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The Effects of Changing Livestock Practices on the Breeding Performance of the Common Raven, Corvus corax, in Northwest Wales

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The Effects of Changing Livestock Practices on the Breeding Performance of the Common Raven, *Corvus corax*, in Northwest Wales

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I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards.

Yr wyf drwy hyn yn datgan mai canlyniad fy ymchwil fy hun yw'r thesis hwn, ac eithrio lle nodir yn wahanol. Caiff ffynonellau eraill eu cydnabod gan droednodiadau yn rhoi cyfeiriadau eglur. Nid yw sylwedd y gwaith hwn wedi cael ei dderbyn o'r blaen ar gyfer unrhyw radd, ac nid yw'n cael ei gyflwyno ar yr un pryd mewn ymgeisiaeth am unrhyw radd oni bai ei fod, fel y cytunwyd gan y Brifysgol, am gymwysterau deuol cymeradwy.

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Glossary

Throughout this thesis terms will be used that the reader may be familiar with, however their personal definitions may not be in line with the context relevant to each term here specifically. It is therefore important to clearly define these key terms to provide a fuller understanding where they appear in the text.	
Key Term	**Description**
Occupied Territory	Refers to a territory that is inhabited by a pair of ravens. A nest site is located within an occupied territory, but breeding doesn't have to occur for territory to be considered occupied. Determined through field visits at beginning of breeding season where various observations (sightings, hearing, physical traces) can confirm raven occupancy.
Nest Site/Site	Refers to the location of a nest within a pairs' territory.
Active Pair	Refers to a pair of Ravens that are occupying a territory and have made an evident attempt to breed whether successful or not. Determined through field visits at the beginning of the Raven breeding season where evidence such nest maintenance by a pair can indicate breeding activity.
Success	Recorded for sites that successfully produce and fledge at least one young. Number accompanying a success denotes total confirmed young fledged. Would be considered as an active site.
Fail	Recorded for sites that fledged no young despite making an attempt to but instead failing at egg or chick stage. Would be considered as an active site.
Young Fledged	The total number of young fledged. Can refer to a group of sites in a given area for a given year, or to individual sites across one or multiple years.
Mean Fledged	The average young fledged from successful breeding sites. Can be for a group of sites in a given area across one or multiple years, or to individual sites across multiple years.
Productivity	The average young fledged from all active breeding sites, i.e. both successful and unsuccessful sites, indicating annual breeding productivity in a given area and year.

Abstract

Intelligent and adaptable, the Common Raven, *Corvus corax*, is one of the most widely distributed passerine birds ranging across much of the Holarctic where it largely exists as an opportunistic scavenger. Much of its success and recent spread in distribution can be linked to recent declines in persecution as well as activities like agriculture which may unintentionally subsidise them. Agriculture is the most widespread type of land management and one of the greatest drivers of environmental change and loss of biodiversity, often reducing species' ability to provide important ecosystem services. Large areas of land in the UK are managed for agriculture, in particular Wales, where notable changes in livestock have occurred since the 1950s. In addition, northwest Wales supports some of the highest population densities of Raven in Britain, and so offers an excellent study area. Here, the relationship between Raven breeding performance and livestock practices on Anglesey and the Carneddau from 2003 to 2018 have been investigated.

On Anglesey, raven breeding performance was negatively related to dairy cattle density and percentage of area farmed. This has likely arisen due to changes in stocking densities of dairy cattle that have occurred in an intensively managed landscape, which may have impacted food availability for breeding Raven pairs. Simultaneously, Raven breeding performance on Anglesey was positively related to area of permanent pasture and area of rough grazing. The former may benefit breeding Ravens by providing less competition from specialist species. On the other hand, areas of rough grazing can support more biodiversity and are commonly associated with sheep, both of which may increase foraging opportunities.

In the Carneddau, the breeding performance of Ravens had no relationship to livestock practices. This is likely explained by the topography and poor agricultural productivity of the region which limits the presence of high intensity livestock practices. This study provides evidence that the breeding performance of Ravens in northwest Wales is more likely to be influenced by changing livestock practices in intensive agricultural landscapes than in extensive agricultural landscapes. While this could have important implications for conserving and managing similar avian scavengers in agricultural landscapes, further research is necessary to better understand the relationships presented here.

Acknowledgments

I would like to thank Julian Driver for allowing me to use his impressive raven dataset, without which this study would not have been possible. Thank you also to both my amazing supervisors, who's guidance and encouragement were invaluable to me throughout this process, and to Prysor Williams and Ian Harris for their help with information about local agricultural matters. Finally, thanks must also be given to my ever supportive parents and partner who never doubted me, even when I wanted to.

To all of you, I am forever grateful.

Introduction

Agriculture is the most widespread type of land management, taking place on over 50% of earth's habitable land, with livestock farming occurring on over 77% of that (Ritchie & Roser 2019). Being so widespread, agricultural activities are one of the greatest drivers of environmental change and loss of biodiversity (Maxwell *et al*. 2016). These activities involve alteration of natural systems through the introduction of artificial elements, e.g. livestock, and often total transformation of the original environment, e.g. deforestation of native forests or ploughing of natural grasslands (Grande *et al.* 2018). This can affect all natural processes in an environment, e.g., individual behaviours and population dynamics of species, the composition of communities, and ultimately the ecosystem services they provide (Grande *et al.* 2018; Inger *et al*. 2016). Scavengers provide important ecosystem services by foraging on carrion, contributing to nutrient cycling and waste removal in the habitats they occur (Peisley *et al.* 2016). However, in more altered, large scale agricultural landscapes numbers of active scavengers can be lower, favouring fewer generalist consumers than in undisturbed rural landscapes (Inger *et al*. 2016; Olson *et al*. 2012). Ultimately, this can reduce the ability of scavenging communities to provide their ecosystem services (Olson *et al*. 2012; Cort és-Avizanda et al. 2012). Avian scavengers are often key components of scavenging communities due to their ability to fly. This allows them to overcome the temporal and spatial unpredictability of carrion, particularly in open environments (Buechley & Şekercioğlu 2016). For example, in Australia research indicated that avian scavengers such as the Whistling Kite (*Haliastur sphenurus*), and the Australian Raven (*Corvus coronoides*), act as major contributors of carrion breakdown in grazing landscapes, which may also reduce the spread of diseases (Peisley *et al.* 2016). However, many avian scavengers, like raptors, are often also top predators. This means they can often be sensitive to major ecosystem changes imposed by agricultural activities and their intensification, being a key factor driving declines in global raptor species (Grande *et al.* 2018).

In the UK, biodiversity is declining at an unprecedented pace, with 41% of species having experienced a decrease in their populations since 1970, and agricultural management being recognised as having the biggest singular impact on biodiversity, with 72% of UK land being farmed in 2019 (Hayhow *et al*. 2019). Populations of farmland birds have decreased by more than 50% since 1970 (Hayhow *et al*. 2019), with specialist species, such as Turtle Doves

(*Streptopelia turtur*) and Grey Partridges (*Perdix perdix*), declining the fastest (Burns *et al.* 2020). Within the UK, Wales has the most extensive area of agriculturally managed land, being 88% in 2019 (Hayhow *et al.* 2019), and is also experiencing declines in farmland birds such as starlings and rooks (Burns *et al.* 2020).

Agriculture in Wales

The dominating upland terrain and wet, mild climate of Wales has greatly influenced the prevalence of livestock farming over crop cultivation (Welsh Government 2019a; Roberts 1959). As such, over 80% of agricultural land is managed for livestock grazing, i.e. approximately 57% permanent pasture and 24% rough grazing (Welsh Government 2019a). The ability of sheep to thrive in upland environments on poor quality land has resulted in their being the dominant type of livestock, although many farms keep both sheep and beef cattle. On the other hand, dairy cattle farming is closely associated with the availability of good quality grazing so typically requires large areas of improved grassland (Welsh Government 2018).

During the latter half of the 20th century sheep numbers in Wales increased substantially after the introduction of the Common Agricultural Policy (CAP) in 1973 when Britain joined the European Union (Pritchard *et al.* 2021). The new policy incentivised farmers to increase their flocks by issuing headage payments on individual sheep (Williams, P. 2021, *pers comm*, March 15th). In north Wales there was an absolute increase of 0.99 million heads between 1980-90, i.e. the highest increase observed in Wales (Fuller & Gough 1999), with many large flocks grazing across Snowdonia at this time (Williams, P. 2021, *pers comm*, March 15th). During the 1990s these large flocks had led to concerns of overgrazing in upland areas, with discussions leading to the introduction of the first National agri-environment scheme (AES), Tir Gofal, in 1999 (Williams, P. 2021, *pers comm*, March 15th). Farmers that joined this AES received payments that compensated income lost from fulfilling its requirements. These included a cap on flock numbers, and seasonal restrictions to upland grazing, both intended to reduce the impact of grazing on upland habitats and landscapes.

The removal of CAP headage payments in 2003 coupled with poor market prices of lamb at this time made it economically unsustainable to keep large sheep flocks. Joining Tir Gofal and receiving compensation for reducing flock numbers thus became the most viable option for an overwhelming majority. This sudden change in incentives, as well as the 2001 outbreak of foot and mouth disease, subsequently drove considerable declines in sheep numbers across Wales from the early 2000s (Williams, P. 2021, *pers comm*, March 15th). Nationally, numbers fell by approximately 18% between 2002 and 2009, but have since increased by just under 16% between then and 2018 (Welsh Government 2019b). These national trends are very similar to those observed in northwest Wales, where sheep numbers fell from 2002 to 2010 by approximately 20%, and began to rise again from 2011, increasing by approximately 17% from then until 2018 (Welsh Government 2019b).

During the initial increase of Welsh sheep numbers, a milking quota was introduced by CAP in 1984 (National Farmers Union 2015). By the 1990s the dairy sector had become economically unviable for many farmers who were forced to leave the dairy industry and sell their quotas to others (Williams, P. 2022, *pers comm*, August 19th; Uberoi 2021). This resulted in decreases of registered dairy producers in the UK, falling by 67% between 1995 and 2020, but also resulted in an increase in dairy herd sizes. As such, between 2008 and 2018 the average herd size increased by 28% across the UK and 40% in Wales (Uberoi 2021).
Milking quotas would remain until 2015, with their removal resulting in further increases in herd sizes, and some farms converting from sheep and/or beef to solely dairy. This has become an increasingly common trend in some areas, one notable example being Anglesey, where its climate and low lying landscape provide grass growing conditions needed for dairy systems (Williams, P. 2022, *pers comm*, August 19th).
Over approximately the past two decades dairy cattle numbers at a national level have remained relatively stable, with changes being more notable at a regional level. For example, from 2004 and 2011 dairy cattle numbers in Wales fell by 10%, followed by a recovery over 7 years, with 2018 levels being similar to those in 2004 (Welsh Government 2019b). Looking more regionally for comparison, in northwest Wales from 2004 to 2011 dairy cattle numbers fell by approximately 15%, followed by an increase of almost 60% over 7 years. By 2018 dairy cattle numbers were 32% higher than in 2004, this being significantly higher than increases reported at a national level (Welsh Government 2019b).

The Common Raven

The Common Raven (*Corvus corax*; henceforth Raven) has a multifaceted relationship with agriculture which is widely acknowledged (Ratcliffe 1997; Shrubb 2003; Lovegrove 2007). More commonly however, the Raven is recognised for its intelligence and a high degree of plasticity in a range of environments, being the most widely distributed of the corvids (Delehanty 2021). This species is found across the majority of the Holarctic, including very dissimilar habitats such as the Canadian high Arctic (Matley *et al*. 2012), the arid Mojave Desert (Kristen & Boarman 2007), and the primeval forests of Poland (Rösner *et al*. 2005. Ravens, like most corvids, thrive as opportunistic omnivores, with their diets and foraging habits varying with location and seasonality. However, in all the environments where they occur, Ravens are foremost important avian scavengers. Research suggests frequently scavenging birds like ravens contribute to the nested structure of scavenging communities, with their presence at a carcass encouraging scavenging by rarer non-specialist scavengers (Selva & Fortuna 2007). For example, Ravens facilitate the discovery and access to carrion by raptors, increasing their survival in the winter months (Orr et al. 2019).
Their generalist nature also applies to their breeding habits, with pairs choosing cliffs and/or trees as nest sites in natural environments, while pairs in semi-natural or anthropogenic environments often choose man-made structures (Harju *et al*. 2018). Availability of food resources and suitable nest sites can influence breeding performance of ravens by determining the proportion of successful breeding attempts (i.e. those that fledge at least one young) and the number of young fledged from those successful attempts (Wilson *et al*. 2019). In recent decades research has demonstrated how human activities can significantly influence both food (Restani *et al*. 2001) and nest site availability (Harju *et al*. 2018), and in many situations has allowed ravens to colonise new areas by making these resources readily accessible where they may have been previously limited or unavailable, e.g. Idaho and Oregon (Steenhof *et al*. 1993), Alaska North Slope (Powell & Backensto 2009), and the Mojave Desert (Kristen & Boarman 2007).

Livestock farming can unintentionally provide ravens indirect resources, such as scavenging and predation opportunities. This can include carrion from fallen stock and afterbirth (Fuller 1996; Fuller & Gough 1999; Newton et al. 1982), or vulnerable newborn stock, and occasionally, their mothers (Ratcliffe 1997). Newton *et al*. (1982) showed that annual clutch size of ravens in central Wales was positively correlated with carrion availability, and peaks in its availability closely corresponded to the breeding season. The same study in central Wales, as well as others in north Wales (Dare 1986) and Southern Scotland (Marquiss *et al.* 1978), also indicates sheep carrion can be a determinant of raven population density, with higher availabilities of carrion increasing the carrying capacity of these areas, allowing population densities to increase. Ravens can also indirectly benefit from the presence of livestock by feeding on grain for stock (Engel & Young 1989; Marquiss & Booth 1986) and invertebrates attracted by dung or disturbed by grazing activity (Marquiss & Booth 1986). In arid and semiarid environments stock tanks and water troughs for cattle can be an especially important source of water, Coates *et al*. (2016) showed that ravens in south-eastern Idaho are more likely to occur where cattle, and water sources provided for them, are also present. While agriculture can benefit raven populations, these populations have the potential to provide reciprocal benefits, but can also be detrimental to livestock farmers. Although primarily scavengers, ravens have been known to predate lambs and ewes that are weak or unhealthy (Ratcliffe 1997). While some published evidence of predation does exist (Ridpath 1953; Ratcliffe 1997), this is often anecdotal and there is a notable lack of reliable, recent reports or research surrounding this issue. Further research to understand the true frequency and costs of raven predation on livestock would be an important contribution to the management of conflict with farmers.

While Ravens' ability to predate can be a detriment to livestock farmers, benefits may also exist from the presence of avian scavengers like Ravens. Efficient removal of carrion by avian scavengers in grazing landscapes may aid in the prevention of globally widespread, costly diseases such as blowfly strike (Peisley et al. 2017). In the UK this reportedly costs the sheep industry £2.2 million a year and financially impacts 99% of sheep farmers (Astley 2016). Sheep become most vulnerable to blowfly strike from March (Price 2016) which is also when Ravens increase their scavenging of carrion to supplement their young chicks (Marquiss & Booth 1986; Ratcliffe 1997). While no official measure of carrion removal by ravens or other avian scavengers has been conducted, previous research has suggested that any reductions in early strike occurrences could aid in preventing strikes later in the season (Lihou & Wall 2019).

While the presence of ravens in agricultural landscapes has potential to create benefits for both, perceived conflicts with human activities have resulted in persecution of raven populations. In Britain ravens were once widespread across lowland and upland habitats, even being a common sight in urban areas like London where their scavenging habits of refuse were recognised as a valued service (Lovegrove 2007; Ratcliffe 1997). By the 17th century however, several factors had converged to precipitate the raven's long and steady decline in both numbers and distribution. Human persecution, being primarily associated with agriculture and game management, already occurred in rural parts of the country where ravens had a reputation as a threat to livestock and game (Ratcliffe 1997; Lovegrove 2007). This persecution became more widespread with the introduction of the 1566 'Vermin Act' which established bounties for the culling ravens and many other native species which came into (true or perceived) conflict with human activities (Lovegrove 2007). Ravens were also impacted by changes in livestock practices, much of this being brought about by the growing popularity of enclosure, which resulted in improved husbandry of livestock and drainage of the land, consequently decreasing mortality of livestock and availability of carrion (Shrubb 2003).

Raven populations became absent from lowland areas, while those occurring in more remote upland landscapes, such as those of Wales and Scotland, were largely unaffected. This is likely due to agricultural and game management in these landscapes being minimal or absent, and nests were often in especially inaccessible locations (Ratcliffe 1997). Raven populations began recovering during the 20th century and can be largely attributed to legal protection and the banning of harmful substances. In 1954 partial legal protection was issued from the Protection of Birds Act, with full blanket protection being issued by the Wildlife and Countryside Act in 1981 (Ratcliffe 1997). During the 1950s and 60s organochlorine pesticides were commonly used in agriculture (Shrubb 2003). This pesticide provided detrimental to many species such as Peregrines (*Falco peregrinus*) and Ravens, due to its capacity to accumulate up food chains and concentrate in top predators and scavengers (Ratcliffe 1980). The pesticides began to decline from 1962 with a voluntary withdrawal of their use, but a full ban would not be issued until 1982 (Shrubb 2003). Since the end of the 20th century, and into the start of the 21st, the raven's population in the UK has subsequently seen considerable expansion in numbers and distribution, reclaiming many ancestral areas where they have been absent for over a century (Wilson et al. 2019; Ratcliffe 1997).

Breeding Ravens in Northwest Wales

Ravens can be found across much of Wales, with most of the country's land cover being upland terrain (Welsh Government 2018) and offering a plethora of nesting opportunities for breeding pairs, most notably in heavily glaciated landscapes such as Snowdonia (Ratcliffe 1997). To date, many studies have been carried out on ravens in northwest Wales where there is a decent record of their breeding ecology (Allin 1968; Ratcliffe 1997; Dare 1986; Driver 2006; Driver 2007).

Beginning in 1946-67 with Allin (1968), observations of breeding territory and nest site use were made in areas of Anglesey, Caernarvonshire, Denbighshire, Merionethshire, and Montgomeryshire, where a preference for cliffs as nest sites was found. In a similar time frame, i.e. 1950-67, Ratcliffe (1997) carried out a huge survey of breeding and population of ravens across Britain and Ireland. During this time Ratcliffe completed the first large-scale survey of breeding ravens in Snowdonia where he recorded a total of 62 breeding pairs, and between 1951-53 he also confirmed at least 14 pairs nesting on sea cliffs of Anglesey.

Another survey of breeding performance of Snowdonia ravens wasn't carried out until 1978-85 with Dare (1986) covering an even larger area than Ratcliffe, and also including the moors and enclosed sheep farms of nearby Migneint-Hiraethog. In Snowdonia an 80% increase in breeding pairs was observed since Ratcliffe's survey 11 years prior, and was thought to be related to increased sheep carrion availability. In Migneint-Hiraethog, the raven population had been stable since the 1950s but at lower breeding densities than in Snowdonia. These were attributed to the scarcity of nest sites and carrion. In both areas observed, food availability was thought to be important in determining future breeding success, being itself strongly influenced by changes in agricultural practices and land-use.

Driver (2006; 2007), being the most recent to date to publish observations of breeding ravens in northwest Wales, reports on various aspects of breeding performance from 1998 to 2005 and covered Dare's previous study areas Snowdonia and Migneint-Hiraethog, as well as much of Colwyn, Bangor-Caernarfon, Anglesey, and the Llyn Peninsula. In Snowdonia there was an increase of 69% in nesting pairs since Dare's survey, and an increase of 173% since Ratcliffe's survey. Driver (2006) suggests this rate accelerated after the 1990s, being strongly linked to increased numbers of sheep stock and carrion. In three years of the study period Driver surveyed sections of the Carneddau mountain range of Snowdonia for sheep carrion,

observing a seasonal peak in carrion availability during the raven's breeding season (March to July), in line with the findings of previous studies (Newton *et al*. 1982).
Even during times of increased persecution, Wales has been recognised as having some of the highest raven densities in Britain, and while its upland nature and availability of nest sites contributes to this, the availability of livestock carrion also has a major influence on their breeding, distribution, and densities (Fuller 1996; Fuller & Gough 1999; Newton *et al*. 1982).

The Present Study

The increase in global raven populations and distributions have already been shown to be detrimental to some sensitive species in the US, i.e. desert tortoise (*Gopherus agassizii*), greater sage-grouse (*Centrocercus urophasianus*), snowy plover (*Charadrius nivosus*) (Berry et al. 2020; Coates *et al.* 2020; Lau *et al.* 2021). In Scotland the number of applications submitted, and accepted, for licences to cull ravens have increased in recent years, with reports of human-raven conflicts becoming more common (Wilson *et* al. 2019). In relation to this, a study (Wilson *et* al. 2019) was commissioned by Natural Scotland to improve understanding of raven populations and the potential for licensed culls to impact on these. In areas such as this where ravens are increasing in number or colonising new ground, and have the potential to impact negatively on threatened species or to livestock, having an understanding of raven population dynamics is important for management of all species involved. It is also important to understand how breeding populations are influenced by certain widespread activities, namely agriculture, as this can be a key factor in determining breeding performance of pairs in an area, and so offers an additional measure to better inform sustainable management.
Having a better understanding of how scavenging bird species such as ravens can be influenced by livestock practices may also have applications in better conserving similar scavenging raptor species in agricultural landscapes, where they can be threatened, and offer valuable ecosystem services can be maximised.

Previous research has presented evidence for relationships between raven populations and livestock, notably sheep in Britain (Newton *et al*. 1982; Marquiss & Booth 1986; Ewins *et al.* 1986), while two similar studies in the US used models to test the relationship between raven occurrence and various environmental variables, cattle presence being seemingly important in both (Coates *et al*. 2014; Coates *et al*. 2016). However, no studies to date have used models to test how long term changes in livestock related practices have influenced the breeding performance of ravens in Britain. Northwest Wales offers a good setting to test this relationship, having one of the highest densities of ravens in Britain (Ratcliffe 1997), and highly varying agricultural landscapes, i.e. Anglesey vs Carneddau, which have experienced some notable changes in livestock practices over recent decades.

In addition, the most recently published material on breeding Snowdonia Ravens was in 2007 (Driver 2007), with none existing for Anglesey breeding Ravens at the time of writing. For the first time then, this study reports such information for breeding ravens on northern Anglesey.

Aims

This study reports on aspects of the breeding performance of Ravens occupying northern Anglesey and the Carneddau region of Snowdonia from 2003 to 2018. Relationships that have occurred between raven breeding performance and local livestock practices in these time frames are identified.

To achieve this, this study had the following key objectives:

i. Exploration of long-term trends in Raven breeding performance data collected from Anglesey and the Carneddau between 2003-2018.
ii. Exploration of long-term trends of selected agricultural practices for Anglesey and the Carneddau between 2003-2018.
iii. Testing for differences in Raven breeding performance between the study areas and across the study period.
iv. Testing for relationships between Raven breeding performance and livestock practices, i.e. breeding ewe density, dairy cattle density, percent area farmed.
v. Understand how relationships differ between a low-lying coastal environment experiencing intensive livestock practices (Anglesey), and a mountainous environment experiencing extensive livestock practices (Carneddau).

Methods

Study Areas

Anglesey

Two areas of northern Anglesey were monitored. The Cemaes-Amlwch area (henceforth only 'Cemaes-Amlwch') spans 8.88km of coastline from Cemaes town (*53°24'55.2"N 4°26'49.9"W*) to Amlwch port (*53°25'02.8"N 4°19'35.3"W*). The Carmel Head area (henceforth only 'Carmel Head') spans 7.43km of coastline from Church Bay (*53°22'25.7"N 4°33'18.6"W*) to Hen Borth (*53°24'25.2"N 4°31'40.9"W*) (**Fig.1**).

Anglesey, Wales' largest island (720km^2, including Holy Island), is a predominately low-lying area, particularly inland, with much of it being less than 50m above sea level (Natural Resources Wales 2014a). Much of the highest land on the island is found coastally, with the highest points being Mynydd Twr (Holyhead Mountain) (220m), Mynydd Bodafon (Bodafon Mountain) (170m), and Mynydd Parys (Parys Mountain) (147m) (Natural Resources Wales 2014b). The northern coast, including Holy Island, is also characterised by sheer coastal cliffs and rocky headlands that provide a prime location for sea bird colonies, as well as other species of conservation interest such as peregrines (*Falco peregrinus*) and red-billed choughs (*Pyrrhocorax pyrrhocorax*) (Pritchard *et al*. 2021). Owing to these factors, many coastal sites around the island are designated as Sites of Special Scientific Interest (SSSI), National Nature Reserves (NNR), Special Areas of Conservation (SAC), and Area of Outstanding Natural Beauty (AONB) (Natural Resources Wales 2014b). The dominant landscape here is one of expansive agricultural land bounded by hedgerows, with the majority of Anglesey being improved grassland (Natural Resources Wales 2014a) for sheep, beef, or dairy cattle. Despite being mostly farmed, heath scrubland vegetation (e.g. heather (*Calluna*, *Erica*) and gorse (*Ulex*) species) is still present, being mostly in the more elevated coastal regions (Natural Resources Wales 2014b). Anglesey is one of the least wooded lowland areas in Wales (Natural Resources Wales 2014a), with the largest woodlands being found at Pentraeth (0.35km^2) and Newborough (7.71km^2). Newborough Forest, planted with Corsican pines (*Pinus nigra*) from 1947-1965, is also known for hosting one of the largest raven roosts ever observed (~1900 individuals in January 1997, Wright *et al*. 2003).

Carneddau

Situated to the north of the Snowdonia National Park, the Carneddau mountain range (*53°11'43.5"N 3°56'34.8"W*) (**Fig.1**) has the largest continuous stretch of upland over 2,500 feet (762m) in England and Wales (Snowdonia Guide 2019), and a total area of approximately 250km^2 (Dare 1986). This richly varied landscape holds the second and third highest peaks in Wales (Carnedd Llewelyn & Carnedd Dafydd respectively) (Snowdonia Guide 2019) alongside moorland plateaus, and deep U-shaped valleys as well as numerous other features formed by retreating glaciers approximately 10,000 years ago (Natural Resources Wales 2014c). Moorland is a dominant landscape type, being dominated by heather species (e.g. *Calluna vulgaris*, *Erica cinerea*, *Erica tetralix*) and unimproved acid grassland habitats (Natural Resources Wales 2014c). Extensive conifer plantations also cover large areas of the Carneddau, most notably around Betws-y-Coed to the south. Deciduous woodland is more abundant in valleys and other lowland areas, such as the Atlantic Oak woodland in Coedydd Aber to the north (Natural Resources Wales 2014c). Many areas of the Carneddau are recognised for their significant ecological value, containing areas of blanket bog and providing ideal conditions for rare invertebrates and arctic-alpine flora, like the Rainbow Leaf Beetle (*Chrysolina cerealis*) and the Snowdon Lily (*Gagea serotina*) (Natural Resources Wales 2014c), as well as a variety of upland birds, many of which are threatened in the UK, such as Chough (*Pyrrhocorax pyrrhocorax*), Red Kite (*Milvus milvus*), and Ringed Ouzel (*Turdus torquatus*) (Pritchard *et al*. 2021). Extensive areas of the Carneddau are recognised as NNR and/or SSSI sites (Natural Resources Wales 2014c). The highly varied, and often challenging, terrain here has a significant influence on human activities such as agriculture, which today is relatively low in intensity throughout the Carneddau and predominately consists of hill sheep farming (Natural Resources Wales 2014c).

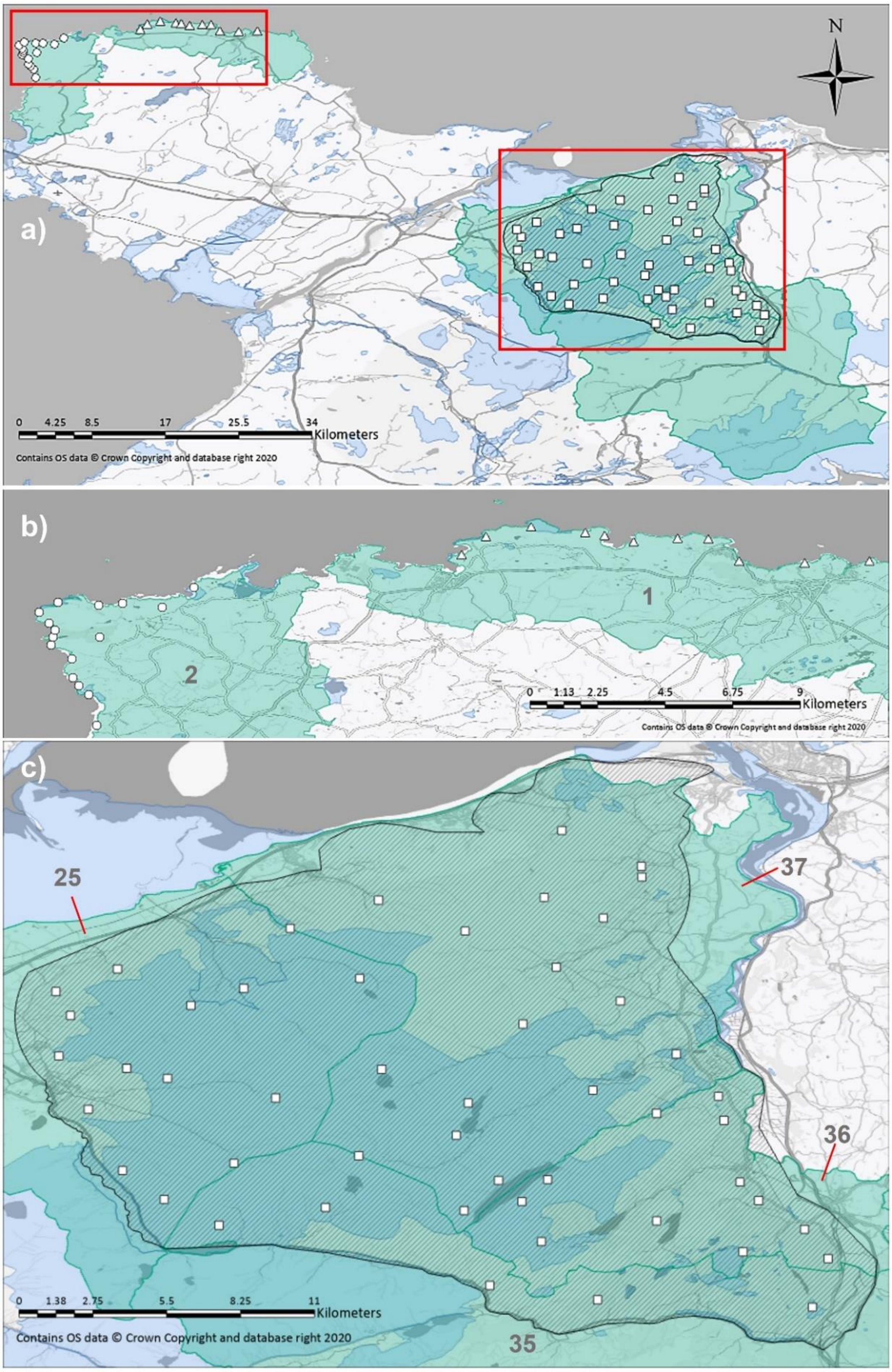

Figure 1. a) Showing both study area regions (within red outlines) in northwest Wales; b) Anglesey, with Cemaes-Amlwch nest sites (*n=11*) shown as 'Δ', and Carmel Head with nest sites (*n=16*) shown as 'o'; c) the Carneddau study area represented by black outlined area with nest sites (*n=52*) shown as '□' within it. Agricultural small areas used in this study are represented by shaded green areas and can be identified by their official area codes. SSSI are also included and represented by shaded blue areas.

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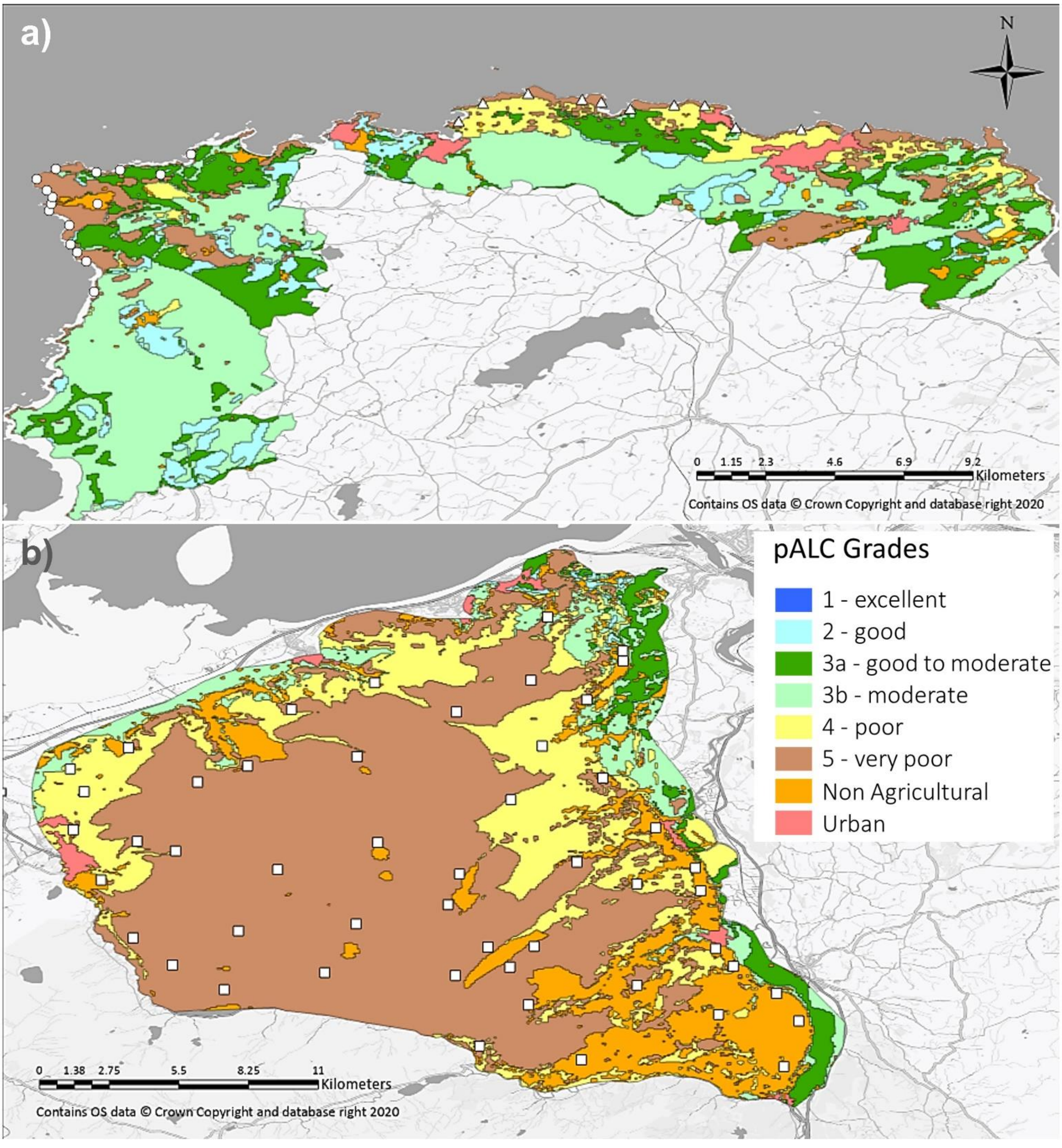

Figure 2. The agricultural small areas according to the Welsh Government Predictive Agricultural Land Classification (pALC) deignated there for the study areas on **a)** Anglesey, with Cemaes-Amlwch nest sites (n=11) shown as 'Δ', and Carmel Head with nest sites (n=16) shown as 'O'; and **b)** the Carneddau study area with nest sites (n=52) shown as '□' within it.

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Data Collection

Collection of raven breeding performance data

All raven breeding performance data used in this study were collected by Julian Driver. Visits to nest sites were made during the Welsh raven breeding period, i.e. late February to early March and usually concluding by June when most active nest sites have fledged their young (Ratcliffe 1997). A standardised survey protocol was followed during all surveys. This included three main conditionally consecutive stages (**Fig.3**): 1) Determining the occupancy status of a territory; 2) Determining if the nest site is active; 3) Monitoring nest contents over breeding season.

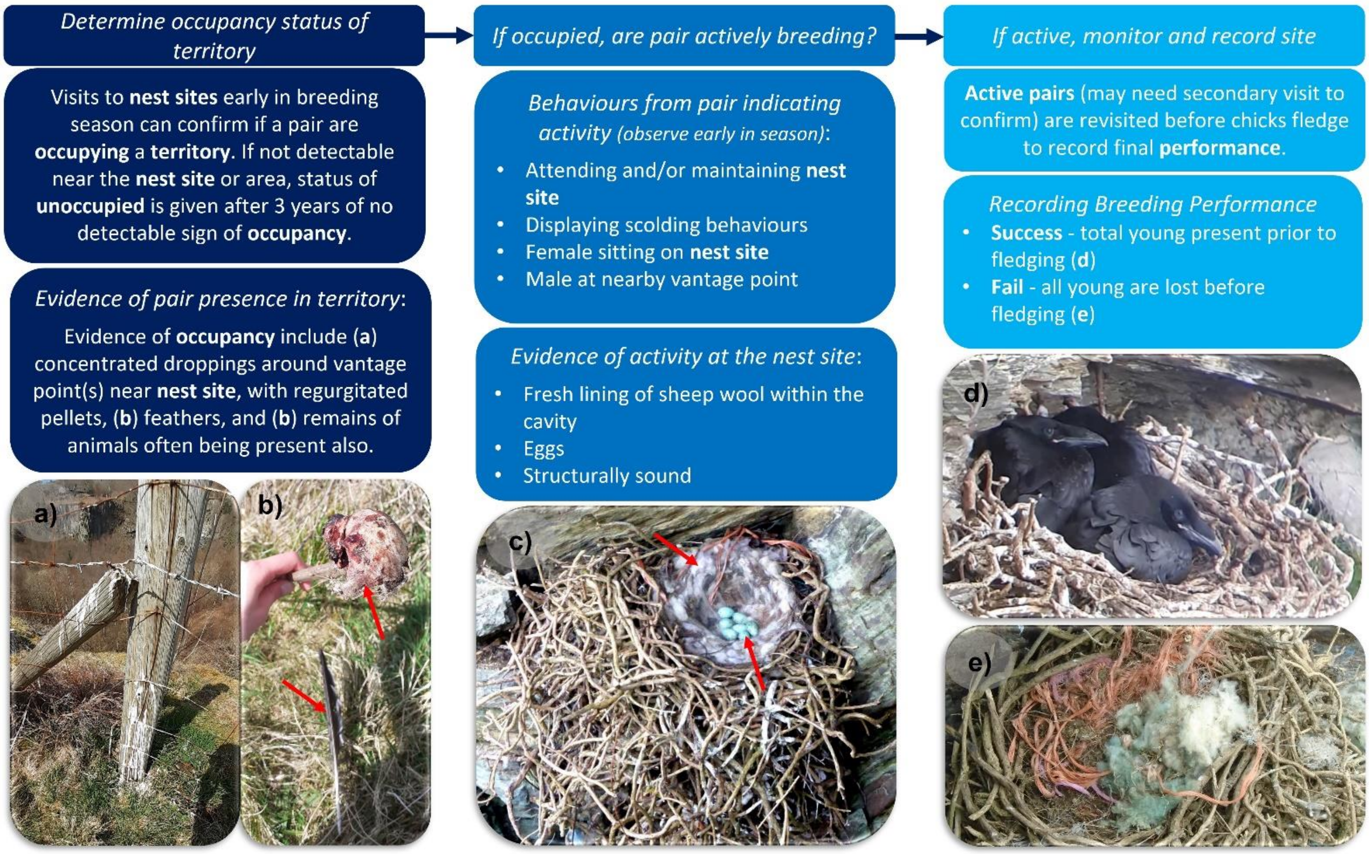

Figure 3. Summarised process of assessing the breeding performance of common ravens in northwest Wales. **a)** Fence post used as vantage point, evidenced by concentrated droppings, as well as **b)** raven feathers and lagomorph remains (indicated by red arrows), **c)** active nest site that has been maintained for breeding season, note fresh wool lining and 7 eggs (indicated by red arrows), **d)** three young in a nest prior to fledging, would have recorded performance of '3' in given year, and **e)** empty nest site that failed at chick stage.

During the spring of 2020 and 2021, the *Covid-19* pandemic restricted the number of possible visits to assess nest sites, including important follow-up visits necessary to confirm breeding outcome of some of the nest sites. Because of this breeding performance data from these years could not be used.

Collection of agricultural data

Data on agricultural practices from 2002 to 2018 were sourced from the Welsh Agricultural Small Area Statistics database (henceforth AgSAS) (gov.wales/agricultural-small-area-statistics-2002-2018). AgSAS is derived from the Welsh Agricultural Survey which is carried out annually on June 1st and provides non-disclosive summary statistics at a small area scale. This information is licensed under the Open Government Licence v3.0.

Notes on Data Quality

In using this dataset a few things must be considered concerning its quality.
Firstly, being a sample survey, some values can be missing. Farms may fail to respond to the survey, and so must have their results estimated, while some may be missed altogether if they are not registered. Therefore, the values for practices in this dataset should be recognised as estimates that can carry a level of uncertainty. Nevertheless, the dataset is the best available measure of agricultural practices in Wales at this scale and has been shown to be good at demonstrating trends in the aggregate estimates over time (Welsh Government 2019b).
Secondly, the annual Welsh Agricultural Survey that AgSAS is derived from omits the number of livestock on common land. This is because common land is used by groups of farms rather than exclusively by one. This may affect both Anglesey and Carneddau agricultural data as seasonal grazing on Anglesey is traditionally utilised by upland farmers. Additionally, some areas of rough grazing across Snowdonia are also common land, meaning these areas of rough grazing are not represented in the dataset (Welsh Government 2022).
Another factor that should be considered is the introduction of the Cattle Tracing System (CTS) in 2004. This replaced questionnaire surveys as the method used to record numbers of cattle at a farm scale, generating more accurate data and requiring less effort on the part of farmers. Due to this, data for dairy and beef cattle is missing for 2002 and 2003.
Lastly, the area of land farmed recorded for an agricultural area may be over 100% in some years. This is because the Welsh Agricultural Survey collects data at the level of individual

holdings, and land owned by the holdings can be spread over a wide area, some of which can be outside of the agricultural small area the owner is based in.

More information concerning this dataset can be found by reviewing the statistical bulletin that accompanies it (Welsh Government 2019b).

Data Preparation

Selection of Anglesey raven breeding sites

The Carmel Head and Cemaes-Amlwch study areas were monitored consistently since recording began in 2003. However, none of the Carmel Head's 16 nest sites were surveyed in 2018 and 2019, and none of Cemaes-Amlwch's 11 nest sites were surveyed in 2019. In addition, one of the eleven nest sites from Cemaes-Amlwch was not surveyed from 2012 to 2017, but visits resumed to the site in 2018.

In this study, Raven sites at Cemaes-Amlwch are reported from 2003 to 2018, and at Carmel Head from 2003 to 2017 due to the missing records in 2018 and 2019 and a lack of adequate data from 2020 and 2021 due the Covid-19 pandemic.

Selection of Carneddau raven breeding sites

In past similar studies, Dare (1986) and Driver (2006) divided Snowdonia into four regions: '*Carneddau'*, '*Central'*, '*South-West*', and '*South-East*', with 555 nest sites being recorded across all. For this study only those occurring within the Carneddau region were selected. The original boundary used by Dare (1986) and Driver (2006) to define this region was used to ensure that all nest sites were occurring within the Carneddau region. Subsequently, 13 sites falling outside the boundary were removed.

Although this region is the most consistently surveyed, having the highest number of recorded nest sites, inconsistencies in the dataset still exist. Every year the total number of nest sites visited during the breeding season varied (mean = 33 [±7.5] range = 19-47 sites visited). In addition, the nest sites represented in the dataset varies from year to year.

The Carneddau breeding performance dataset goes back to 1975, but in this study only data from 2002 to 2018 is used. This is due to the AgSAS dataset only being available from 2002, and like Anglesey, inadequate data exists from 2020, i.e. due to the Covid-19 pandemic.

Exploration of Raven Breeding Data

Using the final selected sites, various breeding performance variables were calculated. These included the number and percentage of occupied territories, active pairs, and successful breeding attempts annually. In addition, the mean number of occupied territories and active pairs were calculated both annually and across all years. Annual 'productivity' has also been calculated for each study area (*i.e. Cemaes-Amlwch, Carmel Head, Carneddau*), ands refers to the average number of young fledged from all active pairs (*including fails*), which gives an indication of local productivity. Productivity is calculated annually and across all years. These parameters were calculated for three areas: Cemaes-Amlwch, Carmel Head and Carneddau.

Editing Agricultural Data

There are 60 variables in the AgSAS for Wales 2002 to 2018 dataset that relate to agricultural practices. However, not all of these were relevant to this study, so only those variables that suspected to influence the breeding performance of ravens were selected. These included total 'area farmed', being an indication of farming coverage, 'livestock' variables, because the link between ravens and livestock, (notably sheep) is well documented (Newton *et al.* 1982; Fuller & Gough 1999; Ratcliffe 1997), and finally 'grassland' variables, as they give an indication of pasture type, i.e. coverage of improved and semi-improved grassland.
As each agricultural small area varies in total size it was necessary to divide the original values of each variable by total area, resulting in % values for area-based measurements, and densities for livestock. This allowed for comparison between each small area. (**Table 1**).

Table 1 Livestock related variables from AgSAS used in this study, with the original variable, converted variable, and definitions of each activity.

Original Variable	Converted Variable	AgSAS Definition of Activity
Breeding Ewes (heads)	Breeding Ewe Density (/km^2)	Ewes aged at least one year used for breeding.
Lambs (heads)	Lamb Density (/km^2)	Aged under 1 year
Dairy Cattle (heads)	Dairy Cattle Density (/km^2)	Females aged over 2 years and any other animals that have already calved split into dairy and non-dairy breeds
Beef Cattle (heads)	Beef Cattle Density (/km^2)	
Area Farmed (hectares)	Area Farmed (%)	Total land on the holding, excludes use of common land
Permanent Pasture (hectares)	Permanent Pasture (%)	Improved grassland at least 5 years old
Rough Grazing (hectares)	Rough Grazing (%)	Sole rights rough grazing only, excludes common land
New Grassland (hectares)	New Grassland (%)	Grassland under 5 years old

Concerning the converted livestock densities, while hectares is the standard measurement of area used in agriculture, km^2 was thought to be more appropriate here due to the ecological nature of this study. Where appropriate however, equivalents will be given in hectares.

Spatial Preparation

The geographical information system (GIS) software ArcGIS Pro was used to establish spatial correspondence between recorded nest sites and agricultural small areas, and to assess the nearest neighbour distances between active sites, and densities of active sites in the Carneddau region.

All recorded nest sites have an OS grid reference that was converted into X, Y coordinates. All locations of nest sites were manually checked to ensure correct placement using original nest location maps provided by Driver, as well as using my own knowledge of the nest sites.

Nest Site Association to Agricultural Areas and Activities of Practices

Both Anglesey sites were each located within their own agricultural small area, Cemaes-Amlwch and Carmel Head being small area 'ISLE01' and 'ISLE02', respectively. The relevant metrics from each small agricultural area were applied to all raven territories occurring within.

The boundary of the Carneddau region, and the distribution of its nest sites, overlapped with four agricultural small areas (25, 35, 36, 37). Half of the nest sites in this area occurred near or on the boundary of two or more small areas. Unique weighted means of agricultural activities were calculated for each of these sites i.e. weighted by how much their estimated breeding territory overlapped in each area. For the purposes of calculating these weighted means, breeding territories were assumed to be $1.5km^2$ in size (based on observations made by Dare (1986) and Ratcliffe (1997) for Snowdonia ravens), with the recorded nest site location as the centre.

Nearest Neighbour Distances of Active Nest Sites

Nearest Neighbour Distances were measured between actively breeding sites for every year, with a yearly average being calculated from those recorded distances. Measurements were made using the '*measure distance*' tool in ArcGIS Pro.

Densities of Carneddau Active Nest Sites

Every year from 2002 to 2018 densities of active nests per $100km^2$ were calculated using the area of the Carneddau boundary ($256.34km^2$) and the number of active breeding sites occurring within it in each year.

Statistical Analysis

All analyses were run in R studio (Version 4.1.2), with Anglesey and the Carneddau having analyses conducted separately of each other. Assessments of the distribution of the datasets were conducted, with Poisson distributions being concluded as most appropriate for both Anglesey and the Carneddau.

Welch two-sample t-tests and Wilcoxon rank sum tests were also run to determine whether various raven breeding performance variables and agricultural practices were significantly different between the Cemaes-Amlwch and Carmel Head study areas.

Investigating the relationship between Raven Breeding Performance and Agricultural Practices

<u>Anglesey</u>

For the Anglesey Raven sites a generalised linear mixed-effects model (GLMM) fitted by maximum-likelihood (ML) from the *'lme4'* package for R was used to test for any significant relationships. All models used *'young fledged'* as the response variable and were fitted with a Poisson distribution (i.e. *family = poisson*). The variables *'year'* (i.e. 2003 – 2018) and *'site ID'* (denoting individual nest sites) were used as random effects. A model was created with all eight agricultural variables (see **Table 1**) included as explanatory variables. The stepwise deletion of the least relevant variables (i.e. by increasing explained variation tested with an ANOVA) was performed until a minimal adequate model was reached. The assumptions of the final model were tested by carrying out *'testDispersion'* and a Shapiro-Wilk normality test on its residuals. The process of running models was repeated until a minimal adequate model was reached, being the model with the lowest Akaike criteria (AIC). Using plots and normality tests from the *'stats'* package for R, the assumptions of the final model were tested by ensuring its residuals were normally distributed. In addition, dispersion tests using *'dispersiontest'* function from the *'AER'* package for R were also run on the final model to ensure no over dispersion was present.

Carneddau

For the Carneddau raven sites a generalised linear mixed-effects model (GLMM) fitted by maximum-likelihood (ML) from the *'lme4'* package for R was used to test for any significant relationships. As with Anglesey, all models used '*young fledged*' as the response variable, and *'year'* and *'site ID'* were used as random effects. All models were fitted with a Poisson distribution (i.e. *family = poisson*) due to the response variable being not normally distributed. The same approach taken with Anglesey for reaching the minimum adequate model was repeated for the Carneddau. Model assumptions and dispersion were also tested for in the same way as Anglesey.

Results

Anglesey Raven Breeding Performance

Nesting Sites' Habitat & Altitude

Across the Anglesey study areas 92.6% (*25*) of nest sites occurred on sea cliffs. The remaining nest sites (*2, both from Carmel Head*) were located in small conifer groves. The mean (±SD) altitude of all Anglesey nest sites was 18.4 (±10.5) m (range = 5 – 40m).

Territory Occupancy

In the Cemaes-Amlwch area from 2003 to 2018 a total of 11 different occupied territories were recorded (7.3±1.2 territories per year, range = 6 – 9 territories per year). In this period the overall territory occupancy gradually decreased, falling by 22.2% (**Fig.4a**).

In the Carmel Head area from 2003 to 2017 a total of 16 different occupied territories were recorded (9.9±2 territories per year, range = 5 – 13 territories per year). Occupancy here showed little change from 2003 to 2009, increased by 30% over the following three years (2009-2012) and then rapidly declined. From 2012 to 2017 an overall decrease of 61.5% in occupancy occurred, with Carmel Head losing an average of 1.6 pairs per year (**Fig.4b**).

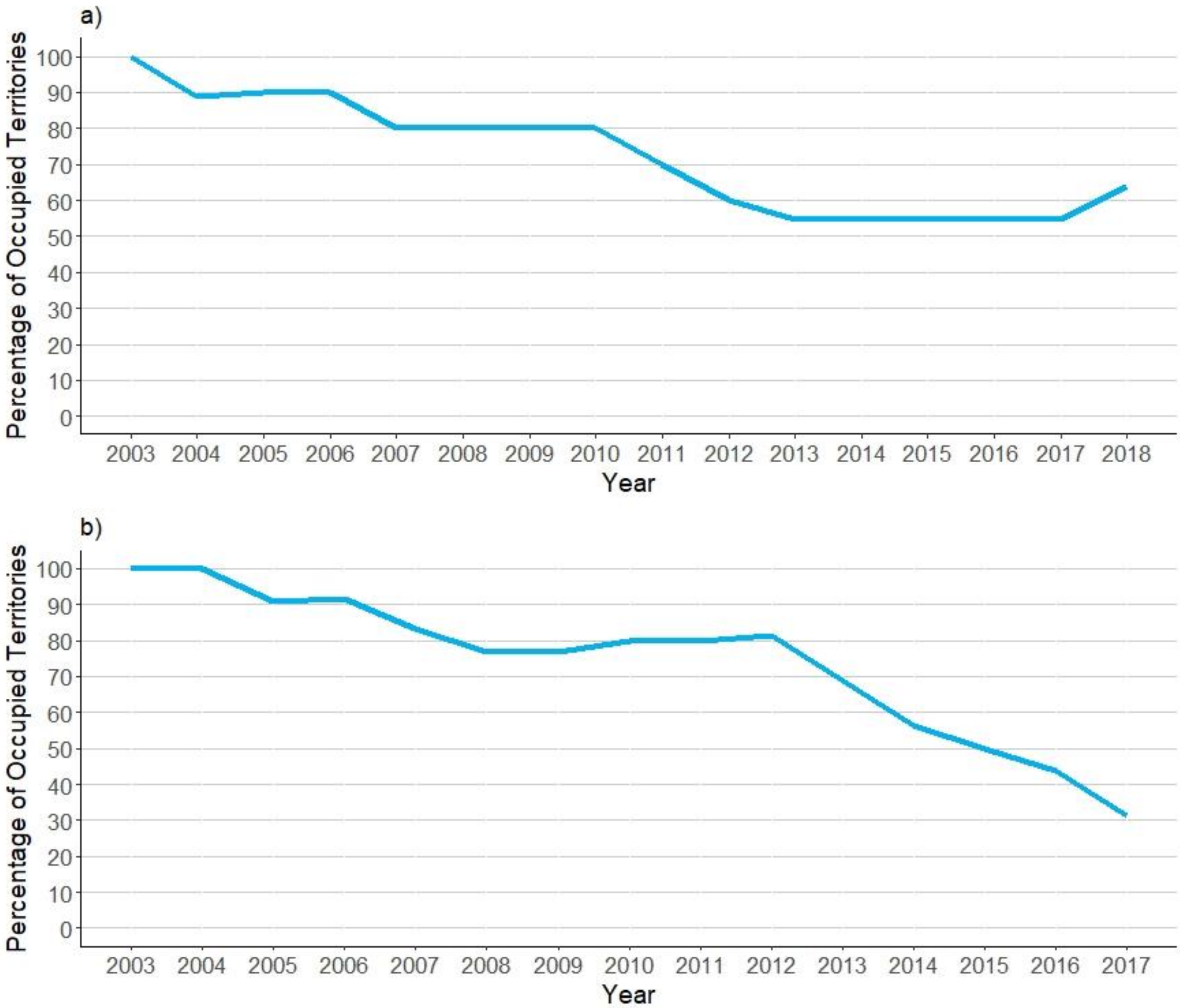

Figure 4. Percentage of recorded occupied territories in **a)** the Cemaes-Amlwch area (2003-18) and **b)** the Carmel Head area (2003-17) on the north of Anglesey.
NB, the dip from 2012 to 2017 in **a)** is due to one site not being visited during that time. Monitoring of site resumed in 2018, hence the increase in occupancy that year.

Breeding Activity, Rates of Success, & Fledging

From 2003 to 2018 in Cemaes-Amlwch there was a mean of 87.2 (±13.9) % actively breeding sites, and a mean of 83.2 (±16.4) % successful breeding attempts during this time (range = 50 – 100%) (**Fig.5a**). Over the study period individual successful sites fledged a mean of 3.1 (±0.6) chicks per year (range = 1 – 6 chicks), and successful sites collectively fledged 16.4 (±4.9) chicks per year (range = 9 – 25). From 2003 to 2018 the mean productivity was 2.6 (±0.6) chicks (range = 1.5 – 3.6 chicks) per active site.

In Carmel Head at each observed nest site ravens made an attempt to breed in every surveyed year, i.e. active breeding sites = 100%. From 2003 to 2017 the yearly mean success rate was 42.9 (±11.3) % (range = 27.3 – 60%) (**Fig.5b**), i.e. 49.2% lower than that of the neighbouring Cemaes-Amlwch area (**Fig.6b**). Over the study period individual successful sites fledged a mean of 2.5 (±0.7) chicks per year (range = 1 – 5 chicks), and successful sites collectively fledged 10.2 (±3.9) chicks per year (range = 5 – 19). From 2003 to 2017 the mean productivity was 1 (±0.3) chicks per active site (range = 0.5 – 1.6 chicks), i.e. 60.4% lower than that of the Cemaes/Amlwch sites (**Fig.6a**).

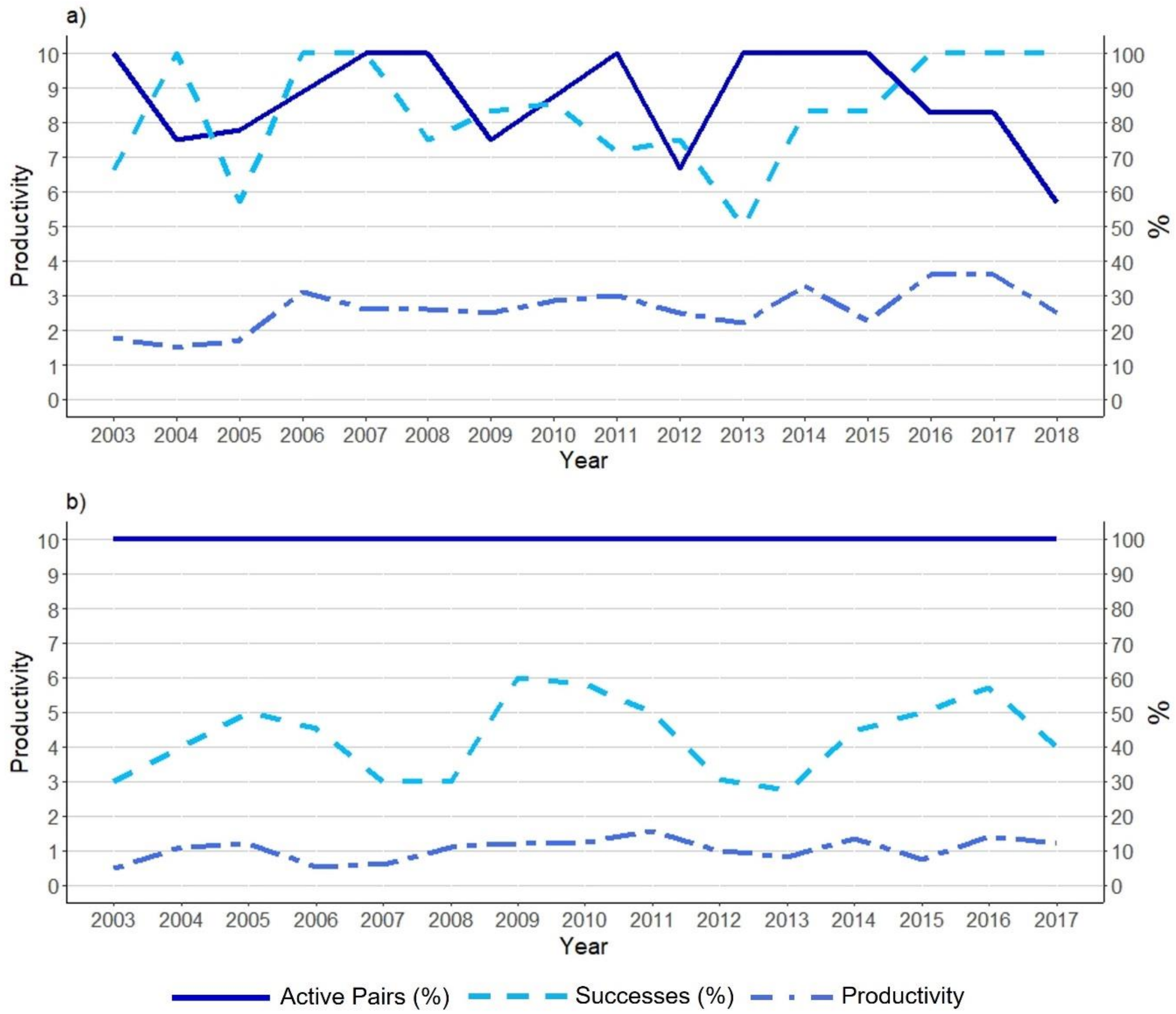

Figure 5. Percentage of pairs actively breeding along with the percentage of successes (secondary y-axis) and the mean productivity (primary y-axis) in **a)** the Cemaes-Amlwch area (2003-18) and **b)** the Carmel Head area (2003-17) on the north of Anglesey.

Nearest Neighbour Distances

On average, the nearest neighbour distances (NNDs) for active nest sites in Cemaes-Amlwch never fell below 1km during the study period, i.e. mean = 1.41 (±0.37) km (range = 1.03 – 2.57km). There was an overall increase in NND over the study period, rising by 148.2% from 2003 to 2018. In the Carmel Head area, average NNDs for active nest sites were never above 1km during the study period, i.e. mean = 0.66km (±0.12) (range = 0.47 – 0.8km). There was a very gradual decrease in NND over the study period, falling by 2.65% from 2003 to 2017.

Testing for Differences Between Study Areas

Anglesey Breeding Performance

Significant differences were found across all observed performance variables between Cemaes-Amlwch and Carmel Head active breeding sites (**Table 2**, **Fig.6**).

Table 2. Results from two sample t-tests and a Wilcoxon rank sum test showing significant differences between breeding performance variables of Cemaes-Amlwch and Carmel Head breeding ravens.

Performance Variables	*Cemaes-Amlwch M±SD*	*Carmel Head M±SD*	*DF*	*t-value*	*p*
Productivity	2.6±0.64	1.03±0.33	22.994	8.7926	< 0.005
Success (%)	84.4±13.9	42.9±11.34	26.754	7.9985	< 0.005
Mean Fledged	3.1±0.64	2.47±0.71	28.156	2.6505	< 0.05
				W	*p*
Mean NND (km)	1.41±0.37	0.66±0.12		240	< 0.005

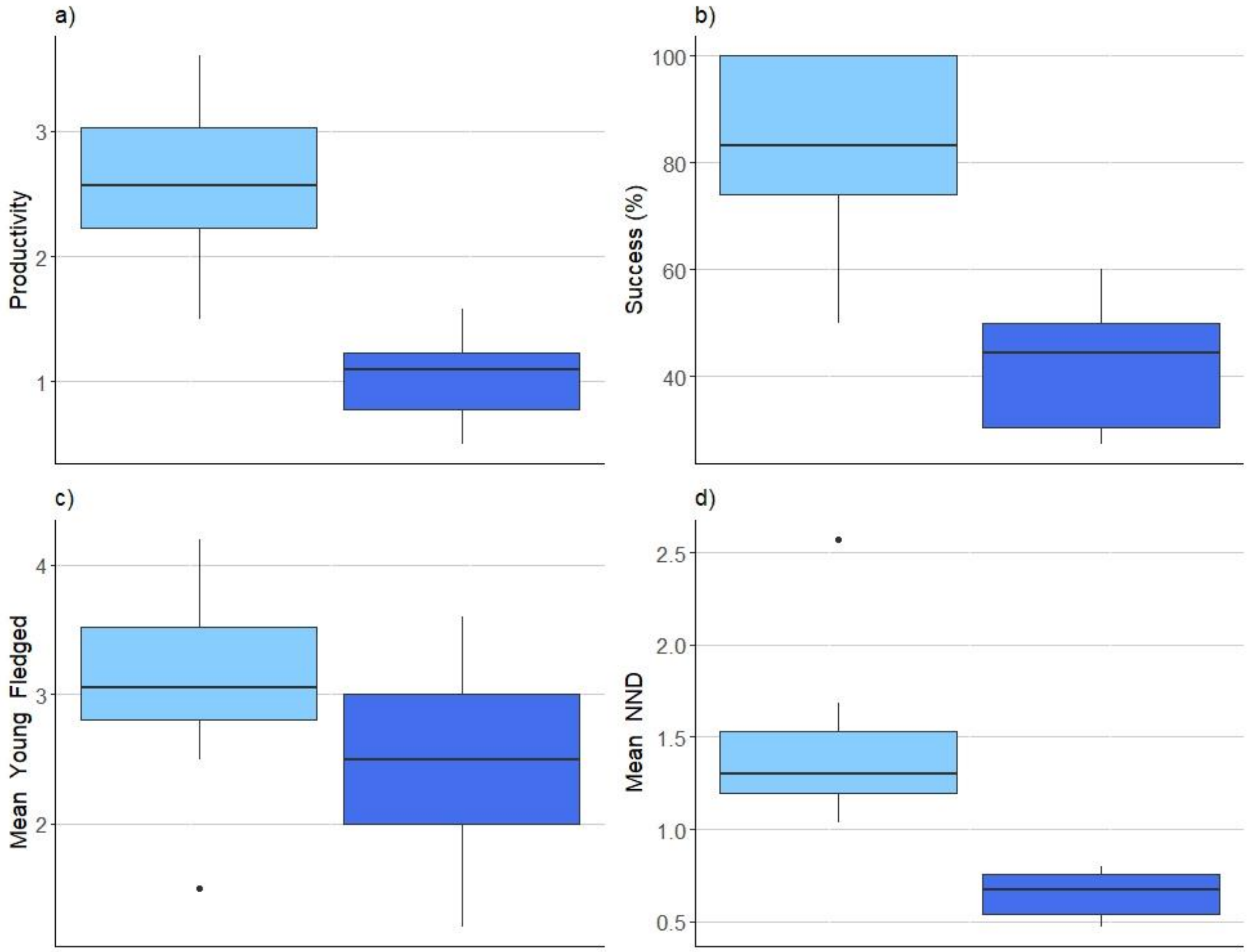

Figure 6. Comparing Cemaes-Amlwch and Carmel Head ravens, **a)** productivity, **b)** rate of success (%), **c)** mean young fledged per successful nest, and **d)** mean nearest neighbour distances (NND) of active sites.

Anglesey Agriculture

Significant differences were found in 6 of 8 agricultural variables observed between Cemaes-Amlwch's ISLE01 and Carmel Head's ISLE02 small agricultural areas (**Table 3**, **Fig.7**).

Table 3. Results from two sample t-tests and Wilcoxon rank sum tests showing significant differences between agricultural variables of Cemaes-Amlwch (ISLE01) and Carmel Head (ISLE02).

Agricultural Variables	*Cemaes-Amlwch M±SD*	*Carmel Head M±SD*	*DF*	*t*	*p*
Lamb Density	146.1±22.8	238.5±28.7	26.7	-9.8768	< 0.001
Beef Cattle Density	17.7±2.3	30.1±2.4	26.4	-14.856	< 0.001
Permanent Pasture	52.6±6.3	69.5±2.9	21.2	-9.6688	< 0.001

			W	p
Breeding Ewe Density	412.9±84.4	277.6±33.3	237	< 0.001
Dairy Cattle Density	2.9±0.97	13.5±6.6	2	< 0.001
Area Farmed (%)	78.3±8.1	98±8.3	10	< 0.001

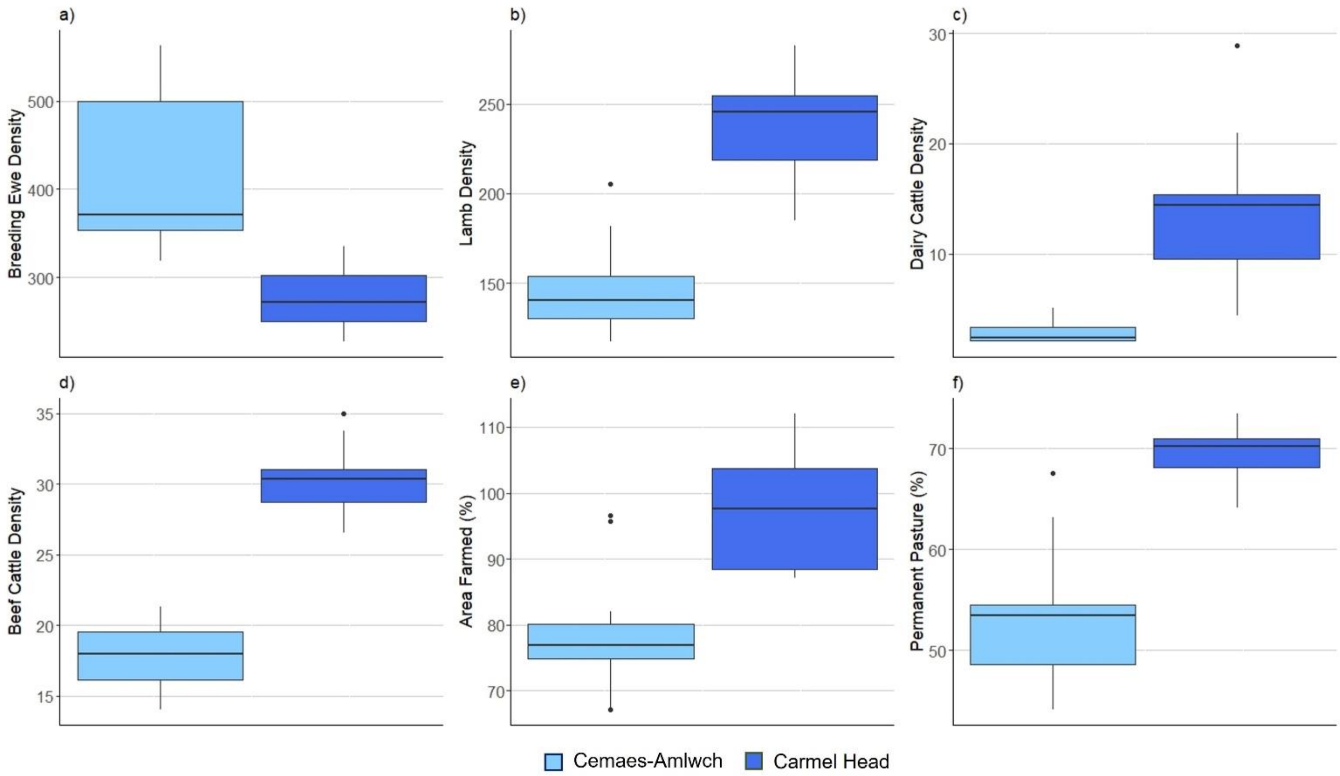

Figure 7. Comparing agricultural activities of Cemaes-Amlwch's *ISLE01* and Carmel Head's *ISLE02*, **a)** breeding ewe density, **b)** lamb density, **c)** dairy cattle density, **d)** beef cattle density, **e)** area farmed, and **f)** permanent pasture. Livestock densities represented as heads/km2, land areas as percentages. (*Contains public sector information licensed under the Open Government Licence v3.0.)*

Anglesey and Carneddau Agriculture

Significant differences were found across all 8 agricultural variables observed between northern Anglesey (ISLE01, ISLE02) and the Carneddau (GYWN25, CONW01, CONWO2, CONW03) small agricultural areas (**Table 4**).

Table 4. Results from a two sample t-test and Wilcoxon rank sum tests showing significant differences between agricultural variables of northern Anglesey and the Carneddau from 2003-2018.

Agricultural Variables	*Anglesey M±SD*	*Carneddau M±SD*	*DF*	*t*	*p*
Area Farmed (%)	87.8±12.8	65.3±15.4	70.2	-7.5039	< 0.001
				W	*p*
Breeding Ewe Density	347±94	254±39		305	< 0.001
Lamb Density	191±53	243±38		1491	< 0.001
Dairy Cattle Density	9±7	2±2		196	< 0.001
Beef Cattle Density	24±7	6±2		0	< 0.001
Permanent Pasture (%)	61±10	31.1±5.8		5	< 0.001
New Grassland (%)	8.8±4.9	3.6±2.2		187	< 0.001
Rough Grazing (%)	12.3±7.1	27.1±11.2		1384	< 0.001

Carneddau raven breeding performance

Nesting Sites' Habitats & Altitude

Forty-nine percent (*27*) of recorded nest sites in the Carneddau were located on cliffs or crags with the remaining 29.1% located in trees (*conifer = 12, oak (Quercus robur) = 3, birch (Betula sp.) = 1),* 16.4% in quarries (*9*), and 5.5% on pylons (*3*). The mean altitude of Carneddau nest sites was 362.2 (±174.6) m (range = 110 – 800m).

Territory Occupancy

From 2002 to 2018, a total of 52 territories were observed as occupied within the Carneddau region, i.e. 31.6±7.8 territories (range = 16 – 47 territories). Overall, mean occupancy was high, at 95.7 (±5) % over the study period (range = 84.2 – 100%), starting at 100% from 2002 to 2007, and being 85.7% in 2018, i.e., an overall decrease of 14.3% (**Fig.8**).

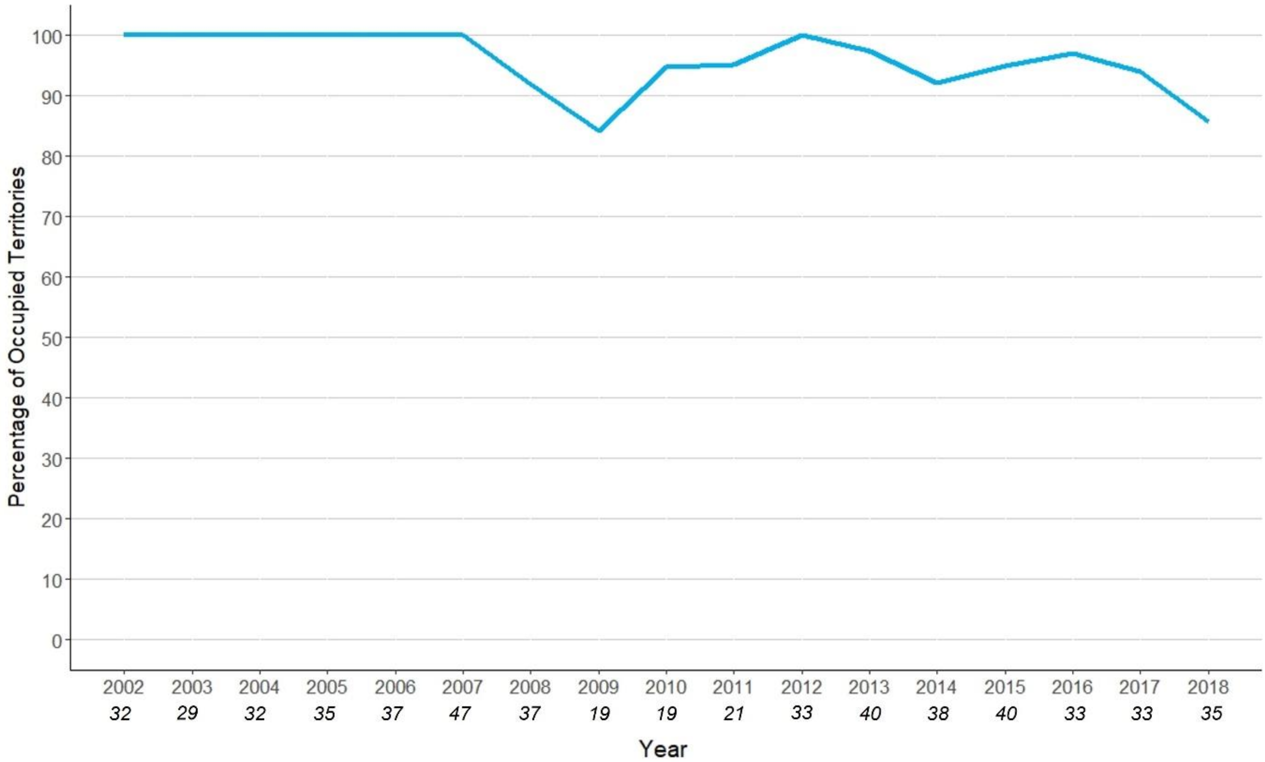

Figure 8. Percentage of territories recorded as occupied (see glossary) in the Carneddau region of Snowdonia from 2002-18. Numbers under each year denote how many territories were visited for surveying that year.

Breeding Activity, Rates of Success, & Fledging

In the Carneddau there was a mean of 64.7 (±16.1) % actively breeding sites per year (range = 42.4 – 89.4%), and declined overall, falling by 31.5% between 2002 and 2018. Percent success, although fluctuating, showed an overall increase of 20%, with a mean of 88.2 (±9.4) % (range = 73.1 – 100%) (**Fig.9**) over the study period. Individual successful sites fledged a mean of 2.2 (±0.48) chicks per year (range = 1 – 5 chicks), and collectively fledged a mean 38.3 (±9.8) chicks per year (range = 25 – 57 chicks). The mean productivity was 1.9 (±0.4) chicks per active site (range = 0.96 – 2.6 chicks) from 2002 to 2018.

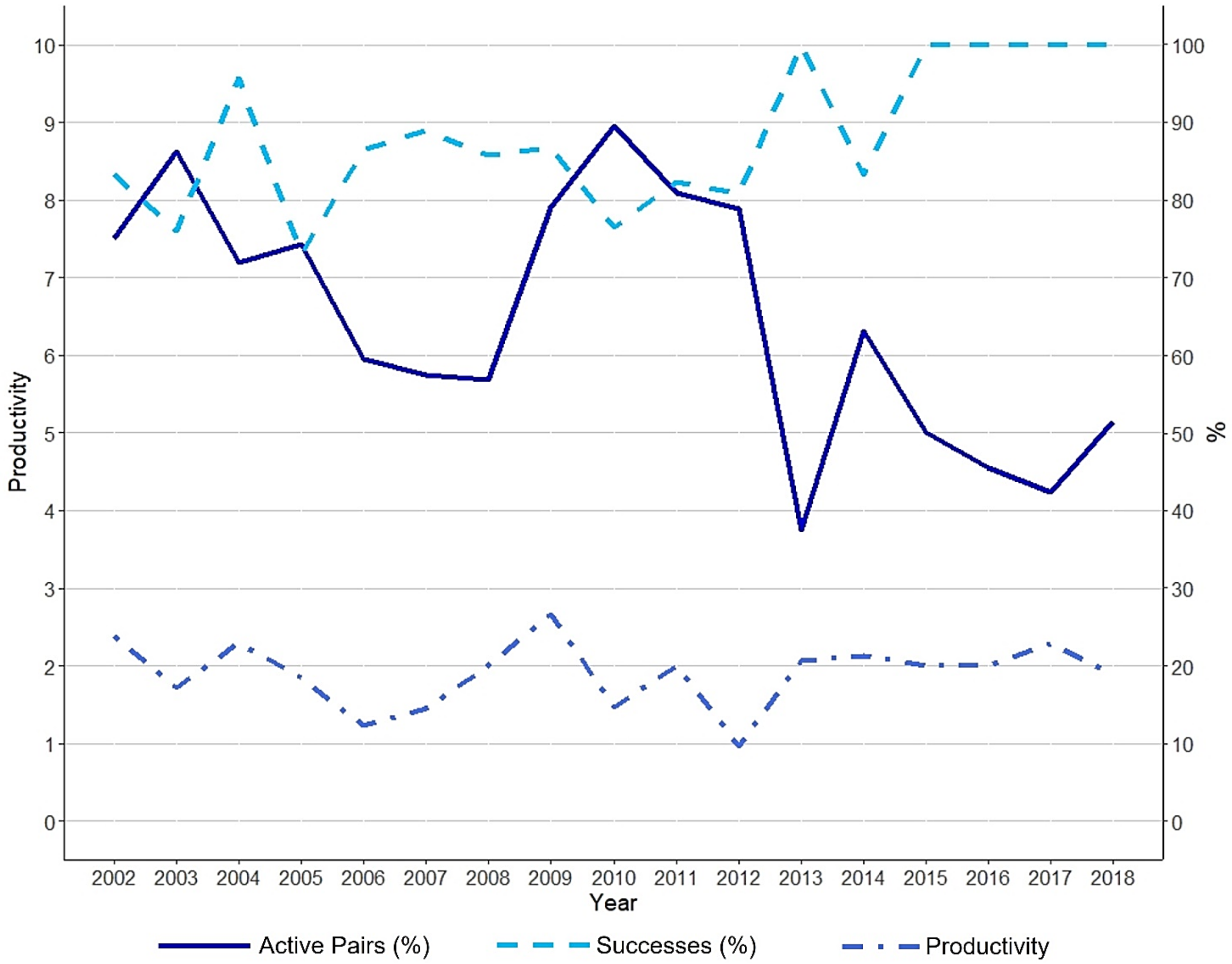

Figure 9. Percentage of pairs actively breeding along with the percentage of successes (secondary y-axis) and the mean productivity (primary y-axis) in the Carneddau region of Snowdonia from 2002 to 2018.

Nearest Neighbour Distances & Densities

The NNDs for active nest sites in the Carneddau only once fell below 2km, i.e. mean = 2.4 (±0.3) km (range = 1.9 – 3km), and increased steadily by 12.1% from 2002 to 2018. Mean estimated density was 8 (±1.7) active breeding sites per 100km^2 (range = 5.5 – 10.5 active sites/100km^2).

Relationships between Raven Breeding Performance and Livestock Practices

Anglesey

A single unit increase in dairy cattle density and area farmed results in an estimated significant decrease of 0.08 ($z = -4$, $p < 0.05$) chicks and 0.05 ($z = -3$, $p < 0.05$) chicks, respectively, in the performance of Anglesey ravens. Simultaneously, a single unit increase in permanent pasture and rough grazing results in an estimated significant increase of 0.06 (z = 2.6, p < 0.05) chicks and 0.04 (z = 2.6, p < 0.05) chicks respectively, in the performance of Anglesey ravens. (Table 5, Fig.10).

Table 5. Output from final generalised linear mixed-effects model (fitted by ML) used to test if select agricultural variables have had a significant effect on the performance variable *'young fledged'* of ravens in the North of Anglesey. A combination of fixed effects giving significant estimates are included, random effect = (1|Site ID) + (1|Year).

Random effects	**Std. Deviation**		**Variance**	
Site ID	0.2085		0.4566112	
Year	9.301e-10		0.0000305	
Fixed effects	**Estimate**	**Std. Error**	**z-value**	**p-value**
(Intercept)	0.65745	0.69601	0.945	0.34486
Dairy Cattle Density	-0.08563	0.02138	-4.005	0.0000621
Area Farmed	-0.04776	0.01613	-2.961	0.00307
Permanent Pasture	0.06287	0.02388	2.633	0.00847
Rough Grazing	0.04213	0.01571	2.602	0.00732

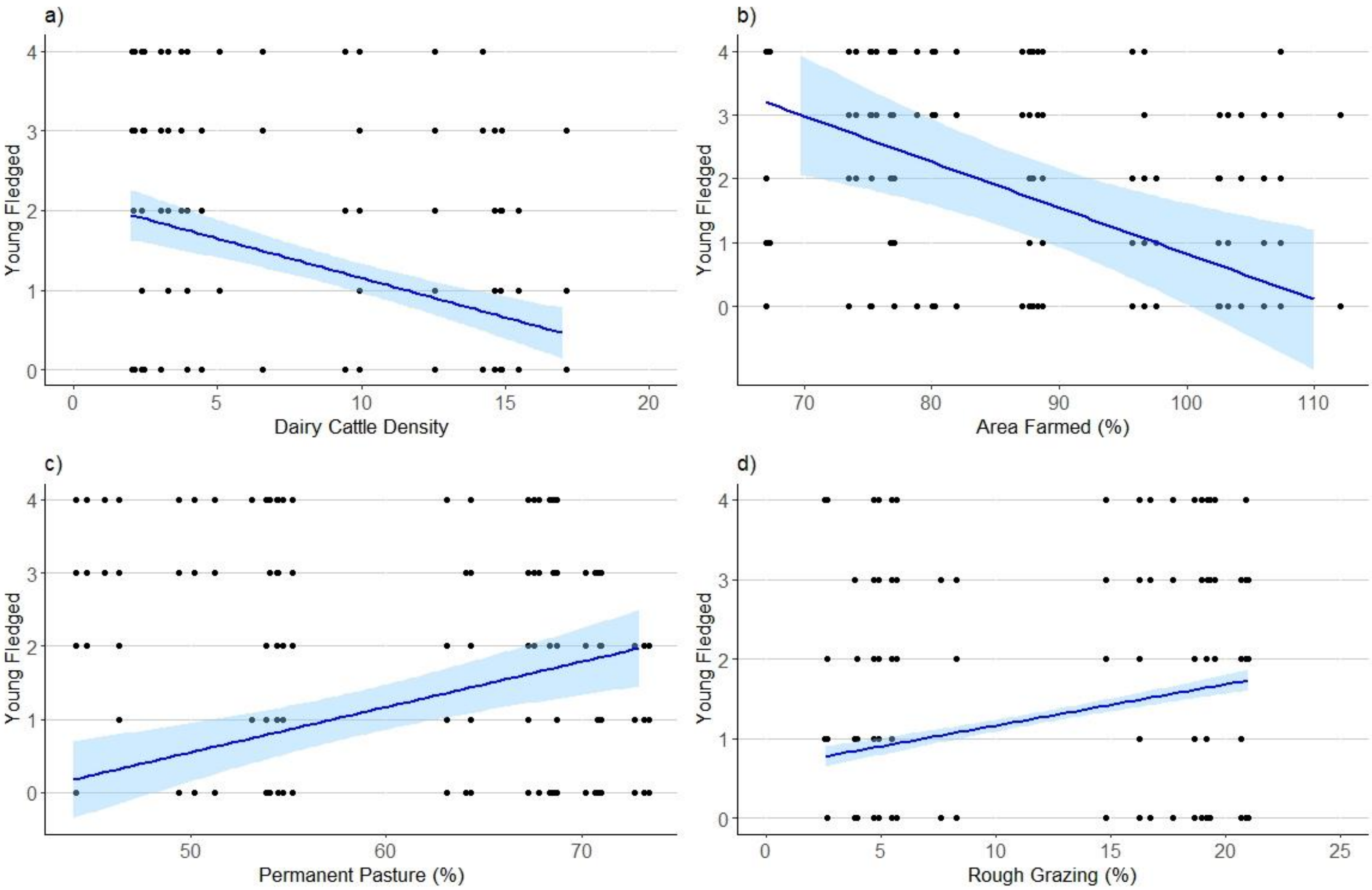

Figure 10. Results from significant relationships between *'young fledged'* of actively breeding Anglesey ravens and **a)** dairy cattle density ($p < 0.05$), **b)** area farmed ($p < 0.05$), **c)** permanent pasture ($p < 0.05$), and **d)** rough grazing ($p < 0.05$) in agricultural small areas *ISLE01* & *ISLE02*.
Livestock densities represented as heads/km2, land areas represented as percentages. Shaded blue area indicates 95% confidence interval of model results, represented by blue line.
(Contains public sector information licensed under the Open Government Licence v3.0.)

Carneddau

In the Carneddau, none of the agricultural variables included here had a significant effect on the breeding performance of observed raven pairs in the Carneddau.

Discussion

Raven breeding performance and livestock practices

This study found the breeding performance of Ravens had a negative relationship with both dairy cattle density and percentage of area farmed, and a positive relationship with both percentage of permanent pasture and percentage of rough grazing between 2003 and 2018, on Northern Anglesey. On the other hand, similar evidence shows Raven breeding performance in the Carneddau region of Snowdonia had no detectable relationship to livestock practices during the same period. These results may be better understood by exploring the differences that exist between the study areas.

Pairs from Carmel Head had significantly lower performance than those from Cemaes-Amlwch during the study period, with Carmel Head's mean young fledged being closer to that of the Carneddau, where altitude has already been shown to be a significant limiting factor on mean fledging rates (Allin 1968; Ratcliffe 1997; Driver 2007). In addition, Carmel Head had the lowest mean productivity, this being an indication of the notably high rates of failure this area experienced. This may be explained by further differences found between livestock practices, with dairy cattle density and area farmed, being significantly higher in Carmel Head's small agricultural area compared to Cemaes-Amwlch's.

On Anglesey it is likely that dairy cattle density and area farmed have jointly affected raven breeding as these practices are commonly associated. Dairy cattle require large areas of improved grassland which involves the reseeding of multiple fields, this practice reportedly increasing over the last decade in northern Anglesey (Pritchard *et al*. 2021; Williams, P. 2022, *pers comm*, August 19th). However, the presence of a positive relationship between Raven breeding and area of permanent pasture (improved grassland over 5 years old) suggests it is not the transformation of the landscape that is detrimental to the breeding performance of Anglesey Ravens.

Being highly adaptive generalists, Ravens are able to modify aspects of their behaviour and ecology. This means they can minimise negative impacts of change and remain unaffected, or even benefit from it, by replacing a natural set of resources with artificial ones (e.g. nesting on anthropogenic structures; Coates et al. 2014 & 2016). In Idaho anthropogenic alterations and loss of natural habitat over a period of four decades were linked to increase in nesting ravens and decreases in other avian scavengers such as Ferruginous Hawk (*Buteo regalis*) (Coates *et al*. 2014). In addition, Ravens were also more likely to nest near agriculture than three other scavenging *Buteo* species (Swainson's Hawk [*Buteo swainsoni*], Red-tailed Hawk [*Buteo jamaicensis*], and Ferruginous Hawk) (Coates *et al*. 2014).

Landscape transformation often results in decreasing biodiversity, with generalist species like Ravens being able to persist by exploiting alternative opportunities in the landscape (Fulller 2000; Coates *et al*. 2016). In these situations, species typical of open habitats may grow dependent on anthropogenic habitats like farmland, making them vulnerable to changes in agricultural practices (Wright *et al*. 2011). For example, livestock can mimic or substitute essential ecosystem services of the wild herbivores they have often replaced (Wright *et al.* 2011). Specialist feeders like chough (*Pyrrhocorax pyrrhocorax*) (Ausden & Bateson 2005) as well as generalist scavengers like Ravens (Ratcliffe 1997; Fuller 1996) may be adversely affected by changes in livestock practices due to indirect changes in habitat maintenance and the provisioning carrion, respectively.

It's possible the notable changes concerning livestock, i.e. dairy cattle and sheep, that have occurred on Anglesey's intensively managed landscape, could be significantly altering some aspect of the environment that has been detrimental to Anglesey raven pairs.

While there can be multiple factors that affect raven breeding performance, the two that are arguably most important are availability of suitable nest sites and adequate food resources. Across both Anglesey study areas, almost all nest sites were located on sea cliffs and mostly in inaccessible areas, where there appears to be no shortage of suitable nest sites (Ratcliffe 1997). It therefore appears unlikely that this has been a limiting factor here, let alone one that could be negatively affected by dairy cattle density and area farmed.

Raven pairs feed on items in proportion to their availability, with their diets varying seasonally (Ratcliffe 1997). Research shows the importance of food availability to Raven breeding performance, with many studies in Britain finding sheep carrion to be most important (Marquiss *et al*. 1978; Newton *et al*. 1982; Ewins *et al*. 1986). Thus, it is more likely that food availability is the a limiting factor for Anglesey raven pairs which could be affected by local livestock practices.

Raven pairs from the coastal areas of Orkney and the Shetlands have been found to forage on a range of seashore items, such as seaweeds and barnacles, as well as eggs from nearby seabird colonise. Although these items did occur with some high frequency, in each scenario these were thought to be more supplementary to pairs' overall diet. (Ewins *et al*. 1986; Marquiss & Booth 1986). In these studies, carrion was the most important source of food in both regions during the Raven breeding season, with a high abundance of sheep carrion supplying Shetland ravens. Those in Orkney on the other hand, relied heavily on lagomorph carrion as beef cattle were the dominant livestock and large mammal carrion was scarce (Marquiss & Booth 1986). In another scenario, lagomorph carrion was also found to become more important in the absence of sheep carrion (Mattingley 1995). While ravens are highly opportunistic in their feeding habits, it appears that the availability of some food items are especially important for their survival in an area, particularly if that food resource doesn't have an alternative substitute.

On Anglesey the increase in dairy farming may have in some cases replaced sheep farming (Welsh Government 2019b). Considering the importance sheep carrion is thought to have to breeding ravens it may seem likely the process of dairy cattle replacing sheep could be influencing the negative relationship due to indirectly reducing carrion availability. However, this study did not find any relationships between ravens' breeding and ewe or lamb density this being true both on Anglesey and in the Carneddau. Sheep densities alone may not always be an accurate indicator of carrion availability, as this is also determined by factors like husbandry and management practices, as well as climate and topography (Fuller 1996). The nature of sheep farming on Anglesey makes it easier for farmers to monitor their flocks and remove dead stock, a practice that became mandatory in 2003 with the introduction of fallen stock regulations (Pritchard *et al*. 2021). In upland landscapes such as the Carneddau on the other hand, the collection of dead stock is unpractical and not mandatory (Daera 2022), which could create further differences in foraging opportunities between the study areas. It should also be considered that many of the studies that found associations between raven breeding and sheep presence in Britain were conducted prior to many of the current regulations and improved standards of animal husbandry (Shrubb 2003). During this time the high stocking rates and poorer husbandry of sheep were beneficial to scavenging Ravens as it resulted in higher sheep mortality and carrion availability (Ratcliffe 1997; Shrubb 2003). However, these stocking rates became economically unviable after headage payments ended, and the introduction of fallen stock regulations resulted in improved husbandry and reduced carrion availability (Williams, P. 2021, pers comm, March 15th). It is likely these changes meant that Ravens didn't benefit from sheep presence as they had previously, and may have therefore resulted in a disassociation between sheep density and Raven breeding performance. In addition, the decline in the economic viability of sheep farming in some cases resulted in conversions to alternative livestock practices that were more profitable, like dairy farming (Williams, P. 2021, pers comm, March 15th). Regions such as Anglesey that possess good grass growing conditions (as demonstrated by pALC, **Fig. 2**) offer an example of this conversion from sheep to dairy cattle farming. This further suggests that increasing dairy cattle density itself is not directly detrimental to breeding ravens, but its effect on other practices (e.g. driving decreases in extensive sheep farming) may be. The grazing systems utilised in dairy farming differ from those in sheep farming, as the former requires intensively managed improved grassland and the latter is associated with both improved and semi-improved grasslands. Also, dairy cattle feeding requirements are higher than those of sheep due to their larger size and nutritional needs, which in turn can create greater grazing pressures where they occur (Ramos et al. 2021). Additionally, in the Welsh lowlands dairy farms have the largest average farm size with large herds (Welsh Government 2019a) which can also result in greater grazing pressures (Ramos et al. 2021). Therefore, it is likely that the conversion from extensive sheep farming to intensive dairy farming has had wider impacts on the local environment and perhaps on the breeding performance of local Ravens.

The intensive management of permanent pasture has frequently been shown to be detrimental to many bird species. This is most notably for specialist species such as insectivores, being affected by the considerable declines in invertebrate species (Vickery et al. 2001; Shrubb 2003). Being a generalist, Ravens are less susceptible to the negative effects of intensive grassland management (Coates et al. 2014). However, to understand how a positive relationship between Raven breeding and the area of permanent pasture could exist, the ideal free distribution theory should be considered. The theory predicts that mobile species will distribute themselves across habitat patches to optimise their fitness (Staude et al. 2021). This means when activities like agriculture alter the quality of habitats specialist species are expected to remain in the remnant habitat patches they require for their needs. Generalists on the other hand can use a broader range of habitats and resources, and so are expected to be more common in altered habitat patches where competition from specialists will be more relaxed (Tregenza 1995; Staude et al. 2021). Evidence demonstrates this trend, with generalists dominating bird communities in agricultural habitats (Lockwood et al. 2000; Devictor et al. 2008). As a generalist occurring in an altered agricultural habitat, it is possible that Anglesey Ravens are benefitting from the reduced competition with species that are more specialist in their habitat requirements.

While areas of permanent pasture can be more commonly associated with dairy cattle, sheep are also grazed in such areas. Despite ewe and lamb densities not being significantly related to Raven breeding in this study, the presence of sheep stock may have influenced Raven breeding performance during the study period, as previously discussed in this section. Considering this, perhaps the areas of permanent pasture that have resulted in a positive relationship to Raven breeding performance were areas where sheep were present.

The positive relationship found between Raven breeding and area of rough grazing may be more easily understood. Abundant evidence has demonstrated that areas of rough grazing support more biodiversity than areas of permanent pasture (Fraser et al. 2014; Hopkins & Holz 2005). Subsequently, the breeding occurrence and success of bird species such as Barn Owl (*Tyto alba*), Cirl Bunting (*Emberiza cirlus*), Yellowhammer (*Emberiza citrinella*), Eurasian Skylark (*Alauda arvensis*) and Song Thrush (*Turdus philomelos*) were higher in rough grazing areas (Bond et al. 2004; Peach et al. 2013). This is a result of higher levels of biodiversity creating greater foraging opportunities for these species, and is likely also related to the positive relationship between rough grazing and raven breeding performance.

While they can occur in areas of improved permanent pasture, sheep stock are predominantly associated with areas of rough grazing. This is due to their ability to thrive on poorer quality land where they may be the only economically viable option (Welsh Government 2018). Thereby it is likely that areas of poorer quality rough grazing land on Anglesey are most frequently grazed by sheep. By this logic, it also follows that these areas will have an absence of dairy cattle, as this species requires high-quality grassland. Considering the negative relationship found here between dairy cattle density and Raven breeding, it is unsurprising that farmland lacking the presence of dairy cattle and the intensive management generally associated with them, would have a positive effect on Raven breeding.

Although not shown to be significantly related to Raven breeding performance in this study, the potential importance of sheep has been discussed in this section. Perhaps similarly to permanent pasture, the presence of sheep may have been beneficial in areas of rough grazing. Simultaneously, an absence of dairy in areas of rough grazing is likely an additional factor in being positively related to Raven breeding performance.

It is likely that the negative relationship Raven breeding has with dairy cattle density and area farmed is related to a reduction in food availability. This could be related to changes in sheep farming that are at least in part associated with increasing dairy farming.
The positive relationship between Raven breeding and area of permanent pasture may be related to these areas of altered agricultural land relaxing competition pressures through the ideal free distribution theory. In addition, permanent pastures can also be grazed by sheep. In these cases, the presence and/or management of sheep stock in improved grasslands could have been beneficial to breeding Ravens, as previously discussed in this section.
Areas of rough grazing are likely positive for breeding Ravens due to the higher biodiversity they can support which can provide better foraging opportunities. As well as this, rough grazing areas will have a strong association with sheep stock and a strong dissociation with dairy cattle, the latter being negatively related to Raven breeding here.

Despite no negative relationships being detected in relation to agricultural practices, the Carneddau experienced declines in occupied territories and active nest sites from 2003 to 2018. This is not likely a reflection of the breeding performance of active breeding pairs', as Ravens simultaneously experienced a steady increase in the rate of successful nest sites, and had little change in productivity.
It should be noted that populations in Snowdonia reported in studies prior to this (Dare 1986; Driver 2006; Driver 2007) were experiencing rapid increases that have been attributed to a surge in sheep numbers from the mid-1970s to late 1990s. This created an unnatural 'raven population boom' that may ultimately have been unsustainable long-term (Driver, J. 2020, *pers comm*, 9th December). Since the early 2000s, sheep numbers have largely declined from their previous inflated state (AgSAS data), and improvements in their management have likely reduced mortality and availability of sheep carrion (Fuller 1996; Shrubb 2003). For example, requirements of AESs like Tir Gofal meant sheep were removed from hill grazing areas across Snowdonia during the winter, being the period when Newton *et al*. (1982) previously reported ewe mortalities were at their highest (77%) in central Wales. It is reasonable to

assume that this reduced seasonal carrion foraging opportunities for Carneddau Ravens. Ratcliffe (1997) also speculated that raven populations must decline if sheep numbers are reduced in the interests of achieving a more balanced management and diverse habitat, especially where higher densities had resulted, such as in Snowdonia (Dare 1986).
This suggests the necessary reductions in sheep numbers, along with an unnaturally heightened raven population, have driven the declines in occupancy, and appears these populations are returning to more sustainable levels. Similar declines in occupancy are also observed on Anglesey, although these Ravens may be further disadvantaged by the more intensive nature of agriculture there. This is indicated by the higher quality pALC grades present and the subsequently higher percentages of area farmed, permanent pasture, and new grassland compared to those areas within the Carneddau.
It is also possible that modern declines in livestock mortality rates from improved husbandry will further reduce the associations between sheep presence and availability of carrion. Therefore, it is possible that future studies will conclude similarly the absence of a relationship between sheep and Ravens in Britain.

Between Anglesey and the Carneddau differences in livestock practices will inevitably occur due to the contrasting topography. Table 4 shows the significant differences in practices occurring between Anglesey and the Carneddau. Additionally, the pALC map (**fig. 2**) further illustrates these differences by showing the extent of potential agricultural productivity in both regions. The Carneddau's upland landscape (i.e. majority of the study area) has very poor potential productivity, in contrast to the Anglesey study areas which have mostly moderate potential productivity.
Extensive farming results in less transformed land and so can support a wider biodiversity than those managed more intensively (Hendershot *et al*. 2020). For example, in France low intensity farmland was found to have a higher abundance of specialist farmland birds than farmland with higher intensities (Doxa *et al*. 2010). Landscapes like the Carneddau, where farming is extensive, will have a higher biodiversity which supports more ecosystem services, and so can promote a more stable and resilient ecosystem (Davidson *et al*. 2017). Due to the topography of the area, nest site availability is unlikely to be an issue for raven pairs' in the Carneddau. Thus, food availability would be the main limiting factor here, as previously noted by Dare (1986), Ratcliffe (1997), and Driver (2006). Considering the more diverse range of

habitats the Carneddau supports it also seems less likely food availability would be limiting pairs' breeding efforts, as their generalist foraging habits allow them to utilise a wide range of habitats (Harju *et al*. 2021).

Thus, the contrasting lack of any relationship between Raven breeding performance and livestock practices in the Carneddau is likely a result of the extensive nature of farming in this region. This is driven by the dominating upland topography of the region which has also resulted in the majority of the area having very poor potential productivity according to the pALC.

Possible limitations

While the data representing livestock practices and raven breeding performance used in this study were the best available options when undertaking this investigation, a few things should be acknowledged. Firstly, it must be considered that other variables of great importance have not been possible to include here, either due to unsuitability or simply not existing. The nature of the Welsh Agricultural Small Areas dataset, being partly based on estimates (Welsh Government 2019b), may have affected the results (*see 'notes on data quality' in methods*).

In relation to the raven breeding data, this has almost entirely been collected by a single individual so may be subject to some collection bias. The standardised surveying method for the collection of raven breeding data, outlined in figure 3, aided in minimising collection bias and observational differences between nest sites. It should be acknowledged however that certain factors were out of our control. This may have resulted in some observational differences occurring and could have led to differences in recorded patterns of occupancy and breeding outcome. These factors include, but are not limited to, ease of observing nest sites, and the timing of visits (date and time of day). To minimise the potential effect of surveying on different days, visits to Carmel Head and Cemaes-Amlwch were mostly carried out over two days only. This also allowed the same time of day to be maintained for visits between the groups of sites. For the Carneddau, while the time of day of visits could be maintained, date of visits was more varied due to the larger number of nest sites and larger area to cover.

Finally, it should be acknowledged that recorded numbers of young fledged from nest sites were based on pre-fledging counts, i.e. counts made of young in the nest during the week fledging of site is estimated. While this method is perceived to be less accurate than post-fledging counts the surveying method was designed to minimise any impacts this could have on the dataset. For example, multiple (usually 3) separate visits to each site are necessary to ensure breeding status recorded that year is accurately made. This also allows for more accurate recording of the total number of young present throughout the breeding season and, ultimately, how many are present prior to fledging.

Conclusions

To the best of my knowledge this is the first time that breeding performance of Ravens has been linked to long-term changes in livestock practices. The negative relationship dairy cattle density and percentage area farmed have to Anglesey Ravens is potentially related to the notable changes in dairy cattle farming in an intensively managed landscape. It is likely this could have affected food availability for breeding Raven pairs and is also possibly related to local declines in sheep farming that have previously been beneficial to breeding Ravens. This may have serious implications for other similar avian scavengers that have more specialist requirements than Ravens and have previously been shown to be more susceptible to changes in the landscape related to livestock (Coates *et al*. 2014; Coates *et al*. 2016). Meanwhile, areas of permanent pasture being positively related with Raven breeding performance may be related to these areas of altered agricultural land having more relaxed competition pressures for generalist breeding Ravens (Tregenza 1995; Staude et al. 2021). Additionally, areas of permanent pasture are likely grazed by sheep, which may be providing some additional benefits for breeding Ravens. Areas of rough grazing being positively related with Raven breeding performance is likely related to higher biodiversity providing better foraging opportunities, and additionally, has a strong association with sheep and a strong dissociation with dairy cattle.

On the other hand, the lack of any relationship between Raven breeding performance and livestock practices in the Carneddau during the same time may be explained by this region's topography. This ultimately restricts the intensity of livestock practices and is likely to ultimately mitigate the negative impacts it can have.

These results suggest that the breeding performance of Ravens in Northwest Wales is more likely to be influenced by changing livestock practices in intensive agricultural landscapes than in extensive agricultural landscapes. With ongoing declines in biodiversity in the UK, and around the world, that are frequently associated with agricultural activities (Hayhow et al. 2019; Maxwell et al. 2016) it becomes ever more important for farmland ecosystems to find ways to increase biodiversity and so promote ecosystem services and a more stable and resilient ecosystem (Davidson et al. 2017).

In addition, this study notes an absence in a relationship between Raven breeding performance and both ewe and lamb densities despite much evidence to suggest its importance to Raven breeding performance. This could be related to a more recent disassociation between sheep density and carrion availability, likely being driven by factors like the abolition of headage payments and the introduction of fallen stock regulations. Finally, breeding performance during the study period indicates both Anglesey and Carneddau Ravens have experienced declines from previously inflated populations that were the result of previous increases in sheep numbers. In the Carneddau current levels of occupation seem comparable to those found by Dare (1986) between 1978-1985, when sheep numbers were still increasing.

Further research relating to this topic should also include a form of dietary analysis which would aid in understanding how pairs' may alter their diet under changes in their territories. In the case of the Anglesey study areas, it would be particularly interesting to know the frequency of seashore items in breeding pairs' diet, both in and out of the breeding season. Studies investigating any relationships between a scavenging species and sheep presence, where carrion is the main factor, should endeavour to find a method that reliably represents carrion availability, or at least should make considerations of local management, topography, climate, and sheep breed, to get a good idea of how carrion may be represented. This would provide a better insight of the broader ecological factors at play that cannot be fully understood from the models in this study.

This study highlights the importance of long term monitoring, in particular reference to the Anglesey nest sites, where continued monitoring may further our understanding of how livestock practices and changes in them can affect Ravens and other similar avian scavengers. This research aids in better understanding how avian scavengers may be affected over time in the agricultural landscapes they often occur, and where their ecosystem services can provide multiple benefits to the landscape. It may also inform additional approaches to understand local population dynamics of a species, where widespread human activities, being commonly related to agriculture, are almost certainly influencing multiple facets of their life histories.

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