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The population status and density of non-native deer in northern Belgium (*Muntiacus reevesi, Cervus nippon, Dama dama*)

Lo status della popolazione e la densità di cervi non-nativi nel nord del Belgio (*Muntiacus reevesi, Cervus nippon, Dama dama*)

Candidate: Sara Pezzatini

Supervisor: Dr. Bram D'hondt

Co-supervisor: Dr.ssa Elena Tricarico and Lynn Pallemaerts

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INDEX

1 Introduction

Humans have significantly altered vertebrate animal communities since ancient times. Apart from driving regional extinctions (He et al., 2018; Loehle & Eschenbach, 2011), humans have also translocated animals outside their native range for purposes like hunting or ornamental use. Any such alteration may cause multiple impacts on the ecosystem and its structure. Species can be non-native and can interact (e.g. compete) with the native species, changing local ecosystems (Allaby & Park, 2013).

A non-native species, also referred to as an alien or exotic species, is introduced by humans, either deliberately or accidentally, to a new region where they do not naturally occur. If such an introduced species causes harm to the environment by becoming widespread, dominant and competitive to native species, the species is said to be an "invasive (alien) species" (Lemoine & Svenning, 2022). In contrast, a native species is a species that occurs naturally in a particular area without human intervention. Its presence in the ecosystem results from various natural processes over time (Allaby & Park, 2013).

The introduction of non-native species can have long term implications for the ecosystems, particularly when these species become overabundant. This issue is especially relevant in the case of ungulate herbivores, introduced in new areas by humans and with increasing populations.

In the last ~200 years, populations of ungulate herbivores, particularly deer, have been increasing across Europe but also in Russia and North America due to human intervention (Fuller & Gill, 2001). Both native and non-native deer population increased in the last decades. Negative consequences occur when deer populations become highly abundant, then perceived as 'overabundant'. The problem with defining overabundance is that there is no clear threshold distinguishing when a population shifts from abundant to overabundant. Additionally, this issue is not limited to non-native species; native deer populations can also reach levels considered overabundant, causing similar ecological and management challenges.

This increase in non-native deer populations in particular can be explained with deliberate and accidental releases of deer into the wild but also with factors including: (1) the increase of forests and woodland areas, (2) changes in agriculture practices providing additional food sources for deer (Brunot et al., 2025), (3) the reduction of extensive livestock husbandry in woodlands, (4) stricter hunting regulations, (5) warming climate (e.g. increased food availability through masting years, decreased mortality of juveniles), and (6) the decline of large predators (Fuller & Gill, 2001).

Deer overabundance can have severe ecological and socio-economic impacts. It affects plants communities, human activities, increase the transmission of infectious diseases, and have cascading effects on other animal species (Côtè et al., 2004). For instance, intense browsing on tree seedlings reduces tree regeneration and growth, necessitating the use of protective measures on newly planted trees (e.g. exclosures). This over browsing can lead to loss of biodiversity, alter vegetation structure and change species composition.

There is an ongoing debate on how herbivory impacts plant biodiversity. Some studies suggest that herbivory reduces threatened species while promoting non-native species; others show the opposite, indicating a need for further investigation. In a very wide survey, Segar et al. (2022) examined the interaction between increasing herbivorous ungulates populations and atmospheric nitrogen (N) deposition on understory plant communities. They found out that (1) higher herbivory levels are linked to an increased species turnover, (2) with low nitrogen levels, herbivory promotes threatened species while reducing non-native and nutrient-demanding ones, (3) with high nitrogen levels, the effects reverse: herbivory suppresses threatened species favoring non-native and nutrient demanding species, and (4) high herbivory levels reduce shrub cover, increasing light penetration amplifying the eutrophication effects (Segar et al., 2022).

Beyond ecological consequences, deer overabundance increases the risk of vehicle accidents and transmission of tick-borne zoonoses due to a rise in tick populations. Additionally, other herbivores can be directly affected by the intense deer browsing competing for resources, while invertebrate and bird communities (Palmer et al., 2015) are sensitive to changes in forest understory (Côtè et al., 2004).

These issues raise questions about the status of the deer population and their management in countries where non-native deer are present and with increasing populations. The present study focused on three non-native deer species in Belgium: *Muntiacus reveesi* (Reeves' muntjac or Chinese muntjac), *Cervus nippon* (sika deer) and *Dama dama* (fallow deer). All three belong to the Cervidae (Goldfuss, 1830), a family of artiodactyl mammals belonging to the suborder of the Ruminantia, comprising 53 species within 18 different genera (Wilson & Mittermeier, 2011).

These species were introduced for different purposes, but all require management due to their significant and varied impacts on natural ecosystems in Belgium. They threaten native deer populations (Branquart et al., 2009), notably roe deer and red deer (see below), by competing for food resources and, in the case of sika deer, through hybridization (Branquart et al., 2013). When the effects of browsing and grazing by these three non-native deer combine with those of native deer browsing, the impacts on the ecosystems are amplified even more.

Managing deer populations, with the objective of mitigating their impact on the ecosystem, is challenging. Among various control methods, hunting has proven to be the most cost-effective to control deer abundance. It involves regional, national and European laws; nature conservation and hunting policies; and considerations of animal welfare; some of which may conflict with each other. Moreover, it requires public support, which is not evident in the case of hunting. For designing the most efficient methods of management, accurate population densities are therefore crucial. Yet, estimating population densities can be complicated, takes time and at the end the true numbers could be underestimated or overestimated (Fuller & Gill, 2001).

In conclusion, controlling deer communities is a complex task for managers and researchers. In Belgium and other countries where large non-native deer population coexist and compete with native species, the situation is especially pressing.

1.1 Native deer species in Belgium

Two species of Cervidae are native to Belgium: roe deer (*Capreolus capreolus*) and red deer (*Cervus elaphus*). As a reference, and because the two species make part of the monitoring during the thesis' work, I briefly introduce them here.

1.1.1 Roe deer

Capreolus capreolus (Linnaeus, 1758), called roe deer, is a small deer species belonging to the subfamily Capreolinae. There are currently five recognized subspecies, including for example *C. c. caucasicus* (Dinnik, 1910) and *C. c. italicus* (Festa, 1925). Its native range is the European continent, where it is widespread. Due to its extensive distribution and stable populations, it is classified as "Least Concern" by the IUCN Red List (Lovari et al., 2016). Between 1955 and 2016, the roe deer expanded its geographic range by approximately 29%, and its population nearly tripled, as indicated by the Living Planet Index (LPI) (Ledger et al., 2022).

The roe deer is small, with a shoulder height ranging from 65 to 85 cm, a reddish to gray-brown coat and a distinctive white rump patch (***Figure 1***). Males grow antlers that can reach up to 20-

25 cm in length, typically simple with 2-3 points. The small size and the small stomach require the roe deer to move and feed frequently throughout the day, favoring soft food like buds, shoots, green leaves and seeds. Roe deer usually have a small home range and are generally solitary animals. However, during summer, females may be accompanied by their fawns, while larger social groups typically involving adults and juveniles, are more frequently observed in winter (Villerette et al., 2006). The species occupies a very wide variety of habitats, from moorlands to coastal habitats, with a preference for wooded habitats. Thanks to their small size, they can move easily in dense vegetation (Sempere et al., 1996).

Figure 1: male (right) and female (left) roe deer. Picture taken with a camera trap in Flanders. © INBO

1.1.2 Red deer

Cervus elaphus (Linnaeus, 1758), the European red deer, is one of the largest members of the Cervidae family. While native to Europe, it has been introduced to other regions, including the United States, Australia and South America. Its wide distribution has led to significant diversification, resulting in more than 10 recognized subspecies. The IUCN listed it as “Least Concern” in the Red List (Lovari et al., 2018) due to the stable populations. Between 1955 and

2018, the red deer expanded its geographic range by approximately 211%, and its population more than tripled as indicated by the Living Planet Index (LPI) (Ledger et al., 2022).

Red deer stags can reach a shoulder height of up to 130 cm, while hinds are slightly smaller, averaging 115 cm. They are heavy-bodied animals with an average tail length of 15 cm. Their summer coat is reddish, transitioning to gray brown in winter. Stags are known for their large and complex antlers which can grow up to 100 cm in length, weigh 6-5 kg and feature multiple branching points (***Figure 2***). Their diet consists of a mix of grasses and leaves, but fruits and seeds become a big source in autumn. Red deer are primarily crepuscular, though they can remain active all day if not disturbed. Home range is variable in size between individuals; males usually have bigger home ranges and are more solitary, while females occupy smaller ranges and live in groups led by a dominant female. Their habitat is very variable (Lovari et al., 2018).

Figure 2: Red deer (Cervus elaphus) family in the wildlife park of Altenfelden, Upper Austria (Wikimedia Commons picture).

1.2 Non-native deer species in Belgium

In Belgium, there are three deer species that classify as non-native: the Chinese muntjac, the sika deer and the fallow deer. Nonetheless, their legal status is somewhat different, as explained below.

1.3 Case study: The Chinese muntjac

The Chinese muntjac (*Muntiacus reevesi*, Ogilby, 1839) is a small deer native to China and Taiwan (***Figure 3***). It belongs to the Cervidae family and to the subfamily Muntiacinae, which retains several ancestral traits (e.g. small body size, presence of antlers and upper canines in males). Currently there are three known subspecies: *Muntiacus reevesi reveesi* (Ogilby, 1838) from mainland China, *M. reevesi jiangkouensis* (Gu and Zu, 1998) from the Chinese region of Guizhou, and *M. reevesi micrurus* (Sclater, 1875) from Taiwan.

The Chinese population was estimated at more than 2,000,000 individuals (Sheng, 1992a), and it was listed as "Vulnerable" in the Chinese Red List due to a declining population caused by hunting and habitat loss (Timmins & Chan, 2016). The population in Taiwan has no estimated size but is considered stable. Outside its native range in Asia, this species is becoming well established in Japan (Timmins & Chan, 2016) and parts of Europe (below).

Figure 3: male muntjac. Picture caught on camera trap in Flanders. © INBO

1.3.1 Species features

Interest in M. reevesi began in 1959 with the first studies, which continued in the following years, including research on its behavior.

The muntjac is a very small deer, with an average shoulder height of 47 cm for the females and 50 cm for the males (Chapman, 2008). The average weight ranges from 10 to 15 kg, with females usually being smaller (Cooke, 2019). The Taiwanese subspecies is slightly smaller than the Chinese one (McCullough et al., 2000).

Males ("bucks") have antlers, while females ("does") do not. The males shed their antlers around May-June, after which a new pair begins to grow, covered in a type of skin called velvet, which is later rubbed off. The antlers are usually simple, with a maximum length of 10 cm (Chapman, 2008). The bucks' faces typically have V-shaped markings ending at the antlers, while the does have darker, diamond-shaped facial markings without antlers (***Figure 4***). This is one of the main characteristics that help distinguish males from females (e.g. on camera trap pictures). Both sexes have long, pointed canine teeth in the upper jaw, known as "tusks". Both sexes have prominent preorbitals glands, large olfactory organs just under their eyes, that showcase the importance of smell for intraspecific communication (Chapman & Chapman, 1982).

Figure 4: V-shaped facial pattern in muntjac male (left) and diamond-shaped facial pattern in female (right). Picture caught on camera trap. © INBO

Signs of their presence in the woodland include black or dark brown dung pellets, footprints, narrow tunnels through the vegetation, damage to plants, and scraping of trees between 40 and 100 cm high (higher heights are reached by standing on the hind legs). Muntjac make fox-like barking sounds, especially from May to October (Cooke 2019).

Studies (Cooke, 2019; Chapman, 2008) and camera trap analyses show that this is a solitary species. Occasionally, groups of two may be seen, most likely a buck and a doe, a doe with her fawn, or two does, usually mother and daughter (Chapman & Harris, 1996). They prefer dense and varied ground-level habitats (Chapman, 2008) such as deciduous woodlands with diverse undergrowth and young plantations. They are accustomed to human presence, and they can easily colonize well-vegetated areas near towns, like cemeteries, railway lines and mature gardens. They inhabit temperate and subtropical zones, and the snow represents the northern limit to their range, as deep or prolonged snow can increase mortality (Cooke, 2019). In Europe, muntjac mortality can occur due to hard winters, hunting and traffic. In Europe, their primary predator is the red fox (*Vulpes vulpes*) which mostly preys on young fawns. Also, European populations are not known to carry diseases, though they can host ticks and lice (Chapman, 2008).

As deer, muntjac are ruminants, but their small size does not allow a complex digestive system. They are not particularly good at processing fibers, which is why they prefer small, highly nutritional morsels over grazing (Cooke, 2019). The most important plants in their diet are brambles (*Rubus* spp.). They can also cause problems in agricultural fields, as they like crops like carrots, potatoes and maize.

This species breeds throughout the year. Bucks are always fertile and does can return to estrus 1-2 days after giving birth, after a gestational period of 7 months (Chapman & Harris, 1996). Males reach sexual maturity at about 9 months while females reach it at 7 months. The mating system is polygynous: a buck typically mates with more than one doe, often preferring those that have already given birth (Cooke, 2019). Males are territorial and mark their home range using facial glands as well as urine and defecation. They are solitary animals, but male ranges can overlap, particularly when there is a female. This can lead to fights between bucks using their antlers and tusks, often resulting in breakage (Cooke, 2019).

1.3.2 Chinese muntjac in Europe

The Chinese muntjac arrived in Europe, specifically in Great Britain, for the first time in 1839, with John Russell Reeves (after whom the species is named), a British East India Company employee and a botanist. Reeves' muntjac was introduced in Woburn Abbey Park in Bedfordshire during the 1890s, where it began to breed. The origin of these first animals is uncertain due to lack of records, but they may have been a mix of mainland and Taiwanese individuals (Cooke, 2019). Genetic evidence indicated that Woburn animals were not the only source of muntjac introduction in Great Britain (Williams at al., 1995), but new studies have concluded that there was likely a single founding event involving only a few females (Freeman et al., 2015).

Over the years, animals from private enclosures were released (either accidentally or deliberately) to increase the abundance for hunting (Chapman, 2021). Finding new suitable habitats, like those in its native range, the muntjac population grew rapidly thanks to their adaptability, broad trophic niche and high fertility. This led to an estimated population of

128,000 individuals in England in the 20th century (Mathews et al., 2018). This large population caused a lot of damage to the local nature. Cooke in his monograph (2019) studied this species for almost 30 years, and in particular its impact on woodland vegetation in southern England. The most notable impacts include damage to coppice regrowth and grazing of the lower vegetation layers, which can alter the plant composition and consequently affect the local fauna.

To prevent a scenario similar to the British one, muntjac has been listed on the 'list of invasive alien species of Union concern', as part of the European Regulation 1143/2014. According to this regulation, muntjac can no longer be kept, bred or traded within the entire European Union (D'hondt et al., 2023).

In Europe, muntjac has been sighted in various other countries, such as Ireland, Denmark, Austria, Poland and the Netherlands (Hollander 2015; Ward et al. 2021; Chapman 2022; Schertler et al. 2024). In all these cases, however, observations of the species have so far proven sporadic and short-lived, probably reflecting recent escapes (or releases) without establishment or reproduction. In contrast, a more permanent presence of muntjac has been observed in Germany (Schulz & Borkenhagen, 2021) and France (Maillard et al., 2024), so that management has become implied. Nonetheless, at present, only in Belgium muntjac is observed very regularly, with clear signs of population establishment, spread and reproduction.

1.3.3 Belgium

In Belgium, the muntjac was first observed in 2004, with sightings increasing from 2012 and peaking in 2020 (D'hondt et al., 2023). The vast majority of observations come from the Region of Flanders. The peak in 2020 could be attributed to recent legal enforcement actions that led people, who were still (illegally) keeping muntjacs, to release them into the wild. Since 2020, muntjac sightings have declined as wildlife management efforts increased under the supervision of the Flemish Government.

The distribution dynamics of *M. reevesi* in Flanders are complex, influenced by both human action and natural processes (Deflem et al., 2022). A genetic study using Single Nucleotide Polymorphisms (SNPs) confirmed distinguishable clusters and familial relationships that can only be explained by human intervention (Deflem et al., 2022; D'hondt et al., 2023). A map with muntjac observations from Flanders is presented below (***Figure 5***). The largest, most dense cluster of observations is situated near the city of Antwerp, where the presence of muntjac also dates back to 2012. The map below utilizes occurrence data from GBIF (GBIF.org, 2025) on top of the invasive species data in Belgium available at www.waarnemingen.be. The data has been filtered for the last five years, showing only verified observations (approved on expert judgement, approved on knowledge rules, and photographic evidence) along with additional trusted datasets.

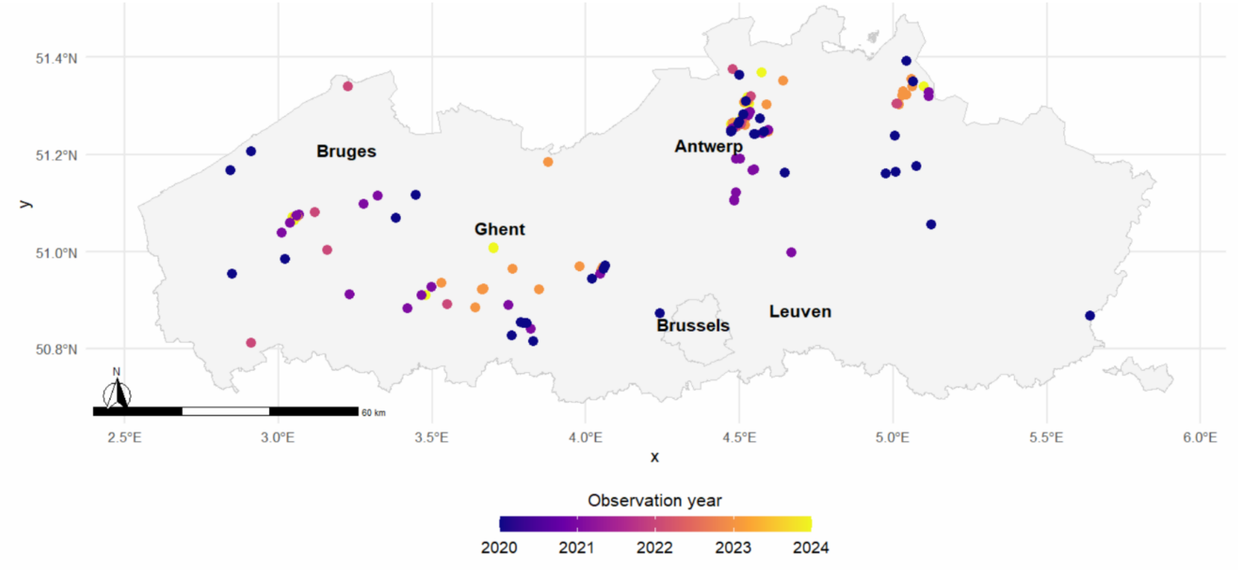


Figure 5: Muntjac observations in Flanders (since 2020, verified observations only). Source: GBIF (2025).

1.3.4 Legal status of muntjac

In line with the species' listing as an invasive alien species of Union concern since 2016 (EU Regulation 1143/2014), muntjac is regarded as an invasive species according to Flemish law. In practice, this means that there are relatively little restrictions for management (e.g. timing of day and year, types of ammunition…), and that there is no limit with regards to the number of animals removed.

1.3.5 Management of Chinese muntjac

Muntjacs can be a significant environmental issue; they impact agriculture and forestry crops, they cause traffic accidents, and they could carry diseases (Cooke, 2019). The biggest problem is their browsing behavior, especially on coppice regrowth, which reduces heights and kills the stems. Additionally, their browsing on seeds of different plant species, new shoots and grasses, at high population densities, can lead to a shift in the lower vegetation layers, creating more space and reducing competition for non-palatable species changing the structure of the ground level (Chapman, 2022). They browse ash, bramble, ivy, and ferns and graze grass and herbs in

April and May, reducing vegetation richness. Protective measures for newly planted trees are required but physical barriers have proven ineffective (Cooke, 2019), so alternative solutions need to be implemented to manage the muntjac's impact on vegetation. As impacts in the United Kingdom become evident, culling efforts have been undertaken against muntjac since about the 1980s (Cooke, 2019). The success in England in the vegetation regrowth following the culling shows the significant impacts muntjacs have on ecosystems and the importance of controlling their populations.

In Flanders, a structured form of local management on muntjac began in a government-owned park east of Antwerp (Park Vordenstein, see below) in 2021. The actions were led by the Agency for Nature and Forest (*Agentschap Natuur en Bos,* ANB), the Flemish authority for nature conservation and forestry. From 2021 to 2022, control efforts involved stalking sessions at dusk and dawn with the purpose of culling the animals to reduce the population and its impact. In 2021, four does were shot and in 2022, six bucks. Camera traps installed in the area confirmed that, after the animals were shot, the numbers quickly recovered (D'hondt et al., 2023). This recovery may have resulted from successful reproduction and the shooting of only bucks in 2022, immigration, or a shift in the animal's activity patterns to avoid human presence. Another ten and eleven muntjac were shot in 2023 and 2024 (mostly during summer), respectively (INBO, unpub.).

1.4 Case study: The sika deer

The sika deer (*Cervus nippon*, Temminck, 1838) is native to Eastern Asia. Its natural range includes countries such as Vietnam, China, Japan, Korea, Taiwan as well as East Russia and Eastern Siberia (Genovesi & Putman, 2006). It belongs to the subfamily Cervinae, and it is closely related to the red deer (*Cervus elaphus*, Linnaeus, 1758), with which it can hybridize (Lowe et al., 1975).

There are more than ten subspecies of *C. nippon* largely due to its extensive native range and the diversity of geographical areas where it lives. Examples include *C. n. grassianus* (Heude, 1884) from China or *C. n. pseudadaxis* (Gervais, 1841) from northern Vietnam. The IUCN has classified this species as "Least Concern" on its Red List (Harris, 2015), primarily due to the overabundant and growing population in Japan. However, some subspecies are classified as "Endangered" or, in some cases, "Critically endangered" or even extinct in the wild, mainly because of hunting and habitat loss (Scalera et al., 2021).

In Europe, *C. nippon*, is considered established in Austria, Belgium, Czech Republic, Denmark, France, Germany, Ireland, The Netherlands and Poland (Bartoš, 2009). Outside the European continent the sika deer was successfully introduced in Armenia, New Zealand, Philippines and United States. Some historic introductions are reported in Australia, Morocco and South Africa (Scalera et al., 2021).

1.4.1 Species features

The sika deer is a relatively large species; the average shoulder height for males ("stags") ranges from 65 to 115 cm while for females ("hinds") it is 60 to 95 cm. Adult stags can weigh between 30 and 140 kg, whereas adult hinds typically weigh between 20 and 90 kg. It has been observed that sika deer from northern regions tend to be larger than those from southern regions (Takatsuki et al., 2024). Despite their size, they are smaller than their close relatives, the red deer, which is one of the key characteristics used to distinguish between the two species. Sika deer are highly social animals, with peak activity occurring at dusk and down (Baiwy et al., 2013).

Cervus nippon has a chestnut-colored summer coat with white spots, transitioning to a grayish/black coat in the winter (***Figure 6***). They may have a black neck stripe, and males can develop a neck mane. The caudal patch is white with black outline on top, crossed by the tail with a median black stripe. Adult stags grow antlers that typically measure 30 to 75 cm in length. These antlers are usually four-pronged and begin growing on pedicles at 6 to 7 months of age, with the first set appearing around twelve months. Velvet shedding occurs in late August or early September, and antler casting takes place in April or May (GBIF, Secretariat, 2023).

Figure 6: male (top) and female (bottom) sika deer (Wikimedia Common pictures).

Both stags and hinds reach reproductive maturity at 16-18 months. The mating system is polygynous, with males maintaining a harem of multiples females during the rutting season, which primarily occurs in fall (September to November). During this time, males compete for females, defend territories, mark vegetation and emit a distinctive call, a repeated high-pitched whistle (another important trait that differentiates this species from the red deer). Calves are born between April and June after a gestational period of approximately 230 days. Single births are typical, while multiples births are rare (Feldhamer, 1980). The sika deer has a high reproductive rate, with an 80 to 90% conception rate and an 85 to 100% adult pregnancy rate (Feldhamer, 1980). They can live up to 15 – 16 years in the wild and as long as 25 years in captivity. Their primary predators in Europe are grey wolves (*Canis lupus*).

In its native habitat, *C. nippon* occupies climates ranging from tropical in the south to cold in the north. Sika deer prefer tropical and warm temperate climates, particularly areas with limited snowfall, as heavy snow is the leading cause of mortality among sika calves during their first year (Perez-Espona et al., 2009). In their native range, they inhabit a wide variety of forest types, preferring early succession stages over mature woodlands, and they can live at altitudes of up to 3000m above sea level. In Europe, the sika deer prefer deciduous or mixed woodland with dense undergrowth and nearby open areas (Perez-Espona et al., 2009). However, they are highly adaptable and can thrive in different habitats provided with some kind of woodland cover. They generally avoid treeless environments (Perez-Espona et al., 2009).

Sika deer are versatile herbivores, anatomically adapted for both grazing and selective browsing. In their native range, their diet varies depending on vegetation and climatic conditions. For instance, the northern population primarily grazes on dwarf bamboo, graminoids and other poorly digestible plants, while southern populations consume more fruits and highly nutritious foods (Takatsuki, 2009). In Europe, their diet composition is highly variable depending on location and includes graminoids, forbs, shrubs, twigs, tree foliage, fruits, fungi and agricultural crops, without significant preferences on any food source (Takatsuki, 2009).

In Europe, this species has the potential to become a highly successful invasive species due to its high reproduction rate, diverse diet, adaptability to various habitats, lack of natural predators and limited susceptibility to European deer diseases and parasites (Scalera et al., 2021).

1.4.2 Sika in Europe

In Europe, this species likely arrived through early introduction (before 1900). These introductions were the result of intentional release into the wild as well as escapes from parks and farms (Bartoš, 2009). The largest European populations are located in the United Kingdom and Ireland, where, after several introductions from 1860 onwards, the sika deer population and its range have expanded rapidly. The UK population was estimated to number 27,000 individuals in 2010. Other free-living populations in Europe can be found in Czech Republic, Germany, Belgium, Ukraine and France but also Denmark, Poland and Hungary.

The exact origin of European sika deer is unknown due to a lack of documentation, multiple introductions, and the mixing and crossing between subspecies (Bartoš, 2009). However, it is known that the first introduction mostly with animals from Japan and other parts of Asia, occurred in Ireland and United Kingdom in 1860 for hunting purposes where subsequently the species began to settle and spread. In the following years, sika deer were reported in various countries in Europe because of intentional introductions for hunting as well as escapes from enclosures and deer parks.

This species has a significant impact on both native wildlife and vegetation. The primary issue caused by sika deer is competition with other deer species (Branquart et al., 2009). They compete with roe deer and red deer for food, space and other resources. Another big issue is the hybridization with red deer: fertile hybrids can occur when sika are introduced but also in their natural range where hybridize naturally (Bartoš, 2009). Sika deer can also affect vegetation through browsing and overgrazing, which can lead to shift in the vegetation layers, damage to some plant species, and the proliferation of others (Bartoš, 2009).

1.4.3 Belgium

The first casual observations of *C. nippon* in Belgium were reported in 2011 in various locations. Two individuals were spotted in Les Marionville in November 2011, and a buck was shot in 2011 in Famenne, in the Walloon province of Namur (Baiwy et al., 2013).

The only known established population of sika deer in Belgium is in Zonhoven, in the Flemish province of Limburg, in an area called “Platwijers”. Sika deer have been present there since 2012 and have been reproducing and spreading. The area has been managed by ANB since fall 2022.

How sika deer arrived in Belgium remains uncertain, but it is possible that their entry pathway involved the natural spread of individuals from neighboring countries, such as Germany, which currently host scattered populations throughout the territory (Baiwy et al., 2013). In the “Platwijers”, however, the sika deer presence is linked to captive populations that appear to have escaped.

The distribution map of the sika deer in Flanders is shown below (***Figure** 7*). The map utilizes occurrence data from GBIF (GBIF.org, 2025) with data of the last five years, showing only verified observations

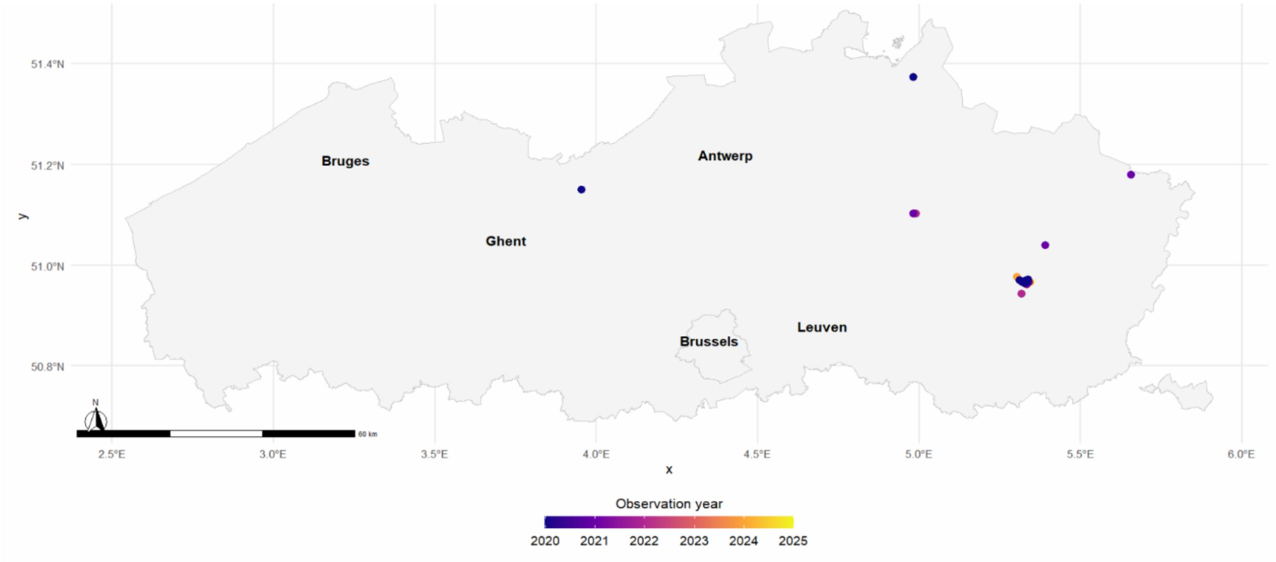


Figure 7: Sika deer observations in Flanders (since 2020, verified observations only). Source: GBIF (2025).

1.4.4 Legal status of sika

Sika deer is considered non-native in Belgium. As with muntjac, this practically means that there exist flexible conditions for management. In contrast to muntjac, however, sika deer is currently still allowed to be kept as a pet species or in husbandry.

Over the years, various European countries carried out a risk assessment for the sika deer, e.g. by Baiwy et al. (2013) for Belgium. Scalera et al. (2021), together with colleagues from the Flemish Institute for Nature and Forest (INBO, i.e., the host institution for this thesis), drafted the official Pest Risk Analysis which is used as the base document for the European Union Commission to consider species inclusion in the Union list.

At European level, its inclusion in the list of invasive, alien species of Union concern is currently being considered as 2025 (Scalera et al., 2021). If the species were to be listed, the captive population should be phased out, and management in Belgium (Flanders) becomes mandatory.

1.4.5 Management of sika deer

The most critical environmental impact of the sika deer is their potential for hybridization with the red native deer. These hybrids are fertile, which pose a serious threat to the genetic integrity of the native species. This is considered the most pressing argument to imply management in Flanders.

Sika deer management in Flanders, specifically in Platwijers, began in September 2022. During the campaign, hunters from ANB dedicated significant hours observing from hunting towers to locate and cull sika deer. In 2022, the campaign resulted in 10 deer being shot, mostly during the evening hours. Of these, four were calves and six were adults, with the majority being females. During the 2023/2024 hunting season, only one deer was culled, a female calf. Genetic analysis of tissues samples from these animals is pending, as to confirm species identity and potential hybridization with red deer (ANB, pers. comm.~~n.d.~~).

In addition to the animals culled in Platwijers by ANB, in 2023, four sika deer were reported to have been culled by private hunters. Furthermore, the local game management unit (*Wildbeheereenheid;* WBE) conducted another campaign in the same region, culling a total of 20 animals. Thus, in total, 35 sika deer have been shot in Flanders to this date. However, this number may not be entirely accurate due to the possibility of unreported animals or confusion with red deer or hybrids (INBO, pers. comm.).

1.5 Case study: The fallow deer

The fallow deer (*Dama dama*, Linnaeus, 1758) is a medium-sized deer native to Eurasia. Specifically, it is native to Turkey, the Italian and Balkan Peninsulas, and the island of Rhodes. Due to its widespread distribution and abundance on the European continent, the fallow deer is classified as a species of "Least Concern" by the IUCN (Masseti & Mertzanidou, 2008).

The species was introduced in Europe in ancient times by Phoenicians, Romans and Normans, as evidenced by some paleontological findings (Davis & Mackinnon, 2009; Osborne, 2013). Most of the present-day population results from more recent introductions. While the European populations are considered stable, in its native range, more specifically in Turkey, the fallow deer has suffered some declines (Arslangündoğdu, et al., 2013). Only one original native population remains in Termessos National Park near Antalya (Turkey), as the species has disappeared from most of its historical distribution. This original population is now endangered due to inbreeding and hunting (Masseti & Mertzanidou, 2008).

The fallow deer is currently present and established in most European countries. In recent years, it has also been introduced to various regions worldwide, including the United States, Argentina, South Africa, New Zealand, Peru, Chile, Uruguay and the Pacific coast of Canada (Masseti & Mertzanidou, 2008).

1.5.1 Species features

Dama dama is a medium-sized, highly social deer with short, high-set heads. Adult does have a shoulder height of 70-80 cm and a weight from 35 to 50 kg. Adult bucks can reach a shoulder height of 85-95 cm and weigh between 50 and 80 kilograms, making them on average 40-60% heavier than females (***Figure 8***). They have a relatively long tail, about 15-20cm in length, which is black on top and white underneath. The white rump patch features a black stripe shaped like an anchor. When threatened, the deer raises its tail, exposing the white rump patch (GBIF, Secretariat, 2023~~n.d.~~).

Figure 8: male (top) and female (bottom) fallow deer in Flanders. Picture caught on camera trap. © INBO

The fallow deer has a very distinctive coat pattern. During the summer, the coat is typically reddish-brown with white spots on the back and upper part of the body. The outer side of the head, neck, chest and belly are white, and there is a black stripe along the back extending from the head to the tail. During the winter, the coat usually turns gray-brown, and the white spots are no longer visible. Newborns also have spotted coats (GBIF, Secretariat, 2023).~~n.d.).~~

Males begin growing their antler pedicles around 7-9 months of age and develop their first set of antlers by one year old. An adult buck (four years or older) has well-palmed antlers averaging 50-60 cm in length. Antlers reach full size at 7-10 years old, after which they may begin to regress (Feldhamer et al., 1988). In August bucks shed their velvet and in April they cast their antlers.

Both sexes reach sexual maturity at about 16 months of age, though males do not typically mate until they are 3-4 years old. The rutting season occurs mainly in October, during which the males emit sounds and groans to the point of exhaustion, often losing 15-20% of their body weight pre-season (GBIF, Secretariat, 2023~~n.d.~~). During this time, males seek out females and compete with other bucks to defend their territories and harems. Females have a gestational period of approximately 230 days, with the peak birthing season occurring in May-June. Newborn fawns can fully accompany their mother after ten days and are weaned at 8-9 months (Feldhamer et al., 1988). Predators of young fawns include the grey wolf *Canis lupus*, the Eurasian lynx *Lynx lynx* and the red fox *Vulpes vulpes* (~~GBIF, n.d.).~~ Masseti & Mertzanidou, 2008).

Dama dama is not only highly social but also active throughout the day, typically engaging in 6-8 periods of feeding, ruminating, and moving. When undisturbed, they are more diurnal, but if they sense danger, such as human activities or the presence of vehicles, they become more crepuscular (Feldhamer et al., 1988). Their home ranges are very small, about 70-200 hectares, and often overlap. This is a very social species; the basic family group consists of a mother with her fawns, even from different years. Females often form large herds, while bucks are usually more solitary. In suitable habitats, herds can number up to 200 individuals (Feldhamer et al., 1988~~GBIF, n.d.~~).

The fallow deer's habitat is highly variable, ranging from open woodland and conifer plantation to Mediterranean scrublands. They can live up to 1,000-1,500 m above sea level (in the Alps, Apennines or Pyrenees), but cold temperatures and prolonged snows set their upper limit. Their diet is very diverse, supported by a large rumen. They primarily graze on grass and ground vegetation, preferring it to trees and herbs. In the Mediterranean area, browsing leaves and buds of shrubs and trees can become an important issue (Masseti & Mertzanidou, 2008).~~GBIF, n.d.).~~

1.5.2 Fallow deer in Europe

Dama dama is a deer species originating from the Eastern Mediterranean region. Over the past centuries, it was introduced across Europe, becoming one of the most well-known and widespread deer species.

The Romans, between the 1st and 5th centuries, were responsible for the first large-scale introduction of fallow deer in Europe. They introduced the species for its aesthetic appeal and for hunting in park. Archeological evidence found in the old Roman Empire territories suggests that the deer was present in these countries during this period (Baker et al., 2024).

After the decline of the Roman Empire, the deer population also declined. During the Medieval period, around the 11th century, their number began to rise again due to deliberate introductions by the European aristocracy. During this time, Dama *dama* became a symbol of wealth and prestige, especially for their elegant appearance.

In the following and more recent centuries, the species continued to spread across the continent. Large populations became established thanks to the species' adaptability. This is the result of the combination of deliberated introductions, escapes from deer park and the role of the exotic animal trade (Masseti & Mertzanidou, 2008).

1.5.3 Belgium

The species is present in Belgium since long time. It was present in the region before the last Ice Age, which drove it back to the Middle East where it survived. For centuries it was absent in Belgium but during the Roman Empire it was brought back. In Herstal, near Liège, a fallow deer skeleton was discovered and studied using radiocarbon dating, which confirmed that it dated back to the Romans time (Pigière et al., 2020).

Over the centuries, populations increased and spread all over Belgium. Today, there are several populations living in the region: some are kept in deer parks or private enclosures, while others live in the wild. The largest known population is currently located in the Drongengoed forest in the province of East Flanders, between the towns of Bruges and Ghent.

The status of the species is very complicated (see below). However, the fallow deer in Flanders needs to be managed to control the population density and prevent its impacts such as overgrazing and competition with native species.

The distribution map of the fallow deer in Flanders is reported below (***Figure 9***). The map, as the others above, utilizes filtered occurrence data from GBIF (GBIF.org, 2025).

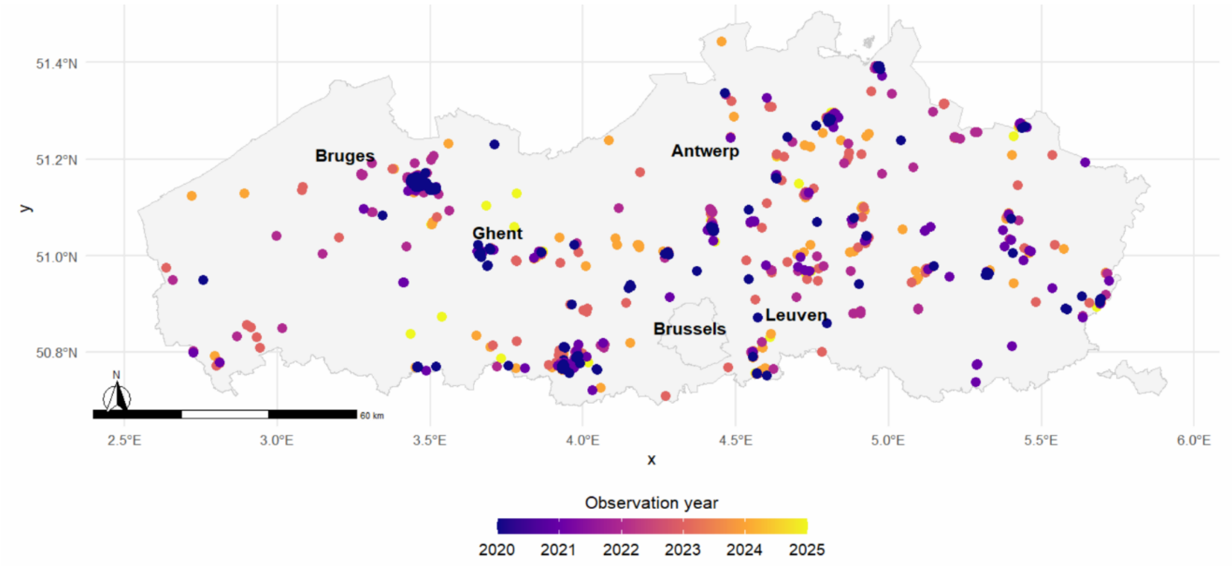


Figure 9: Dama dama observations in Flanders (since 2020, verified observations only). Source: GBIF (2025).

1.5.4 Legal status of fallow deer

The fallow deer has a complicated situation in Belgium. Although clearly a non-native species on scientific (biological and historical) grounds, it is legally considered a game (huntable) species according to Flemish law. This is partly motivated by the fact that the species presumably has a long history of introductions, dating back to ancient (Roman) times.

In practice, its status as a game species implies that management needs to fully adhere to the legislative framework for hunting. Among practical implications (e.g. timing, ammunition, permits…), this also implies that fallow deer can only be shot according to pre-set targets.

Its environmental impacts are considered moderate, and it has been categorized as a species with moderate risk in Belgium by Branquart et al. (2009).

1.5.5 Management of fallow deer

The management of the fallow deer is not simple in Flanders. The populations need to be controlled because of the potential problems caused by the high density of this species: they can cause very severe damage to ecosystems and their browsing on woodlands can alter the vegetation communities and lead to biodiversity loss (Massetti et al., 2008). At the same time, the population cannot be eradicated because it is a legitimate game species. In Flanders, the official hunting season for the fallow deer is from 1st October to 31st December for everyone with the legal requirements (more details below).

1.6 Density estimation

Estimating the density of a population is essential when assessing the status of species, especially when there are non-native and invasive species that are under management.

There are several methods to estimate the population density, including census, sampling with transects, the kilometric index and capture-mark-recapture. These methods require significant amount of time and effort; they could also be very challenging and expensive. Some of them need animals with individual marks to be identified but not every species has natural markings, and some species are difficult to spot because they can be elusive or active at night (Rowcliffe et al., 2008).

In 2008, a new model was developed to overcome these problems and estimate population density using camera traps, without the need to recognize each animal individually (Rowcliffe et al., 2008). Camera traps are a non-invasive method to study animal populations; they can operate for hours both day and night, in difficult habitats and conditions, saving researchers time, effort and money. Testing the method in an enclosed animal park with known density, Rowcliffe et al. (2008) described for the first time this new technique, named the "Random Encounter Model" (R.E.M.).

The idea behind this method is to calculate the population density by considering the animal's trapping rate, its speed, and the camera trap detection area. In order to do that there are some steps that need to be followed: first the area must be calibrated and animal movement parameterized. After this, the analysis can be performed. I used this technique to estimate the densities of several species in the present thesis.

1.7 Study objectives

The aim of the thesis was to monitor and assess the status of key populations from three non-native Cervidae in the Region of Flanders (northern Belgium). Their status was studied at population level by focusing on (1) the oldest, and presumably largest, population of Chinese muntjac, (2) the only known population of sika deer, and (3) the biggest population of fallow deer in the region. Their presence, density, diurnal activity and behavior were studied using camera traps during the autumn and winter of 2024-2025.

The project contributes to the understanding of these dynamics trying to develop more effective management strategies to mitigate the ecological effect of deer overabundance in the northern half of Belgium (the Region of Flanders). To better understand these populations, I used camera traps to study their behavior and activity patterns, and I estimated the density of the populations through advanced techniques.

For muntjac, the goal was to detect the presence of the species in the park and calculate the density of the population, identify the most frequented areas, and analyze the diurnal activities to maximize the stalking efforts in the attempt to completely remove this Union-listed species locally.

For the sika deer, the aim was to determine whether the species was still present in the area following the culling campaigns of the last years, and whether the native red deer was present, so potentially holding a risk of hybridization.

Lastly, for the fallow deer, there was a need to monitor the population density to correctly inform any future management decisions (e.g. hunting quotas). I also monitored the roe deer population density to evaluate potential changes due to competition with *Dama dama*, as well as the density of the red fox, the primary predator of fallow and roe deer fawns in the area.

2 Materials and methods

2.1 Study sites

The studies sites for this project were located across the Region of Flanders (***Figure 10***), in line with the objectives and the different study species: ‘Park Vordenstein’ and ‘De Inslag’ for muntjac in the province of Antwerp, ‘Platwijers’ for sika deer in the province of Limburg, and ‘Drongengoedbos’ for fallow deer in the province of East Flanders.

A total of 82 cameras were placed for this study:

- 32 cameras for *Muntiacus reevesi*,
    - 16 in Park Vordenstein,
    - 16 in De Inslag.
- 14 cameras for *Cervus nippon* in Platwijers,
- 36 cameras for *Dama dama* in and around Drongengoed.

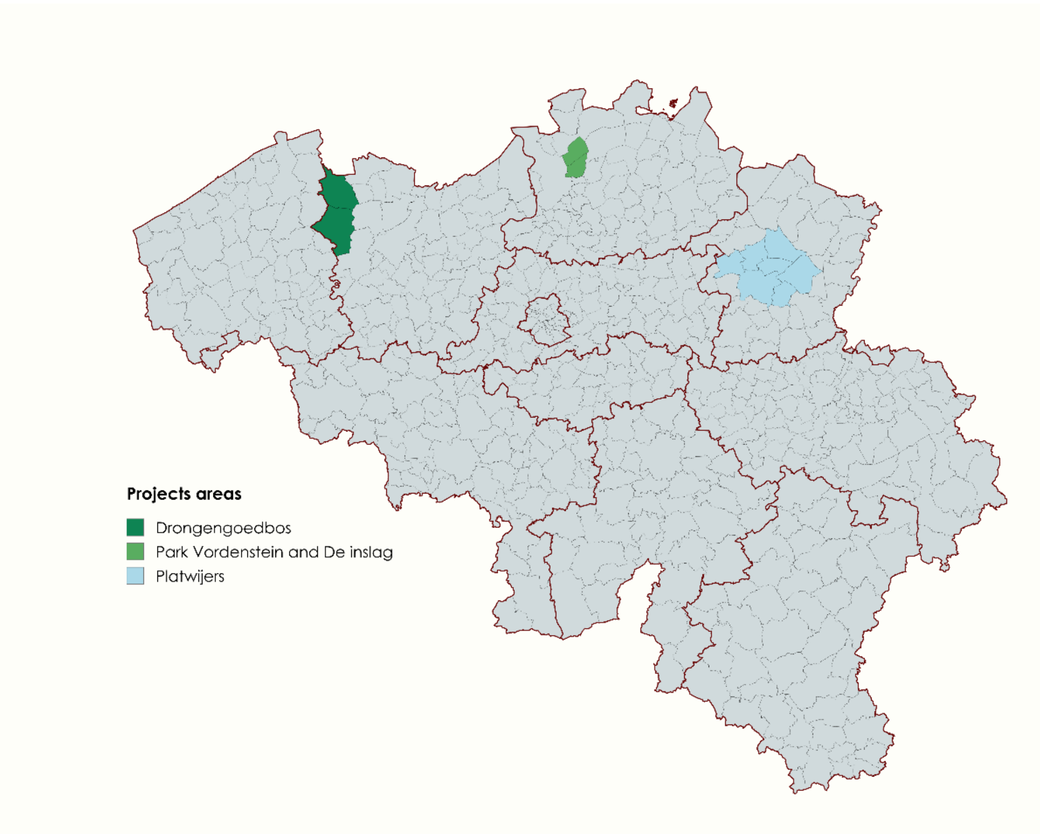


Figure 10: General location of the study sites. Shown are the involved municipalities (color) with respect to the Belgian provinces (dark lines).

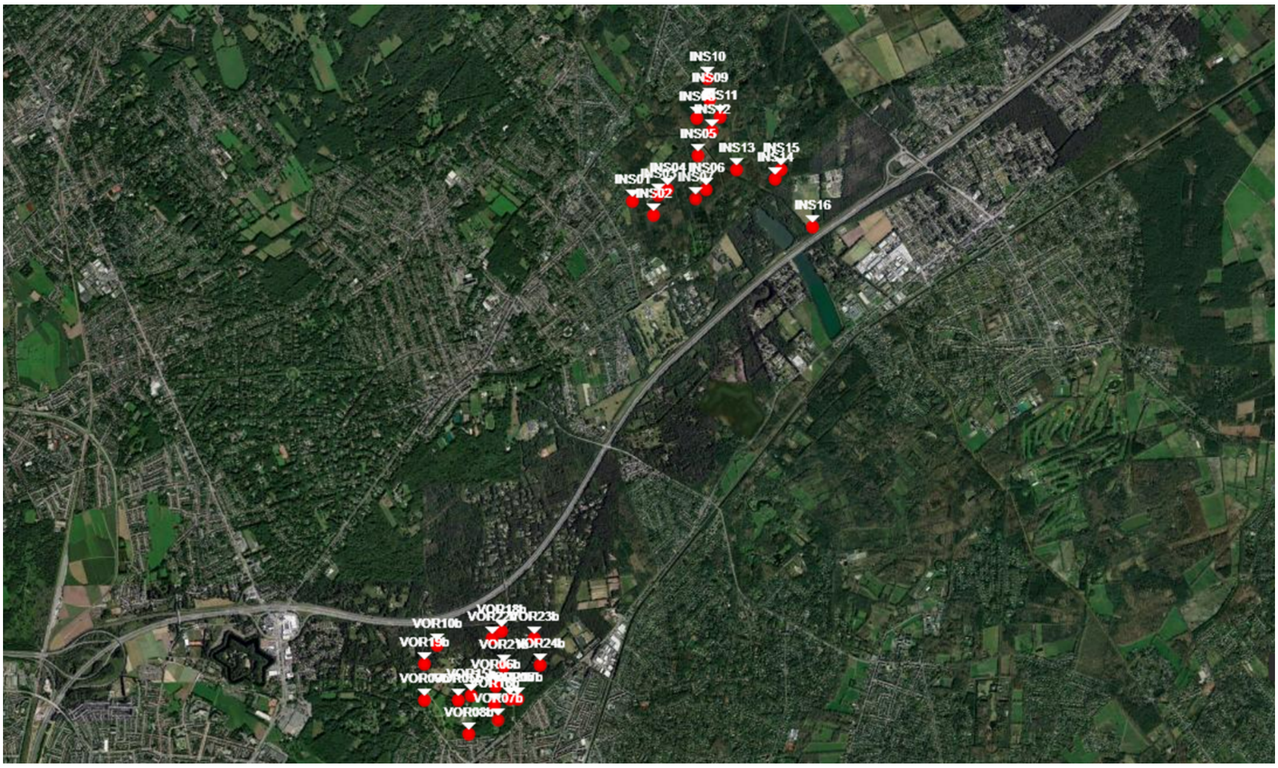
2.1.1 Park Vordenstein and De Inslag (muntjac)

The best-known muntjac population in Flanders is located in the eastern part of the city of Antwerp, in two suburban forest areas known as Park Vordenstein and De Inslag (municipalities of Brasschaat and Schoten). The muntjac population originated from a private estate close to Park Vonderstein, as confirmed by genetic analysis (Deflem et al., 2022). Indeed, the genetic analysis showed close relationship among individuals from the park, the estate, and animals within a 10-kilometers radius.

Park Vordenstein is a 137 hectares domain mostly owned by the Flemish Government and managed by ANB, with a smaller portion privately owned (D'hondt et al., 2023). The park has both aesthetic value and ecological value. 87 hectares are classified as forest, which is dominated by *Pinus sylvestris*, *Betula* spp. and *Fagus sylvatica*, with *Rhododendron* spp., *Rubus* spp. and *Pteridium aquilinum* as the most common species in lower layers. A moat surrounds the area, serving as a natural boundary. To preserve the natural value, the park is closed to the public by night and dogs are not allowed at all. In 2020, Park Vordenstein became the starting point for muntjac management efforts, under the supervision of ANB and INBO (D'hondt et al., 2023) (see above).

De Inslag is a 147-hectares area located approximately 10 km from Park Vordenstein, still within the suburban area east of the city of Antwerp. The domain is also managed by the ANB, in collaboration with Natuurpunt (ANB, 2025). Since around 1600, the area was converted from heathland into arable and pastureland, and later became forested. During both World Wars, significant damage was inflicted on the area, including the construction of the Antitank Canal, which still runs through the domain as an important barrier for animal movement. Reforestation began around 1950, and now the forest is dominated by *Pinus sylvestris* and *Larix* spp. Recent plantings aim to increase the prevalence of deciduous trees. The area is important for the breeding of amphibian species and also provides habitat for a variety of birds species, as well as roe deer and foxes. De Inslag is open to the public from sunrise to sunset and there are a lot of walking trails and picnic areas. Dogs are allowed on a leash (ANB, 2025).

The 16 cameras in Park Vordenstein were placed in 2020 while in 2024, another 16 additional cameras were installed in the nearby area, De Inslag, to monitor the population there too. The camera stayed up in the winter/spring months, from November to May. During the years of the whole work, some locations were changed and relocated due to stealing problems, cameras defections or movements of other species. The locations of the 32 camera traps in the parks are shown on the map (***Figure 11***).



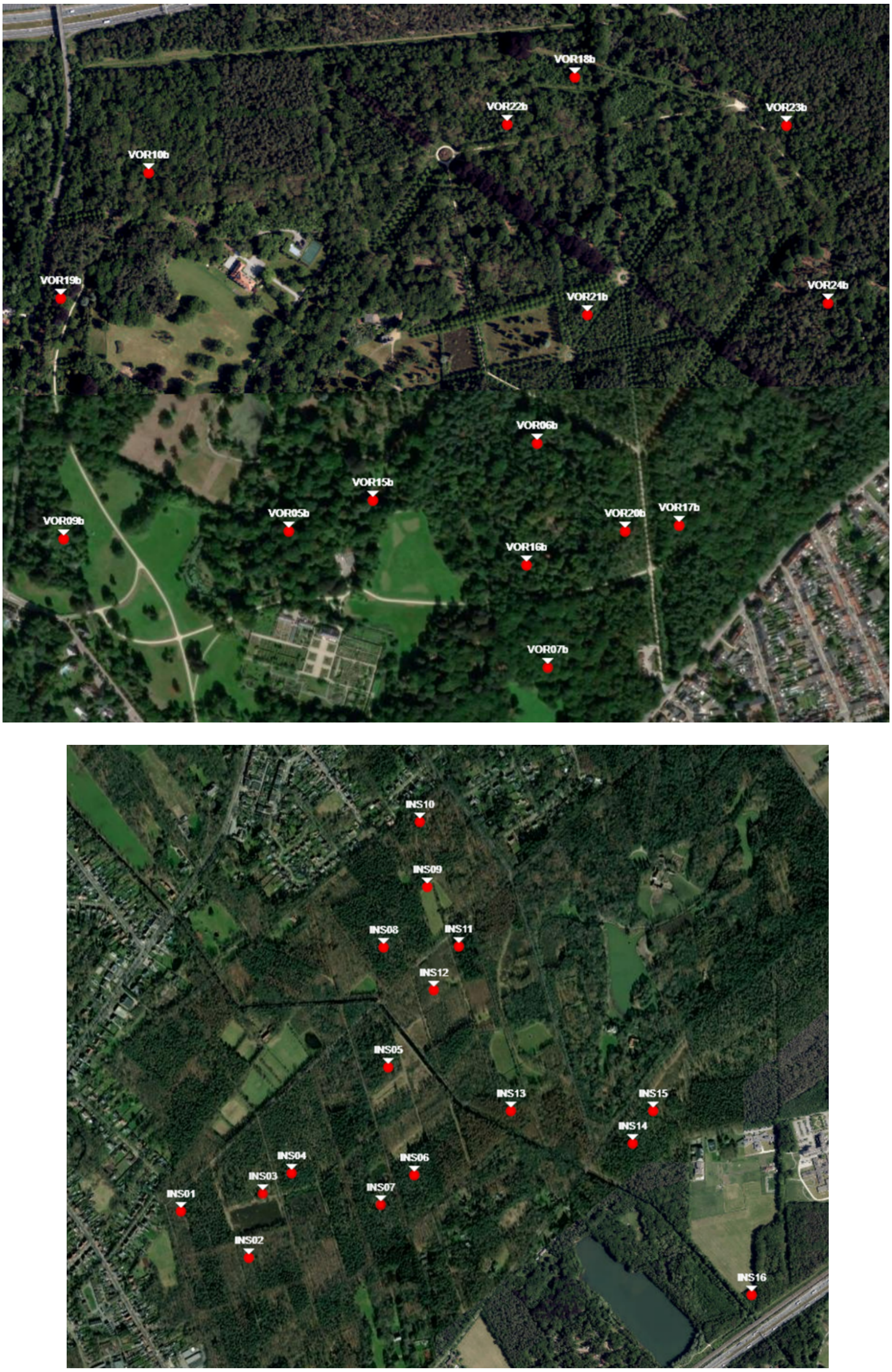


Figure 11: Park Vordenstein and De Inslag deployments location (top: the two study sites and their surroundings; middle: Park Vordenstein, detail; bottomt:De Inslag, detail).

For the muntjac's project, camera traps data were collected over a period of about five months. The cameras were installed at the two locations on 14th and 20th November 2024. They were placed in the same positions used during the previous year of the project, and the area was recalibrated each time I went to retrieve the SD cards. The last pick-up took place on 9^{th} and 10^{th} April 2025, with two intermediate collections in January and February (none in March 2025).

2.1.2 Platwijers (sika deer)

As previously mentioned, the only known sika population in Belgium is in the Flemish province of Limburg. Specifically, the population inhabits Platwijers, a part of a larger area known as the Wijers, which includes over 1,000 ponds spread across eight municipalities (Hasselt, Genk, Heusden-Zolder, Houthalen-Helchteren, Zonhoven, Lummen and Diepenbeek) (***Figure 12***). The Platwijers area itself is approximately 100 hectares, including fishponds, reed beds, grasslands and wetlands and it is particularly renowned for its birdlife. In facts birdwatching facilities such as observations towers can be found here (ANB, 2025).

The ponds are man-made, originally created for mining iron and peat from the soil. Later, they were used for fish farming, especially the breeding of carp, which remains a significant activity in the municipality of Zonhoven. The level of the water in the ponds is controlled by a sophisticated system of dikes, streams, inlets and outlets (De Wijers, Regional Landscape Lage Kempen, 2025~~n.d.~~).

This zone is a unique combination of nature, tourism and culture and serves as a habitat for many rare plants and animal species. That's why a significant part of the area is now part of the Natura 2000 network and is protected by the European Union. The area is actively managed by a partnership of multiple organizations, including ANB (De Wijers, Regional Landscape Lage Kempen, 2025).~~n.d.).~~

On the 4^{th} of October 2024, 14 cameras were installed in the area for the first time, selecting locations with signs of the animals with the local forester. The cameras were placed all around the site to study the population: their locations are reported in ***Figure 12.***

Figure 12: Platwijers deployment locations.

For this study, data were collected over a period of about four months. The last SD card retrieval took place on 25th February 2025.

2.1.3 Drongengoed (fallow deer)

The Drongengoed forest is the largest forest in the province of East Flanders, spanning 750 hectares of natural landscape between Bruges and Ghent (municipalities of Aalter and Maldegem). Within the forest lie remnants of ancient heathland. The land was reclaimed around the 13th century and largely transformed into a forest. However, traces of the original heathland remain, with plants such as heather (*Calluna vulgaris*, *Erica* spp.) or *Drosera* spp (sundew). The area is home to various native animals, including locally rare bird species such as nightjar (*Caprimulgus europaeus*) and raven (*Corvus corax*), and mammals such as roe deer. The area is open to the public, offering trails for walking, cycling, and horse riding as well as a visitor center and guided walks. In the forest, there is a military terrain, managed by both military and ANB, that includes a landing strip (ANB, accessed 2025~~n.d~~).

The forest is managed collaboratively by several partners but the most important are: ANB, the municipalities, and the military government. Together with the researchers from INBO, the foresters oversee the management of ~~the wildlife~~wildlife in the area, with particular attention to the fallow and roe deer populations (ANB, accessed 2025~~n.d~~).

In Drongengodbos, the hunting on the ANB terrains officially started in 2023 after a hunt in 2019 sparked public controversy (INBO, pers. comm.). It takes place for one week in January, February and March not even in the official hunting season for this species ~~(ANB, n.d.)~~.

The first inventories of fallow deer here were made around 2010, estimating the population trend using the Kilometric Index. The Kilometric Index (KI) consists of surveying fixed trails and counting animals observed along the way. The index is then obtained by dividing the number of animals spotted by the total of distance covered (Pallemaerts et al, 2024). The first years of data (2010-2014) showed a very low population, around 1 to 2 deer spotted per km, then around 2020, increased, showing a population growing every year, going from around 4 deer/km to more than 6 deer/km (***Figure 13***).

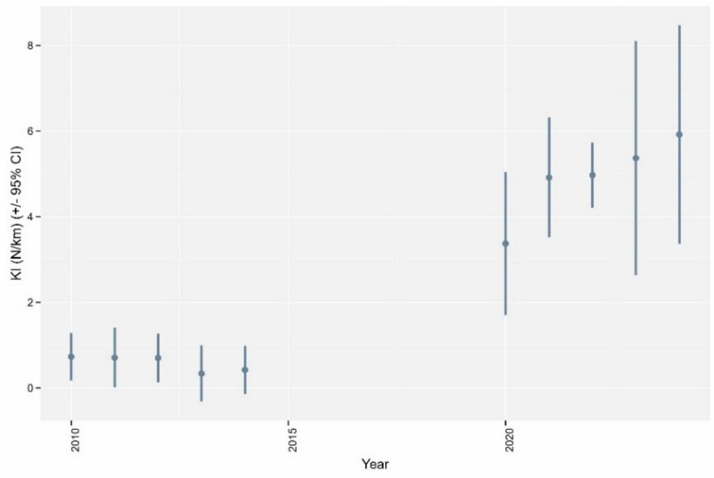


Figure 13: KI results in Drongengoed from 2010 to 2024. © INBO

ANB started the official request for a management project in 2020 after seeing the growing population in the forest. After the first report (Casaer et al, 2021), the 9-year management project started in 2022 with 36 camera traps working in the area from the end of the year continuously. The first license hunt in the ANB terrains was in 2023 and deer were killed and reported with the surrounding Game Management Unit shootings. There was an increase in the number of animals killed since this area was added to the hunts (***Table 1***): ***Figure 14*** shows the results of the management of the area with the largest fallow deer in Flanders.

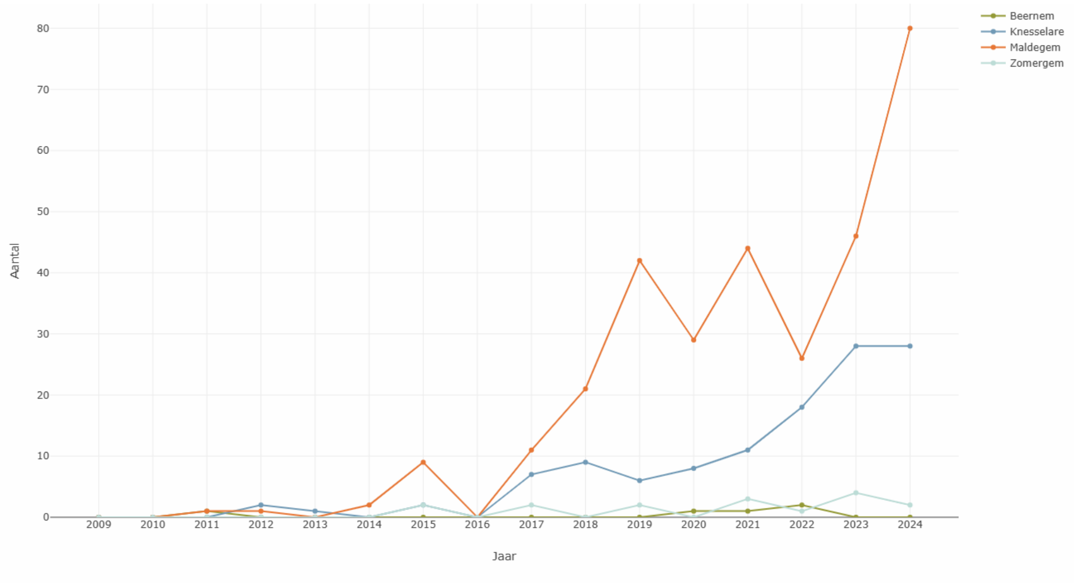


Figure 14: Report of killed fallow deer in four Flanders locations in the last 15 years (2009-2024). Orange line shows killings in the area of Drongengoed, other lines represent killings in the surrounding GMU. Data from 2023 include hunts in the ANB terrains in Drongengoedbos (faunabeheer.inbo.be).

Year	Location	Number of fallow deer shot
2023	Drongengoed	46
2024	Drongengoed	80
2025	Drongengoed	27

Table 1: Licenced hunt results of fallow deer in Drongengoed.

In Drongengoed forest, several volunteers were involved in the project; they maintained the camera trap network by monthly collecting SD cards and checking the batteries; they also annotated the pictures on Agouti (see below). For this specific study, I used a subset of the camera trap dataset (September to December 2024) to calculate the fallow and roe deer densities, as well as those of the red fox, the locations of the 36 camera trap is shown below (***Figure 15***).

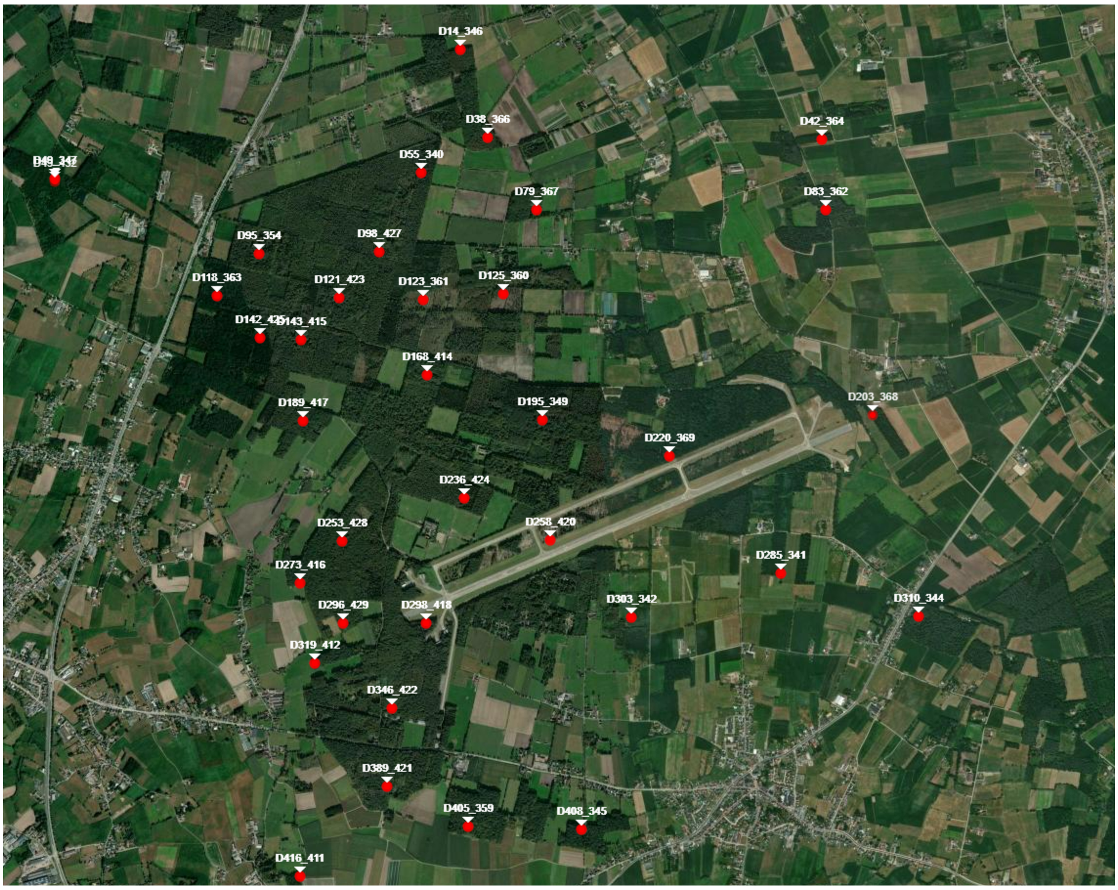


Figure 15: Drongengoed deployments locations.

2.2 Camera traps

For the present study, I used camera traps from the company Reconyx (United States). I used the HC600 Hyper Fire model for the muntjac project and the Hyper Fire 2 model for the sika and fallow deer projects. Both cameras are equipped with a Passive Infrared (PIR) motion detector and a nighttime infrared illuminator (Reconyx Hyper Fire instruction manual, 2017; Reconyx Hyper Fire 2 user guide, 2023).

The cameras operate with 12 AA-cell batteries (Energizer Ultimate Lithium) that function from 60°C to -40°C. The performance of both the camera and the battery can vary depending on several factors, including camera settings (e.g., videos are more demanding than pictures), animal activity, temperature, and age of the camera, all of which can affect its operational duration (Reconyx Hyper Fire instruction manual, 2017; Reconyx Hyper Fire 2 user guide, 2023).

The motion detectors of the Hyper Fire and Hyper Fire 2 can detect movements up to 30 meters away. It consists of two horizontal detection zones and triggered if two conditions are present: (1) an object with a different temperature than the background is present within the detection zones, and (2) that object moves in it. The coverage area of the PIR motion detector spans a 40° field of view up to 30m (***Figure 16***) (Reconyx Hyper Fire instruction manual, 2017; Reconyx Hyper Fire 2 user guide, 2023).

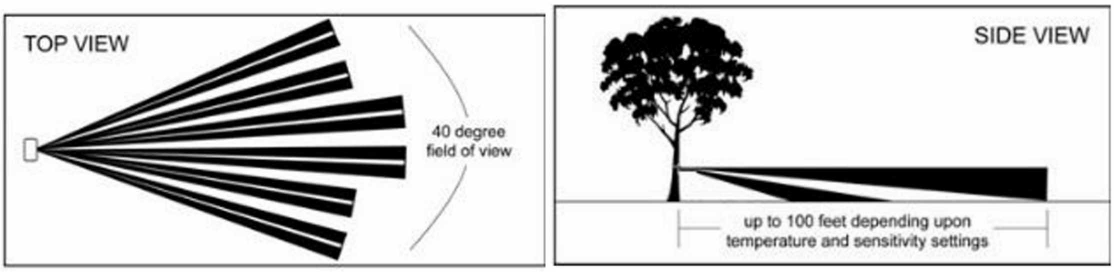


Figure 16: PIR motion detector coverage area (Reconyx Hyper Fire and Hyper Fire 2 user guide).

If the camera detector is triggered, it is set to take a sequence of 10 pictures. After capturing 10 pictures, if the animal is still present (detected by heat and movement), the camera will take another sequence of 10 pictures, continuing the process until no heat or movement is detected. The camera was also set to automatically take a single picture at midday and at midnight (i.e. timelapse photos) as a control of the camera's functioning. The photos were stored on a 32GB SD card, which was replaced approximately monthly.

2.2.1 Camera trap setup

Cameras were armed and mounted on trees at selected positions, with the help of the study site's forester (ANB) and other experts. They were placed away from roads and hiking trails. For the study sites on muntjac and fallow deer, the locations were chosen randomly. For muntjac, this was fully random, while for fallow deer, randomization was achieved through a regular grid with individual cells chosen by means of a GRTS model (Generalized Random Tessellation Stratified) (Stevens & Olsen, 2004). Although at local level, for the muntjac and sika deer project, slight shifts up to some decameters were allowed to optimize detection (e.g. towards animal trails in the vegetation), in the fallow deer one the camera was always facing North. This randomization of positions was a prerequisite for the application of the density estimation using REM (see below).

For sika deer, where no density estimation was planned, the cameras were positioned non-randomly, in favor of maximal detection (i.e. inspired by the presence of faecal pallets, trails, footprints or signs of browsing).

The cameras were protected by a rugged, weather-resistant case and secured to trees using a Python cable lock by Masterlock (Reconyx, 2023) to prevent theft, even though the cameras also had a security code that avoids use by unauthorized users.

The cameras were always placed 50 cm above ground to optimize species detection and were positioned facing North to prevent false triggers caused by sunlight and heat (***Figure 17***).

Figure 17: INBO Hyper Fire 2 camera trap in Platwijers.

2.3 Agouti

About once a month, the camera traps were checked (either by INBO researchers, by local volunteers, or by myself, depending on the project) during a field visit, and the SD cards were retrieved (and replaced by empty ones). All retrieved images from the cards were then analyzed with the help of Agouti.

Agouti is a non-profit initiative of Wageningen University (The Netherlands) and the Research Institute for Nature and Forest (INBO) that helps organize, process, and store camera trap images (Agouti.eu, 2025~~, n.d.~~). The platform offers an interface where users can create projects, collaborate on them, upload images, annotate them with species identification and characteristics, and export them (***Figure 18***) (Casaer et al., 2019).

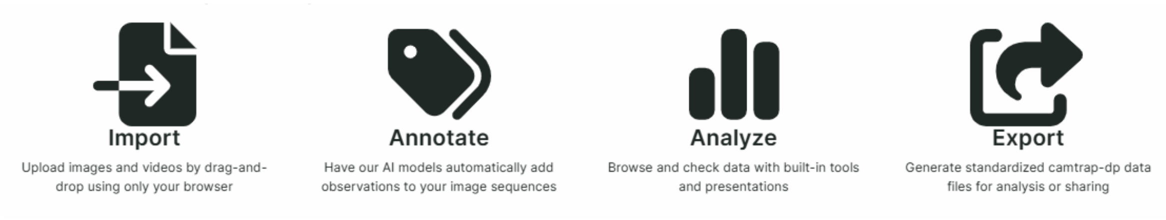


Figure 18: Agouti workflow (Agouti.eu).

The workflow is as follows:

- After collecting the camera data from the field, the users can upload the entire contents of the SD card on the platform, creating deployments with the camera trap's locations (Agouti.eu, 2025~~, n.d.~~).
- Agouti automatically groups the images into sequences representing the same event using the timestamp on the pictures and other metadata. If the sequences are more than two minutes apart, Agouti will consider them as two separate sequences.
- Users can manually annotate each sequence with one or more observations, adding the species, number of animals, sex, behavior and notes (***Figure 19***). Agouti also offers the possibility to annotate images using different Artificial Intelligence (AI) models. The base model classifies images as "blank", "contains an animal" or "human". If an animal is detected, a second classifier adds an observation and attempts to recognize it. The AI-annotated pictures can then be validated by the users (Agouti.eu, 2025~~, n.d.~~).

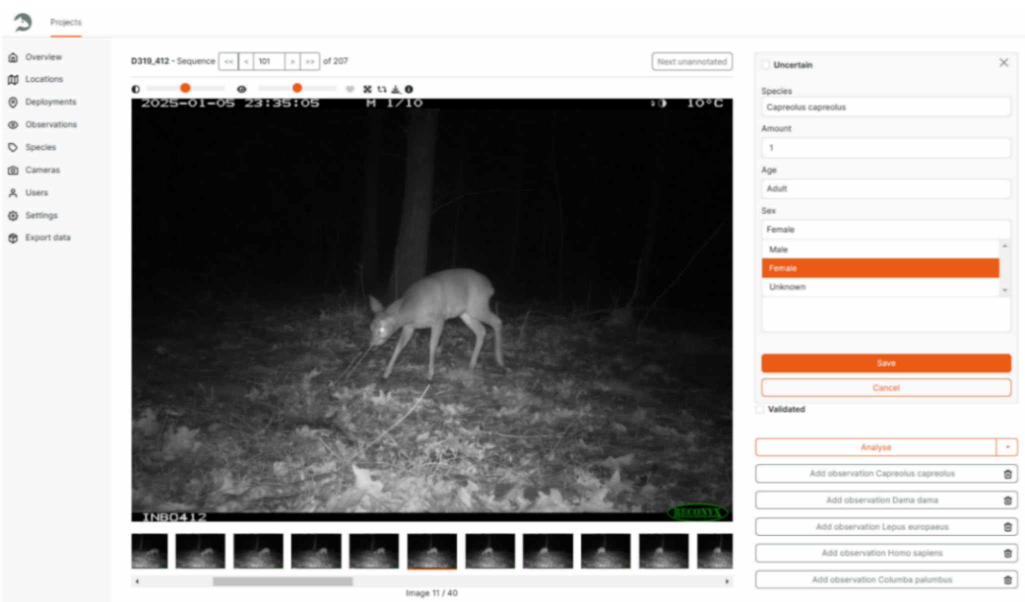


Figure 19: overview of the manual annotation process on Agouti.eu.

- After the annotation process, the data can be analyzed with built-in tools such as animal tracking (Agouti.eu, 2025~~, n.d.~~). This is extra data preparation for specific models.
- At the end of the work, the data can be exported as a Camera Trap Data Package (Camtrap DP; Desmet et al., 2024) and used for analysis in software like R (Agouti.eu, 2025~~, n.d.~~).

For the present thesis, each case study had its own project in Agouti (***Figure 20)***. For the muntjac and sika deer, I annotated the pictures manually, while for the fallow deer project, I used also AI recognition with the Western Europe v4a model (Agouti.eu, 2025~~, n.d.~~) as well as annotation by the local volunteers.

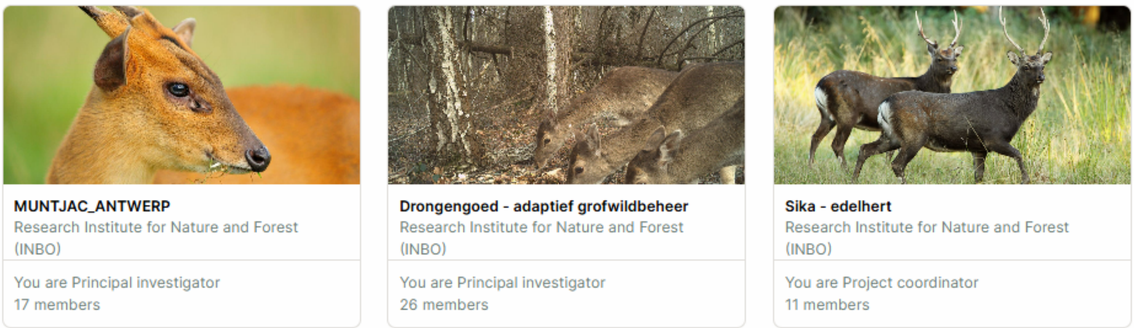


Figure 20: projects overview in Agouti (Agouti.eu).

2.4 R.E.M.

In the muntjac and fallow deer projects, I estimated the densities of species by means of the Random Encounter Model (R.E.M.) developed by Rowcliffe et al. (2008). This allows for the estimation of densities without the need for individual recognition. Thanks to camera trap work and the animal tracking process on Agouti (detailed explanation in the following chapters), I was able to obtain all the parameters needed for this analysis. Combining these parameters in the following formula, the population density can be calculated.

2.4.1 Calibration

For the density formula described by Rowcliffe et al. (2008), almost all the parameters can be obtained from the camera trap data; the only missing parameters are the animal's speed (v), detection radius (r) and detection angle (θ, theta). To calculate the animal's speed using camera traps, I first calibrated each deployment (see below). r and θ are defined by the first tracked point. The first protocol for deployment calibration was finalized in 2022 by the ENETWILD consortium (Casaer et al., 2022).

To calibrate each deployment, I used a straight pole (PVC tube or wooden stick) marked with duct tape every 20 cm, extending up to 1 meter of height. Multiple bands of duct tape can be used to mark the increasing height, e.g. one band equals 20 cm, and four bands equal 80 cm (Casaer et al.,2022). The top of each group of bands corresponds with the given height. The bottom of the pole is placed to the ground and then moved around the camera's detection zone to have pictures taken at different positions. The pole must always be perpendicular to the ground (checked with a level) and held in position for 5/10 seconds to allow the camera to capture pictures. For each deployment, it is important to obtain 10, ideally 20, clear different pole locations (Casaer et al., 2022). For more accuracy, if the camera is moved for SD card changes or other reasons, the calibration must be repeated. Also, to ensure the camera is triggered, especially when the pole is far from the camera in the detection zone, another person should be present to move and trigger the camera (***Figure 21***).

Figure 21: example of deployment calibration in the field. © INBO

After calibrating the camera's detection zone in the field, to calculate the animal's speed, I needed to record the height of the tape on the stick in Agouti, allowing the system to determine the precise distances and positions within the area. Agouti has a specific section in the “annotation” part that allows to indicate the height of two points on the stick in the calibration pictures (***Figure 22***) and then calculate the animal’s speed based on this information.

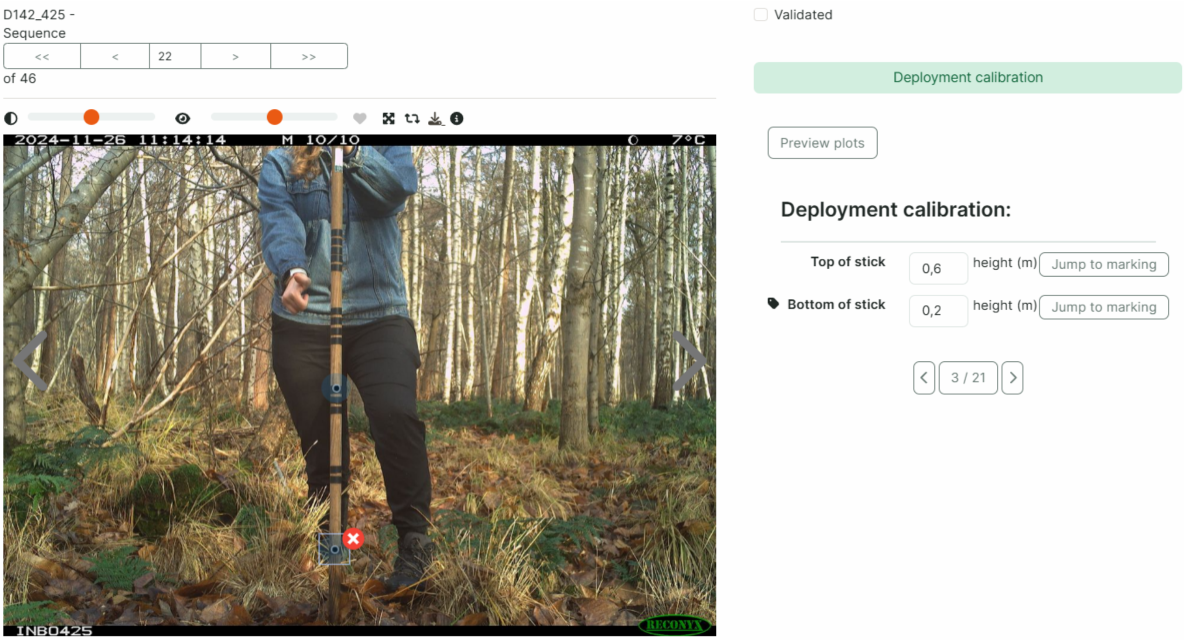


Figure 22: Deployment calibration process on Agouti.eu.

Once every calibration point on the field was recorded in Agouti, animal tracking, the final step to obtain their speed using camera traps, could be calculated.

2.4.2 Animal tracking

Animal tracking is the final step in calculating the animal’s speed, r and θ for population density estimation. “Animal tracking” means following the position of the animal in the pictures taken by the cameras and recording its precise location in each image. Using measurements obtained from the deployment calibration and the time stamp on the photos, the system has all the necessary data to calculate the speed of the animals based on the distance covered in time.

To track an animal using Agouti’s built-in tools, I selected one of the deer’s hooves, ideally the first visible in the picture of the first animal and follow its trails in the subsequent photos. By clicking on the points where the same chosen hoof touches the ground, a trail appears, showing the positions of the animal within the camera’s detection zone (***Figure 23***). The system is now able to calculate the speed, position, angle, direction of the animal tracked.

Figure 23: tracking of a roe deer across a series of pictures using Agouti. © INBO

Tracking was not always possible; sometimes the animals were running, jumping, lying on the ground, or too close to the camera, making it impossible to see the hooves and obtain at least two points to create the trail in the camera's detection area. These observations were not used to calculate speed, radius, or angle.

For the muntjac project, I tracked each muntjac directly in Agouti. Each muntjac observation was treated as independent, even if there was more than one muntjac in the same images. Therefore, each muntjacs had its own tracking, if possible. For the fallow deer project, I tracked only one animal per sequence, ideally the first one. Typically, *Dama dama* appeared in groups, and only one of them was tracked. Also, in this project, the density of roe deer and red fox population needed to be estimated too. Due to the large number of images to track, I did not track directly in Agouti, instead, I used an R script to extract the relevant sequences.

2.5 R

Once I finished with the annotation of the observations and the tracking of the study species, I exported the data from Agouti. The export comes out as a camera trap data package (Bubnicki et al., 2023) in a zip file with all associated data: observations, species, deployments, media, times and location.

This Agouti export was read into RStudio (Posit Team, 2023) to perform the analyses. First, packages from the "tidyverse" group (Wickham et al., 2019) such as "dplyr" (Wickham et al., 2024) were used to manipulate the data in the dataset and filter, order, organize them to visualize what needed.

For plots, maps and graphs I used libraries such as "ggplot2" (Wickham, 2016) and "leaflet" (Cheng et al., 2024). For the main analysis, I used the packages "camtrapR" (Niedballa et al., 2016) and "camtrapdp" (Desmet et al., 2024) to manage, format and manipulate camera trap data. To estimate the densities with the Random Encounter Model (R.E.M.), I used the R package "camtrapDensity" (Rowcliffe, 2024).

For each project, I studied the activity patterns of the focal species based on the timestamp of each observation. The analysis was performed in RStudio, primarily using the "activity" package (Rowcliffe, 2019) for modeling and visualizing patters, and the "suncalc" package (Thieurmel & Elmarhraoui, 2019) to calculate the solar times in radians.

Representing animal activity in radians allows for a circular and continuous visualization of daily activity, which is more appropriate for highlighting rhythmic behaviors that repeat over a 24-hour cycle, compared to the linear standard 24-hour format. Additionally, since sunset and sunrise shift with both season and latitude, and many species adapt their behavior based on natural light rather than clock time (Vazquez et al., 2019), this correction was necessary.

A comparison between the patterns of the species living in the same area was made to determine if the patterns came from the same underling distribution or were statistically different. It was performed using the compareCkern() function from the activity package (Rowcliffe, 2019), which implements a kernel density-based randomization method (Rowcliffe et al., 2014)

All the analysis carried out in R with the previously mentioned packages, are reported in the following table (***Table 2***) showing in which project it was performed according with the different aims.

Analysis	*Muntiacus reevesi*	*Cervus nippon*	*Dama dama*
Presence (site level, camera trap level)	✓	✓	✓
Frequency (camera trap level)	✓	✓	✓
Diurnal activity	✓	✓	✓
Density (REM, site level)	✓		✓
Crowding behavior (number of individuals per sequence)	✓	✓	✓
Sex (male/female)	✓	✓	
All behavior (frequence)	✓		
Reproductive behavior (timing)	✓		
Interaction with other species	✓	✓	✓
Density of co-occurring species (roe deer and red fox)			✓
Management	✓	✓	✓
Artificial intelligence (AI) (use in the project)			✓

Table 2: Analysis and information of the focal species.

2.6 Behavior keys

For the muntjac project, I also analyzed the focal species behavior to identify any unusual patterns and to study intersex interactions. To do this, I added a "behavior" section in Agouti. The list of behaviors from which I could choose was designed by experts at INBO after a year of observation. Each time a muntjac appeared in a sequence, I selected one of ten different following behaviors:

- **Caring** – animal licks another animal.
- **Unclear** – animal or behavior is not clearly visible.
- **Walking, general** – animal passing by; sniffing, investigating, or without associated behavior.
- **Running, tail up** – animal passes by alarmed (raised tail).
- **Licking stone** – animal shows interest in, or uses, mineral lick.
- **Grazing, head low** – animal consuming vegetation (head lower than shoulders).
- **Grazing, head high** – animal consuming vegetation (head higher than shoulders).

- **Other, comment** – animal exhibits other interesting behavior, add a comment to describe it.
- **Estrus: pursuit** – buck closely pursues goat.
- **Estrus: conflict** – buck fighting with buck.

When annotating behaviors, I followed a priority hierarchy: any behavior different from walking was given precedence, to better highlight other, more informative or less frequent behaviors, considering walking as a default activity that often occurs alongside more analytically relevant actions. If multiple behaviors occurred in a sequence, I recorded the most prominent or obvious one, so that every observation is linked to only one type of behavior.

2.7 Life stage

For the muntjac and sika deer project, I also tried to determine the life stage of the focal species. In deer, life stage is typically assessed through dental arc analysis (De Marinis & Toso, 2015). However, in this study, we attempted to determine the life stage using camera trap images, relying on observable traits such as the body size of the animal and the presence and size of antlers in males.

Determining the life stage of the recorded animals, however, proved to be more challenging than expected. As a result, this information was annotated as "unknown" (NA) in the dedicated section on Agouti for the muntjac, while an attempt was made for the sika deer. In some cases, this was easy, but in others it was more challenging due to factors such as partial visibility, lack of clear distinguishing sex or life stage features, poor lighting, or the animals being too far from the camera. In such cases, we also annotated the *Cervus* individuals as "unknown" (NA).

1 Results

3.1 Muntjac

Overall, all the 32 cameras across the two parks worked well throughout the study period (***Figure 24***). A few experienced minor issues considered acceptable "noise", such as small branches in front of the camera or slightly tilted cameras. At some locations the cameras were replaced due to frequent false triggers (mostly black pictures), while others did not work for a certain period of time during the study.

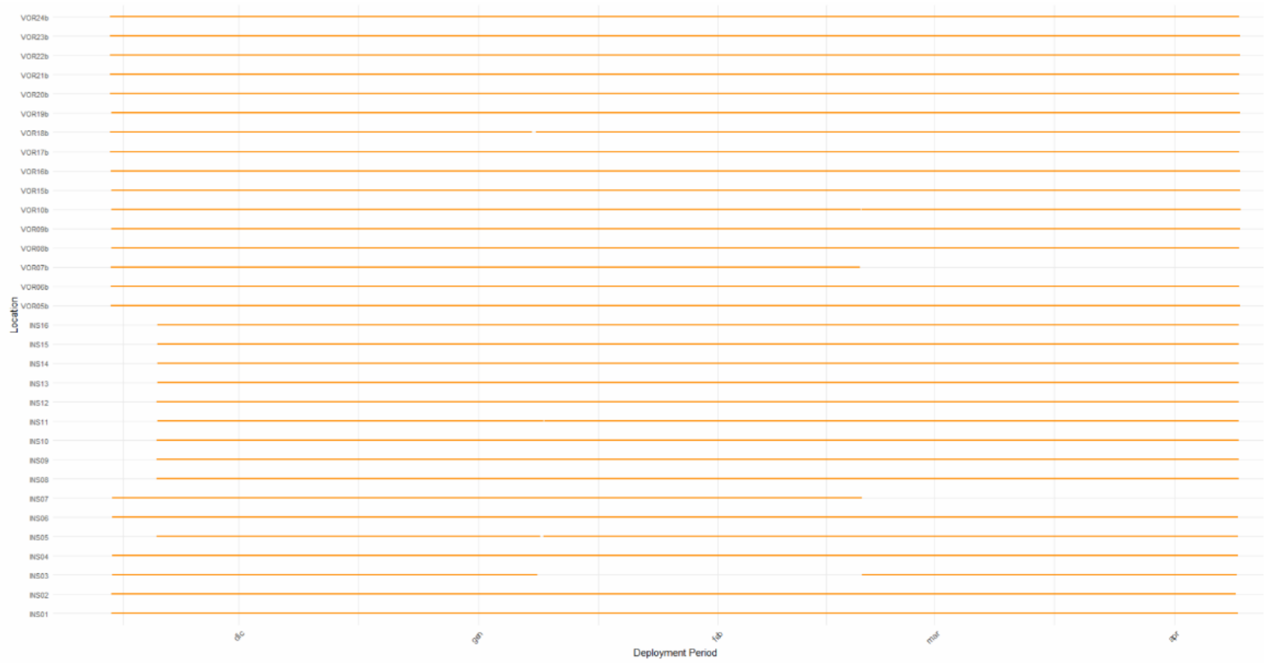


Figure 24: Overview of the start and end times (i.e. deployments) in Park Vordensatein and De Inslag. R

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3.1.1 Presence

The cameras in Park Vordenstein and De Inslag recorded a total of more than 2,350 wildlife observations. Excluding sequences of *Homo sapiens* and dogs, the most frequently observed species was roe deer, with 1,633 sequences representing 68% of all observations. Red fox was the second most frequently seen species in the area, making up 15.13% of the total.

Other species commonly recorded by the CTs (camera traps) in the area included hares (*Lepus europaeus*, 2%), domestic cats (*Felis catus*, 1%), individuals from the genus *Martes* and *Sciurus* *vulgaris* (respectively 0.9% and 1.85%), as well as a variety of bird species such as common wood pigeon *Columba palumbus* or *Parus major*.

Chinese muntjac was the third most observed species, with 125 recorded sequences, representing 5.27% of all observations. As expected, being a solitary species, 109 of the muntjacs sequences (87.2%) showed a single individual in the pictures, while only 16 sequences captured two muntjacs together (***Figure 25***). No groups of three or more were observed.

Of the 16 sequences featuring two muntjacs, 11 involved individuals of opposite sex, and five involved individuals of the same sex. Their behavior in these encounters is discussed in more detail in paragraph 3.1.3.

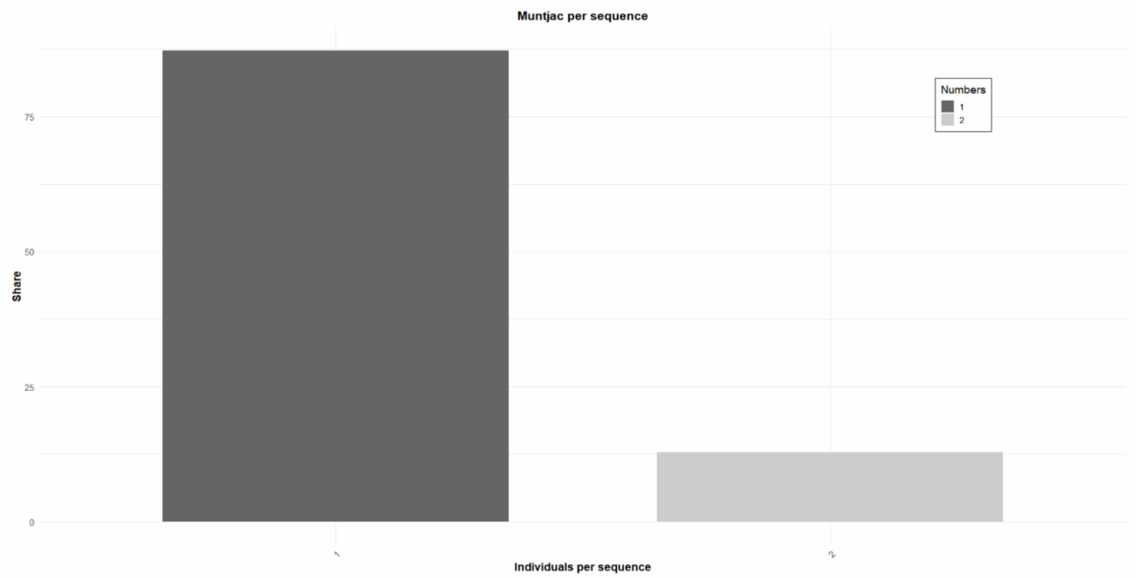

Figure 25: number of individuals of muntjacs per sequence.

Thanks to their distinctive facial markings and the presence of antlers in males, identifying male and female muntjacs was not too complicated, if image quality allowed: females and males seemed to be balanced in the population (***Table 3***). Life stage for this species was annotated as "unknown" (NA).

SEX	COUNT	PERCENTAGE
FEMALE	58	41.13
MALE	55	39.00
NA	28	19.86

Table 3: Muntjac sex share.

Two sequences showed muntjacs in the presence of other species. In one case, a muntjac appeared alongside a common wood pigeon, and in another, with a roe deer. In both instances, the muntjac was a female, and no notable interspecific interactions were observed. The muntjac was simply walking through the area, sniffing and investigating, while the other animal was also present with a similar behavior.

Muntjac presence was recorded at 9 (out of 16) locations in Park Vordenstain and at 9 (out of 16) locations in De Inslag. The most frequently visited deployment was, by far, VOR23b, situated on the northeastern edge of the park, where 61 muntjac sequences were recorded, almost half of all muntjacs observations (***Figure 26***). Other frequently visited sites in the southern part of the park included VOR05b, VOR08b and VOR07b with respective 15,10 and 8 sequences recorded (***Figure 26***).

In contrast, muntjac presence in De Inslag appeared to be less prominent. The locations with the highest numbers of sequences were INS13, INS14, INS15 and INS16, all situated along the southeastern border of the park (***Figure 26***).

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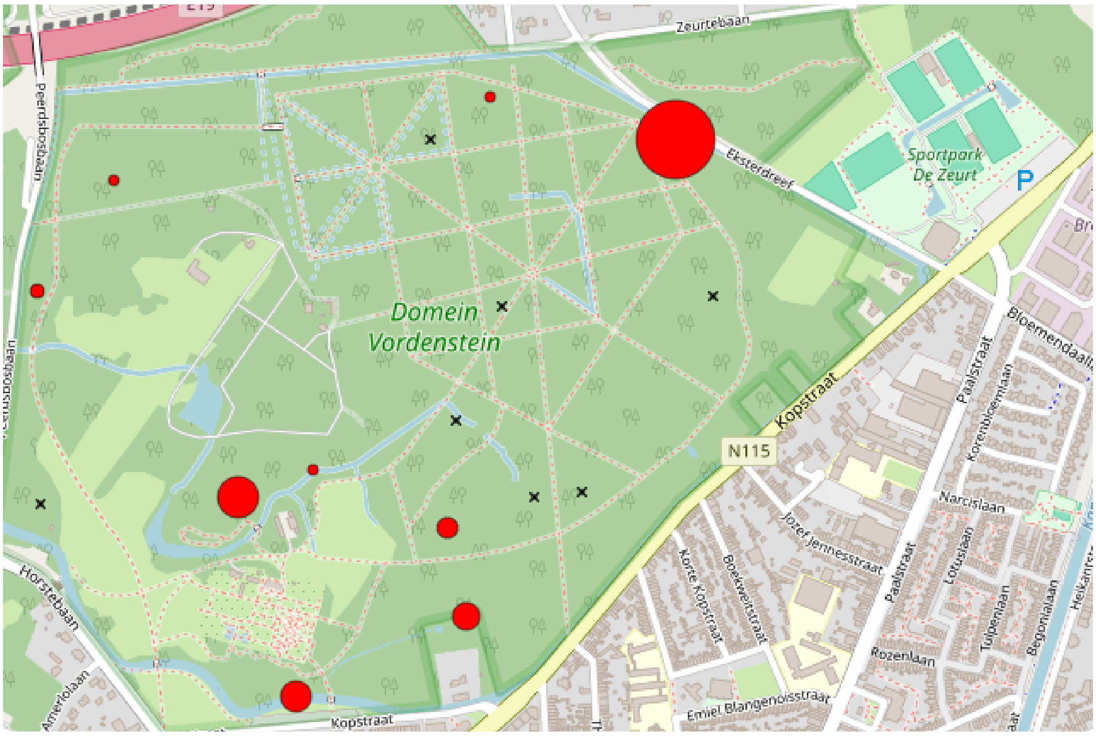

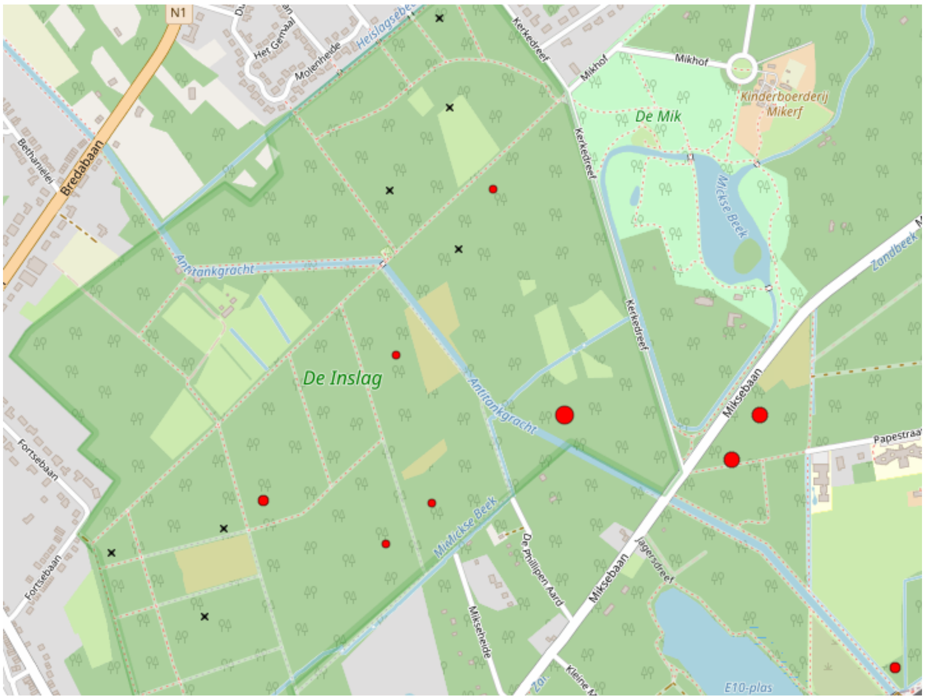

Figure 26: Muntjac presence in Park Vordenstein (top) and De Inslag (bottom). The bigger the sphere, the more sequences. X = no sequences.

3.1.2 Diurnal activity

Muntjacs were most active around sunset and during the night, rarely during daylight hours (***Figure 27***).

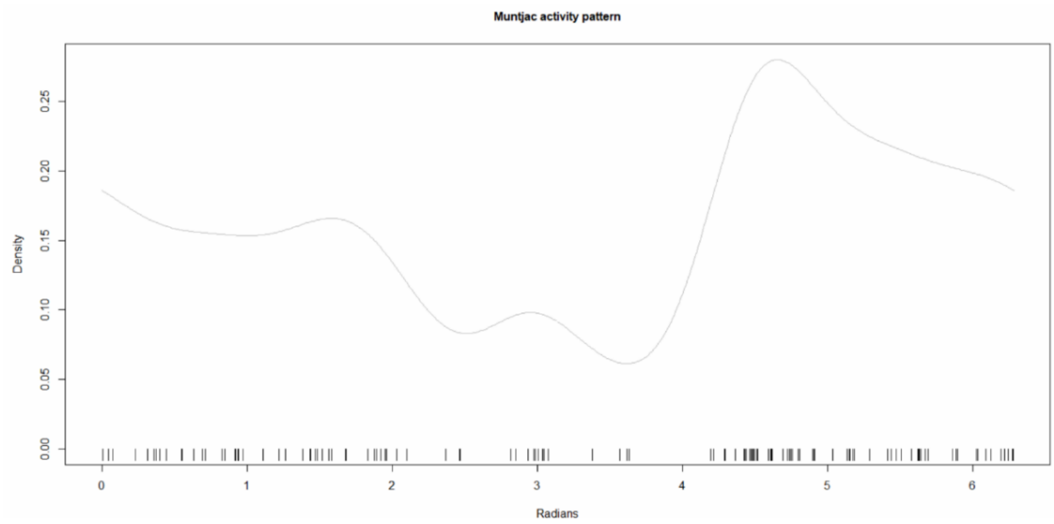

Figure 27: Muntjacs activity pattern. Time of day is shown on the x-axis in radians (0 corresponds to midnight, ± 1.5 to sunset, and ± 4.5 to sunset). Raw data at the bottom of the graph.

The statistical randomization tests did not show any difference between the distributions of muntjac and roe deer activities, even if roe deer tended to be more active during the day, especially around sunrise and sunset (***Figure 28***).

Looking at the activity patterns of *Homo sapiens* in the park, their paths rarely overlap with those of the muntjac (***Figure 28***).

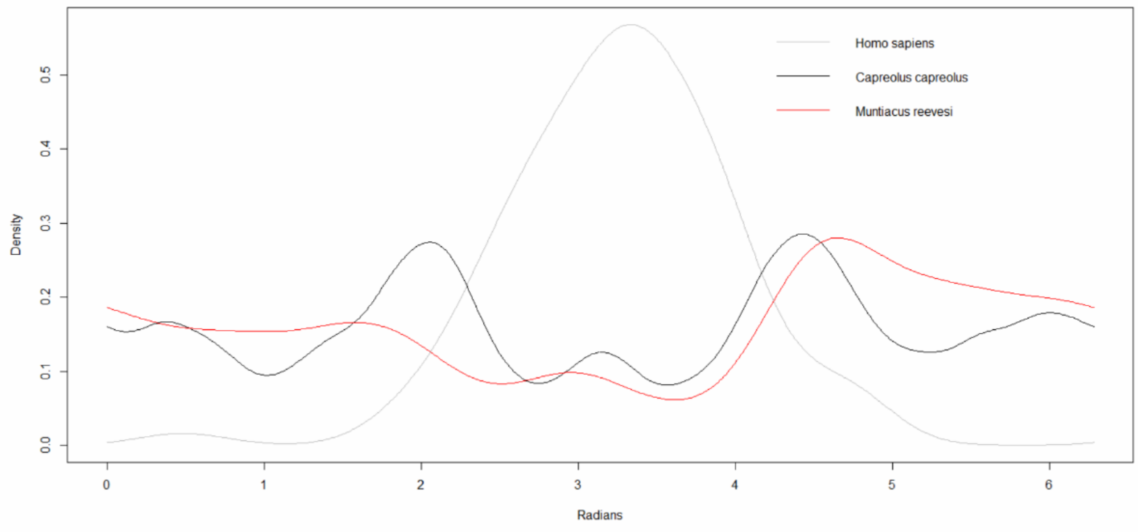

Figure 28: Muntjacs, roe deer and Homo sapiens activity pattern. Time of day is shown on the x-axis in radians (0 corresponds to midnight, ± 1.5 to sunset, and ± 4.5 to sunset).

3.1.3 Behavior

The most common behavior observed was simply walking without engaging in any notable activity, followed by running and grazing (***Figure 29***). Some behaviors, such as caring or licking stone (observed only at the location of VOR16a in Park Vordenstein, where a mineral block was present for a part of the study period), were very rare and have only been recorded once or twice since the project began in 2021 (***Figure 29***).

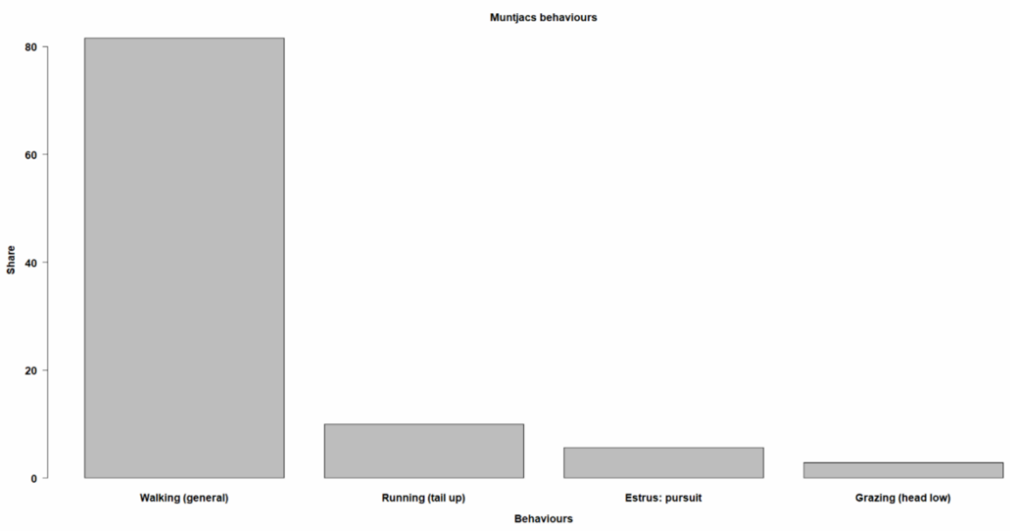

Figure 29: observed muntjacs behaviors.

When individuals of both sexes were together, in most of these sequences, the female was seen walking or running through the area, followed shortly after by the male, which was closely trailing her (***Figure 30***), being the typical estrus behavior, where the male follows the female during her receptive period.

Figure 30: intersex behaviors.

An analysis of observations including both a female and a male show that 72.7% of the behaviors are associated with estrus.

3.1.4 Density

The R.E.M. analysis for this species was carried out separately for the two parks. The results indicate that the species' density is very low in both areas (***Tables 4 and 5***). The model estimated the presence of 0.50 (95% CI: 0.16 – 1.50) and 0.16 (95% CI: 0.06 – 0.43) muntjac per km² in Park Vordenstein and De Inslag, respectively. Nonetheless, the observations indicate at least one male and female in each of these study sites. Considering the very low model estimates (and their confidence values), the small size of the areas (little over, and little less than a 1 km², respectively), and the observations, the results thus suggest that as few as a single couple are present per area.

Muntjac in Park Vordenstein	Estimate	Standard Error	Coefficient of variation	Lcl95	Ucl95	n	Unit
Density	0.50	0.30	0.61	0.17	1.50	NA	n/km²
Radius	7.74	0.55	0.07	6.66	8.81	88	m
Angle	31.92	2.64	0.08	26.75	37.09	93	degree
Activity_level	0.55	0.07	0.13	0.41	0.70	116	none
Active_speed	1.14	0.15	0.13	0.84	1.44	90	km/hour
Overall_speed	15.19	0.19	0.19	9.57	20.86	NA	km/day
Trap_rate	0.05	0.57	0.57	0.01	0.11	16	n/day

*Table 4: REM results in Park Vordenstain. **Estimate** refers to the point estimate of each parameter; **Standard Error** (SE) represents the uncertainty around the estimate; **Coefficient of Variation** (CV) is the ratio between SE and the estimate (CV = SE / Estimate), indicating relative precision; **Lcl95** and **Ucl95** denote the lower and upper bounds of the 95% confidence interval, respectively; **n** is the number of observations used for each parameter; **Unit** indicates the measurement unit. Reported metrics include: **Density** (estimated number of individuals per area), **Radius** (average detection distance), **Angle** (camera detection angle), **Activity level** (proportion of time the animal is active), **Active speed** (average speed during active periods), **Overall speed** (average daily movement speed), and **Trap rate** (detection frequency per day).*

Muntjac in De Inslag	Estimate	Standard Error	Coefficient of variation	Lcl95	Ucl95	n	Unit
Density	0.17	0.09	0.52	0.06	0.44	NA	n/km²
Radius	8.44	1.52	0.18	5.46	11.42	88	m
Angle	36.32	9.22	0.25	18.24	54.40	93	degree

Activity_level	0.31	0.10	0.32	0.11	0.50	116	none
Active_speed	1.21	0.24	0.20	0.74	1.69	90	km/hour
Overall_speed	9.03	3.41	0.30	2.34	15.71	NA	km/day
Trap_rate	0.010	0.01	0.52	0.01	0.02	16	n/day

Table 5: REM results in De Inslag. reporting the: standard error, the coefficient of variation, the lower (Lcl) and upper confidence interval (Ucl)at 95%. See caption of Table 4 for definitions.

3.2 Sika deer

All 14 cameras functioned and captured images for most of the 140 days of the project (***Figure 31***). A few of them stopped working prematurely for about a month due to battery issues or incorrect setup (for example, PW008 during the second month of operation and PW012 during the third). Most of the time, the camera took pictures without any issues.

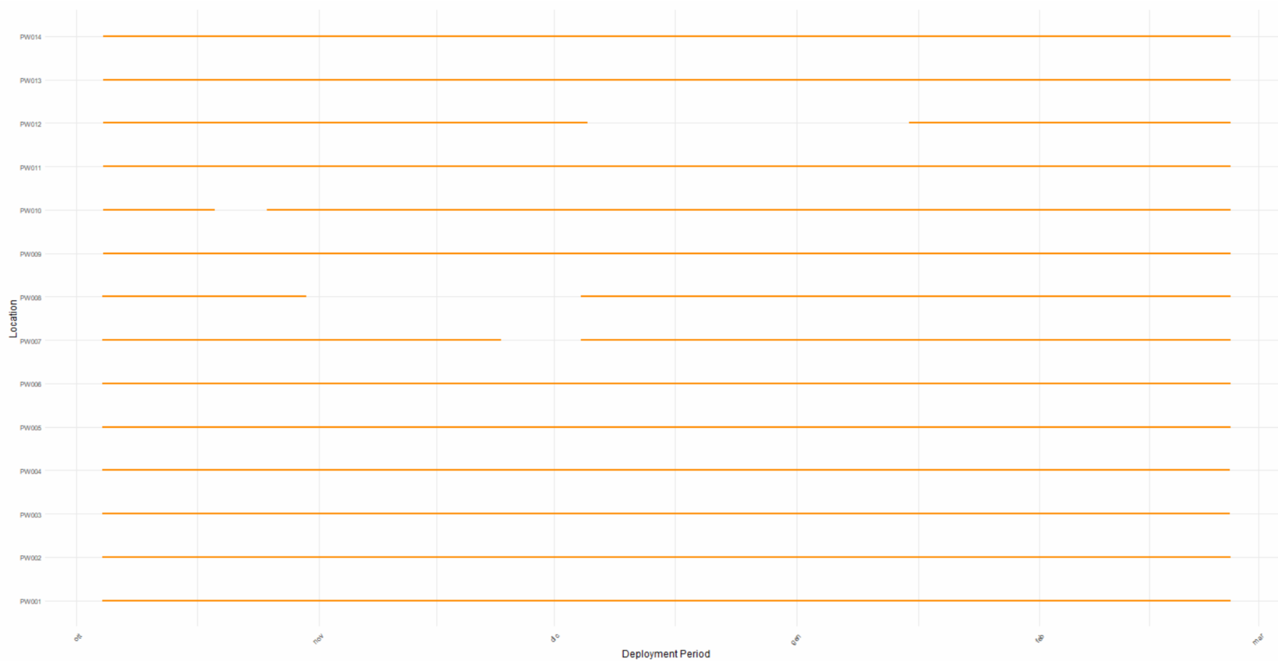

Figure 31: Overview of the start and end times (i.e. deployments) in Platwijers.

3.2.1 Presence

During these four months of camera trap monitoring, more than 3,500 sequences of animal movement were recorded in the deployments. The most frequently captured species in the CT's images was the roe deer with over than 1,000 sequences – accounting for more than 30% of all observations. Hares and wild boars (*Sus scrofa*) were commonly observed, representing approximately 16% and 8% of the total sequences, respectively.

Platwijers is a very well-known birdwatching area, and this was reflected in the results, with many birds appearing in the camera traps footage. Numerous wetland bird species were seen in locations near ponds, including members of the genus *Anser* or *Ardea*, and occasionally *Cygnus* and *Parus*.

Predators were also frequently detected in the area. Species from the genus *Martes* accounted for nearly 4% of the observations, while red fox made up 7%. Occasionally, raptors (family Accipitridae) and owls (order Strigiformes) were also observed.

For the focal species sika deer, some challenges with identification were encountered. For over 600 recorded sequences of *Cervus* individuals, it was not possible to confidently determine whether they were sika deer (*Cervus nippon*) or red deer (*Cervus elaphus*). The two species are very similar in appearance, and distinguishing between them using only camera trap images resulted to be difficult.

Sika deer are generally smaller and lighter than the red deer, but without precise measurements, this trait alone is not reliable. Coat coloration can also be misleading: red deer typically have a more reddish coat, while sika deer display white spots. However, during the autumn and winter months (the study period), these spots become much less visible. Additionally, young red deer fawns present white spots. Other distinguishing features include a neck mane, black stripes along the back and neck, and black lines on the rump patch and hind legs, but again, these are often hard to spot, especially in blurry or low-light images.

In many cases, the photos were not clear enough to allow for accurate identification. When animals were too close to the camera, captured during nighttime, in motion, or only partially visible, it was nearly impossible to confidently determine the species. Also, the potential presence of hybrids in the area has made species-level identification even more complicated. For these reasons, it was decided to annotate all such sequences at genus level (*Cervus*).

Among the sequences labeled as *Cervus*, almost 50% showed a single individual. Around 25% of the pictures captured two *Cervus* together, and 12% showed three. Larger groups were also observed in the area, with 39 sequences (7%) showing four deer together, and some sequences showing groups of up to 14 individuals (***Figure 32***).

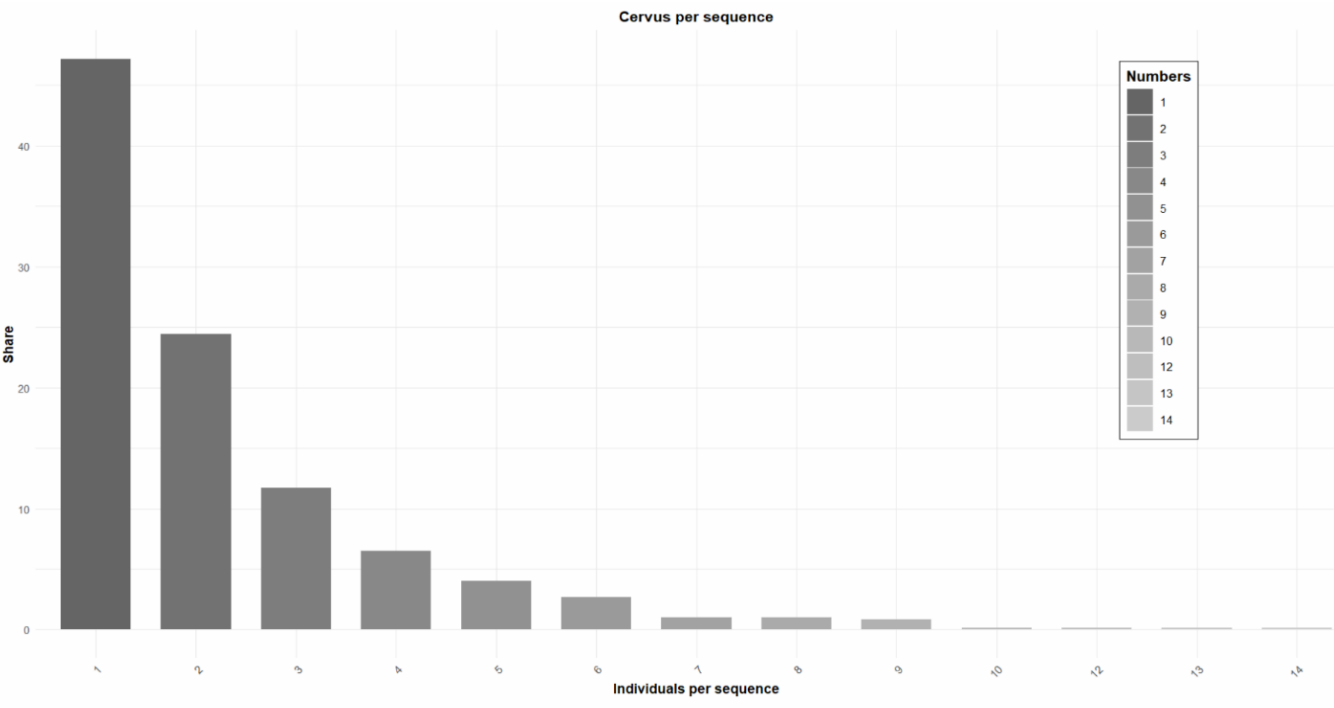

Figure 32: number of individuals of Cervus per sequence.

When possible, we also attempted to identify the sex and life stage of the *Cervus* individuals in the images. Most of the identified individuals were female and adults (***Tables 6 and** 7*).

SEX	COUNT	PERCENTAGE
NA	454	55.10
FEMALE	223	27.06
MALE	147	17.84

LIFESTAGE	COUNT	PERCENTAGE
ADULT	485	58.86
NA	176	21.36
JUVENILE	133	16.14
SUBADULT	30	3.64

Table 6 and 7: Cervus sex and lifestage share

Out of the 600 *Cervus* sequences, four showed deer in the presence of other species. Two sequences captured *Cervus* alongside roe deer, and the other two Cervus with hares. There were no observed interactions between the two species.

All 14 deployments recorded images of *Cervus*. The most frequently visited location was PW005, with 235 sequences taken there (***Figure 33***). This camera was placed near a private *Dama dama* enclosure, in a densely wooded area bordered by a small stream and opening into a large field far from any roads. PW002 and PW001 were also highly active, with respectively

166 and 55 sequences of *Cervus* recorded (***Figure 33***). These two sites are located at the edge of a dense forest, adjacent to a big field crossed by the deer and commonly used for grazing. The least active locations were PW014 and PW009, which are situated near ponds and close to residential areas (***Figure 33***).

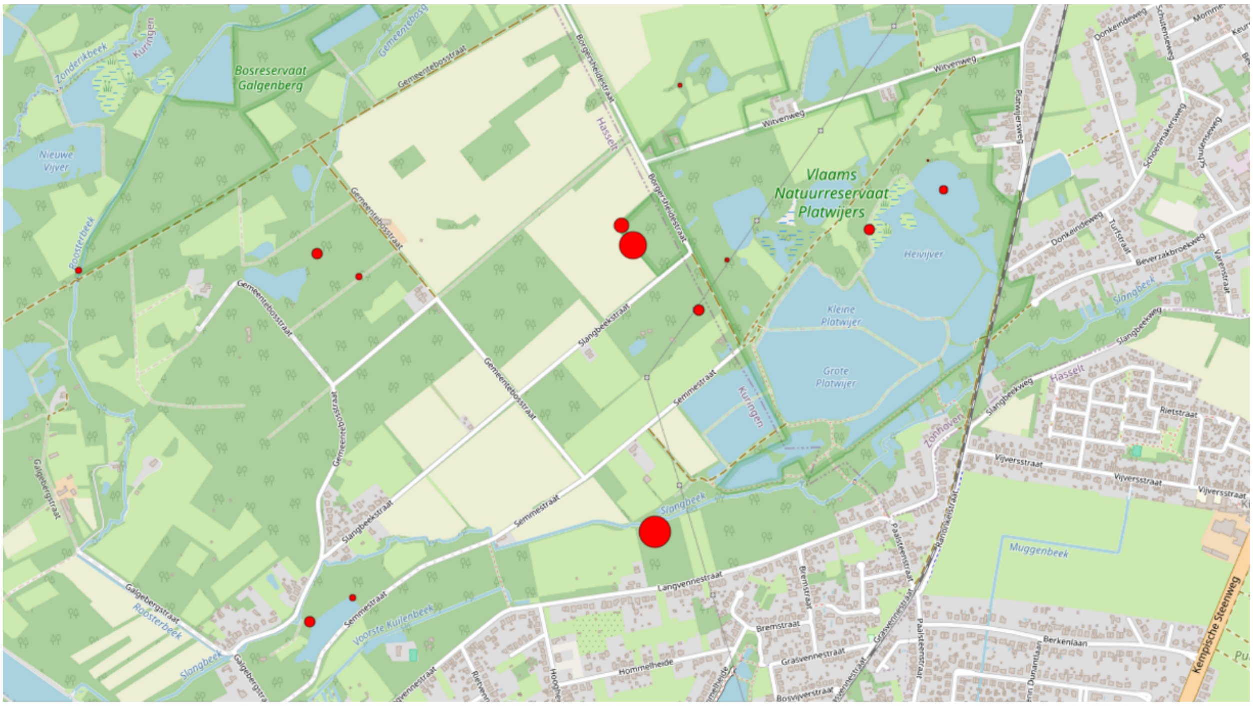

Figure 33: Cervus presence in Plawijers. The bigger the sphere, the more sequences. X = no sequences.

3.2.2 Activity

Spotting deer in Platwijers during the daytime was not easy. During one SD cards change, a large group on a very early and foggy morning was observed, but aside from that, sightings were rare. Analysis of the camera trap data confirmed that this is a highly crepuscular species, with most activity occurring around dawn and dusk (***Figure 34***).

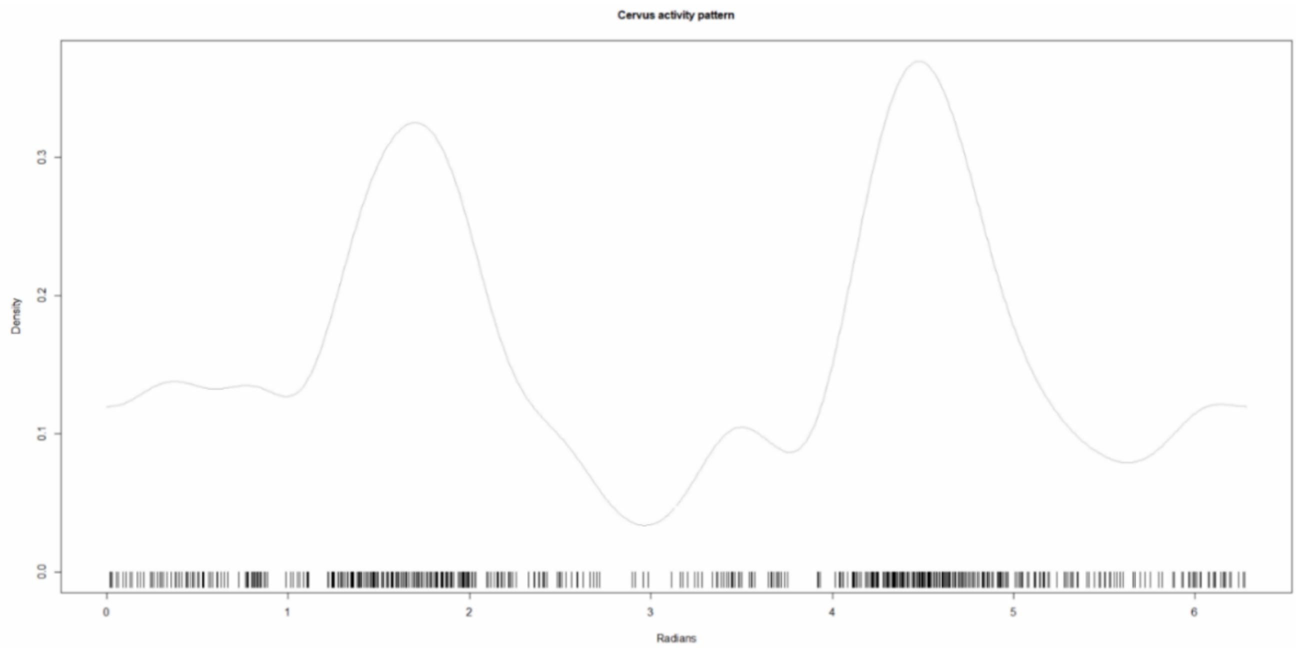

Figure 34: Cervus activity pattern. Time of day is shown on the x-axis in radians (0 corresponds to midnight, ± 1.5 to sunset, and ± 4.5 to sunset). Raw data at the bottom of the graph.

3.3 Fallow deer

90 days of data from each of the 36 cameras in the area were obtained during the study period (***Figure 35***). Some cameras were changed due to malfunctions (always triggered) and others stopped recording before time because of low batteries and other general problems. Most of them worked well and each time they were moved to change the SD card; the calibration of the area was repeated.

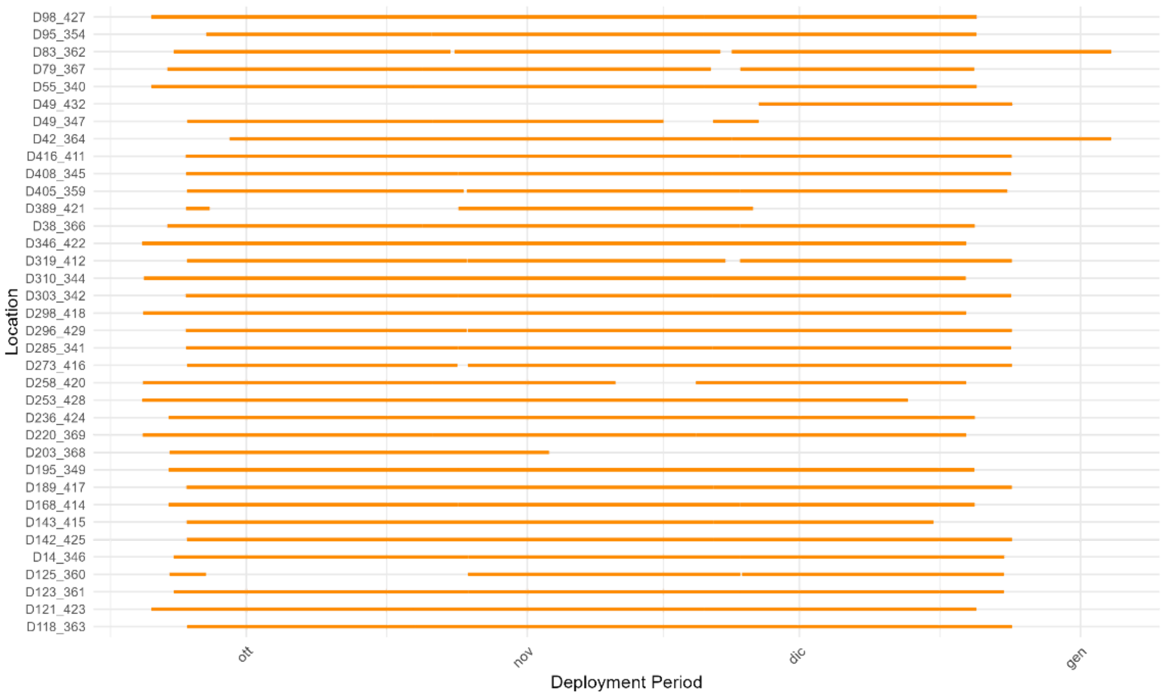

Figure 35: Overview of the start and end times (i.e. deployments) in Drongengoed.

3.3.1 Presence

Lot of sequences of movements were taken by the cameras, more than 4000. Multiple species were recorded in the area; from the domestic dog (*Canis lupus familiaris*) and cat (*Felis catus*) to the genera *Martes* and *Lepus*. Multiple species of birds were observed, for example *C. palumbus*, *Turdus merula* and *P. major*.

79 sequences of *V. vulpes* were obtained in these months and more than 2,300 sequences of roe deer. In more than 70% of the sequences, just one individual of roe deer was present but there were some with two roe deer (22%), three (6%) and bigger groups up to roe eight deer all together (2%). Sequences of roe deer and red fox were relevant in this project because they were part of the Random Encounter Model analysis to estimate the density of their population.

The focal species, the fallow deer, was observed in 1,579 sequences. Most of the pictures showed just one animal alone with 43.76% share but, being a very social species, it appeared very often in large groups, up to 24 *Dama dama* all together (***Figure 36***). 25.9% of the sequences showed two fallow deer together, while 28.12% of the pictures were with 3 to 9 animals together (***Figure 36***). It is quite common for females to live in groups of three; in fact, many of the sequences showing three animals included a female with a newborn and a one-year-old fawn. 2.22% represented large groups of animals seen from 12 times (10 individuals per sequence), 5 times (12 individuals per sequence) or just one time (14/17/22/24 individuals per sequence) (***Figure 36***).

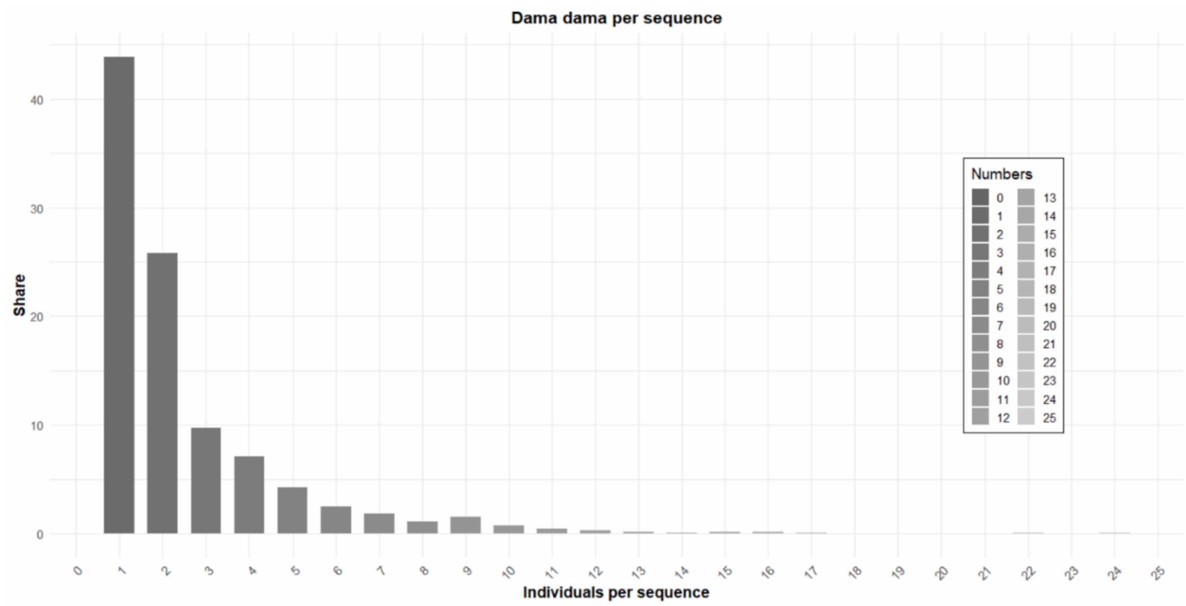

Figure 36: number of individuals of Dama dama per sequence.

In 22 sequences, the fallow deer was present with other species. Two of these sequences showed it with cows (*Bos tauros*), two with *Turdus merula* and 3 with *Lepus europaeus.* The other 15 sequences show the species with *C. capreolus*. No particulars interactions were observed between the fallow deer and the other species present in the picture.

The fallow deer was observed in almost every deployment in the area of Drongengoed (***Figure 37***). Only four deployments on the border of the area close to roads and urban areas did not show the species. On the other hand, the most frequented deployment was D168_414, in the center of the area with 277 sequences, followed by three other deployments in the middle of the area with more than 100 sequences of fallow deer each (***Figure 37***).

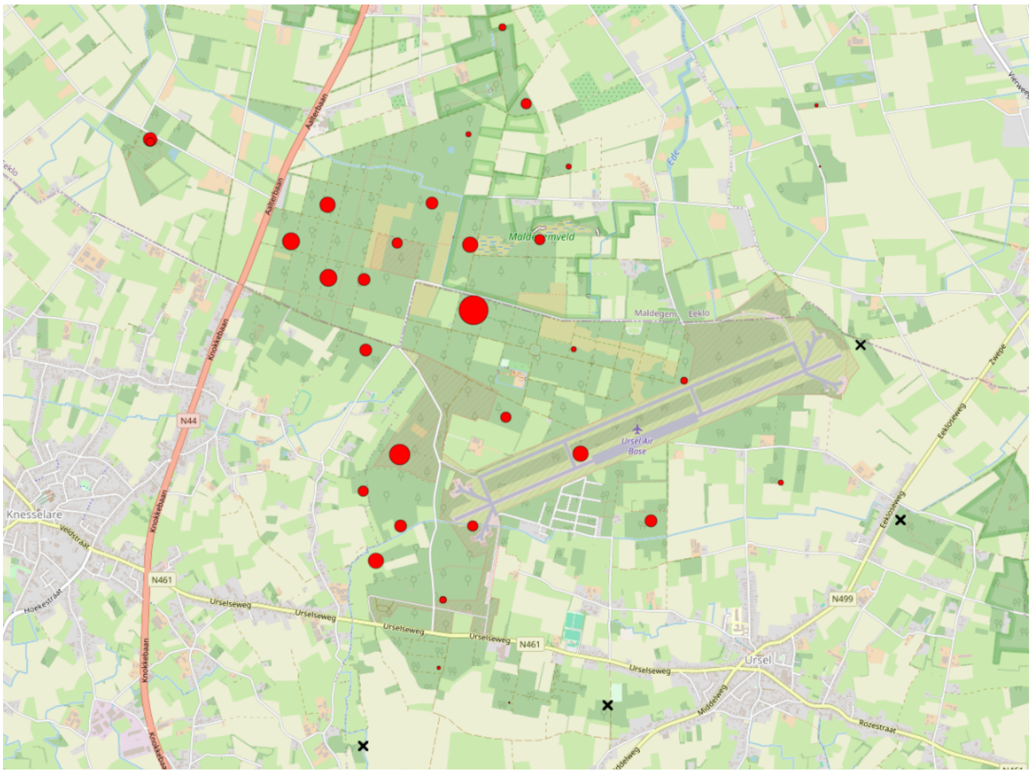

Figure 37: Dama dama presence in Drongengoed. The bigger the sphere, the more sequences. X = no sequences.

3.3.2 Activity

The patterns showed three peaks of activity; animals were more active at sunset and sundown hours with a smaller peak at noon. In general *Dama dama* is active all throughout the daylight while during the night, they don’t move much (***Figure 38***).

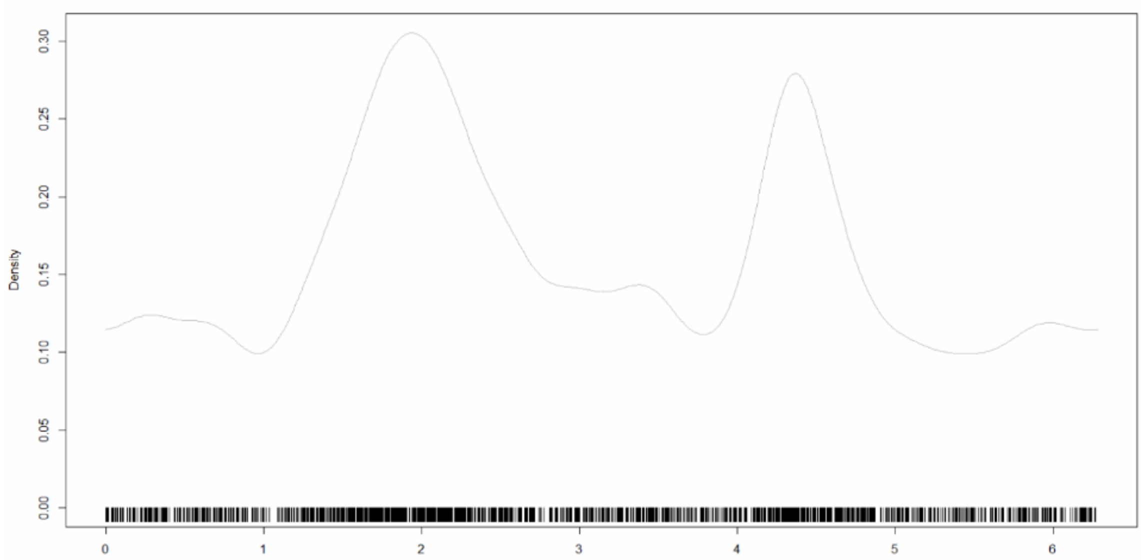

Figure 38: Dama dama activity pattern. Time of day is shown on the x-axis in radians (0 corresponds to midnight, ± 1.5 to sunset, and ± 4.5 to sunset). Raw data at the bottom of the graph.

The fallow deer activity statistically differed from the one of the roe deer ($p < 0.001$; ***Figure 39***), with fallow deer being more active than roe deer during the day and roe deer being more a crepuscular species.

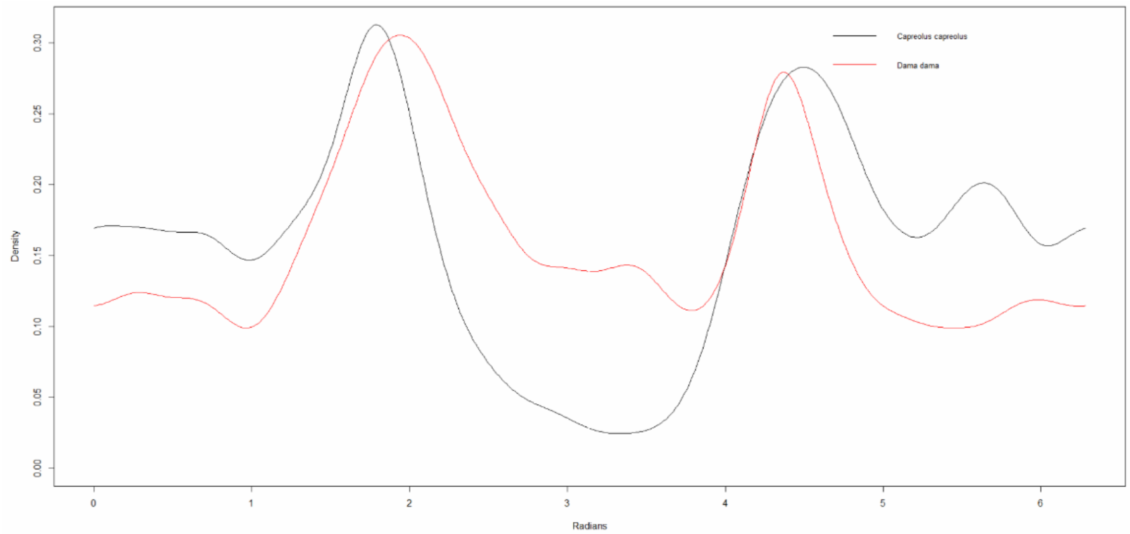

Figure 39: Dama dama and Capreolus capreolus activity patterns. Time of day is shown on the x-axis in radians., where 0 = 00:00 (midnight), π/2 ≈ 1.57 = 06:00 a.m., and 3π/2 ≈ 4.71 = 06:00 p.m.

3.3.3 Density

After fitting the model and running the analysis, the result for the fallow deer was 24.57 (95% CI: 16.42 – 36.76) animals per km^2 (the total area is 750 hectares, 7.5 km^2) (***Table 8***).

Fallow deer	Estimate	Standard Error	Coefficient of variation	Lcl95	Ucl95	n	Unit
Density	24.57	5.10	0.21	16.42	36.76	NA	n/km²
Radius	9.60	0.16	0.02	9.29	9.92	1086	m
Angle	39.99	1.17	0.03	37.70	42.29	1144	degree
Activity_level	0.39	0.02	0.04	0.36	0.42	3993	none
Active_speed	0.64	0.40	0.06	0.57	0.72	1120	km/hour
Overall_speed	6.02	0.44	0.07	5.15	6.88	NA	km/day
Trap_rate	1.22	0.23	0.20	0.80	1.75	37	n/day

Table 8: REM results for fallow deer in Drongengoed reporting the: standard error, the coefficient of variation, the lower (Lcl) and upper confidence interval (Ucl)at 95%. See caption of Table 4 for definitions.

With the estimate density, the active speed estimated was about 0.67km/hour and the overall speed 6.02 km/day.

The roe deer population estimated density for this period of study resulted to be 31.50 (95% CI: 22.05 – 45.00) animals per km² (***Table 9***) and for the red fox 0.23 (95% CI: 0.07 – 0.70) animals per km² (***Table 10***)

Roe deer	Estimate	Standard Error	Coefficient of variation	Lcl95	Ucl95	n	Unit
Density	31.50	5.78	0.18	22.52	45.01	NA	n/km²
Radius	8.077	0.13	0.02	7.82	8.33	1290	m
Angle	39.87	1.12	0.03	37.66	42.08	1358	degree
Activity_level	0.379	0.07	0.44	0.34	0.41	323	none

						9	
Active_speed	0.49	0.03	0.05	0.44	0.55	130 7	km/hou r
Overall_spee d	4.53	0.31	0.07	3.92	5.14	NA	km/day
Trap_rate	0.99	0.17	0.17	0.68	1.33	37	n/day

Table 9: REM results for roe deer in Drongengoed reporting the: standard error, the coefficient of variation, the lower (Lcl) and upper confidence interval (Ucl)at 95%. See caption of Table 4 for definitions.

Red fox	**Estimate**	**Standar d Error**	**Coefficien t of variation**	**Lcl95**	**Ucl95**	**n**	**Unit**
Density	0.23	0.14	0.61	0.08	0.70	NA	n/km^2
Radius	8.93	0.92	0.10	7.12	10.74	49	m
Angle	25.31	3.06	0.12	19.31	31.31	52	degree
Activity_level	0.29	0.05	0.16	0.19	0.38	88	none
Active_speed	2.41	1.02	0.42	0.40	4.42	50	km/hou r
Overall_spee d	16.58	7.57	0.46	1.74	31.42	NA	km/day
Trap_rate	0.03	0.01	0.40	0.01	0.05	37	n/day

Table 5: REM results for red fox in Drongengoed reporting the: standard error, the coefficient of variation, the lower (Lcl) and upper confidence interval (Ucl)at 95%. See caption of Table 4 for definitions.

4 Discussion

This thesis has provided various insights into the status and densities of non-native deer populations in the Region of Flanders (northern Belgium).

4.1 Muntjac

From the muntjac monitoring, it is possible to confirm that this internationally regulated species of Union concern is still present in the study area in the eastern suburbs of Antwerp. Camera trap monitoring recorded multiple muntjacs sightings in both park Vordenstein and De Inslag over the five-months duration of the project. The results on muntjac behavior, activity patterns, and reproductive habits helped better understand this invasive species and identify the best management strategies. In Park Vordenstein, the animals were most frequently observed at the locations at the edges of the park, whereas in De Inslag, the central areas were the most visited. Thanks to these findings, the ANB was informed that the northeastern edge of the park had the highest muntjac activity (camera location VOR23b). As a result, they installed an additional camera at that location, using a cellular model that allows for immediate transfer of images over the network. In this way, a quick management response was possible in case of increased activity, and this effectively led to the shooting of two muntjac (a buck and a doe) only a few days after the monitoring for the thesis ended.

In the present study, muntjacs showed a clear bimodal activity pattern, with peaks around dawn, dusk and nighttime and reduced activity during the day. This crepuscular behavior is consistent with studies from Great Britain, where the species is most frequently observed in crepuscular hours, mostly between December and May, with a peak in April and a minimum in July (Cooke, 2019). They are on the move for about 70% of the day, typically in five periods of activity lasting 3 to 4 hours, and rest periods of 1 to 2 hours (Blakeley et al, 1996). Similar to my observations, *M. reevesi* in its native range in Asia also shows a clear bimodal activity pattern, with peaks around dawn and dusk (Wang et al., 2024). The consistency across regions and seasons suggests that crepuscular activity may be an inherited trait of the species. However, it could also reflect behavioral adaptations to human disturbance, particularly given that the two study areas differ in public accessibility (e.g. dogs are allowed in De Inslag but not in Park Vordenstein). Further comparative analysis may help disentangle intrinsic behavior from context-dependent responses.

Muntjacs are a highly elusive species and spotting them in the wild is extremely difficult. During the project period, hunters and foresters spent considerable time attempting to track the species in both parks with the best equipment and at the best times. In most cases, these efforts were unsuccessful and did result in a single sighting. This may also be due to the low population densities within the parks.

The observed muntjacs did not really show remarkable or abnormal behavior; the general activity pattern recorded on camera was consistent with normal muntjac behavior (Chapman et al., 1993). When a female and a male were recorded in the same sequences, over 70% of the time, the male exhibited reproductive behavior. All such sequences, where males were observed following females, were recorded between November and February. No reproductive behavior was observed from mid-February to early April. Although the literature (Cooke, 2019; Chapman, 2008) describes the reproductive activity of *M. reevesi* as aseasonal, the present study (although not covering a full year) did not detect any reproductive behavior for nearly two months during the study period. More data collected across additional months will be needed to determine whether this species truly breeds throughout the year.

At both study sites, even the upper boundary of the density estimates from the R.E.M. was below 2 per km², whereas the pictures clearly showed at least one buck and one doe to be present at this scale. Therefore, the results from the model are not entirely accurate. Yet the overall impression is that muntjac are very rare at both sites, indeed, and so the estimated densities obtained from the model are likely to be near the true number of muntjacs in each park. The R.E.M., as currently performed, is thus found to have its merits in assessing the population size, though improvements might be needed. There are examples in the literature where R.E.M. was also proven not entirely reliable. An Italian study (Balestrieri et al., 2016) on the pine marten (*Martes martes*) showed that this method underestimated the population density by approximately 60% when compared with genetic methods (fecal analysis). This discrepancy was attributed to errors in parameters estimation used for the analysis, non-random camera placements, and non-random animal movements. Another study by Cusack et al. (2015), which estimated lion densities in the Serengeti, found that R.E.M. overestimated the population size when compared with estimates based on individual recognition. This overestimation was likely due to the non-random placement of the cameras, which were often located near isolated trees in the savannah. By filtering all the images, taking only the pictures taken at night, during the wet season, and within woodland habitats, the overestimation of lion densities was reduced. This suggests that lion movements were biased during the day and in precise conditions, by a tendency to seek shade in open areas (Cusack et al., 2015).

In the present study, all the parameters required for the analysis were carefully calculated. The underestimation observed in the model may have been influenced by the relatively low number of muntjac observations over the five-month period, which could have resulted in insufficient data for the tracking, needed for accurate population density estimation. This is in line with findings by Palencia & Barroso (2024), who showed that when applying the R.E.M., too few camera trap sequences can significantly undermine the reliability of density estimates, particularly for low-density or cryptic species. Other potential factors that could have influenced the model, over insufficient detections, could include suboptimal camera placement, or biased by the proximity to trails, human activity, roads, buildings and biased animal activity. Muntjacs movements within the parks may be influenced by the presence of humans during the day and their absence during nighttime and twilight hours. As a result, I likely obtain an underestimation of the population in both study sites with our model. I am confident that the actual population is larger than the one that was estimated by the model, so that I cannot fully rely on the R.E.M. for this project and must consider its results with some skepticism. When working with elusive species in fragmented habitats (Balestrieri et al., 2016), it is advisable to complement the R.E.M. with more traditional population estimation methods (Cusack et al., 2015), to overcome lack precision of the R.E.M. where such imprecision is present. Studies from Great Britain report muntjac population densities generally higher than those observed in Belgium. Specifically, Wäber et al. (2013) found densities ranging from 20 to 50 individuals per km² in managed forest areas, while Hemami et al. (2005) reported maximum densities up to 60 individuals per km² in particularly favorable habitats. Similarly, Dolman et al. (2008) observed variable densities but generally within the range of several tens of individuals per km². Even given inaccurate R.E.M estimations, it is clear that the results of the present study reflect low actual densities of the muntjac's population in the parks. These low numbers indicate that the situation in northern Belgium is currently still far from that in the UK, and that there is still an opportunity to manage the population or even try to eradicate the species from the region.

4.2 Sika deer

The results obtained from the sika deer (*Cervus nippon*) study are not as certain or conclusive as those from the other two projects. Using fourteen camera traps installed in the Platwijers area, in the province of Limburg, a significant number of individuals from the genus *Cervus* were detected in the study site. Unfortunately, it was not possible to confidently distinguish between the native red deer (*Cervus elaphus*) and the non-native sika deer (*Cervus nippon*), which have both been previously reported in the area in the past years. The camera trap images were not enough reliable species-level identification.

Although many of the observations captured single individuals, it appears that large groups were also present in the area. The deer are primarily active during the early morning hours and around sunset. Based on the general daily activity and behavior observed, nothing unusual was reported. This was consistent with the information reported in literature for the behaviors of the species under natural and low-disturbance conditions (Putman et al., 2011).

To ensure accurate species identification, especially in a context where hybrids may be present, image recognition from camera traps alone is not sufficient. Physicals traits such as coat coloration, the presence of a dorsal black stripe, marking on the hind legs, white spots (in sika) and general size differences are not consistently visible or clear in the pictures. Additional data collected in other seasons, particularly summer when the sika's white spots are more visible on the coat, may improve the identification of the species. However, the most important conclusion is that genetic analysis is necessary to confidently determine species identity and to detect potential hybrids, which are even more difficult to distinguish based on appearance alone. Recent innovations, such as automated acoustic monitoring using deep learning and anomaly detection frameworks, have shown remarkable success in identifying deer species based on vocalizations and activity patterns (Enari et al., 2019; Salem et al., 2024). Nevertheless, while these tools greatly enhance non-invasive monitoring capacity, they are not suitable for detecting hybrids, making genetic analysis irreplaceable for accurate species and lineage identification.

Several studies (Abernethy, 1994; Goodman et al., 1999; McDevitt at al., 2009) have highlighted the challenges in distinguishing between these two species, particularly in areas where they coexist. The authors of these studies (Abernethy 1994; Goodman et al., 1999; McDevitt at al., 2009) used a range of genetic techniques including satellites markers, mitochondrial DNA, and diagnostic protein isozymes, to assess the extent of hybridization within their study areas and to accurately assign each individual to the correct species. These studies also examined the level of genetic introgression and emphasized that identification based solely on external phenotypic traits can be misleading (McDevitt et al., 2009).

In previous years, deer culled on the ANB-managed terrains in the Platwijers area, were subjected to genetic screening at a laboratory in France. Unfortunately, the results are not yet available. However, once received, they will provide clearer insights into the presence and distribution of sika and red deer in the area, and whether any hybrids have been identified.

4.3 Fallow deer

The fallow deer study revealed a high number of animals present in the study area. Almost every camera trap location recorded the presence of the fallow deer, with the exception of a few sites located at the edge of the forest. This may indicate that the animals are more present in the inner parts of Drongengoed forest, where the vegetation is denser, human activity is lower, there are fewer roads and urban areas, and where hunting is prohibited, for the majority of the year, within the designated protected zone.

Due to the large volume of data collected during this project, artificial intelligence (AI) was employed to assist with the annotation process. Deployments with a high number of sequences were processed using AI. This significantly reduced the workload; however, the sequences involving the focal species still needed to be manually validated. AI performed well in distinguishing between the different species but had more difficulty in accurately identifying the number of individuals in an image. Almost every sequence containing *Dama dama*, *Capreolus capreolus* or *Vulpes vulpes* identified by artificial intelligence was carefully reviewed and corrected when necessary. Some observations of the study species may even have been missed during the validation process, because the AI could have annotated them as non-focal species and I did not check these. This could have led to a slight underestimation of population densities. However, since there is still a large number of observations, this is unlikely to have significantly affected the analysis. Overall, the AI tool present in Agouti proved to be a valuable asset, as it allowed us to skip the annotation of blank images, vehicle or non-target species enabling me to focus primarily on validating the sequences of interest.

The analysis of fallow deer activity patterns revealed that this species is highly active during both sunrise and sunset, as well as during daylight hours (Sandor et al., 2013). When compared to roe deer, clear difference in activity patterns emerge, particularly since the roe deer tend to be much less active during the day, as confirmed by the statistical analysis.

The results also highlighted the social nature of fallow deer. A substantial number of observations, more than 30% of all sequences, recorded groups ranging from three individuals (common for females with a newborn and a yearling) up to as many as 24 in a single sequence.

Using the R.E.M., the fallow deer population was estimated at 24.57 animals per km^2. Given that the study area is approximately 7.5 km^2, this corresponds to an estimated total population of around 180 fallow deer in the forest. The roe deer population was estimated to be 31.50 individuals per km^2 while the red fox population was approximately 0.23 individual per km^2 . In 2023, the estimated population densities were 43.79 individuals/km^2 for fallow deer, 29.52 for roe deer, and 0.37 for red foxes (Tomsin, 2024). These results suggest that the recent culling efforts have been effective in reducing the fallow deer population. Meanwhile, the increase in the roe deer population may be attributed to a reduced competition for resources with fallow deer. As previously demonstrated by Ferretti et al. (2011), this species tend to dominate shared habitats and negatively affect the spatial distribution of roe deer. Nonetheless, although the fallow deer population appears to have decreased since last year, the density remains high in the Drongengoed forest, and further management actions are still necessary. According to Putman et al. (2011), densities exceeding 4 individuals per hectares can already lead to serious damage to forestry and inhibit natural regeneration. Moreover, biodiversity may also be negatively affected, as many studies cited by the authors indicate that deer densities above 8 individuals per km^2 are associated with reduced vegetation structure and lower bird species richness (Putman et al., 2011).

Hunting females and young ones could be an efficient method to respond the overabundance but even hunters have been reluctant to these reforms, preferring males, which are valued as game trophies. Another control methos is the relocation but it is expensive and relocated deer do not remain in the area of release (Côtè et al., 2004). Extending the hunting season in the area by few additional weeks or focusing hunting efforts on (young) females and juveniles for a bigger impact on the population could be more effective strategies, as described in several studies (Milner et al., 2006; Comte et al., 2025). These approaches may help better control this controversial non-native species yet, also valued as a game species.

5 Conclusion

Thanks to the present study, a better understanding of the population status and density of three non-native deer species in northern Belgium (the muntjac *Muntiacus reevesi*, the sika deer *Cervus nippon*, and the fallow deer *Dama dama*) was achieved.

For the invasive muntjac, the stable presence of a small number of individuals in the study area was confirmed. Although population densities estimated through the R.E.M. may not be entirely accurate, due to the limited number of observations and potential bias in animal activity, the low densities estimated were likely realistic in this case. This suggests that successful control or even eradication may still be achievable, avoiding a scenario similar to that observed in the UK, where muntjac population densities are extremely higher.

For sika deer, camera trap image recognition alone was insufficient to confidently distinguish the non-native *Cervus nippon* from the native red deer (*Cervus elaphus*). Phenotypic appearance and body size can be misleading, especially in areas where the two species coexist and where hybridization may occur. While many individuals from the genus *Cervus* were observed in the study area, genetic data will be essential to accurately identify species and detect potential hybrids.

The situation regarding fallow deer in Flanders remains complex. Although the species is non-native, it was introduced centuries ago, has experienced periods of absence and then reintroduction, and is now a game species, thus not subject to eradication but sustainable harvest to maintain the population for the future. Fallow deer population has declined in recent years, most conceivably due to the hunting pressure. The native roe deer population in the study area appears to be increasing, likely benefiting from reduced competition for resources. However, given the still high density of fallow deer, further management actions are required to maintain an ecological balance.

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