THE UNIVERSITY OF HULL

The Detection and Quantification of Deer Populations for Impact Management on Thorne Moors; Humberhead Peatlands National Nature Reserve

being a Thesis submitted for the Degree of
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by

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Executive Summary

Wildlife management often requires adjusting the density of a specific species within the environment and are usually justified around meeting the objectives of landowners. This study focussed upon Thorne Moors (Humberhead Peatlands NNR) and the ecology of the deer species present on site: red deer (*Cervus elaphus*) and roe deer (*Capreolus capreolus*). This study evaluated deer activity and impact levels on site, estimated population abundances and habitat use, and tested a novel method of improving the daytime detection of deer.

This study utilised the deer activity and impact survey method used by The Deer Initiative; selected as a consistent method and allowing the data to incorporate into the annual reports of The Deer Initiative. The random encounter model was used to estimate abundance with trail cameras, and the utility of thermal imagers for the daytime detection of deer was tested by a series of transects.

Deer activity and impact was High and Moderate-High (respectively), with an estimated 311-333 red and 59-63 roe deer on site. Five Reeve's muntjac deer (*Muntiacus reevesi*) were observed during field studies, though none were detected by camera. The surveys with thermal imagers detected significantly more deer during the daytime than surveys with binoculars; and it was identified that the deer were more active at twilight then during hours of daylight.

The activity and impact of deer demonstrated that the red deer population was at too high a density (17km^{-2}). The abundance estimates would assist in providing approximate targets for future culls. The selectivity index performed demonstrated that the deer were congregating on the "Waterway Footpaths" – providing a corridor on site for deer stalkers to consider active management. The

deer were most active during the twilight and were best detected with a thermal imager; assisting the deer stalkers in locating optimal areas to be active.

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Thank you.

Declaration

I can confirm that all work presented in this thesis is my own, original, work and is not being submitted for any other degree or award.

Thomas W. Logan

For William Conroy, my Great Grandfather, on his one hundredth birthday;

a centurion, an inspiration, and my namesake – many happy returns.

Chapter 1.

Introduction

1.1. Introduction

Animals and humans in modern Britain are in constant competition for allocation of resources and habitat. This inevitably leads to high levels of persecution upon wildlife by the humans that exist in their extant ranges; requiring constant, regular, and effective management for future success of both the natural environment and anthropogenic activities. The traditional persecution of species, such as bears, wolves, and lynx, have led to their national extinctions in the UK (Blake, *et al*., 2014; Flower, 2016; Raye, 2017; O'Regan, 2018).

Complexity-stability theory explains that the richness of biodiversity in any given environment has a linear impact upon how stable that environment is (Kondoh, 2007; van Altena, *et al*., 2016). When observing a complex food-web, there are always key roles that must be fulfilled (observed easier in the form of a food chain) for a stable environment; such as the primary producer, primary consumer, secondary consumer, tertiary predator, and apex predator. Within the webs, the relationships between each of these roles can be complex; with numerous overlapping exploitations. Species can be redundant within a food-web as different species can occupy the different roles under different conditions. However, when the web structure breaks down, the complexity of the environment can be significantly altered.

The environment of Great Britain was, historically, species rich with highly complex food-webs and had key species occupying all levels of the food chain (MacDonald, *et al*., 1995; Robinson & Sutherland, 2002). Modern Britain is missing all previously extant species to a key position in the food chain; there are no apex predators. The previously extant predators were: European grey wolf *Canis lupus lupus*, European brown bear *Ursus arctos*, and Eurasian lynx *Lynx*

lynx (Blake, *et al*., 2014; Flower, 2016; Raye, 2017; O'Regan, 2018). With the non-existence of apex predators in Britain, other methods have been engaged to manage wildlife for multiple reasons, including the benefit of landowners and the benefit of the animals themselves. These methods are termed “wildlife management”.

This study was performed on the deer species present at the Thorne Moors site of the Humberhead Peatlands National Nature Reserve. The nature reserve is located near Goole in East Yorkshire and is of national importance, having gained SSSI status for both plants and animals. The site is surrounded by arable farmland; currently growing oilseed rape, sugar beet, potato, and carrot. These crops are all highly palatable to the deer population residing upon the moors.

The study site is currently home to two species of deer: red deer *Cervus elaphus* and roe deer *Capreolus capreolus*; with regular sightings of Reeve’s muntjac deer *Muntiacus reevesi*. The roe deer have been present on this site for longer than living memory, whilst the red deer were introduced to the site by deer farmers around the 1960’s (D. Hinchliffe, pers. Comm.). Conflict has developed between Natural England (majority landowners and operators of the moors) and the local farmers/landowners as to the best approach towards local deer management. The research of this thesis has focussed upon analysing the current activity and impact levels of deer upon the study site, estimating the abundance of each deer species on site, and trialling a novel method of improving the daytime detection rates of deer.

1.2. Managing Wildlife in the UK

Wildlife management is the term given to a series of methods utilised by humans to control the population sizes of wild animals (Riley, *et al*., 2002). The driving factors behind the management of wildlife populations are usually focussed towards minimising conflict between wildlife and anthropogenic activities. There are many methods available for use in managing wildlife, all of which have merit in their application, and drawbacks. Three of these such methods are: contraception (Asa & Porton, 2005), translocation (Craven, et al., 1998), and culling (Treves & Naughton-Treves, 2005).

Contraception is a method of suppressing hormone expressions that induce the oestrus cycle in the females of a species by utilising medications (Asa & Porton, 2005). These can be administered in two ways: through intramuscular injections, or orally through tablets (Kirkpatrick, et al., 2011). Administering this medication to wildlife would require the injections to be administered by a dart gun or by first capturing the animal to inject, whilst the oral medication would need to be administered through supplementary food sources (Nettles, 1997; Asa & Porton, 2005; Kirkpatrick, 2007). Contraceptives are temporary in nature and require regular administering to maintain effectiveness (Turner & Kirkpatrick, 1991), which can lead to potential challenges with both time and financial constraints (Guynn Jr, 1995; Nettles, 1997; Asa & Porton, 2005). The advantages of using contraceptives include public approval from using methods that do not involve killing animals (Grandy & Ruthberg, 2002), which would increase funding from animal rights groups, and the method is affective at reducing reproductive output for a single year (Warren, 1995). However, the method has many disadvantages for its use in wildlife management. These include: the costs of implementation, the retardation of expressing natural behaviours (Grandy & Ruthberg, 2002), and the further complications of non-target species ingesting oral contraceptives (Garrott, 1995; Nettles, 1997; Asa & Porton, 2005; Kirkpatrick, 2007). For animals that are not the target species, the consequences could potentially be fatal as the chemical compositions of mammal hormone secretions differ between species. Turner and Kirkpatrick (1991) identified that the contraceptives that worked in feral horses had unexpected side effects in the local rodent populations; which as a prey species would lead to further potential poisoning of predators (including raptors and snakes). Warren (1995) argued that wildlife biologists should only recommend the use of contraception in limited cases, set by a criterion that included usage on ecologically sensitive species, and to reduce the risk to non-target species by using injected contraceptive. Injected contraceptives are, however, difficult to administer to wild species. Affective administration to highly gregarious species (such as red deer) is an expensive and time-consuming endeavour.

Translocating animals involves moving an animal (or animals) from one area to another; this can be for conservation purposes, pest management, or a solution to human-wildlife conflict (Griffith, *et al*., 1989; Craven, *et al*., 1998). Translocation (as a method of managing wildlife) is expensive, time consuming, holds high risk of stress and disease (Woodford, 1993; Reinert & Rupert, 1999; Germano, *et al*., 2009), and requires appropriate environments/habitat for the animals to be relocated to (Griffith, *et al*., 1989). Translocations are usually performed as a method of removing “problem” animals from an environment, as an alternative to culling the animal (Craven, *et al*., 1998; Molony, *et al*., 2006). For example, this is a regular occurrence in the Northern Territory of Australia where there are regular, negative, interactions between humans and saltwater crocodiles (R

Thomas, Pers. Comm.). Translocation is a regular management technique used in conservation biology with endangered species (such as crocodiles and wolves) to increase genetic diversity between isolated populations (Griffith, *et al*., 1989; Boyce, *et al*., 2011; Batson, *et al*., 2015). However, there is a high risk of disease transmission between isolated populations that are translocated to a new area, and the stresses of the move can be detrimental to the animals being relocated, such as mountain chicken frogs and timber rattle snakes (Woodford, 1993; Reinert & Rupert, 1999; Germano, *et al*., 2009). This method is not used regularly in abundant species (such as deer) with regular migration between populations (Boyce, *et al*., 2011). In the UK, translocation of deer would be an expensive endeavour to move an animal that is highly abundant in most areas of the country. This would be moving a problem from one area to another – therefore not a solution) to a problem of over-abundance and high density (Boyce, *et al.*, 2011).

Culling animals for wildlife management is a management method used to actively reduce (or prevent the increase of) the abundance of the selected species (Treves & Naughton-Treves, 2005). This is a method utilised in areas where there are high levels of human-wildlife conflict and is used to reduce disease transmission between species (Barlow, *et al*., 1997; Smith and Cheeseman, 2002; Lloyd-Smith, *et al*., 2005; Cross, *et al*., 2007; McDonald, *et al*., 2008; Harrison, *et al*., 2010). Though an expensive endeavour (through licencing, equipment purchase and equipment maintenance), the financial rewards through the sale of animal based products (such as venison) makes culling a regular method used in the UK. Culling deer, for example, is a self-regulating economy that encourages humane dispatch of animals whilst affectively managing the density of animal populations (Bradshaw & Bateson, 2000). However, culling as a method of controlling disease transmission has become a controversial topic in the UK, for example Badger culls to counter Bovine TB. The culls have operated under the assumption that the removal of badger to a population threshold will reduce the risk of disease transmission. However, this assumption was negated by the study from Lloyd-Smith, *et al*. (2005) who determined that population threshold does not impact the rate of disease transmission. According to Lloyd-Smith, *et al*. (2005) reducing a population of animals by a percentage rather than positively identified infected individuals would likely increase disease transmission; the statistical likeliness of targeting non-infected animals is significantly higher than targeting infected animals (Smith & Cheeseman, 2002).

With a lack of apex predators in the UK, the natural balancing affect upon biodiversity that is derived from complexity-stability theory (that would have come from wolves, bears and lynx) does not occur; therefore biodiversity becomes unstable (Kondoh, 2007; van Altena, *et al*., 2016). It is argued that should apex predators return to the UK, the increased complexity would work to stabilise biodiveristy and reduce the need for wildlife management. There is currently a popular movement in the UK and abroad to consider the reintroduction of previously extant apex predators, whom many believe would reduce the populations of deer to a more sustainable level (Nilsen, *et al*., 2007). This movement is consistent across Europe, and is heavily supported by the European Union habitats directive which requires all member states to "…consider the reintroduction of all previously extant species." However, without the introduction of such species wildlife management maintains the most effective methods of promoting biodiversity and reducing wildlife impact on anthropogenic activities.

The formulation of management plans requires information on the species residing within the landscape. Effective management plans are required in the

UK to reduce the probability of negative impacts upon the environment, which can occur when deer are in high density for the area they reside (Cooke & Lakhani, 1996; Cooke, 2007; Cooke, 2009). To improve the management plans in place at Thorne Moors (and the local landscape), the information required by the stakeholders was to first evaluate the problem; this was done so using the deer activity and impact survey method (Chapter 2). Once impact levels were identified, it was then required quantify the size of the source of activity and impact; this was performed by applying the random encounter model of estimating density to a camera trapping study (Chapter 3). Knowledge on the current habitat usage of the deer of Thorne Moors (Jacob's Selectivity Index – Chapter 3) assisted in the understanding of how the deer were using the moors. Finally, a method of improving the efficiency of management by improving the rates at which land managers detect deer was required (Chapter 4).

Without the formulation of effective management plans for wild deer populations, animal and plant species face an increased risk of population decline from over-disturbance, or risk irreparably damaging natural environments from a lack of biodiversity (Connell, 1978). Overall it is clear that the effective management of wildlife is required to aid the conservation of target species and environments (Mawdsley, *et al*., 2009).

1.3. Ecology of the Cervidae species in the UK

The family Cervidae (deer) are a grouping of ruminant ungulates extant throughout the world; ranging from sub-arctic zones, to temperate zones, and the tropic zones close to the equator (Wilson & Reeder, 2005). Deer display high levels of variation in body size, home range sizes, and vary their reproductive and migratory patterns based on the zones they may be found. For example, reindeer (*Rangifer tarandus*) from the sub-arctic regions have the largest migration of any terrestrial mammal (up to 5,000km per year) and a set breeding season (Pruitt, 1979; Staaland & White, 1991; Bartels, 2001); whilst muntjac deer, from the tropics, have a small migration range and no set breeding season (Wilson & Reeder, 2005; Ward & Lees, 2011).

Historically, deer were present in the UK before the last ice age, in which the deer species natively associated were the red, roe and fallow (*Dama dama*) deer. Of these species, only the fallow went extinct prior to the ice age, whilst the red and roe migrated to warmer climates and re-colonised as the ice rescinded (Geist, 1998; Sykes, 2004). Modern Britain is now home to six species of deer, ranging across all areas of the Island (Figure 1.1): *Cervus elaphus* (red deer) – native species, *Capreolus capreolus* (roe deer) – native species, *Dama dama* (fallow deer) – naturalised species (post-reintroduction in the 11th century), *Cervus nippon* (sika deer) – invasive non-native species, *Hydropotes inermis* (Chinese water deer) – invasive non-native species, *Muntiacus reevesi* (Reeve's muntjac deer) – invasive non-native species (Acevedo, *et al*., 2010).

The fallow, *Dama dama*, became extinct in the UK prior to the ice age and was later reintroduced by humans; therefore, the fallow is now considered to be a naturalised species (Sykes, 2004). The introduction is mostly attributed to the

Normans around the 11th century, however there is zooarchaeological evidence suggesting the Romans had attempted introductions to Britain; although there is conflicting evidence as to the success of introductions pre-11th century. Therefore, it is accepted that the fallow was established after the 11th century Norman introduction (Sykes, 2004; Sykes, *et al*., 2011; Sykes & Carden, 2013).

The sika deer, Chinese water deer, and muntjac deer are all invasive non-native species (INNS), having been introduced to Britain within the last 250 years (Freeman, *et al*., 2016). All three species pose risk to the native deer species, for example muntjac deer are highly destructive and regularly outcompete native deer (Freeman, *et al*., 2016), whilst sika deer hybridise with the native red deer (Wyman, *et al*., 2016) causing a dilution of the naturally occurring genetics. These attributes are detrimental to natural environments, with the destruction of ecosystems, and directly impact the biodiversity of the environments they are alien to.

With a lack of natural predators, unmanaged deer can pose significant challenges for management of the local ecosystem, reducing stability of biodiversity in the area (Connell, 1978; Last & Gardiner, 1981; deCalesta & Stout, 1997; Putman, *et al*., 2011). These environmental impacts, caused by deer populations, can lead to a reduction in biodiversity within the local environment (Cooke, 2009). The over-browsed, and damaged, flora would naturally be used as habitat to many species of invertebrate, and also be a stable food source to many other species. The impacts occurring from unmanaged deer can be detrimental to the availability of food (and habitats) for other species, and, therefore, negatively impacts biodiversity. These environmental impacts will be explored in Chapter 2.

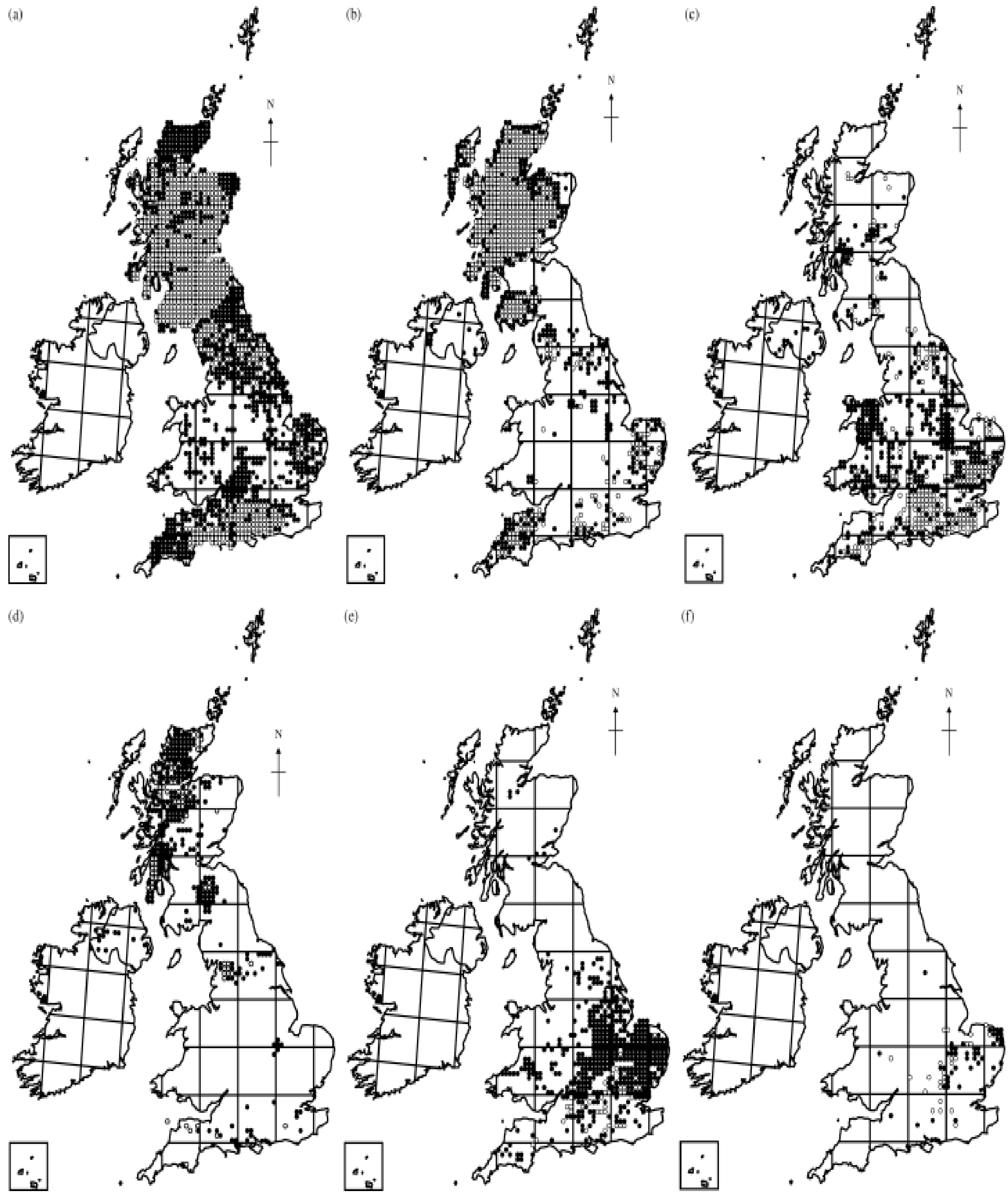

Figure 1.1. The distribution of the deer species of the UK between 1972 and 2002. Open circles represent observations made to 1972, whilst closed circles represent observations made between 1973 and 2002. (a) Roe deer; (b) Red deer; (c) Fallow deer; (d) Japanese sika; (e) Reeves' muntjac; (f) Chinese water deer. The grids are 100km². Resource credit: Ward (2005), with permission.

1.3.1. Red deer (*Cervus elaphus*)

Red deer (*Cervus elaphus*) are the largest terrestrial mammal naturally occurring in Britain and are a charismatic species of the British countryside (Figure 1.2.). The species is highly gregarious, spending their year in majority single sex groups until the rut season; when they create larger herds to commence competition for the rights to reproduce (Asher, 2011). This species is only susceptible to predation by large carnivores, such as wolves, which no longer naturally occur in the UK (Nilsen, *et al*., 2007). As a result of this the red deer population of the UK is completely unchallenged in their ecosystem and is therefore growing in abundance to an unsustainable rate. This has led to over-browsing of wild areas (to be explored in Chapter 2) and requires active management to reduce the negative impacts (DeCalesta & Stout, 1997).

Figure 1.2. Young Red stag in the woodland strip south of the Natural England depot on Thorne Moors. Photo credit: Thomas Logan, with permission.

The 'rut' season for red deer occurs during September and October, with some breeding occurring in November for opportunistic males (stags) not dominant enough to compete for a large grouping of hinds to themselves (Clutton-Brock, *et al*., 1982; Asher, 2011). This leads to occasional late calving as late as September – outside of the expected parturition, typically occurring between May and June (Clutton-Brock, *et al*., 1982). During the rut season, the males reduce their foraging effort, become highly aggressive, and become territorial over their harem of females (Reby & McComb, 2003); calling loudly to demonstrate territories and fighting all potential competitors; including non-Cervidae species (Clutton-Brock, *et al*., 1982).

Red hinds produce a single calf from each successful breeding season, expressing lower levels of fecundity to the other deer featuring in this study (roe and muntjac deer), which can be attributed to the size of the species. There is a trend in the largest of homeotherms worldwide to be low in fecundity, suggested to be as a result of the body size of the animal, and therefore the overall energy expenditure involved in both the gestation and the maternal/paternal care during the rearing of the young (Allaine, *et al*., 1987). Another reason for the fecundity of this species is that they are an extreme example of adapting to a 'K' breeding strategy (Asher, 2011). The stags migrate to the rutting grounds for breeding at varying times throughout the rut period depending on the individuals' dominance over other males (Jarnemo, *et al*., 2017), whilst the hinds determine the areas to which the rut is competed based on the foraging availability.

Cervus elaphus are typically a seasonally migratory species, using the migration process to access abundant feeding grounds. The migrations occur during times when both the quality and quantities of food are near depleted (Latham, *et al*., 1999) – and also migrate for the rutting season (Asher, 2011). This strategy of migrating for food availability is explained clearly using the optimal foraging theory, by not migrating unnecessarily to access lower quality food sources then those that are already accessible (Pyke, 1984). Migration of red deer can relate towards some behavioural plasticity in the presence of species disturbance and is regularly observed during times of high hunting efforts upon deer by humans (Bonnot, *et al*., 2017).

Red deer react very negatively to disturbances caused by humans, with a higher rate of avoidance of human settlements to either roe or muntjac deer (Jiang, *et al*., 2008). Home range size of red deer follows the availability of food on a year-to-year basis, with the smallest home range being the areas with substantial supplementary feeding (Reinecke, *et al*., 2014).

1.3.2. **Roe deer (Capreolus capreolus)**

Roe deer (*Capreolus capreolus*) are a forest dwelling species of deer in the UK (Last & Gardiner, 1981; Lovari, *et al*., 2017). The roe (Figure 1.3.) is a medium sized deer species, approximately 75cm in height (Klein & Strangaard, 1972), and specialises in eating deciduous woodland plants (Lovari, *et al*., 2017), however can be very generalist in feeding (Latham, *et al*., 1999) when conditions dictate necessity. This species has the widest dispersal range of any deer species across Britain (Ward, 2005). The dispersal and density of the species is so high that it was predicted by Ward (2005) that by 2015, roe deer would “be present within 79% of all 10km squares.” This national occupancy was predicted from the extrapolating historical range expansions and modelling population growth rates from that data (Ward, 2005). The roe deer is a species that expresses significant levels of behavioural plasticity with regards to gregariousness. This deer species spends most of the year in small family groups of does and fawns, with the remaining time spent nearly exclusively solitary, however under extreme circumstances (such as high levels of disturbance by muntjac) the roe deer can form herds (Andersen & Linnell, 1997).

Figure 1.3. A Roebuck in the woodlands on the periphery of the northwest of the Moors near the Creykes Gate. Photo credit: Thomas Logan, with permission.

The rut season occurs between July and August and is signalled by an increase in gregarious behaviours expressed by the species; and by an increase in aggression and vocalisations by males (Reby & McComb, 2003). During the rut season, bucks maintain territories that overlap several females with whom they would breed. The males who do not hold a territory are unsuccessful in breeding for that rut.

Roe deer have the highest levels of fecundity of British deer, with some (usually younger) does regularly being capable of gestating (and birthing) two kids each breeding season (Hewison, 1996). Parturition occurs between May and June, around the time of year containing high abundance of high-quality food.

Roe deer are not a migratory species, and instead only move between forest habitat patches for breeding and feeding purposes (Wahlstrom & Liberg, 1995). However, this species disperses widely around the environments in which it lives, and form home ranges that overlap others, even during times of increased territoriality; especially during the rut season (Wahlstrom & Liberg, 1995). The movement of roe deer can be influenced by the impact and influence from the disturbances caused by humans (deCalesta & Stout, 1997; Jiang, *et al*., 2008). The home range sizes of roe deer appear to have no significant differences between bucks and does, with a variation in home range size demonstrating a behavioural plasticity towards a larger home range in areas with reduced access to woodlands (Hewison, *et al*., 2001; Herfindal, *et al*., 2005; Pellerin, *et al*., 2008; Lovari, *et al*., 2017).

As previously stated, roe deer are a forest dwelling species and therefore concentrate feeding efforts upon forest/woodland plants (Lovari, *et al*., 2017), specifically on fresh growth from coniferous trees and lower level shrubs and ferns (Latham, *et al*., 1999). Roe deer are classed as concentrate selectors – an adaptive feeding strategy allowing them to make best use of the food available (Hoffman, 1989; Ferretti, *et al*., 2008). The increased vigilance of the roe deer to predation risk is demonstrated by avoiding high quality food resources during levels of high hunting pressures (Hewison, *et al*., 2001; Bonnot, *et al*., 2017). As a forest species that are highly susceptible to hunting from cryptic, arboreal hunters, such as lynx (Okarma, *et al*., 1997), roe deer have become a species that are constantly alerted to any interference during feeding. Therefore, they are quick to react and move during feeding at any and all disturbances (Ferretti, *et al*., 2008).

The roe is susceptible to predation by large carnivores, and traditionally by forest dwelling cat species, such as the Eurasian Lynx, however none of these carnivores currently exist in the UK due to extinction by persecution (Hetherington, *et al*., 2006). Due to a lack of predators in the UK, the roe deer will continue to rise in population if they are left unmanaged, leading to over-browsing of the UK's forests. Therefore, this may drive forth the requirement of active management to control population sizes and ensure their effective movement around habitat patches (Last & Gardiner, 1981; Hewison, *et al*., 2001; Putman, *et al*., 2011; Bonnot, *et al*., 2017).

1.3.3. **Reeve's Muntjac Deer (*Muntiacus reevesi*)**

Reeve's muntjac deer are the smallest deer species currently existing in the UK; standing at a maximum of 52cm tall at the shoulder (Chapman, *et al*., 1993). The muntjac (Figure 1.4.) is an invasive non-native species (INNS), having been introduced to Britain approximately 90 years ago (Freeman, *et al*., 2016) from the tropics of south east China (Lister, 1984; McCullough, *et al*., 2000). This species poses extensive competition to the native deer species and environments of Britain, for example muntjac deer are highly destructive to woodland habitats (Cooke & Farrell, 2001) and regularly outcompete native deer sharing the same environments (Freeman, *et al*., 2016) – specifically directly competing with the native roe deer for resources such as territory and food (Hemami, *et al*., 2004; Hemami, *et al*., 2005).

Muntjac are mostly a solitary species whom express variation in gregarious behaviours demonstrated between the sexes. Bucks (males) live a primarily solitary lifestyle, expressing highly territorial behaviours. This contrasts with seasonally breeding deer, such as red deer, whom are known to group together in bachelor herds during the times of year outside of the breeding season (Asher, 2011). Instead, as a non-seasonal breeder, muntjac bucks are constantly prepared to reproduce and maintain solitary territories all year round (Barrette, 1977; Yahner, 1978; Geist, 1998; Asher, 2011). Muntjac does (females) are found to wander between different buck's territories, living in small family groups where some females may remain with their mothers for the first year or two of their adult lives, and any infants that the mother may be nursing at the time (Chapman, *et al*., 1997). Groupings of muntjac are normally found at a low number (rarely higher than five individuals), showing that muntjac deer express similar gregarious behaviours to the native roe deer (Chapman, *et al*., 1997). The unusual aspect of muntjac social organisation is the small territories and home ranges they occupy (Barrette, 1977; McCullough, *et al*., 2000; Acevedo, *et al*., 2010); a single roebuck territory can contain many muntjac buck territories (Chapman, *et al*., 1993).

Muntjac deer are the only species of deer in the UK to breed without an established breeding season. This can pose challenges to muntjac bucks in the development of their antlers and, therefore, inter-sexual competition. The development of antlers is not driven by reproductive seasonality as it is in temperate zone deer species (Chapman & Chapman, 1982). Muntjac bucks instead compete to mate by use of their extended canine tusks – therefore, reproductive success is higher in younger bucks whom have not lost (or excessively damaged) their tusks from previous fighting (Chapman & Chapman, 1982; Chapman & Harris, 1991; Chapman, *et al*., 1997).

Figure 1.4. An adult muntjac buck. Photo credit: gailhampshire, reproduced under the Creative Commons Attribution 2.0 Generic License.

The muntjac deer has a higher fecundity rate to red deer, and a similar fecundity to roe deer. Their gestation period lasts 7 months, after which the muntjac doe gives birth to a single offspring (Chapman, *et al*., 1984). Muntjac does are capable of conceiving within days of giving birth and can fall pregnant before reaching a year old. With the lack of breeding season, and the ability to produce a single offspring every 7 months, it is possible for a muntjac doe to successfully rear three infants (individually) over a 2-year cycle (Chapman, *et al*., 1984). An adaptation of muntjac deer is their ability to commence their oestrus cycle and conceive within days of giving birth; enabling the highest levels of recruitment possible for this tropical species (Chapman, *et al*., 1997).

Muntjac, like all deer species, are an ungulate browser species with a ruminant stomach digestive system. Being a tropical species, they are specialists in living in dense woodland and eating the growth of woodlands plants and trees (McCullough, *et al*., 2000). In the UK they have become a generalist feeder, demonstrating preferences towards understory vegetation and fresh growth of coppiced plants (Cooke & Lakhani, 1996). The muntjac is highly adaptable, utilising any food sources available to them in woodland environments; and is therefore considered a concentrate selector (Hoffman, 1989). As concentrate feeding strategists, the muntjac can survive the harsh conditions of a temperate winter as a result of their ability to utilise any available energy sources (Chapman, *et al*., 1993; Cooke, 1997). Although a herbivorous species, deer can be observed to utilise animal sources of protein. Observations upon muntjac stomach contents have identified small animals and eggs to make up a minor percentage of their diets, resulting from direct predation to ground nesting birds, such as the nightjar (Geist, 1998; Hemami, *et al*., 2005).

As an invasive, non-native species, muntjac deer are known to regularly have adversely negative impacts upon the ecosystems in the UK – impacting both mammals and plant species (Cooke & Lakhani, 1996; Flowerdew & Ellwood, 2001). This can be seen in the adverse relationship at both a local and regional-scale level, with clear changes in bird populations occurring with changes in woodland deer populations (Cooke, 1997; Cooke & Farrell, 2001; Hemami, *et al*., 2005; Newson, *et al*., 2012). The study by Newson *et al*. (2012) has shown that once a population of woodland deer exceeds a threshold amount (dependent upon the size of the environment involved) the bird populations will become adversely affected. Like the impacts upon birds, negative impacts to the ecology of mammals in woodland habitats may be observed to be directly impacted by muntjac activity (Flowerdew & Ellwood, 2001). Small mammals, such as hares, are in direct competition with woodland deer for feeding patches. As a result of the dominant nature of muntjac, hares are less successful when in direct competition and require feeding patches away from muntjac for greater success in feeding (Flowerdew & Ellwood, 2001). The damage to flora can be observed by damage to the regrowth of coppiced woodland flora. This leads to the requirements of woodland managers to place electric fencing around sections of regrowth to encourage plant growth and reduce the risk of overgrazing by muntjac (Cooke & Lakhani, 1996).

1.4. Aims and Thesis Structure

This study's primary aim was to obtain information upon the conditions of the nature reserve with regards to deer population levels and environmental impact. This information was collated and analysed by performing activity and impact surveys, a camera trapping schedule, and a survey comparing the effectiveness of detecting deer between thermal imagers and binoculars. Prior to this study, there were no reliable estimates of population abundance of deer upon the moors, with no measurements of deer impact on site. Therefore, this study aimed to analyse the activity and impact levels of deer upon the moors, to produce an accurate estimation of the population abundance and landcover selectivity of deer, and to trial an improved method of detecting deer during the daytime. The results of this study, and methods utilised, could then be used to assist in the formulation of a unified, landscape-scale approach towards local deer management.

Chapter 1. Introduction.

This chapter introduces the study and sets out the aims and objectives. Within this chapter, the study site (Thorne Moors) is described, as is the ecology of the deer species present upon the Moors.

Chapter 2. Assessing the activity and impact levels of the deer of Thorne Moors.

The survey technique used to determine the activity and impact levels of deer upon the site was the Activity and Impact Survey method established by The Deer Initiative. This method is based on the method *sensu* Cooke (2007). These surveys consider the evidence of both the activity of deer (e.g. racks, slots, dung, deer seen) and the environmental impacts of deer (e.g. bark stripping, browsing, fraying). This method was used to bring the data into a national standard to be used by The Deer Initiative in their national databases.

Chapter 3. Estimating the densities and abundance of the deer across Thorne Moors.

We used trail cameras to obtain data which was analysed using the random encounter model *sensu* Rowcliffe, *et al*. (2008) to estimate the density and abundance of the deer species on Thorne Moors. The model estimated the abundance of red and roe deer and attempted to estimate the abundance of the muntjac deer. The model functions by gaining independent information on the detection zones and trapping effort of the cameras, and independent estimates of the average group size and average daily speed of movement for each species. Combining this information with the camera trapping events by the cameras (two-minute intervals in trapping events) the method produced an estimated abundance. Bootstrapping was then used to produce a mean abundance level and 95% confidence interval of the data.

Chapter 4. Daytime Detection of British Native Deer.

This chapter trialled a new method to improve the daytime detection rates of deer by the usage of Thermal Imagers. This method directly compared the accuracy of thermal imagers with binoculars in their abilities to detect deer in the environment. By the usage of a stringent methodology and following the times of day described by the Deer Act 1991, this method functions to assist deer stalkers in the generation and execution of deer management strategies.

Chapter 5. Discussion.

The final chapter summarised the overall impact and abundance of the deer of Thorne Moors. It also identified the methodology to detect the deer of Thorne Moors. The chapter then summarised how the information for each chapter of this study could combine to better understand the ecology of the deer of Thorne Moors. Finally, the chapter identified the future work required to continue and improve upon the work performed in this Thesis.

1.5. The Study Site

The Humberhead Peatlands National Nature Reserve's site "Thorne Moors" was the site selected for this study (Figure 1.5.). The Humberhead Peatlands NNR is made up of a combination of two sites, Thorne Moors and nearby Hatfield Moor (Natural England, 1986; Natural England, 2017). Thorne Moors is a 1900ha site situated near Thorne, in South Yorkshire, and is surrounded by arable farm land; used primarily for agricultural production. The site is an important nature reserve for its biodiversity, earning SSSI (Site of Special Scientific Interest) status as a direct result of its vast biodiversity of both animals and plants, (Natural England, 1986); and although accessible to the public, the site is under-developed to maintain natural status. The site is currently managed via a European Union grant to restore the peatland bog to its previous condition. In order to complete this, the site managers installed a multi-million-pound water pumping station to manage the water level and is deliberately removing the birch wood to assist in the restoration of wetlands. At current, there is active management of Rhododendron taking place on site – an invasive species of plant that is aggressive in its growth and spread, and particularly unpalatable to the mammal species on site. According to Natural England (2007) the moors contain multiple plant species (including mosses, bracken, heather and birch) and multiple animal species (including invertebrates, ground nesting birds, raptors, reptiles, amphibians, and mammal species). The importance of the site is shown largely in the breeding/wintering habitats for birds, such as: nightjar (*Caprimulgus europaeus*), nightingale (*Luscinia megarhynchos*), and snipe (*Gallinago gallinago*) – the nightjar population has significant national importance, exceeding 1% of the British breeding population (Natural England, 1986).

The moors are home red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), and an increasing population of Reeve's muntjac deer (*Muntiacus reevesi*). According to the local deer managers, the roe deer have been on the moors for longer than living memory, whilst the red deer only entered the site around the 1960's from deliberate releases from local deer farms. The muntjac deer have been occasionally seen on site for approximately 5 years. There is no active deer management taking place upon the Moors, whilst there is an active Deer Management Group (consisting of multiple local land owners) for deer on the lands surrounding the moors.

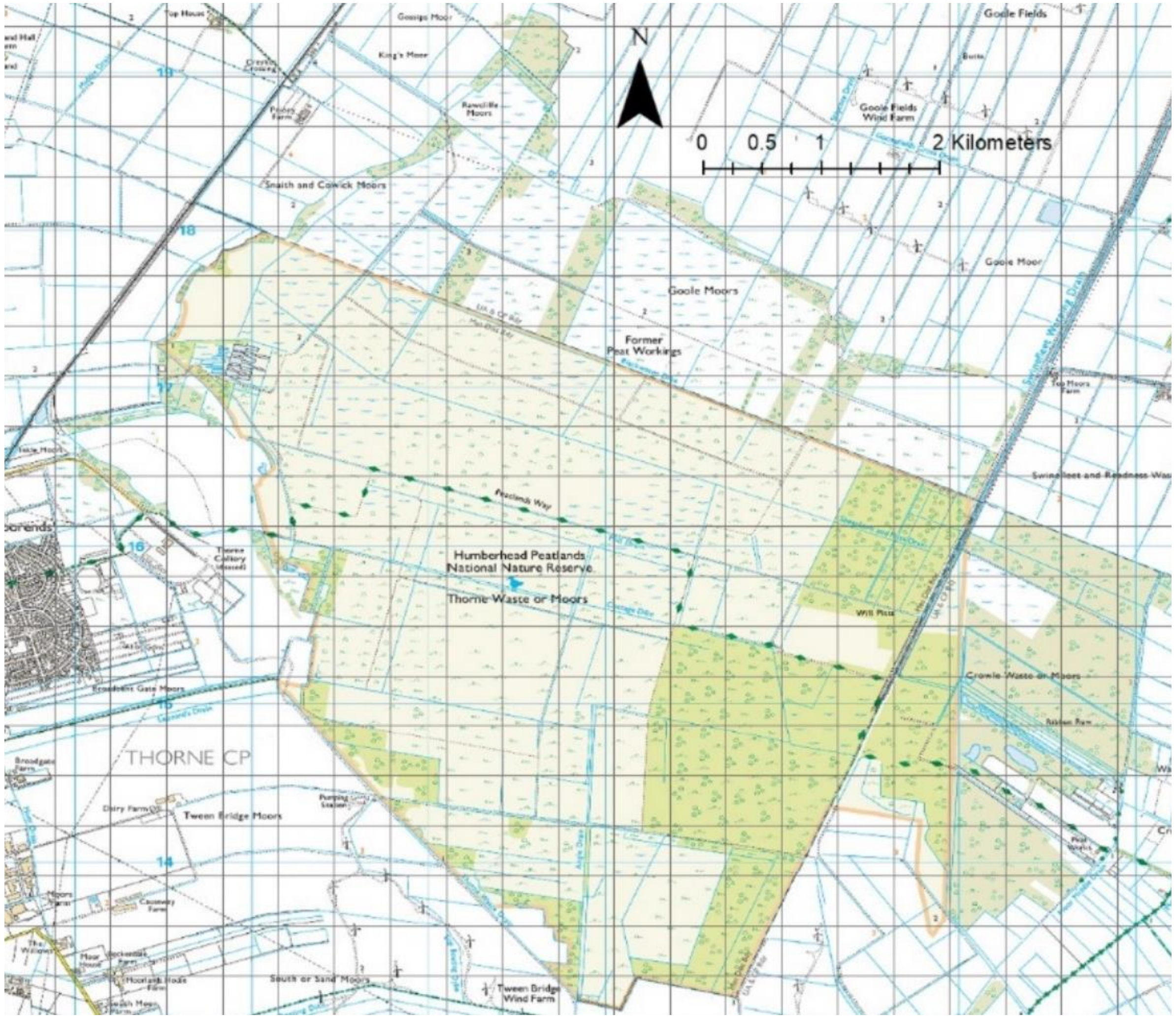

Figure 1.5. A map of Thorne Moors developed using the British ordinance survey. Thorne Moors is located on the South Yorkshire and Lincolnshire border in the UK; north of the M180, east of the M18 and south of the M62. Map credit: Thomas Logan, with permission.

1.6. Ethical Statement

This study posed no ethical or legal, problems with regards to the usage of the site, or impact upon the wildlife. All permissions for site usage were gained from the major land owners, and therefore operators, of the national nature reserve. The mammals, reptiles, birds and invertebrates (and plant life) of the site are protected by the Wildlife and Countryside Act (1981); with added emphasis due to the SSSI designation to the moors. There were signs in place upon the moors to warn patrons that camera activity was happening, and there was no direct contact with the animals on site. The study was approved by the University of Hull's ethics committee without any concerns raised.

Chapter 2.

Assessing the Activity and Impact Levels of Deer on the Moors

2.1. **Introduction**

A keystone species is one with a significant impact on the environment around it that is disproportionately large relative to that of other species, such as apex predators (Mills, *et al*., 1993). The family Cervidae (deer) are a grouping of species residing in Britain that can be defined as a keystone species (Mills, *et al*., 1993).

Unregulated populations of wild ungulates, such as deer, can pose significant challenges for management of the local ecosystem and can reduce the stability of biodiversity in the area (Connell, 1978; Last & Gardiner, 1981; deCalesta & Stout, 1997; Putman, *et al*., 2011). The mechanics by which deer impact the environment include their feeding methods, damage to trees, and trampling from large herd sizes (Cooke & Lakhani, 1996; Cooke, 1997; Cooke & Farrell, 2001; Cooke, 2007; Cooke, 2009). These mechanics are not generic to all deer species, instead there are specificities to each species depending on each species' behavioural ecology. For example, muntjac deer include the eggs of ground dwelling birds in their diets (Cooke & Farrell, 2001), highly gregarious deer, such as red deer, can trample open moorland damaging the plant life (Zamora, *et al*., 2001), and sika deer create bores into the trunks of trees which can cause irreversible damage to a tree (Shimoda, *et al*., 1994).

Assessing the impacts and activity levels of mammals upon the local environment is essential for the production and application of wildlife management strategies (Conover, 2001; Fryxell, *et al*., 2014). Methods used to asses impacts of animals on the environment vary based upon the behavioural ecology of the species being assessed (Fryxell, *et al*., 2014). Deer impacts in the UK are quantified using the

Activity and Impact Survey method developed by The Deer Initiative from the work of Cooke (2009).

The relationships between biodiversity and the frequencies and intensity of deer impacts are suggested to form an inverted U-curve; like that of the intermediate disturbance hypothesis (Connell, 1978). This u-curve predicts that low levels of deer impact would likely result in lower levels of biodiversity, and that significantly high levels of deer impact would lead to a direct decline in biodiversity from over-exploitation of food sources and destruction of habitats (Mitchell & Kirby, 1990; Gill, 2000; Flowerdew & Ellwood, 2001). Therefore, there is a section of this u-curve at which maximum biodiversity would exist from population size that does not over (nor under) exploit the environment. The benefits to be seen from this intermediate level of impacts include: the spreading of seeds, producing manure, and browsing/grazing some plant life which in turn encourages fresh growth (Mills, *et al*., 1993; Gill, 2000; Flowerdew & Ellwood, 2001; Cooke, 2009; Putman, *et al*., 2011).

This chapter aimed to quantify the impact and activity levels of the deer of Thorne Moors over a single winter. This was enacted by utilising the deer Activity and Impact Survey method produced by The Deer Initiative as an adaptation of the work *sensu* Cooke (2007). This method was enacted by performing two surveys either side of the winter and analysing the data for difference. The data collected included the activity levels of deer (such as racks, slots and dung) and the impact of deer (such as browse lines, fraying, and bark stripping).

The hypothesis of this chapter was that there would be an increased level of activity and impacts on site between the beginning and the end of the winter. This hypothesis was considered based upon the impact levels experienced by local farmers upon their crops during the spring and summer time, acting as a supplementary food source to the deer (D. Hinchliffe, Pers. Comm.). This is consistent with the work of Gill (2000) who found a link of increased environmental impact by deer during times of lower food availability. Therefore, with no supplementary feed available over winter, it could be predicted that deer impacts would increase over the winter months.

2.2. Materials and Methodology

2.2.1. Deer Activity and Impact Surveys

This study utilised an existing method of surveying the environment for indicators of environmental impact caused by deer. The Deer Activity (Table 2.1.) and Impact (Table 2.2.) Survey method is used at a national scale (across both England and Wales) by The Deer Initiative; developed as an extension of the work performed by Cooke (2007). The method is best applied to woodland environments and was therefore suitable to Thorne Moors – given the large woodland areas within the study site. The surveys took place at the beginning and the end of the 2017/2018 winter (end of November and late March/April 2018) to obtain a before and after snapshot of the pressures applied to the environment by deer over the winter months.

The surveys were performed by the principle investigator, whom had limited experience of utilising this method prior to this study but undertook prior training with The Deer Initiative in identifying signs and how to appropriately interpret them. The surveys were taken from walking a series of 22 pre-determined transects (between 500m-1km in length), per survey, with a total of 37km of transects between the two surveys. Along each transect the principle investigator recorded the frequency at which each sign was detected (Table 2.1. and 2.2.). These transects were selected using ArcMap 10.5.1 to provide an even coverage of the study site while avoiding large water bodies and without overlapping (Figure 2.1.). Otherwise, transects were positioned at random with respect to the environment, such that they did not follow established footpaths and tracks.

The age of deer impact required interpretation to accurately record the "current" deer impact levels on the moors. A method utilised to determine the age of impacts (Table 2.2.) include observing the colouration and moisture levels of the plant life impacted; fresh damage to the bark of a tree leaves a moist, brown coloured wood behind whilst historic damage goes grey and dries out. Also considering the seasonality of behaviours in deer is useful for identifying impact age. For example, fraying from red deer occurs on trees when deer are removing velvet from their antlers (usually around August) by rubbing against the tree and damaging the bark, whilst some fraying occurs from roe deer bucks establishing territories in preparation for the rut (around February).

The frequency of all signs of activity and impact identified in this study were recorded on a notepad and later recorded using the electronic application "Survey 123 for ArcGIS" on a computer, using the electronic forms made available by The Deer Initiative.

Table 2.1. A summary of the indicators to activity levels of deer, with brief descriptions as to their application, adapted from the Activity and Impact Survey method (Cooke, 2007).

Activity Indicator	Brief description
Deer Seen	Record how many of each deer species are seen. For highly gregarious species record group detections, for others record individuals. Seeing one deer in a 1km transect = Low, more than 10 per 1km transect (all species combined) scores High.
Dung	Tally in groups of pellets (group = 6 or more). Seeing 1 pellet group during the survey score Low, 30 or more groups per km scores High.
Couches	Where deer have lain down, leaving flattened or scraped areas of vegetation (often oval shaped). 1 couch in the survey scores Low, 10 or more per km scores High.
Scrapes	Often seasonal in nature, and sometimes possible to identify the species. Scrapes are areas of cleared ground using the legs of the animal. 1 scrape in the whole survey scores Low, 10 or more per km scores High.
Wallows	Often seasonal in nature, and usually possible to identify deer species (only Red, Fallow and Sika regularly wallow). 1 wallow in the whole survey scores Low, 4 or more per km scores High.
Racks (Deer Paths) and Slots (individual foot marks)	Individual slots can be useful to identify species and may be the only evidence of deer in low densities. Deer racks are more obvious, long lasting and gives indication to pressure of usage. Species responsible for racks can be determined by: dung, slots, height of browsed vegetation, and height of tunnels (particularly common in Muntjac). Racks are divided into categories of: rarely used, lightly used, frequently used, and heavily used. 1 rack in a survey give a score of Low, 20 or more racks per km with some in the frequently used grade (or above) score High.

Table 2.2. A summary of the indicators to impact levels of deer, with brief descriptions as to their application, adapted from the Activity and Impact Survey method (Cooke, 2007).

Impact Indicator	Brief Description
Fraying	Often seasonal and localised. Fraying is the rubbing of bark off of trees using antlers – larger deer species can move onto thrashing (adding broken branches/stems to the bark removal). Only tally fraying <1 year old. 1 fraying site in the survey scores Low, >20 per km scores High.
Bark Stripping	Normally associated with Red, Fallow and Sika. With fresh damage, the width of the teeth marks can differentiate deer from rabbits and squirrels. Count individual stems, or clusters as a single appearance. 1 bark stripped stem/cluster in the survey scores Low, >5 per km scores High.
Broken Stems	Occurs when deer break stems to browse shoots higher than they could reach. The height of the stem can help identify the species. 1 broken stem in the survey scores Low, >10 per km scores High.
Browse Line	May be clearest with leaves on the trees but can be clear in winter. The height of browsing can indicate the species present at the time. Moderate deer densities can lead to the expectation of a browse line visible when looking through the wood at 50-180cm.
Browsing	Deer are selective browsers; therefore, it is important to concentrate on significant plants – e.g. climbing ivy and bramble are invariably browsed when deer are present.
Coppice <2m (<1m where only muntjac are present)	Recently coppiced stools with all new growth or older growth approximately <2m. They may be individual or in groups. Examine at least 20 representative stools throughout the site, estimating the percentage of stems with damaged shoots. The more evidence of higher percentage increases the intensity of the impacts.
Live basal shoots or older coppice or tree boles	Old coppice stools and mature trees continue to produce new shoots from the base, the tops of which are within reach of deer. Look at >20 representative stools/trees spread throughout the site and estimate the percentage of new/live shoots that are damaged. Each stool gets a mark in the percentage ranges, and a score is made from that.
Seedling/saplings	Sample no less than 20 seedlings at each area, randomly selected, to stop to look for damage. Each group of 20 is a tally mark in a percentage region. The highest marked area determines a score between Low-High.
Bramble	Most common species of bramble are highly palatable to deer so a good indicator of impacts. Between a range of little browsing and most/all browsed, usage of the tally sheet to determine a score between Low - High
Grazing	Deer of all species selective graze ground flora. A list of palatable plant species to be used as an indicator. By concentrating on these species (such as Honeysuckle, Oxlip, Bluebell, and Dogs Mercury), a range of no impact to high impact can be listed as a tally.

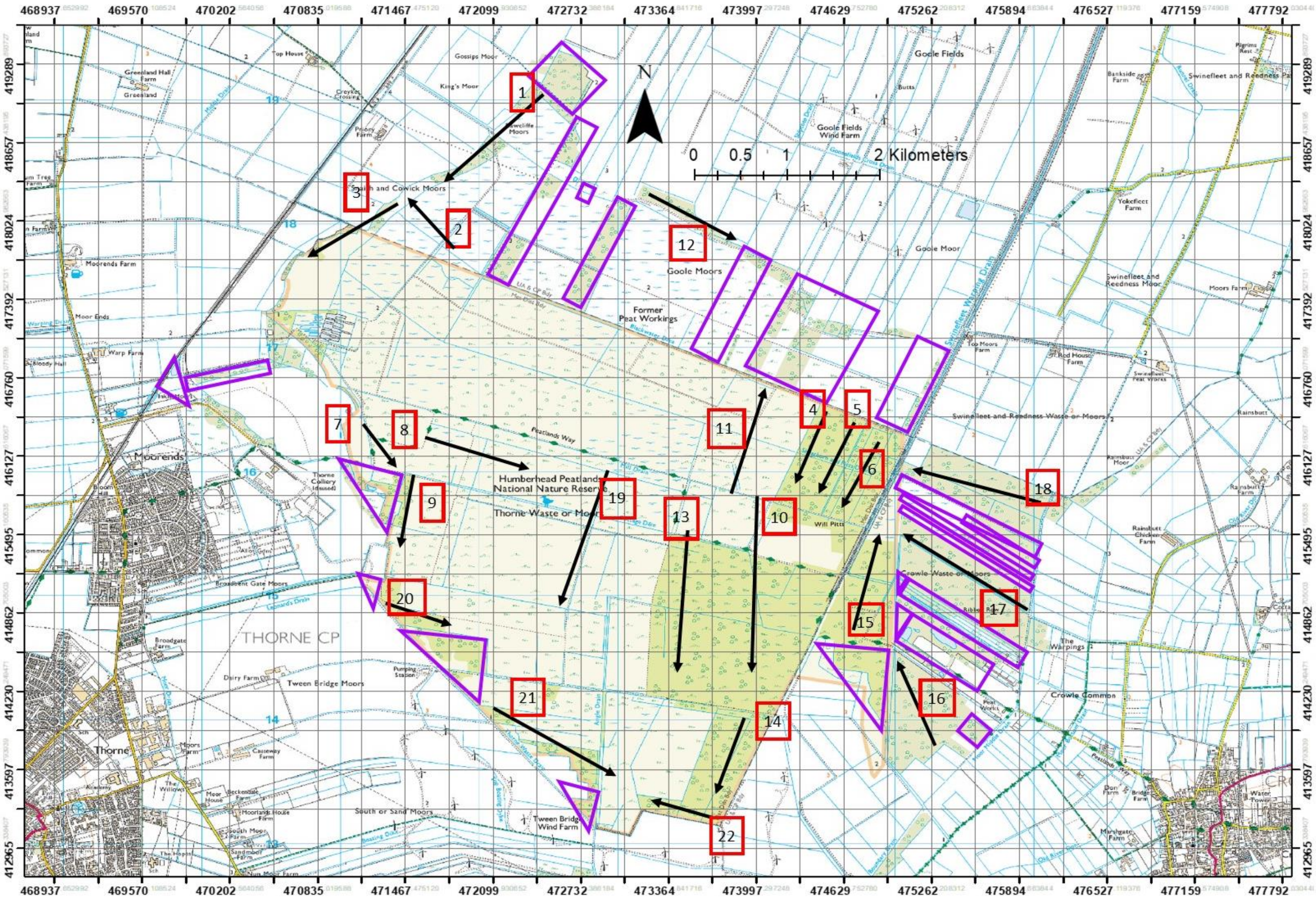

Figure 2.1. The transect schedule of the activity and impact surveys at Thorne moors. The transects on this map (black arrows with numbers in red boxes) are used for guidance to show the general path of the areas investigated, allowing for adaptation when required in the field, yet ensuring repetition of measurements for later investigation. The purple outlined polygons are the areas of the Moors not owned by either Natural England or Lincolnshire Wildlife Trust.

2.2.2. **Statistical Analysis**

The distributions of the activity and impact data were tested using a Shapiro-Wilk test for normality and was determined to not be evenly distributed; the data was left skewed. Data were log-transformed to permit use of a paired t-test to evaluate the difference in the median levels of activity and impact between the two survey times (Dytham, 2011; Ennos & Johnson, 2018). All analysis for this chapter was performed using IBM SPSS 25.

2.3. **Results**

2.3.1. **Data Summary**

In total 44 transects were surveyed, divided into two surveys of 22 transects each (Figure 2.1.). The average signs observed per survey (inclusive of all transects per survey) are summarised below (Table 2.3.). The signs were recorded per kilometre (km^{-1}). For transects not 1km in length, the sign frequency was expressed as the number observed per km and was assessed against the scoring criteria (Tables 2.1. and 2.2.). The signs identified are considered to mostly be caused by the red deer due to the height of browse lines (requiring a large animal), tree impacts (bark stripping is associated mostly to red, sika and fallow deer (Table 2.2.)), and from the behavioural ecology (for example roe deer are unlikely to use wallows). However, there were multiple overlaps (such as coppice browsing) between species therefore it is only a consideration and not definitive.

2.3.2. **Activity and Impact Levels**

The activity and impact surveys performed during November revealed a median activity level of Moderate, and Low impact (Table 2.4.). The second surveys performed during March/April revealed a median activity level of High, and impact level of Moderate-High (Table 2.4.). The range of scores per transect (Table A.1.) demonstrate areas where the changes had taken place between November 2017 and April 2018.

The difference was tested using a paired t-test of the activity and the impact levels between the two surveys. The activity levels were significantly different between the two surveys ($t = -3.858$, $df = 21$, $p = 0.001$). The impact levels were also significantly different between the two surveys (t = -6.240, df = 21, p = 0.001). Therefore, the null hypothesis can be rejected as there was a significant increase in activity and impact levels upon the moors between the surveys.

Table 2.3. Summary of the average observations recorded from the 22 activity and impact survey transects, over the two surveys performed. All indicators beginning with "A)" are activity indicators, whilst "I)" represents impact indicators.

Activity/Impact Indicator	**Pre-Winter Average (km^{-1})**	**Post-Winter Average (km^{-1})**
A) Deer Seen	3	8
A) Dung	16	27
A) Couches	4	7
A) Scrapes	2	4
A) Wallows	4	7
A) Racks and Slots	8 (frequently used)	17 (frequently used)
I) Fraying	8	17
I) Bark Stripping	3	9
I) Broken Stems	2	7
I) Browse Lines	4 (favoured species only)	8 (favoured and un-favoured species browsed)
I) Browsing	50% (favoured species)	75% (favoured and un-favoured species browsed)
I) Coppice <2m	4	12
I) Live Basal Shoots	N/A	N/A
I) Seedlings/Saplings	N/A	N/A
I) Bramble	50% Browsed	>75% Browsed
I) Grazing	50-60% favoured species	90% favoured species, 30% un-favoured

Table 2.4. The median and 95th percentile range of the activity and impact scores across 22 transects during two surveys. 1 = None, 2 = Low, 3 = Low-Moderate, 4 = Moderate, 5 = Moderate-High, 6 = High.

	Pre-Winter Activity	**Pre-Winter Impact**	**Post-Winter Activity**	**Post-Winter Impact**
Median	4	2	6	5
Lower 95th	3	1	3	2
Upper 95th	6	6	6	6

2.4. Discussion

There was a clear increase in deer activity and impact on Thorne Moors over the winter months. These increases were likely to have occurred from a reduced availability of food sources to the deer populations over this period of no plant growth. The seasonal changes in the rates of deer impact were identified by Gill (2000) in environments with reduced food availability. The indicators of deer impact recorded during activity and impact surveys are usually reliant on palatable species of flora available to deer during the spring/summer months – such as fresh growth upon brambles and dogs mercury (Cooke, 2009). During the November surveys, the principle investigator had to observe the level of impact upon both palatable and unpalatable species to increase understanding which floral species needed to be closely observed for signs of impact. This allowed the study to observe changes to activity and impact levels during a time of reduced food availability.

November is the ending of the rut season; a time of year where male red deer eat less food as they have focused their energies upon reproduction (Geist, 1998; Asher, 2011; Jarnemo, *et al*., 2017). It is also the time of year the local farmers will have completed the crop harvest and started preparing the fields for the next growing season. With the removal of external food sources to the moors, and a reduction in natural forage on the Moors, it was predictable that there would be an increased impact on the remaining flora. The time period between November and March is also outside the legal close season for shooting deer in the UK (as described by the Deer Act 1991) – something regularly performed on the periphery of the moors. Within this period, the deer were highly active on the moors during the hours of twilight and night-time (see Chapter 4). With this increased usage of the moors by the deer, during the period of increased shooting pressure, the impact levels of the moors likely increased with the deer's foraging intensity. Red and roe deer are particularly sensitive to the activities of humans and regularly change behaviours as a direct result of increased human activity (Benhaiem *et al*., 2008; Jiang *et al*., 2008). This would need further study to determine whether the shooting pressure around the moors has a direct impact on the deer's use of space.

The increase in deer impact implies the deer focussed their activity and impact in the areas where they were less disturbed upon the moors. This is consistent with the work performed by Benhaiem, *et al*. (2008) and Jiang *et al*. (2008) whom identified that both red and roe deer avoided areas where human disturbances were high. With the deer moving towards areas of lower disturbance, it becomes evident that those areas would experience a higher level of activity and impact. The difference between the gregarious behaviours expressed between red and roe deer would also affect the levels of impact each species produces. Roe deer live in smaller densities than red deer on Thorne Moors (see Chapter 3) and the males express territorial behaviours (Cederlund, 1983; Geist, 1998), therefore the risks of roe causing wide-ranging, negative impacts upon the moors are lower than that of red deer (Gill, 2000). The high density expected of red deer was observed through large group sizes on the moors (see Chapter 3).

The deer Activity and Impact survey method is a good generic indicator of the levels activity and impact in a given environment, and is very effective at identifying trends and change in those levels during annual surveys (Cooke, 2007). However, one of the primary limitations of this method includes the advice of the Deer Initiative method statement that change does not occur throughout a season, which has been discredited by the results of this study. Another limitation is the inability to positively identify the impacts of each species of deer in environments with overlapping species. In an environment, such as Thorne Moors, that has a combination of red deer (tall species) and roe deer (short species) the impact of roe deer upon browsing will be near impossible to quantify as a result of the taller browse lines created by the red deer (Cooke, 2009). This is also a considerable problem in an environment that includes sheep/goats, which impact the environment in a similar way to deer (Cooke, 2009). The final limitation of the method is the interpretations of the data collected. With this method, the highest level any single indicator hits is the level that is recorded for that transect (Cooke, 2007; Cooke, 2009). Therefore, if one source was considered high impact (such as bark stripping) yet all the other sources were considered moderate (such as browsing) the survey would be recorded as High impact.

This chapter generated a set of activity and impact survey transects to create a starting point for later studies follow. These surveys were not calibrated and therefore their accuracies have not been tested. The lack of calibration, and therefore accuracies tested, has occurred due to a lack of previous data to draw comparisons from. Therefore, the surveys performed in this chapter have instead created the opportunity for continued monitoring of activity and impacts on Thorne Moors to quantify whether there is change between years. This would function to calibrate the testing on site and would further benefit the long-term management plans of the moors, allowing managers to make decisions upon increasing or decreasing efforts to reduce activity and impact from the changes shown between years.

2.5. Conclusion

The comparison of deer impact and activity from before winter to after winter revealed an increase in both over time. The median activity and impact levels of the moors were High and Moderate-High respectively. The increased impact levels appeared on the moors over the winter months, when the availability of forage was more restricted. Future, annual, surveys are required upon the moors to provide information on any patterns/changes over time in relation to any changes in management.

2.6. **Summary**

The six species of deer found in Britain are keystone species to the environment. They are important to the natural environment of Britain, playing a significant role in the modification of physical structures of the environment and facilitating in the distribution of plant seed. However, unregulated deer populations (naturally or otherwise) can pose a significant risk to biodiversity. These risks to biodiversity derive from the overexploitation of food sources and subsequent displacement of species from habitats.

Using the deer activity and impact survey method used by The Deer Initiative, this study functioned to measure the levels of activity and impact of red and roe deer upon Thorne Moors. By performing 2 surveys, one before and one after the winter, the change in activity and impact levels was evaluated over this time

This study summarised that the median level of deer activity was High, and the median impact level of deer was Moderate-High. There was a significant increase in both activity and impact over the winter months. This could be due to an increased usage of the moors by the deer during the hunting season; using the moors as a protective refuge from hunting as there is no active management of deer on site. A secondary reason is likely from a reduction of the arable crops from the surrounding farmers' fields during winter, forcing the deer to instead focus on the remaining food sources on site.

This study identified an overexploitation of the available foraging areas of the site. When levels are consistently Moderate-High and upwards, there becomes a significant risk to the richness of biodiversity in the environment.

Chapter 3.

Estimating the Densities and Abundance of the Deer across Thorne Moors

3.1. **Introduction**

Accurately estimating the density and abundance of keystone species in a given environment is an essential tool to professional ecologists and wildlife managers. Without reliable estimates, the challenge of measuring the health of both the environment and biodiversity becomes near impossible (Conover, 2001; Legg & Nagy, 2006). The information of species density/abundance is required for reporting conservation concerns and establishing both landscape objectives and management plans (Legg & Nagy, 2006).

The UK is currently home to approximately 1.7million deer across the six extant species (A. Boston, Pers. Comm.). Assessing the abundance of deer in specific regions is an essential element to the management of wild deer populations in the UK. As an island population, without apex predators, the sensitivity to food webs is increased, leading to a risk of instability of biodiversity (Kondoh, 2007; van Altena, *et al*., 2016). See Chapter 2 for the mechanisms by which deer impact biodiversity.

When measuring the density of mammals (such as deer), there are many methods of doing so to choose from, and each such method contain features that make it more appropriate than others under particular circumstances. When estimating densities of species, there are three main approaches available for quantifying abundance (Putman, 1984; Buckland, *et al*., 1993; Webbon, *et al*., 2004; Uno, *et al*., 2006); which are: indexing methods (for gauging relative size between populations or change over time), indirect methods (e.g. dung counting), and direct methods (e.g. distance sampling). Of the numerous methods of estimating abundance available, there were two particular methods commonly used to quantify mammal abundance and one that is a recent development.

These were: distance sampling (direct method), faecal count measurements (indirect method), and density estimates calculated using trail camera data (direct method).

Distance sampling requires the estimation of the probability of detecting an animal; this is given as a product of the detection distance of randomly placed transects or points (Buckland, *et al*., 1993; Jathanna, *et al*., 2003; Marques, *et al*., 2006; Thomas, *et al*., 2010). A major assumption of distance sampling is the random placement of transects with respect to the wild populations (Buckland, *et al*., 1993). This assumption is based upon a mathematical requirement of movement being independent of established footpaths (Buckland, *et al*., 1993; Jathanna, *et al*., 2003).

Using faecal counts as a measurement of mammal density is a method that has been used by ecologists throughout the 20th century (Caughley, 1964) and was still in use at the beginning of the 21st century (Webbon, *et al*., 2004). Faecal counting as a measurement is still used today due to it's reliability as a measurement (Ferretti, *et al*., 2016). The method involves surveying transects or plots for the number of piles of faecal droppings present (Putman, 1984). These data are analysed to estimate density by dividing the groups of dung km^{-2} by time (the number of days between consecutive surveys or time taken to decay) multiplied by the defecation rate (Plumptre & Harris, 1995).

Trail cameras can be used to determine the relative density of a given species simply by estimating the trapping rate – number of photographs per unit of time (Rowcliffe, *et al*., 2008). The Random Encounter Model (REM) *sensu* Rowcliffe *et al*. (2008) is a method of estimating the abundance of populations via the use of trail cameras. REM was proposed as an alternative to other methods of estimating abundance by estimating without individual recognition and the potential inconsistencies that would arrive from wrongful identifications on a capture/recapture analysis (Rowcliffe, *et al*., 2008). Previous methods of estimating abundance using camera traps did not estimate the probability of detection, which the REM is able to estimate (Silver, *et al*., 2004; Wegge, *et al*., 2004; Kelly & Holub, 2008; Rowcliffe, *et al*., 2008).

By determining the detection field of the camera in use, a model can be used to describe the contact rate between animal and trail camera. The Random Encounter Model provides a linear scale of trapping rate with species density. However, the density estimate requires independent measurement of four key variables: average animal group size and average daily speed of movement (biological parameters), and the distance and angle within which the cameras detect animals (mechanical parameters).

This methodology was initially tested upon closed populations of Patagonian mara *Dolichotis patagonum*, Reeve's muntjac deer *Muntiacus reevesi*, Bennett's wallaby *Macropus rufogriseus*, and Chinese water deer *Hydropotes inermis* at an animal park in the UK (Rowcliffe, *et al*., 2008); and has since been used on multiple occasions on wild populations (Cusack, *et al*., 2015; Lucas, *et al*., 2015; Carvaggi, *et al.,* 2016). The preliminary testing at Whipsnade Zoo by Rowcliffe *et al*. (2008) found accurate abundance estimates for muntjac, wallaby, and Chinese water deer when compared with the Zoo's bi-annual census of animals. The inaccuracy between abundance estimate and census of mara occurred from biased camera placements based upon prior knowledge of the species' distribution. The tests at the animal park were performed with the cameras placed at 0.75m above ground to target the medium-sized species, with delay period between photographs of two minutes. The cameras were also moved by Rowcliffe *et al*. (2008) every fortnight (when possible) to cover the whole site within a short time due to the restricted number of cameras available. However, the use of REM does have some potential issues to consider when utilising the model. For example, during the initial testing of the model, Rowcliffe, *et al*. (2008) identified that biased positioning of cameras based on prior knowledge of how animals used the environment, causing an over-estimate of population abundance. The model also requires independently collected data on the average daily speed of movement and the average group size of each species. Gathering of such information is time consuming and (in the case of purchasing equipment required to track the average daily speed of movement per species) expensive. A final issue with this model is the production of unrealistically tight confidence intervals, which would be an area for future study to improve the model.

The primary aim of this chapter was to provide an estimate of the densities and absolute abundance of the deer species of Thorne Moors. REM was chosen due to the availability of trail cameras to the study, also because the flooded nature of the site made other methods difficult to perform. A secondary aim was to analyse the sensitivity of the parameters of the REM of this study to identify any further work that may need to be performed. The final aim was to evaluate the habitat use of each species on the moors between seasons.

This study hypothesised that both species deer would use all woodland areas disproportionately more than the availability of that landcover type. This hypothesis is consistent with the behavioural ecology of red and roe deer, whom are both woodland dwelling species with a browsing feeding strategy (Cederlund, 1983; Clutton-Brock, *et al*., 1987; Flowerdew & Ellwood, 2001; Benhaiem, *et al*., 2008; Jiang, *et al*., 2008; Acevedo, *et al*., 2010).

3.2. Materials and Methodology

3.2.1. Cameras and Camera Settings

There were ten cameras placed in the field per deployment, and this was made up from four different models of trail camera. This was due to the cameras being loaned by different organisations. The cameras used in this study were: Essential E2 x1 (Bushnell, Kansas, USA; www.bushnell.com), Recon Force Extreme x1 (Browning, Utah, USA; www.browning.com), RC60 x7 and HC500 Hyper-fire Semi-covert IR x1 (Reconyx, Wisconsin, USA; www.reconyx.com).

This study focussed upon surveying medium to large sized deer, therefore the cameras were placed between 0.75 and 1m above ground level. Cameras were placed to face a direction between West North West and North North West whenever possible. These directions were selected to reduce the impact of investigator bias and also to reduce impacts from the Sun upon the trail cameras' heat sensors. Occasionally it was inappropriate to place cameras in that direction due to dense foliage. In that circumstance, the cameras would be rotated towards North East, or moved to another tree for placement. The consistent direction of placement reduced the risk of investigator bias upon the study. The cameras were placed as close as possible to pre-selected GPS coordinates within the grid point required of the camera placement and was angled as close to 90^{o} to the ground as possible.

To be included as an animal encounter "event" as an input for 'y' (Eqn. 3.1.) there were a few essential criteria. The first criteria is that the image had to have enough clarity for a positive identification of the species in the image. The second criteria was there had to be a 2-minute delay between consecutive photographs of a positively identified species; consistent with Rowcliffe *et al*. (2008). If another species of deer were identified during the 2-minute delay then that would count as a separate “event”. The camera trapping survey for this study took place from the 7th December 2018 to the 6th June 2019. During this time, there were three memory card failures and a single camera stolen; these cameras were recorded to have a zero result.

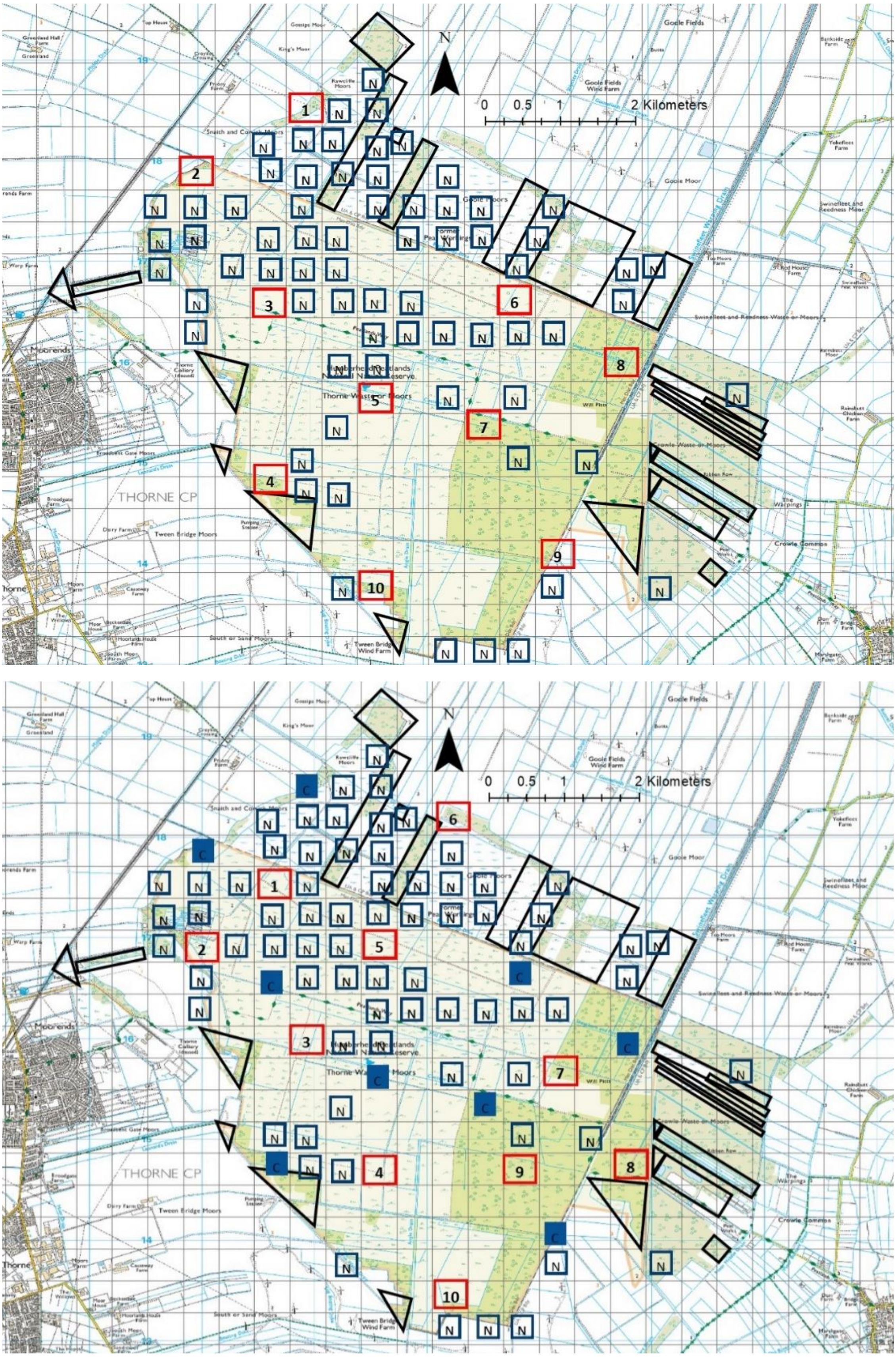

Figure 3.1. The first (top) and second (bottom) camera placements used in the roaming camera grid designed for this study. The red boxes with numbers are the cameras in deployment, the blue outlined box with an N are the areas where a camera could not be fixed, the blue filled box with "C" are where cameras were previously placed, and the black outlined polygons are the areas of the Moors not owned by either Natural England or Lincolnshire Wildlife Trust.

3.2.2. **Camera Deployment**

Thorne Moors is approximately 1900ha in size, with approximately 1130ha of land accessible for the deployment of trail cameras (based on a 10ha grid system). The remainder is flooded wetland. Given the size of the space available, the potential consequences of red deer movement ecology, and the availability of 10 trail cameras, it was determined that the moors would be most appropriately divided into a 10ha grid system. This was generated using a 1:25,000 Ordinance Survey map of the site within the software ArcMap 10.5.1 for GIS (Figure 3.1.). Cameras were deployed between November 2017 and June 2018.

Cameras were deployed across the moors as widely as possible during the first distribution (i.e. borders, internal areas, wet woodland, peatland, and dry woodland). Subsequent camera deployments were no closer than 20ha and no further than 30ha from the previous distribution, with all cameras moving clockwise around the site. Hectares were selected for recording area in this study to remain consistent with the recording performed by Natural England. This enabled complete coverage of the moors throughout the study, with every region of the site under surveillance during each camera deployment.

During the camera trapping schedule, it was not always possible to adhere to the exact grid planned at the start, usually due to a lack of suitable trees to attach a camera to, or the area in question was inaccessible due to flooding. When it was not possible to place a camera, the following deployments' plan was consulted to determine an appropriate location to place a camera. When one was found, the coordinates of where the camera was subsequently placed was recorded and the camera trapping grid was appropriately updated and adjusted for the following deployments. Inappropriate locations for cameras were also marked onto the maps (navy-blue box containing an "N", Figure 3.1.).

3.2.3. **Estimating Animal Densities**

The random encounter model used for estimating abundance required independently obtained data for the parameters of the model. These parameters are: average group sizes of the animals, their average daily speed of movement, and the mechanical parameters of the cameras (detection distance and angle). The average group sizes were estimated from visual observations via a thermal imaging camera and binoculars along transects, as described in Chapter 4. Average daily speed of movement for each species was taken from the literature because it could not be quantified empirically during this study (Jeppensen, 1990; Pepin, *et al*., 2008; Rowcliffe, *et al*., 2008) - These papers were selected as they were considered to be the most similar to these deer populations and environments.

The detection zones of the cameras were measured by walking a series of transects perpendicular to the camera, at varying distances. Combining the detections triggered with the use of a measuring tape and a compass enabled the estimation of total distance covered by the cameras, plus the angle. Each type of camera used during this study (4 types of camera) was tested twice to generate an average detection field of the four camera types to be used in the final analysis.

The density of groups of each species was estimated using Eqn 3.1. The result was multiplied by the average group size of each species to estimate the density of individuals. This was multiplied by the area (in km^2) of the study site to calculate an estimate of the total abundance of each species on Thorne Moors.

Eqn 3.1. $D = \frac{y}{t} . \frac{\pi}{vr(2+\theta)}$

Where:

D = Density (individuals (km^{-2})),

y = Camera trapping events,

t = Time of camera trapping effort (in days),

v = Average Daily Speed of Movement (km/day),

r = Detection distance of the camera (m),

θ = Angle of the camera detection zone (radians).

3.2.4. **Data analysis**

Variance was estimated by randomised resampling of the camera placement trapping events (parameter y of Eqn 1.) via 1000 repeats of bootstrapping (Efron & Tibshirani, 1993). The resampled data produced 1000 repeats of the density estimate from which the mean and standard deviation were calculated. Variance in the independently estimated parameters (Table 3.2.) was assumed to be low for the mechanical parameters (with the limited repeats of measurements), whilst the biological parameter of group size constituted multiple estimates and were expressed as the appropriate averages (mean for roe and muntjac, median for red) for these estimates. The precision of the independent estimates of average daily speed of movement (v) was not included in calculations as they were derived from singular literature sources per deer species; although variance was measured within those sources.

3.2.5. **Sensitivity Analysis**

The sensitivity of the random encounter model (Eqn. 3.1.) to uncertainty in each parameter was tested by varying the parameters that were outside of the investigator's control. With t (time of camera trapping effort in days) being under complete control of the surveyor, this was not included in the sensitivity analysis. The remaining parameters (y, v, r, and θ) were tested by varying the parameters by ± 5%, 10%, 25%, and 50% of their original value and comparing density estimates using Eqn 3.2.

Eqn. 3.2. Parameter Sensitivity Index *sensu* Haefner (1996):

$$SI = \left(\frac{(Da\ -\ Dn)}{Dn}\right) / \left(\frac{(Pa - Pn)}{Pn}\right)$$

Where:

SI = Sensitivity Index,

Da = The altered value of Density,

Dn = The original value of Density,

Pa = The altered parameter value,

Pn = The original parameter value.

3.2.6. **Selectivity Analysis**

The selection of landscape type used by the deer of Thorne Moors was analysed using a Jacob's Selectivity Index. The landscape was divided into the four main landcover types:

Dry Woodland – areas of woodland on the moors on dry ground. For example, the woodlands of the North West boundaries,

Wet Woodland – areas of woodland on the moors on wet/flooded ground. For example, Will Pitts woodland,

Wet Scrubland – areas of the moors with scrub like plant on flooded/wet ground and peatland. This is a large, dominating feature of the moors,

Waterway Footpaths – areas of the moors with large, open water bodies and a mosaic of grass pathways connecting them.

The camera trapping efforts (camera trapping events and camera trapping days) were used to ensure continuity. Selection (D) of each landcover type varies from -1 (strong negative selection) to +1 (strong positive selection) – any values close to zero indicate that landcover is used proportionate to availability.

Eqn. 3.3. Selectivity Index *sensu* Jacob (1974):

$$D = \frac{(r - p)}{(r + p - 2rp)}$$

Where:

D = Jacob's Selectivity Index

r = The proportion of habitat used

p = The proportion of habitat available

3.3. **Results**

3.3.1. **Data Summary**

There was a total of 113 camera placements over 1671 camera trapping days (Eqn. 3.1. parameter t). Overall there were a total of 423 red deer detections, 226 roe deer detections, and 0 muntjac deer detections (Eqn. 3.1. parameter y).

The average group sizes of deer (Chapter 4) were derived from 33 red deer detections and 37 roe deer detections. In addition, muntjac were observed on five occasions. The red deer average group size was expressed as the median and 95^{th} percentile range, whilst roe was expressed by the mean and standard deviation. Therefore, the average group sizes were: 8 red deer per group with a 95^{th} percentile range of 2-147, and 2 roe deer per group with a standard deviation of 1-3.

There were eight walk tests performed for the camera detection zones, producing an average range of 25.9m (Eqn 3.1. parameter r) and an average angle of 0.69 radians (Eqn 3.1. parameter θ). These walk tests were all performed between 11am and 3pm in February 2018.

3.3.2. **Deer Abundance on Thorne Moors**

Across Thorne Moors, the abundance estimates for red and roe deer were characterised by narrow ranges (Table 3.1.). There were no camera trapping events for Muntjac deer, making it impossible to gain a population estimate for the muntjac of Thorne Moors using the REM.

Red deer had an average population abundance of 322 individuals across Thorne Moors. This exceeded the absolute minimum population of 217 red deer observed in a single group during the daytime detection surveys (Chapter 4).

The Roe deer had an average population abundance of 61 across the Moors. There was no absolute minimum population estimate for Roe deer since they do not cluster in large groups.

3.3.3. **Sensitivity Analysis**

The average daily speed of movement, in km per day (parameter v), had the greatest impact on the estimated density of both species when estimated through REM (Figure 3.2.). The remaining parameters had less impact on estimates.

3.3.4. **Selectivity Analysis**

The red deer of Thorne Moors actively selected towards using two landcover types of the moors, and actively selected against using two others (Figure 3.3.). The landcover types were: dry woodland (the periphery woodlands of the moors), wet woodland (the woodlands within the moors), wet scrubland (the majority landcover type of the moors, encompassing much of the middle of the moors), and waterway footpaths (the mosaic of grass pathways around the open water areas of the moors – these are the primary method of moving from one side of the moors to the other). The wet woodlands and waterway footpaths actively selected were areas of the moors with high levels of tree coverage (and food availability) and are the pathways to areas with high food availability. The red deer congregated around the waterway footpaths more so than in any other landscapes of the moors (Table 3.2.). The red deer actively selected against the wet scrubland in the middle of the moors, and the dry woodlands to the moors' periphery (Figure 3.3.).

The roe deer positively selected all landcover types of the moors, apart from the wet scrubland which they selected against (Figure 3.4.). This follows the red deer in using the waterway footpaths to move from one feeding area of the moors to another, whilst making use of all the woodlands available.

Table 3.1. The average density and abundance of red and roe deer across Thorne Moors.

	Red Deer	**Roe Deer**
Mean Density (km^{-2})	17	3
Standard deviation	3.2	0.6
Mean number of animals in 1918.6ha sampling area	322	61
Maximum estimated population	333	63
Minimum estimated population	311	59

Table 3.2. The Median and percentile ranges of red deer group sizes per camera per landcover type of Thorne Moors.

Zones	**Median**	**Upper 95th**	**Lower 95th**
Dry Woodland	1	5	1
Wet Woodland	1	9	1
Wet Scrubland	1	15	1
Waterway Footpaths	3	13	1

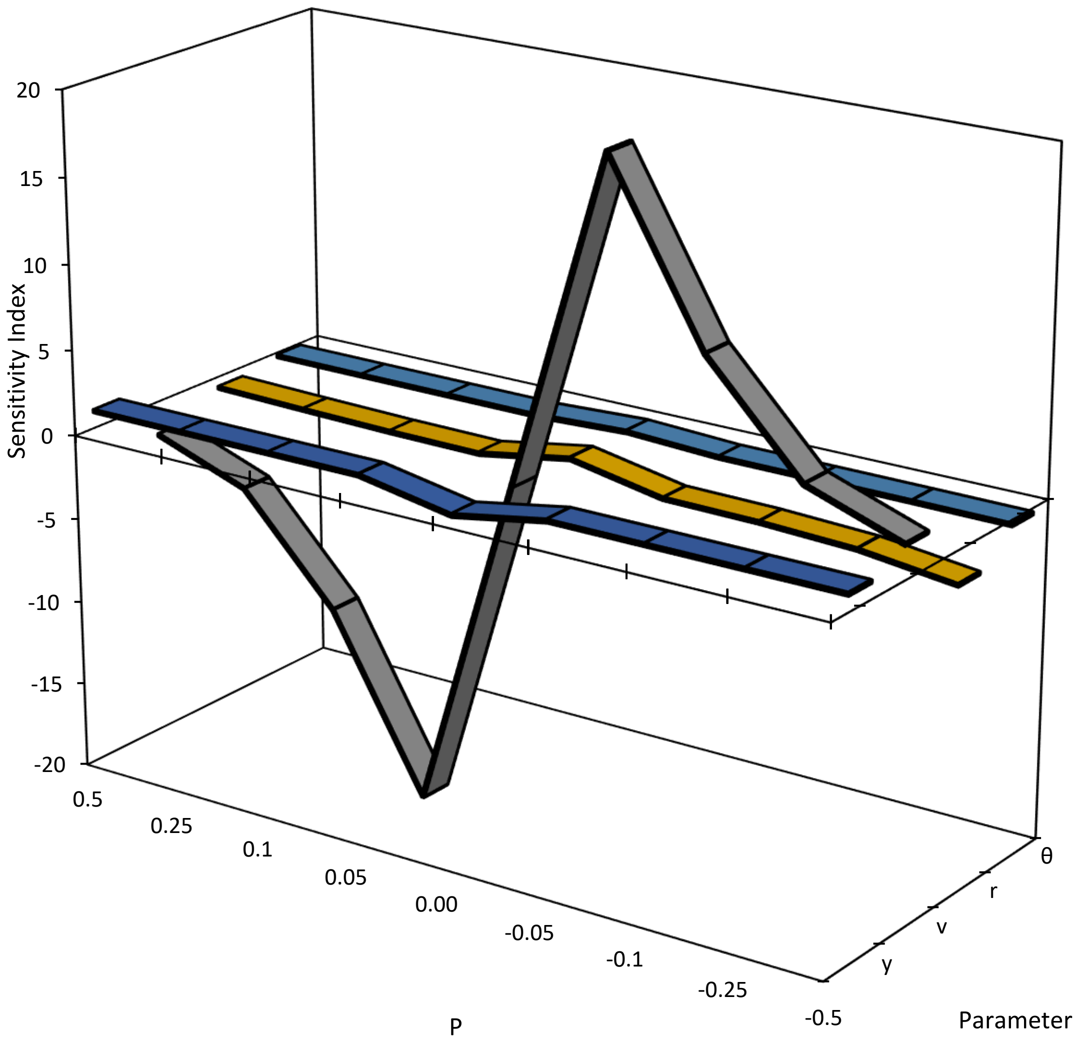

Figure 3.2. Sensitivity analysis of each parameter upon estimated density using the Random Encounter Method. The original parameter values were varied between ± 0.05, 0.1, 0.25, and 0.5 (axis labelled p) of their original value. Y is the camera trapping events, v is the average daily speed of movement, r is the detection range of the cameras, and **θ** is the cameras' angle of detection (in radians).

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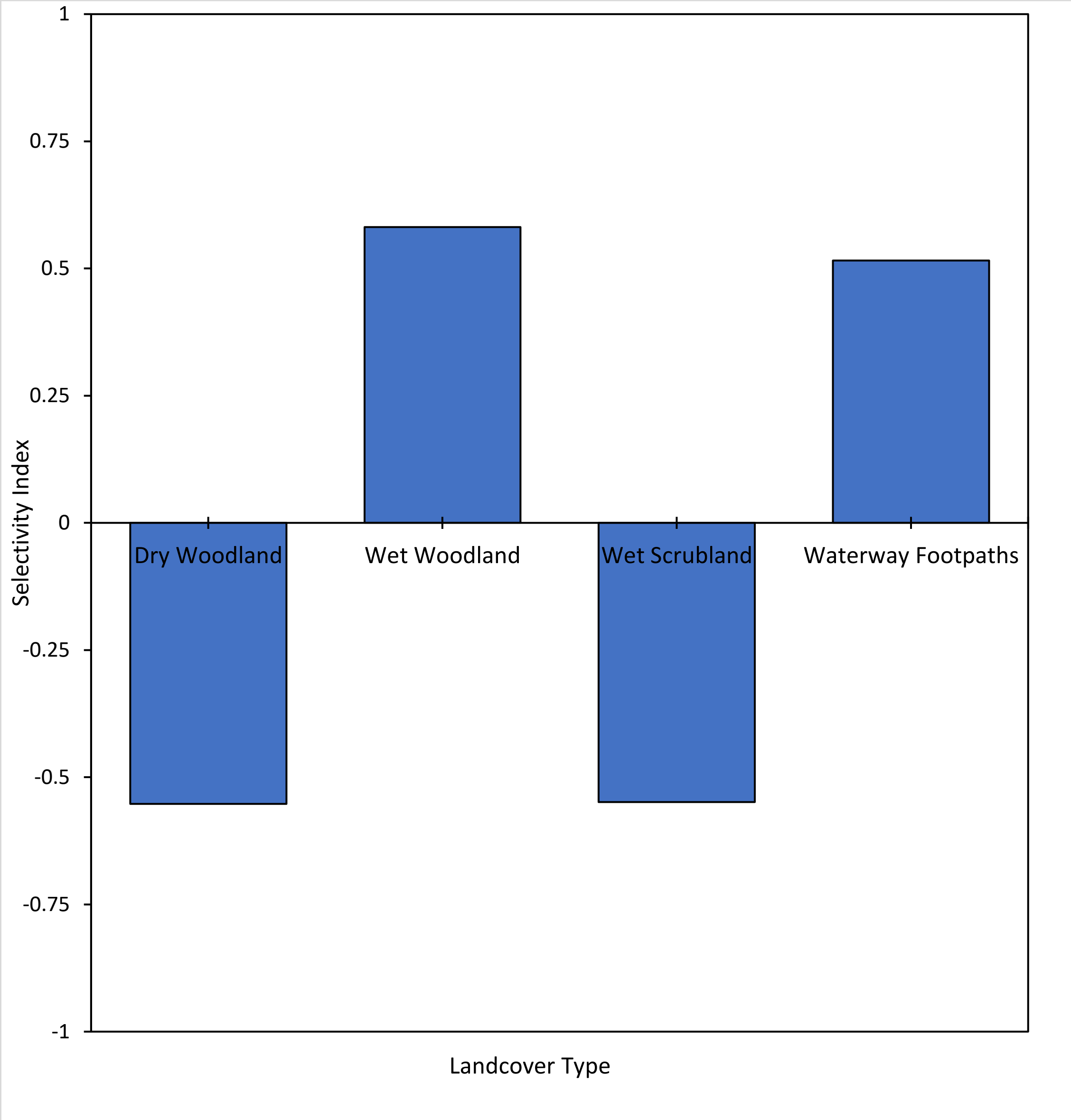

Figure 3.3. The selectivity analysis of the usage of landcover types by red deer on Thorne Moors. Positive values are areas the deer use more relative to their availability, whilst negative values are landcover types used less relative to their availability.

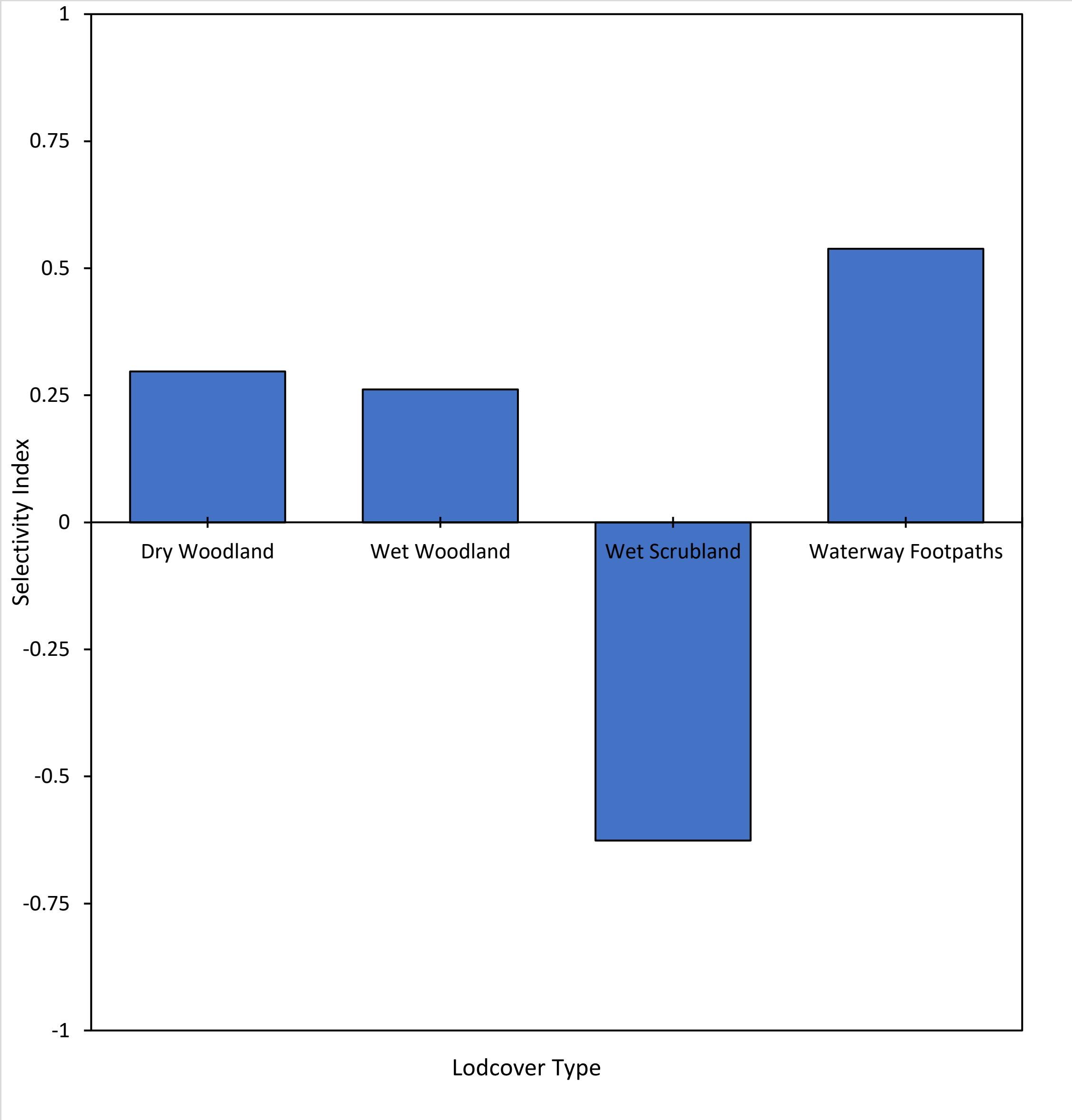

Figure 3.4. The selectivity analysis of the usage of landcover types by roe deer on Thorne Moors. Positive values are areas the deer use more relative to their availability, whilst negative values are landcover types used less relative to their availability.

3.4. Discussion

This study has provided the most accurate estimates of deer populations seen on Thorne Moors to date. The current methods of estimating the population of deer utilised in unison between the local farmers and Natural England are to drive around the site, on the agricultural land, with thermal imagers counting how many deer they spot, as well as unified observations from outside the moors, observing towards the boundary woodlands for measurement. It is estimated by the group that there were approximately 150-175 red deer detected, and approximately 40 roe deer (D Hinchliffe, Pers. Comm.). The estimate of 175 red deer from this local group is significantly less than the 322 (average) red deer estimated in this study, whilst the 40 roe deer from the DMG is close to the 61 (average) estimated in this study.

Thorne Moors is a site with an area of $19km^2$ and a red deer population density of $17km^{-2}$. Comparing this population to the red deer on the Isle of Rhum (an island with an area of $12km^2$), where the deer are at a density of $18km^{-2}$ (Clutton-Brock, *et al*., 1986) there is a clear consistency in the population density of a closed environment. Conversely, a red deer study across $14km^2$ in Spain registered deer density to be up to $60km^{-2}$ (Acevedo, *et al*., 2008). The study in Spain was performed in an open environment with no boundary restrictions from a lack of habitat (or otherwise) whilst the study on Rhum provides an environment with some similar qualities to that of Thorne Moors – the population is isolated and incapable of leaving the area (beyond feeding upon farmers crops). By identifying a similar density of red deer between the two sites, and Rhum being an island smaller than Thorne Moors by $7km^2$, this appears to be an estimate that sits within similar studies. The density of deer of Thorne Moors is likely kept to the size it is currently at by the active management performed by deer stalkers on the periphery of the moors There are also natural levels of mortality throughout the winter which would maintain consistent population over the course of a year – recognised by the principle investigator who encounter skeletons and corpses of deer (that died from natural causes) throughout the study. Throughout the rest of the year, the deer are most likely sustaining themselves throughout the legal closed season (The Deer Act 1991) from the crops the farmers grow (Chapter 2).

For this study, it was impossible to provide an abundance estimate for muntjac on Thorne Moors due to a lack of camera trapping data. This does not confirm the absence of muntjac, instead it demonstrates a lack of detection by the trail cameras used in this study. In total, 5 individual muntjac deer (3 bucks and 2 does between November 2017 and April 2018) were observed across multiple areas of the moors; confirming a low-density population. The lack of trail camera detection events on this species could imply a limitation of this study derived directly from the effectiveness (and accuracy) of the trail camera placements. If, for example, cameras were placed too high for muntjac to trigger the camera then that may explain the lack of detections. However, as the placement height of this study was consistent with that of Rowcliffe, *et al*. (2008) during their study, which included muntjac. Therefore, this is an unlikely limitation of this study; though this should be further evaluated.

The REM density estimates were produced based on the assumptions that animals move randomly and independently of each other. The assumptions of random movement independent of others (Rowcliffe, *et al*., 2008) is unrealistic with gregarious ungulate species (Clutton-Brock, *et al*., 1982; Georgii & Schroder, 1983; Geist, 1998). Therefore, by multiplying the density estimate produced by

REM (Eqn 3.1.) by the average group size of the species, the assumption of random, independent, movement is then placed at the group level, rather than at the level of individuals.

The abundance estimate of a specific site is estimated under the assumption of a closed population. This provides a snapshot of the site, assuming there is no migration of the animals, and no recruitment/death (Rowcliffe, *et al*., 2008). However, this snapshot from REM fails to measure variance of other factors that may hold relevance to the population estimates – such as time taken to perform the surveys. With the seasonal behaviours of deer, such as rut and parturition (Reby & McComb, 2003), and the legal close season (The Deer Act 1991) being predictable events, it should be a priority to perform studies during times that avoid peaks of mortality and recruitment. There should also be a concerted effort to perform a camera trapping schedule as fast as possible to reduce variance of the data (Roberts, 2011). By selecting a time of year away from peak mortality/recruitment, and by performing surveys quickly (in this case through more cameras to deploy), the surveyor would gain more accurate estimations than that obtained in this study from a six-month camera trapping schedule with limited cameras available.

The estimate produced by REM was strongly influenced by the value given to the parameter v. Thus, it is important to use an accurate estimate of v for an accurate estimate of population size. To ensure the estimates are as accurate as they can be, further study will be required on the deer of Thorne Moors to calculate their average daily speed of movement per species.

An additional function of this chapter was to develop a method of evaluating habitat use across the whole site despite limited camera availability. The decision to use (approximately) fortnightly camera deployments offered a good balance between widespread coverage, continuous sampling of each landcover type, and numbers of detections per camera. The creation of such a distribution schedule for a large site (such as Thorne Moors) is evidently important when observing species that express seasonal variations of behaviour. Deploying cameras in neighbouring cells of a grid and then shifting the block of cameras across the grid over time to cover the site, as used by Rowcliffe *et al*. (2008), would risk either underestimating or overestimating the abundances of deer should they have seasonal habitat selection on the moors that either were opposite to or coincide with camera deployments. The method used in this study covers a broader scale of the site per camera distribution reduced the risk of inaccurate estimations resulting from seasonal behaviours.

3.5. Conclusion

To conclude, there was a large estimated population of red deer residing on Thorne Moors, with an absolute minimum population of 217 red deer comprising a single group detecting during chapter 4. This population estimate exceeded all previous estimates and population counts performed by the local Deer Management Group on the moors. Thus, an inconsistency in approach towards previous attempts to estimate abundance is evident, therefore further study upon the site is required to estimate changes over time.

There were also a modest number of roe deer on site, living in low densities. Low density populations of roe deer are common in areas with dense populations of large herding ungulates such as red deer (Jiang, *et al*., 2008; Acevedo, *et al*., 2010) so this population density was to be expected. There were very few muntjac deer living on Thorne Moors, residing at very low densities.

It is evident from the results of the sensitivity analysis that the random encounter method is most influenced by the parameter ‘v’ (average daily speed of movement). This demonstrated the importance of getting this information right for using REM on this data set.

The random encounter model produced credible estimates of population abundance for this study. However, further work on the average daily speed of movement of the deer of Thorne Moors, using GPS radio collars fitted to both red and roe deer, may improve estimate accuracy.

3.6. Summary

The act of estimating the abundance of wildlife populations is important for measuring the health of the environment and to generate plans for improving both the success of specific wildlife populations and maximising biodiversity. There are multiple methods available to measure species abundance; including faecal counts, distance sampling, capture re-capture, and trail camera measurements. The method utilised by this study required the use of trail cameras. The method selected, the random encounter model (REM), is relatively new and offers greater flexibility then has previously been realised. Here, a new methodology of camera trap distribution was developed (the roaming camera grid) to estimate population abundance and evaluate seasonal habitat selection.

The REM (Eqn 3.1.) functions by analysing trapping rate with independently gathered biological and mechanical parameters to produce estimates of animal density. The sensitivity of density estimates to these parameters was analysed and identified the average daily speed of movement of animals as the most sensitive parameter. An estimate of density was not produced for muntjac deer as none were detected by camera, however this does not therefore reveal an absence of muntjac on site; 5 muntjac were positively observed during the study. Using the REM an abundance range for both red deer and roe deer was produced; between 311 and 333 red deer, and between 59 and 63 roe deer. To improve estimate accuracy, further work is required on the average daily speed of movement of animals within this population.

Chapter 4.

Daytime Detection of British Native Deer

4.1. **Introduction**

Effective and accurate detection of large mammals is essential for surveying purposes. The reliability of detection of species are required for indexing surveys (high population detection with low variation in detection probability); and abundance surveys require data on the proportion detected. When surveying a highly cryptic species, such as deer, the difficulty of detection is highly evident (Gill, *et al*., 1997; Smart, *et al*., 2004); and is made especially difficult when the animals in question engage in nocturnal and crepuscular activity (Geist, 1998). These difficulties exist with many species including (but not limited to): deer, the European hare *Lepus europaeus* (Petrovan, *et al*., 2011), European badgers *Meles meles* (Shepherdson, *et al*., 1990), and the red fox *Vulpes vulpes* (Lovari, *et al*., 1994). Petrovan *et al*. (2011) demonstrated the difficulties posed for detection by cryptic, nocturnal species. With low detectability rates, the estimated proportion (as opposed to the detected proportion) of the population was large, increasing the estimate uncertainty and therefore making informed decision making for conservation very challenging. This impact on detection probability was further supported by Legg and Nagy (2006) who described the ineffectiveness of most examples of animal monitoring due to poor detection rates of cryptic animals. The detected proportions in those studies lead to high uncertainty levels in estimates (Legg & Nagy, 2006; Petrovan, *et al*., 2011).

The lack of effective detection has led to inaccurate information being used to inform policy and decision makers on the priorities for conservation science (Legg & Nagy, 2006). This can be detrimental to the populations of species present when considering the possibilities of animal culls or the priorities for specific environmental protections. Field *et al*. (2007) concurred: a lack of effective detection in the field reduces the effectiveness of data collection, reducing the accuracy of estimates and therefore acts as a hindrance to bridge the gaps between research and policy making.

Deer are a highly cryptic, and predominantly crepuscular, group of species, displaying high levels of behavioural plasticity with regards to the time of day they are most active (Geist, 1998). This plasticity comes as a direct response to environments where predators, or major disturbances (including human disturbances), are present (Connell, 1978; Latham, *et al*., 1999; Benhaiem, *et al*., 2008; Jiang, *et al*., 2008; Bonnot, *et al*., 2017). During times of high disturbance, deer will move towards a behavioural pattern which avoids the times of day to which the disturbances occur as much as possible. However, during times of low disturbances deer have been recorded to express more diurnal behaviours (Georgii, 1981; Geist, 1998; Clutton-Brock, *et al*., 1982; Jiang, *et al*., 2008). The crepuscular/nocturnal activity combined with the highly cryptic nature of deer can make population control particularly challenging.

Under the Deer Act 1991 no deer may be shot between the hours of one hour after sunset until one hour before sun rise. Without effective detection rates, the risk of highly uncertain estimates and inconsistent detectability is increased, therefore improving the detection rates of deer has become a priority in Britain. Multiple studies using thermal imagers to detect wild ungulates have been performed over the last 4 decades, and the limitations regularly cited the studies have included the overall cost of the equipment used, lack of clarity of images (in earlier studies). From these studies, there has been reliance on the use of aircraft for study (Naugle, *et al*., 1996; Dunn, *et al*., 2002; Collier, *et al*., 2011; Chrétien, *et al*., 2016), nocturnal studies on foot (Butler, *et al*., 2006; La Morgia, *et al*., 2015), and inconsistent approaches towards the hours of daytime active, including both daylight and twilight, to be active (Naugle, *et al*., 1996); and therefore not accounting appropriately for data variance.

The key aim of this chapter was to compare a method of detecting deer in the landscape during the daytime hours (as described by the Deer Act 1991) using a thermal imager, with the more traditional use of binoculars. This chapter also aimed to provide accurate information on the best times of day to maximise deer detection.

This study hypothesised that there would be a significant increase in the detection rates of deer using a thermal imager over the use of binoculars. This is consistent with the increased detections of mammals and ungulates across multiple sources (Boonstra, *et al*., 1994; Butler, *et al*., 2006; Franke, *et al*., 2012) – although there have been limitations in thick woodland environments (Haroldson, *et al*., 2003; Witczuk, *et al*., 2018). This study further hypothesised that the detection rates of deer would be significantly increased during the twilight hours of daytime over the daylight hours. This is consistent with the behavioural ecology of deer, which are a crepuscular species that express variations in activity times. These variations of activity times can be a switch towards either diurnal or nocturnal activity patterns, which is commonly influenced by the risk of predation (Mitchell, *et al*., 1977; Georgii & Schroder, 1983; Chapman, *et al*., 1993; Benhaiem, *et al*., 2008; Jiang, *et al*., 2008).

4.2. **Materials and Methodology**

The equipment used for this study was a pair of 10x50 binoculars (SkyGenius, Massachusetts, USA; https://skygenius.cc/), and a FLIR BHS-XR hand-held thermal imager (FLIR Systems, Inc., Oregon, USA; http://www.flir.co.uk/home/). The binocular specification was similar to those commonly used by deer stalkers around the study site.

The thermal imager used was deliberately old (newer models offer much greater thermal discrimination), using a 5x optical zoom, and was easily portable, using a changeable function of white and black for hot indicators used in detection (Figure 4.3.). This model of thermal imager was selected for the study in order to provide a minimum level of performance, lower than what might be expected from more modern equipment that is nevertheless available to the average UK deer stalker.

Transects were surveyed across Thorne Moors using binoculars or the thermal imager from the 21st February to the 14th March 2018. The decision as to whether the thermal imager or binoculars would be used first per transect was taken via a toss of a coin on the night before the surveys. The transects were then re-surveyed on a subsequent day using the other piece of equipment.

Each transect constituted a straight line of up to 0.5km in length, usually along existing tracks and footpaths. A single surveyor walked all transects to maintain consistency in sampling, and the imaging equipment selected was used to search for deer. Each group of deer (defined as one or more deer), the number per group, and the species detected was recorded on a data sheet.

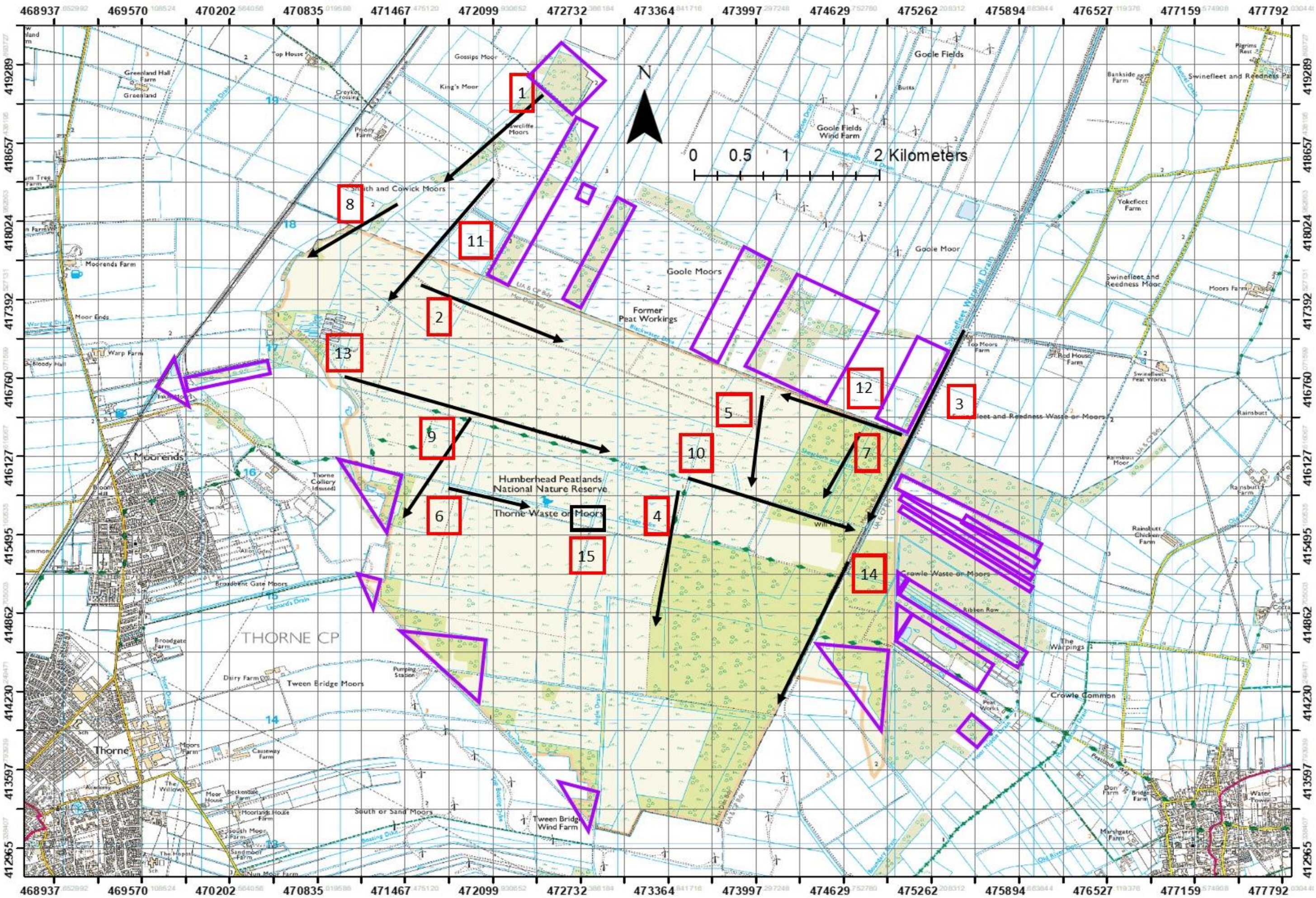

Figure 4.1. Map of Thorne moors showing the pre-determined transects (black arrows) for the detection rates study. The red boxes are numbered to show the order in which each transect was surveyed. The purple outlined polygons are the areas of the Moors not owned by either Natural England or Lincolnshire Wildlife Trust - however the black box with number 15 is a static high platform used to survey.

When selecting the next transect to use, the investigator had pre-determined, numbered, routes with a specific order in which to complete them. This ensured that the routes used were far enough apart that there was a low risk of the animals moving from one transect to count them again in the neighbouring transect (Figure 4.1.). By selecting a sequential system of transects the risk of double-counting deer, by keeping transects independent of each other, was reduced.

The surveys were performed between the hours of 05:25 – 19:05 and were conducted on each transect during the hours of daylight (between sunrise and sunset) and during twilight (up to 1 hour before sunrise and up to 1 hour after sunset) to be consistent with the definition of daytime given in the Deer Act 1991. Therefore, the total surveys performed were two separate surveys upon each transect during the daytime, and two separate surveys performed upon each transect during the twilight. The pairs of surveys per transect were separated by at least two days, as were the usage of both pieces of detection equipment upon the transect. Surveys (60 surveys) were then repeated to increase sample size.

4.2.1. **Statistical Analyses**

To compare the detection rates of deer between detection methods and times of day, generalised linear models (GLzM) were used (Zuur, *et al*., 2007). GLzMs are designed to evaluate the effects of multiple variables and factors simultaneously on a dependent variable.

The data gathered for analysis were hierarchically structured (survey within transect) count data (numbers detected per transect). The type of model fitted was therefore a Poisson loglinear model with surveys nested within the transect.

Separate models were constructed for each species (red and roe deer) and summarising detections as number of groups per transect and number of individuals per transect. The predictors used to build the models were the time of day observations took place, and the detection equipment used; this was divided into the categories of Twi/Day and Bin/TI. Twi is twilight (the hour prior to sunrise, and the hour following sunset), Day is the hours of daylight (the time between sunrise and sunset), Bin is binoculars, and TI is thermal imager.

The full model comprised of main effects and the 2-way interaction. Models comprising each main effect were also fitted individually. These tests were then reported with the test statistic, degrees of freedom, and Akaike's Information Criterion (AIC). Models with only significant terms and the lowest AIC scores were selected for interpretation (Appendix). All statistical analyses for this chapter were performed in IBM SPSS Statistics 24.

4.3. Results

4.3.1. Data Summary

A total of fifteen transects, between 200m (such as Will Pits' woodland (Figure 4.1. – point 7)), and 500m (the Limestone Road (Figure 4.1. – point 13)) were surveyed. Each transect was walked four times (twice with the thermal imager, twice with the binoculars) during the hours of daylight and four times during twilight. The median and range of group sizes of both deer species (Table 4.1.) was calculated due to the data being skewed to the left. These group size ranges demonstrated a clear variation of gregarious behaviours expressed by red deer during different times of the day. The data collected (Table 4.2.) were divided between individual and group detection rates and by the equipment used to detect them.

Table 4.1. Summary of group sizes for the deer of Thorne Moors, divided between time of day seen (daytime and twilight) and species of deer. The data were highly skewed and therefore the median is reported with the range (from minimum to maximum) in brackets and the number of sightings with an asterisk. These groups were observed with both binoculars and a thermal imager.

	Red	Roe
Daytime	6 (6-6) *2	1 (1-4) *11
Twilight	22 (6-187) *19	2 (1-8) *37

Table 4.2. Summary of the detections of deer on Thorne Moors. This is divided between groups and individuals of each species, and the detection equipment used to detect them.

	Red Deer		Roe Deer		Total Deer	
Detection Equipment	**Groups**	**Individuals**	**Groups**	**Individuals**	**Groups**	**Individuals**
Thermal Imager	13	336	36	46	49	382
Binoculars	8	127	12	16	20	143
Total	21	463	48	62	69	525

4.3.2. **Daytime Detection Rates**

4.3.2.1. All Deer

Group encounter rates across both species of deer were significantly affected by the explanatory variables (omnibus test: Likelihood Ratio Chi-Square = 35.779; df = 2; p = < 0.001 (Figure 4.2.)). The total number of deer groups detected was significantly higher (from both explanatory variables) with the use of the thermal imager in comparison to binoculars (Wald Chi-Square = 9.608; df = 1; p = 0.002; AIC = 220.282). The total number of deer detected significantly affected by the explanatory variables (omnibus test: Likelihood Ratio Chi-Square = 601.708; df = 2; p = < 0.001). The total number of deer detected was significantly higher (from both explanatory variables) using the thermal imager over binoculars (Wald Chi-Square = 88.631; df = 1; p = < 0.001; AIC = 1996.145). There was a significant increase in detection events (from both explanatory variables) during the twilight hours of the day, as compared to the daytime hours; both as groups (Wald Chi-Square = 19.609; df = 1; p= < 0.001), and as individuals (Wald Chi-Square = 200.744; df = 1; p = < 0.001).

4.3.2.2. Red Deer

Group encounter rates of red deer were significantly affected by the explanatory variables (omnibus test: Likelihood Ratio Chi-Square = 15.764; df = 2; p = < 0.001 (Figure 4.2.)). The total number of red deer groups detected was insignificantly higher (from both explanatory variables) with the use of the thermal imager in comparison to binoculars (Wald Chi-Square = 9.911; df = 1; p = 0.34; AIC = 114.56). The total number of red deer detected was significantly affected by the explanatory variables (omnibus test: Likelihood Ratio Chi-Square = 588.195; df = 2; p = < 0.001). The total number of deer detected was significantly higher (from both explanatory variables) using the thermal imager over binoculars (Wald Chi-Square = 76.663; df = 1; p = < 0.001; AIC = 2092.233). There was a distinct difference in median group sizes of red deer between the twilight and daytime categories (Table 4.1.). This suggests that the increased number of red deer detected using the thermal imager is a result of the larger group sizes during the time of day with lowest visibility (i.e. twilight). That idea is supported with the red deer of Thorne Moors being significantly more detectable (from both explanatory variables) during the twilight hours; both as groups (Wald Chi-Square = 8.600; df = 1; p= 0.003) and as individuals (Wald Chi-Square = 147.206; df = 1; 0 = < 0.001).

4.3.2.3. Roe Deer

Group encounter rates of roe deer were significantly affected by the explanatory variables (omnibus test: Likelihood Ratio Chi-Square = 23.126; df = 2; p = < 0.001 (Figure 4.2.)). The total number of roe deer groups detected was significantly higher (from both explanatory variables) with the use of the thermal imager in comparison to binoculars (Wald Chi-Square = 9.346; df = 1; p = 0.001; AIC = 182.74). The total number of deer detected significantly affected by the explanatory variables (omnibus test: Likelihood Ratio Chi-Square = 36.31; df = 2; p = < 0.001). The total number of roe deer detected was significantly higher (from both explanatory variables) using the thermal imager over binoculars (Wald Chi-Square = 12.007; df = 1; p = < 0.001; AIC = 229.396). There was a significant increase in detection events (from both explanatory variables) during the twilight hours of the day, as compared to the daytime hours; both as groups (Wald Chi-Square = 10.314; df = 1; $p = 0.002$), and as individuals (Wald Chi-Square = 17.587; df = 1; $p = < 0.001$).

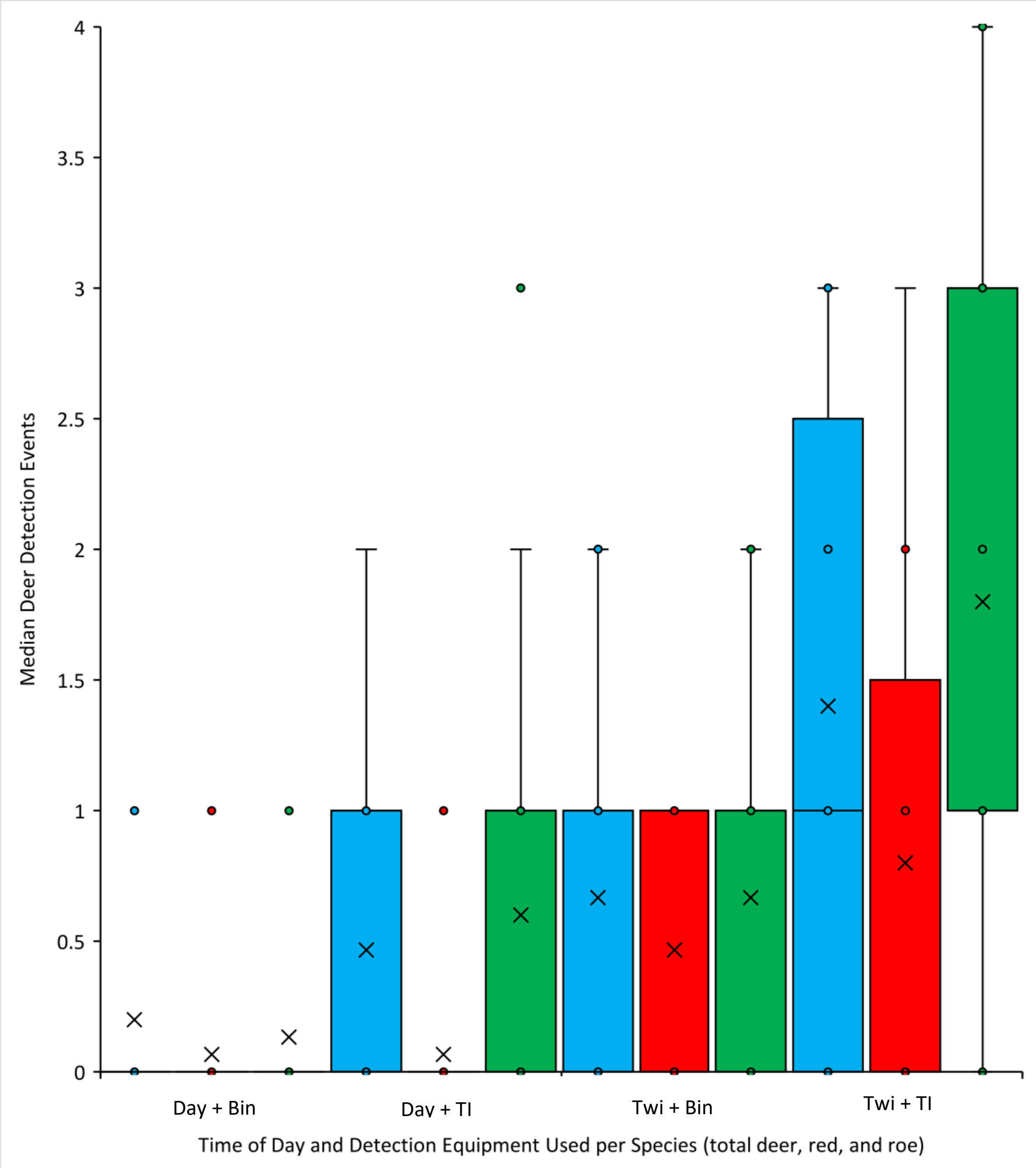

Figure 4.2. Box plot showing median (x), 75% quartile (box) and 90% quartile (whiskers) of deer detection events. Blue plots are for total deer detection, red boxes are for red deer detections, and green are for roe deer detections. The four detection conditions are: Day (hours of daylight), Twi (hours of twilight), Bin (binoculars), and TI (thermal imagers).

4.4. **Discussion**

The results above show that red and roe deer were significantly more detectable during the twilight hours of each day. There is also significance in increased detection rate (during both the twilight and daytime hours) from the use of thermal imagers over using binoculars for each of the categories of: roe deer (groups and total detected), red deer (total detected) and total deer (groups and total detected). However, the number of red deer group detections were not significantly different using a thermal imager or binoculars; though they were detected significantly more during twilight. The group sizes of red deer were larger during the twilight hours over the hours of daylight (Table 4.1.), which probably explains the reduced group detection rate at twilight. These crepuscular to nocturnal activity patterns is consistent with the work of Jiang *et al*. (2008) whom concluded a preference to activity during twilight and night time. The variation in group sizes of red deer across different times of the day is further supported by Mitchell *et al*. (1977) whom reported increased group sizes during the twilight and night time when compared to the daylight hours. Therefore, the lack of significant difference in group detection rates suggests that the twilight detections represented a higher proportion of the red deer herds, and hence detected a larger proportion of the total red deer population.

The results have further demonstrated a significant increase in the detection rates of deer, using a thermal imager over binoculars. Across all three deer classifications (total deer, roe deer, and red deer) there was a significant increase in the number of deer detected during the twilight hours as compared to the hours of daylight. The results above indicate it is likely that the variation in gregarious behaviours of the deer species studied has a significant impact on the number of group detection events. The results also indicated that the times of day at which deer are likely to be most active significantly affects the detection probability of deer (Latham, *et al*., 1999; Legg & Nagy, 2006).

Previous studies performed by Butler *et al*. (2006) and La Morgia, *et al*. (2015) were all focussed upon studying deer during the night time with thermal imagers. Those times were selected as it was considered that daytime surveys using the thermal imager would be ineffective. This chapter has demonstrated that night time surveys are not the only way to affectively monitor deer. The study by Naugle *et al*. (1996) utilised an aircraft during inconsistent hours spanning between 12:00 and 18:00 during the winter months of the northern hemisphere. Therefore, the data collected in that study would have been skewed from inconsistency when considering deer activity times. The study's performed by Naugle, *et al*. (1996), Dunn, *et al*. (2002), Collier, *et al*. (2011), and Chrétien, *et al*. (2016) were all reliant upon the use of aircraft over quick time surveys, following long transects of several kilometres. These surveys all encountered difficulties in thermal imaging through dense vegetation (such as woodland) with the brief time spent over the top and the restricted view through the woodland canopy. This study has demonstrated that a portable, hand-held thermal imager is capable of detecting deer through dense vegetation – although the thermal imager is limited in usage when the view is obstructed.

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Figure 4.3. Two images of deer through the thermal imagers. The top image is a large herd of red deer at approximately 350-400m on a farmers field; using black as the hot indicator. The bottom image shows three red deer hinds approximately 40m away in dense vegetation; this image used white as the hot indicator. Photo credit: Thomas Logan, with permission.

Within this study, the highest numbers of detections were identified during the twilight hours of the day for both species of deer. This is in keeping with the crepuscular behavioural patterns recorded in all deer species throughout multiple previous studies. Behavioural adaptations away from crepuscular/diurnal activity patterns towards crepuscular/nocturnal activity is regularly recorded in areas of high predation pressure (Geist, 1998; Jiang, *et al*., 2008). Deer are prey species, expressing plasticity in vigilance behaviours for predator avoidance. Each species demonstrates some variation in their reactions to predation pressures – such as red deer adjusting the locations of where they feed, and both red and roe changing their daily activity patterns to avoid the time of day their predators are active (Geist, 1998; Okarma, *et al*., 1997; Hewison, *et al*., 2001; Odden, *et al*., 2006; Nilsen, *et al*., 2007; Benhaiem, *et al*., 2008; Ferretti, *et al*., 2008; Jiang, *et al*., 2008; Bonnot, *et al*., 2017). The rate of disturbance upon the deer by hunting pressure from people may have led to higher vigilance behaviours in the deer. With the smaller roe deer expressing lower levels of gregarious behaviour, it would likely be harder to detect the animal in the environment with binoculars compared to a thermal imager; whilst large deer whom are highly gregarious are easily spotted with binoculars.

With the rate of disturbance to deer significantly increasing (with increased human activity and hunting pressures) outside the legal close season, deer are rarely sighted during daytime (Geist, 1998; Benhaiem, *et al*., 2008; Ferretti, *et al*., 2008; Jiang, *et al*., 2008; Bonnot, *et al*., 2017). These studies findings were consistent with the results of this study, which identified the deer as significantly more detectable outside the hours of daylight. However, further study occurring during the legal close season would be required to measure the activity patterns of deer during the daylight hours under reduced disturbance. The detection rates of this study, combined with work demonstrating deer activity and behavioural adaptations, suggests that the deer were using the cover of darkness to safely express their gregarious behaviours and used this time for foraging (Latham, *et al.*, 1999). This implies that the increased mortality rates, and subsequent stresses, experienced by deer during the open season (when this study took place) may have affected the times when the deer are most active.

4.5. Conclusion

In conclusion, this study has demonstrated that a thermal imager is a significantly more affective equipment at detecting the presence of these deer when compared to binoculars; and that detection of these deer is increased during the twilight hours. The use of a thermal imager significantly increased the rate of detection of all deer combined, individual roe deer, and individual red deer seen but not red deer groups. There was also significant increases in the detection rates of deer during the twilight hours surveyed. This knowledge of detection variability could help to improve the methods used by industry professionals in carrying out their duties of surveying deer (or culling them). This would assist by improving the accuracy of their detections and assisting in identifying the locations where deer are present.

The aim of the study was to provide an effective methodology for the development of effective deer surveys. This method should also be used in assisting the development of management plans for deer in their respective environments and landscapes. The deer stalkers would likely gain a significant advantage in terms of deer detections by using a thermal imager during the hours before they are legally allowed to shoot in order to avoid areas of low deer activity. Improved deer detection rates avoid the risk of time-wasting waiting in a high seat (or stalking) in an area of limited deer activity on the day. This is important for deer management with the female open season operating during the winter months where days are at their shortest. During the season effective visibility can also be at its lowest from fog/mist around the twilight hours. Improving the detection of wild deer from thermal imagers would counter the problems created by the winter season; therefore, increasing the efficiency of wildlife managers in performing effective culls.

4.6. **Summary**

The effective detection of animals is vital to any management programme and ecological survey. Detection rates of any animal are required to be as accurate as possible, especially so when such surveys are used to assist in developing management plans. By using both a thermal imager and binoculars, this experiment functioned to create a direct comparison of this equipment in terms of their utility for the detection of deer during the daytime; defined as an hour pre-dawn to an hour post-sunset by the Deer Act 1991.

The results of the study demonstrated that when using a thermal imager in comparison with binoculars, there was a significant increase in the detection of all deer, roe deer and numbers of red deer (p = <0.05). However, there was no significant difference in the detection of red deer groups (p = >0.05). The results further indicated that deer had a significantly higher detection rate during the twilight hours than during the hours of daylight (p = <0.05).

Red deer are highly gregarious, whilst roe deer live solitary/in small groups. The difference in detection rate using a thermal imager and binoculars varied between the two species, and this may have been associated with differences in gregariousness. This may further correlate with the more cryptic nature of the two species; with roe deer being more cryptic than red deer.

Therefore, this chapter demonstrated that the deer are easier to detect using thermal imagers instead of binoculars and are most detectable during the twilight. This knowledge may help develop improved survey designs for deer, more reliable interpretation of citizen science data on deer collected during the daytime and may help deer managers more efficiently monitor and target deer during control programmes.

Chapter 5.

Discussion: The Detection and Quantification of Deer Populations for Impact Management on Thorne Moors

5.1. Introduction

The environmental impact levels associated with deer are regularly attributed to the population density of deer to the environment they reside within (DeCalesta, 2017; Russell, *et al*., 2017). The impacts of deer upon the environment include bark stripping, fraying, and over-browsing vegetation; these negative impacts directly affect biodiversity (Mills, *et al*., 1993; Cooke, 2009). The aim of this project was to quantify the activity and impact levels of deer upon the study site, to quantify the abundance and densities of the deer species residing there, and to evaluate a method of detecting deer on the site. Thorne moors is designated as a SSSI for the animals and plants found on the site (Natural England, 1986; Natural England, 2017) but is also surrounded by arable farmland, which could be adversely impacted by the presence of deer from excessive browsing and trampling damage; an impact common with high density deer populations in an agricultural landscape (Langbein, 1997; Latham, *et al*., 1999; Kirby, 2001; Cooke, 2007; Cooke, 2009). The two species established on site are the two native deer species found in Britain (red and roe); with roe having been present on Thorne Moors for longer than living memory, whilst red deer were first recorded on site in the 1960s (D. Hinchliffe, pers. Comm.). With the median activity and impact results on site showing significant abundance of both, the estimated population sizes for each species and daytime detection rates would both be of benefit to the local landowners. This information would assist in creating targets for both responsible and sustainable management of the deer to meet the objectives of both the NNR and other stakeholders.

5.2. Management of the deer of Thorne Moors

The estimates of deer population size on Thorne Moors (Chapter 3) cannot be used alone to assess whether there are "too many" deer on site (Barlow, *et al*., 1997). However, the results of the activity and impact surveys (High and Moderate-High respectively) suggest that deer are at too high a density for the resources available upon the moors. Combining the estimated density of deer with the activity and impact levels on the moors implies that a red deer density of $17km^{-2}$ (Table 3.1.) was too high for Thorne Moors. The population abundance estimate would assist in the generation of cull targets to be met by the local wildlife managers to meet the objectives of the landowners (Barlow, *et al*., 1997). Using the target of culling utilised by the Thorne Moors DMG during the 2017/18 season (one half of the females), and the assumption of 1.5-2 females per male in red deer herds (Clutton-Brock & Lonergan, 1994), a target of culling between 102-110 red hinds would be appropriate. In this study, both the activity and impact scores and the population density/abundance estimates are uncalibrated, increasing the risk of the results not being accurate. Therefore, the cull would require a culling effort 33% above 110 hinds (to decrease population) or below 102 hinds (to increase population). The DMG's seasonal target focussing upon culling the females for population control is consistent with the strategies regularly formulated on estates in Scotland and other parts of the UK (MacMillan & Leitch, 2008). By estimating the population density before culls (and continued monitoring of activity and impact levels), a collation of data could eventually be used to generate density estimates that maximise biodiversity within the environment better utilise the environmental benefits of deer as a keystone species (Nielsen, *et al*., 1997; Jordan, *et al*., 2007).

With deer only legally being allowed to be culled 1 hour before dawn to 1 hour after sunset outside the legal close season, the improved detection of deer during this period could help deliver the cull more efficiently. The daytime detection surveys (Chapter 4) demonstrated the benefits of thermal imagers in detecting deer, clearly indicating that twilight (the shortest time available to deer stalkers) was the time of day when more deer could be observed. The knowledge of the best time of day to be active, and both identifying and not identifying deer in the landscape where they have been preparing to stalk deer, would improve the efficiency of deer stalkers (Boonstra, *et al*., 1994; Gill, *et al*., 1997; Ditchkoff, *et al*., 2005). This would be achieved by stalkers using the thermal imagers to identify whether deer are present in the environment prior to the daytime hours described by the Deer Act 1991. If deer were not identified, then the deer stalkers would know to move areas until they detect deer; they would then set up and prepare to shoot once they are within the legal hours to do so. Therefore, utilising the activity and impact levels as an environmental indicator (Stout, 1997), deer abundance estimates to produce cull targets (Ratcliffe, 1984), and knowledge of deer detection, this report would assist in strategising deer management (Barlow, *et al*., 1997).

The selectivity analysis performed in Chapter 3 showed the areas of the moors selected for and against by both deer species (Jacobs, 1974). By combining the output of the selectivity indices and the median red deer group sizes (per camera per landcover type; Table 3.3.), site managers could identify locations where they could most profitably concentrate their efforts for conserving the environment. Should active management of deer on the moors become implemented, the results of the selectivity analysis would become a useful tool for assisting the success of culls by demonstrating the areas where deer are most likely to be found. The positive discrimination by red deer towards the “Waterway Footpaths”, plus the large group sizes that congregated there mean that these would be logical locations to focus initial efforts. However, safe culling of deer might be too challenging here, as water does not provide a safe backstop for a bullet. Therefore, with knowledge of where the deer congregate upon the moors and that these waterway footpaths connect habitat patches together, it becomes clear as to where active management should be concentrated (should active management be permitted on site).

5.3. Deer Activity and Impact levels upon the moors

Chapter 2 identified that the median deer activity and impact levels were High and Moderate-High respectively, but impacts were not uniformly distributed across the site. The Jacob's selectivity analysis of camera trapping data (Chapter 3) demonstrated that both the red and roe deer actively discriminate against using wet scrubland (Figure 3.3. and Figure 3.4.). Avoidance of wet scrubland is consistent with the behavioural ecology of both red and roe deer whom are specialists in temperate forest/woodlands (Chapman, *et al*., 2009; Drucker, *et al*., 2011). These discriminations further coincide with the lower levels (and ranges) of activity and impact recorded from transects 8, 9, 19, and 20 (Table 2.5.). If these transects were removed from the analysis of activity and impact due to the disproportionate use of this landcover type to its availability, the median result for the moors becomes High for both measures. This demonstrated that, from both sets of data being consistent with each other, the variation in habitat selectivity plays a role in the varying levels of activity and impact on site (Staines & Welch, 1984; Gill & Beardall, 2001). This suggests that whilst the average score of activity and impact for the site is a useful summary for recording purposes, it is important to understand variation within the site because not all of the habitat would be most suitable for deer. Therefore, understanding the variation allows a true representation of deer activity and impact on the habitat types that are at higher risk.

Deer are a keystone species in their environment with disproportionate impacts upon biodiversity to that of other species (Mills, *et al*., 1993). As a browsing ungulate specialising in woodland habitats, deer are capable of altering biodiversity across all levels of the food chain (Mills, *et al*., 1993; Lovari, *et al*., 2017). Deer are, however, selective eaters with clear preferences to the food they eat whilst it is in abundance (Hoffman, 1989; Ferretti, *et al*., 2008). Some plant life, such as silver birch, can be used as an indicator of high levels of deer impact from its lack of palatability to deer. Impacts upon silver birch were only recorded during this study in the second survey (at the end of the winter), when other food sources had already been utilised; this is consistent with the observations of Van Hees *et al*. (1996). When deer browsing impacts exceeded moderate levels, as they did in this study, the deer populations were at a density above that which creates positive impacts upon the environment (Tremblay, *et al*., 2007). This is consistent with the work of McGraw and Ferundi (2005) whom simulated that negative impacts occur when browsing exceeds 50% of the palatable flora. This suggests that should management objectives of the deer be concentrate towards reducing deer density (until a maximum of Moderate activity and impact levels occur), it would become possible to estimate population density thresholds at which negative impacts begin to occur.

The positive impacts of deer on temperate woodlands must, however, be considered when producing landscape objectives. The browsing of seedlings and shrubs reduces foliage density and opens the understory, subsequently increasing germination of plant life closer to the woodland floor which is essential for invertebrate populations (Gill & Beardall, 2001). Therefore, maintaining deer populations at a level generating between a Low to Moderate activity and impact level would enable the positive impacts of deer to occur (Mills, *et al*., 1993).

The activity and impact method used for measurement by this study could be improved from their current application. The Deer Initiative's method statement recommends the surveys are performed in the spring time and that only a singular assessment is required per year as there will be no significant change within a year. However, this study has demonstrated that there was a significant change in activity and impact levels when measuring between the beginning and end of winter. This could be explained by the seasonality of the resource availability influencing space use by deer as they seek the most abundant food resources during the months of limited food availability (Latham, *et al*., 1999; Putman & Staines, 2004).

The current method in use for managing the deer populations of the study site involve discriminatory, strategic culls organised by the local deer management group on the sites periphery. Last seasons' culls were focussed upon approximately one half of the female deer and leaving the younger red stags alone to encourage the development of more mature stags (D. Hinchliffe, pers. Comm.). These culls are performed to meet the objectives of the landowners. Should the operators of the NNR contemplate active management upon the site, the land operators can use the information of current activity and impact levels to develop and adjust current landscape objectives and wildlife management strategies.

5.4. Deer abundance and habitat use on Thorne Moors

The moors are currently home to established populations of red and roe deer; and supports a low-density population of Reeve's muntjac deer which are occasionally sighted by Natural England staff and local walkers (observations reported to the principle investigator). The red and roe deer populations had previously been estimated by thermal imaging and unified observations by the local DMG from outside of the moors, observing towards the periphery for measurement. These surveys regularly produced estimates between 175-200 red deer, and approximately 50 roe deer, with no information on Reeve's muntjac. During this study the abundance of red and roe deer (Chapter 3) was calculated using trail camera data and the random encounter model (Rowcliffe, *et al*., 2008). From estimating red abundance to be between 311-333 deer (Table 3.1.), and the roe population to be between 59-63 deer (Table 3.1.), the estimate population size of red deer was therefore underestimated by the DMG. A reason for the Thorne Moors DMG underestimating the population is from their measurements assuming all animals have been observed and produces an absolute population; without accounting for detection probability.

It has been recorded that there are segregations between the different sexes of red deer during feeding – a segregation that significantly increases during the winter when food is at a lower availability (Clutton-Brock, *et al*., 1987). These results support the conclusion of Clutton-Brock *et al*. (1987) that stags are less tolerant of low plant biomasses than hinds and can be excluded from preferred feeding habitats by indirect competition (Clutton-Brock, *et al*., 1987). This segregation of deer by sexes may also help explain why the estimates of red deer abundance produced by the Thorne Moors DMG are inconsistent with that of this study. With a significant portion of red stags, approximately one third of the population (Clutton-Brock & Lonergan, 1994), being displaced, the detection probability will be significantly lowered by those segregations.

There were no images of Reeve's muntjac on the trail cameras, making it impossible to quantify how many were on site. This demonstrates that REM is probably not a useful tool for quantifying low-density populations from low-encounter rates; problem that would have repeated itself should the study have utilised an alternative method of estimating density such as a distance sampling approach (Thomas, *et al*., 2002). However, if the study had utilised occupancy modelling (an approach that estimates occupancy of a site when detection is less than 1) then occupancy probabilities could have been produced for muntjac deer (MacKenzie, *et al*., 2002; MacKenzie & Nichols, 2004). It must be noted that throughout the study the investigator encountered individual muntjac deer five times on site (both bucks and does) in different geographical locations of the moors. Therefore, it is likely that there was a low-density population of muntjac occupying the site.

The random encounter model required data on average group size collected during the thermal imaging surveys (Chapter 4). The estimates were gathered from 15 transects surveyed eight times each using a combination of a thermal imager and binoculars (and between the hours of daylight and twilight). With random selection of detection equipment and independent, hierarchical transect structures, there was little opportunity for investigator bias to be involved in the estimates of average group size (Greenland & Morgenstern, 1989). A comparison of methods to detect deer was performed by Daniels (2006) where he compared the accuracies and cost-effectiveness of: distance sampling on the ground, using a helicopter with a camera (which may be problematic in woodlands), using a helicopter with a thermal imager, and faecal-counts on the ground. Daniels (2006) concluded that the Helicopter with camera counts provided the best estimates of red deer with the lowest cost per deer counted. It was concluded that there were low levels of investigator influence, the sensitivity of the animals to human disturbance was not impacted, and each survey took place over a single day to provide an immediate population estimate with the assumptions of no mortality or recruitment. However, the conclusion by Daniels (2006) of thermal imaging being less effective than a camera is inconsistent with this study. Chapter 4 demonstrated the effectiveness of detecting deer using a thermal imager compared to binoculars (which uses a daylight lens in the same way a camera does). Therefore, the use of a helicopter with a camera is likely to be influenced by detection probability, which the estimates produced could not have calculated. This demonstrates that the method for detecting deer utilised by the surveys of this study were most likely the most effective available to use.

According to Focardi *et al*. (2001), the method of estimating abundance known as spotlighting generates high density estimates that are underestimated and biased, a problem partially solved with distance sampling. However, distance sampling relies upon sample size to account for variance from detection probabilities. The use of thermal imagers improved sample sizes collected (compared to spotlighting) of red deer, brown hare and European rabbit which led to improved estimates from increasing the detection probability (Focardi, *et al*., 2001). This is consistent with this study's results of higher detection rates from using a thermal imager of binoculars, which produced a large sample size. However, there was a difference in the group detection rates of red and roe deer, demonstrating a difference of density between species. This required discrimination in the interpretation of the data as to the differences in gregarious behaviours expressed by each species. This was consistent with the work of Hemami *et al*. (2007) whom identified that a unified approach across all species was unfeasible and required adjustments to the methodology to detect different sized species expressing different levels of gregarious behaviours. It was also identified by Hemami *et al*. (2007) that differences in detection occurred between species within different plant growths, therefore concluding that stratifying habitats was required to improve accuracy despite it requiring increased survey efforts.

Another piece of essential information was the average daily speed of movement of each deer species on Thorne Moors. This was gained by selecting data most likely representative of the populations and environment from the literature. Ideally the data would have been collected from the deer of Thorne Moors using radio/GPS collars as these would have provided the most accurate information for this deer population. Given that the results of the sensitivity analysis (Chapter 3) revealed that changes to this parameter's value had a substantial impact on the population size estimate, this information clearly requires the most accurate data possible.

The calibration of indices for abundance reduces the uncertainty from a lack of parameter data and can calculate elusive species (Rovero & Marshall, 2009). However the model from Rowcliffe *et al*., (2008) was demonstrated to be a possible solution to standardising monitoring programmes whilst reducing costs whilst studying remote areas. This would be subject to precise and continuous calibration, and complete independence of camera trapping efforts. This study provided as close to independent camera trapping as possible (through consistent deployment approaches) and gaining the parameter data independently and through multiple re-tests (apart from parameter v which was carefully selected from the literature). Therefore, the conclusions of Rovero and Marshall (2009) are consistent with the approach taken within this study.

From this study, the deer were identified to actively discriminate between different landcover types disproportionately to their availability; such as selecting wet woodlands disproportionately more than their availability (Figure 3.3. and 3.4.). The areas selected by both red and roe deer were the areas with the highest levels of activity and impact on site. The time of year in which these impacts took place coincides outside the legal close season for female deer from the Deer Act 1991. This increase in activity on the moors was detected during the twilight hours during the daytime detection surveys of chapter 4. During twilight, the red deer are more active with a higher average group size then during the hours of daylight (Table 4.1.). During a study by Carranza *et al*. (1991), the deer studied were found to be mainly crepuscular and nocturnal in activity, with restricted diurnal activity patterns. The study concluded these findings to differ from studies of northern European populations (Carranza, *et al*., 1991); yet this preference towards crepuscular and nocturnal activity was prevalent in the populations of Thorne (a northern European population). The study of Carranza *et al*. (1991) does, therefore, support the conclusions of this study that the deer are more active and detectable during the twilight and hours of night. With an increased activity level of deer during twilight, and statistically low detection rates during the hours of daylight (chapter 4), this demonstrated an adaptation towards more nocturnal activity patterns in the deer (Jiang, *et al*., 2008). With this occurring outside the legal close season, it implies that areas of the moors have become a refuge to the deer in response to the cull efforts from the local landowners on the periphery of the moors.

5.5. **Further work**

This study has successfully identified the deer activity and impact levels on the moors, provided estimates of population abundances, and identified the locations and times of day when deer were most active. However, more questions have arisen as a consequence of this study.

Moving forward from this study, the first area that should be continued by the local stakeholders are the deer activity and impact surveys to quantify change over time. By following the transects and survey times set out in this study, any whom read the methodology would be able to continue the surveillance of the moors for deer impact and activity. This would allow the measurement of changes over time and the recording of emerging patterns in activity and impact against which to evaluate the achievement of management objectives and to set management priorities for the future season. Nevertheless, the activity and impact method may benefit from improvements. The method currently fails to account for the role local agriculture can play upon the activity and impacts experienced on site. This is because the foraging behaviours of the deer would be different to those without high quality agricultural food sources that are easy to access (Putman, 1986; Putman & Moore, 1998; Wilson, *et al*., 2009). Deer are a prey species whom are highly sensitive and create adaptations to their behaviours in response to hunting pressure. Roe deer (for example) will change their feeding strategies and home ranges as a direct response to high levels of hunting pressure from humans (Benhaiem, 2008; Ferretti, *et al*., 2008). Therefore, another problem identified is that the method is applied at the site-scale, whereas deer operate at the landscape-scale. It would be recommended from this to incorporate a wider range of landcover types to provide a landscape-scale assessment that can also be examined at the transect level, which is consistent with the work by Morellet *et al*. (2007), whom recommended monitoring of populations, habitat features and the interactions between the two. (Morellet, *et al*., 2007)

The second area that needs to be addressed from this study is the lack of information on the average daily speed of movement of both the red and roe deer of Thorne Moors. Until this information becomes available, the estimates reported in this thesis cannot be confirmed as accurate since they may be biased. However, should the results of average daily speed of movement become available, an update can be made readily available for a final estimate. Evaluation of each species' speed of movement using GPS collars over the course of at least one year on a mixture of males and females would be advisable. The use of a year as a time-frame would be to incorporate the seasonality of deer behaviour.

The final recommendation of further work to be performed resulting from this thesis is to perform a wider landscape-scale analysis to incorporate the Humberhead levels region. To include Hatfield Moor (the other half of the Humberhead Peatlands NNR) and a wider range to include farmland and other "wild" areas of the region, would provide a greater understanding of how deer interact with the regions' environment, and which deer species are present. To further include occupancy models of each species in the region would provide a mathematical estimate of occupancy when detection rates are less than one (MacKenzie, *et al*., 2002). The benefits of occupancy modelling would be the mathematical modelling of the likeliness of detecting the target species with a low detection probability. This would be beneficial to this site for modelling muntjac deer on Thorne Moors (MacKenzie & Nichols, 2004).

5.6. Conclusion

This study aimed to evaluate the levels of activity and impact on Thorne Moors, to estimate the density and abundance of the deer species on site, and to evaluate the daytime detection rates of deer. These were all achieved within this study through enacting activity and impact surveys, a camera trapping survey, and detection surveys during the daytime. The site had median activity and impact levels of High and Moderate-High respectively, and 311-333 red deer and 59-63 roe deer were estimated on site. Thermal imagers were determined to be more effective at detecting deer during the daytime, and the deer on Thorne Moors were more active during the twilight then the daylight hours. This study has demonstrated where further work is required to improve the methods utilised and how to improve the accuracy of the abundances estimated.

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Appendix A

Table A.1. The upper and lower range of activity and impact per transect. 1 = None, 2 = Low, 3 = Low-Moderate, 4 = Moderate, 5 = Moderate-High, 6 = High.

Transect	**Activity (Low – High)**	**Impact (Low – High)**
1	5 - 6	3 – 5
2	4 - 5	2 – 4
3	5 - 5	4 – 5
4	6 – 6	6 – 6
5	6 – 6	6 – 6
6	6 - 6	5 – 6
7	4 – 4	2 – 3
8	4 – 4	2 – 2
9	3 – 3	1 – 3
10	5 – 6	5 – 5
11	4 – 5	2 – 5
12	6 – 6	3 – 6
13	5 – 5	4 – 5
14	6 – 6	4 – 6
15	4 – 6	2 – 5
16	4 – 6	2 – 5
17	4 – 6	2 – 5
18	4 – 6	2 – 5
19	2 – 2	1 – 2
20	3 – 3	2 – 2
21	3 – 4	2 – 4
22	4 - 6	2 - 6

Appendix B

The generalized liner models performed in chapter 4 were originally arranged to perform a combination of main effects analysis of the predictor categories on the dependent variables, and to further perform 2-way analyses of the predictor categories. After completion of these original analyses, there were no significant results in the 2-way analysis of predictors, alongside a lack of significant results with the main effects analysis of red and roe deer. Two such tests had identical test statistics, degrees of freedom and p values to each other of both the main effects test and 2-way model. It was therefore decided to re-run the analysis using only the main effects analyses with more degrees of freedom available. After the re-run tests were performed, the AIC scores were compared to each other and it was found that the main effects only analyses held significant results with lower AIC scores. Therefore, these tests were the ones used for this studies analyses.