coastal pastures. *Biological Conservation*, **132**, 343-350.

Watkins, C.M.H (2007) Farmyard manure application as a management tool for conservation breeding waders on lowland wet grassland. PhD Thesis. Harper Adams University College.

Webb, J., Loveland, P.J., Chambers, B.J., Mitchell, R. & Garwood, T. (2001) The impact of modern farming practices on soil fertility and quality in England and Wales. *Journal of Agricultural Science*, **137**, 127-138.

White R.E. (2006*) Principles and Practice of Soil Science: The Soil as a Natural Resource.* 4th Edition. Blackwell Publishing, Oxford, UK.

White G.C. & Garrott, G.C. (1990) *Analysis of Wildlife Radio-tracking Data.* Academic Press, London.

Whittingham M.J. (2011) The future of agri-environment schemes: biodiversity gains and ecosystem service delivery? *Journal of Applied Ecology*. **48**, 509-513.

Whittingham, M.J. & Evans, K.L. (2004) The effects of habitat structure on predation risk of birds in agricultural landscapes. *Ibis*, **146 (Supp2)**, 210 - 220.

Whittingham, M.J., Percival, S.M. & Brown, A.F. (2000) Tine budgets and foraging of breeding golden plover *Plovialis apricaria*. *Journal of Applied Ecology*, **37**, 632-646.

Wilkinson, M. (1998) Changes in Farming Practice 1978 to 1990. ADAS Contract Report to ITE. ADAS Huntingdon, UK.

Wilson, A.M., Ausden, M. & Milsom, T.P. (2004) Changes in breeding wader populations on lowland wet grasslands in England and Wales: causes and potential solutions. *Ibis*, **146 (Suppl 2)**, 32-40.

Wilson, J.D., Evans A.D & Grice, V.G (2009) *Bird Conservation and Agriculture*. Cambridge University Press, Cambridge.

Wilson, A., Vickery, J. & Pendlebury, C. (2007) Agri-environment schemes as a tool for reversing declining populations of grassland waders: Mixed benefits from Environmentally Sensitive Areas in England. *Biological Conservation*, **136**, 128-135.

Wilson, A.M., Vickery, J.A., Brown, A., Langston, R.H.W, Smallshire, D., Wotton, S. & Vanhinsbergh, D. (2005) *Bird Study*, **52**, 55-69.

Zhang, W., Ricketts, T.H., Kremen, C., Carney, K. & Swinton, S.M. (2007) Ecosystem services and dis-services to agriculture. *Ecological Economics*, **64**, 253-260.

Zuur A.F., Ieno E.N. & Smith G.H. (2007) *Analysing ecological data*. Springer Science+ Business Media, New York.

Zuur A.F., Ieno E.N., Walker, N.J. & Smith G.H. (2009) *Mixed Models and Extensions in Ecology with R*. Springer Science+ Business Media, New York.