Contents

INTRODUCTION

CHAPTER 1. BACKGROUND TO THE STUDY

1.1. Ungulate browsing and ungulate dynamics in Romania

Wildlife management aims to regulate population sizes by either increasing, decreasing, or maintaining them at an optimum level (Hardalau et al., 2024). Historically, game populations declined significantly until effective management strategies were implemented. The resurgence of wild ungulates, particularly in the Cervidae family, began in the mid-20th century due to regulated forestry practices, modern game management, and hunting regulations (Apollonio et al., 2010), as well as the lack of large carnivores (Kaczensky et al., 2013). Even though large carnivores have recovered in some areas (Chapron et al., 2014), the predator-prey balance has not been restored, leading to impressive growth in ungulate populations (Bijl & Csányi, 2022; Burbaitė & Csányi, 2009; Burbaite & Csányi, 2010). While high ungulate densities indicate successful management, they also create ecological and economic challenges, as well as issues regarding social acceptance (Apollonio et al., 2017; Valente et al., 2020). Overpopulation can exceed the carrying capacity, causing significant damage to agriculture, forestry, and human safety through vehicle collisions. In several European countries, such as Romania, supplementary winter feeding is used to mitigate crop damage (Murray et al., 2016); however, this practice is prohibited in countries such as Switzerland and the Netherlands (Hackländer & Trouwborst, 2019).

One of the most significant types of damage currently affecting forest ecosystems is browsing. 'Ungulate browsing refers to all forms of feeding damage other than bark stripping, including the removal of twigs, shoots, leaves, needles, buds, or flowers' (Gill, 1992a) cited by (Hardalau et al., 2024). The damage occurs in both natural and artificial regenerations, with the primary factor influencing the intensity of browsing being the high density or overabundance of ungulates.

In Romania, the problems related to ungulate browsing were first signaled in a study (Onofrei, 1969), which suggested the use of polyethylene bags to prevent damage caused by ungulates in young pine (Pinus sp.) plantations in the Forest Administration of Cerna. A later study (Cioflec, 1978), recorded damages of up to 90% for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L.) caused by roe deer (*Capreolus capreolus* L.) during harsh winters and mentioned, for the first time, the use of "*Cervacol*" as a better repellent than the polyethylene bags. Additionally, the establishment of large monocultures of Norway spruce, influenced by communist policies, correlated with a drastic reduction in gray wolf populations, lead to significant damage from browsing by roe and red deer (*Cervus elaphus* L.) (Ichim, 1964, 1971, 1987, 1989b, 1989a). In 1978 (Popescu C, 1978), discussions regarding the problems posed by ungulates in young coniferous forests arised. The research suggested the adoption of treatments that prioritize natural regeneration, alongside the use of fencing as a preventive strategy. Building on these foundational studies, numerous subsequent investigations into ungulate browsing were carried out, mainly concentrating on the northeastern part of Romania and specifically analyzing coniferous stands in mountainous regions (Vlad, 2007; Vlad et al., 2011; Vlad & Popa, 2007). In the rest of Romania, scientific studies addressing ungulate browsing on broadleaved species are relatively scarce, with only one study providing a comparative assessment between Romania and Germany (Schulze et al., 2014). Browsing has been briefly mentioned as a secondary problem caused by ungulates in four doctoral theses (Herman, 2002; Maris, 2011; Pei, 2022; Rusu, 2014).

1.2. Aim and objectives of the study

The aim of this study is to investigate the growth and expansion of ungulate populations, as well as the intensity of browsing activity, at the European, national, and local study area levels. Furthermore, this research seeks to quantify deer abundance, assess silvicultural characteristics, and analyze the occurrence of browsing. Through a comprehensive examination of these factors, the study aims to provide valuable insights into the dynamics of ungulate browsing in forest ecosystems and identify effective management solutions.

The objectives of the study are the assesment of:

- The impact and expansion of the ungulate browsing phenomenon at the European and national levels;
- The growth trends of red deer, roe deer and fallow deer population in Baltics, Central and Eastern Europe;
- The impact of ungulate browsing on oak stands and the influence of different stand and plant characteristics at the main study area level;
- The overabundance of red deer, roe deer, and fallow deer within the main study area.

1.3. Material and methods

1.3.1. Study area

The current study area can be divided into two distinct categories: macro and micro areas based on the analyses conducted. The macro areas are represented first by the European continent, where the evaluation of browsing impact was performed; second, by the Baltics, Central, and Eastern Europe, where the analysis of ungulate growth took place; and third, at the national level, where both browsing and growth trends were analyzed. At the micro level, referred to as the main study area from now on, five hunting grounds (HG) are included, encompassing both agricultural, forest ecosystems or other types of terrains.

The main study area is located in the northwestern part of Romania, close to the Hungarian border, in the Western Plain region, within the administrative area of the Tinca, Oradea and Salonta municipalities in Bihor County. It overlaps five hunting grounds: HG 25 Boboștea, HG 26 Păușa, HG 30 Peri, HG 31 Goroniște, and HG 35 Oșand (Figure 1.1).

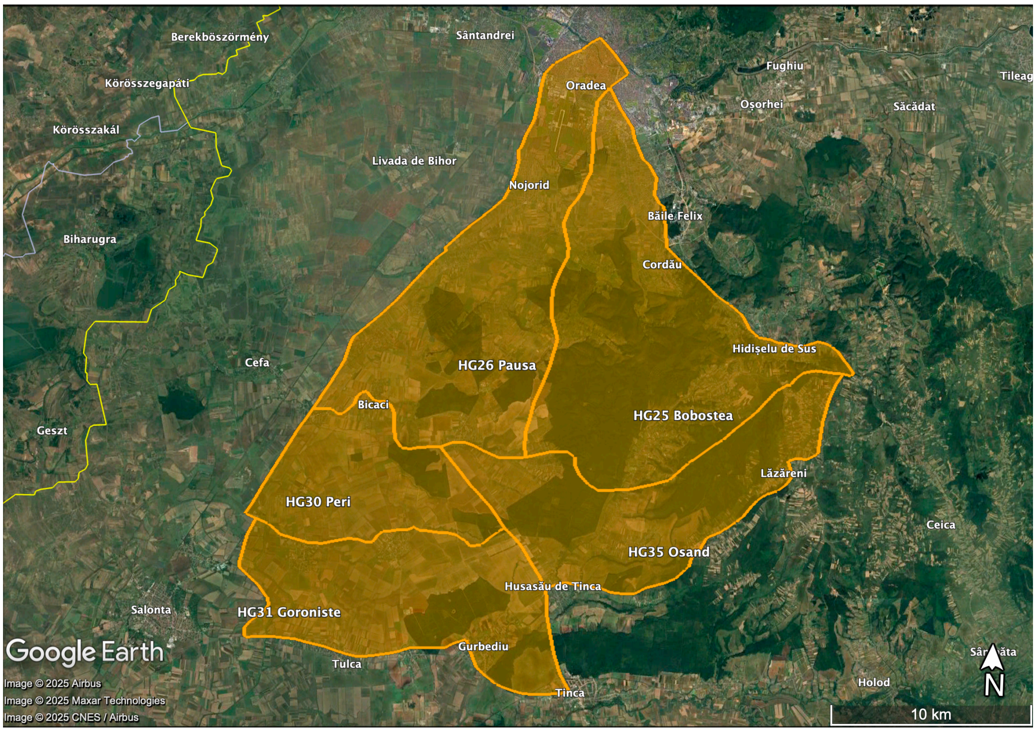

Figure 1.1. Map of the hunting grounds and forest stand included in the study

(Source: Hardalau D. based on Ionescu et al., 2025)

The total area amounts to 43,570 hectares, of which only 43,282 hectares are considered suitable for wildlife production. From a wildlife management perspective, the main study area is divided according to different land use types: water (0.3%), forested areas (31.1.%), agricultural area (53.9%), meadows (13.7%) and others (0.9%),. From a silvicultural point of view, the forests in the main study area are primarily managed by the Forest Administration of Tinca, following national silvicultural management plans and regulations.

From a geographical perspective, the territory is located within the Carpathian Province, specifically in the Pannonian Depression Subprovince. It lies in the Banato-Crișana Plain Region, within the High Plains Subregion, and also encompasses the Western Piedmont Region.

1.3.2. Ungulate species

The red deer (*Cervus elaphus* L.) (Figure 1.2) is one of the largest and most widely distributed deer species in the world, known for being one of the biggest ungulate species in Europe, after the moose and reindeer (Cotta et al., 2001). It has a reddish-brown coat, which tends to fade into a more grayish hue in winter (Cotta et al., 2001). Males, or stags, typically weigh averages 240-250 kg, females, known as hinds, are generally smaller, weighing 80 to 130 kilograms, while the calves weights between 7-12kg at birth (Cotta et al., 2001).

The fallow deer (*Dama dama* L.) (Figure 1.4) is a medium-sized deer species distinguished by its unique appearance and varied coloration, which can be categorized into four variants: menil, brown (often adorned with white spots on the back and flanks), albino, and melanistic (Chapman & Chapman, 1980; Ueckemann & Hansen, 2002). Adult males, known as bucks, typically weigh between 70 and 120 kilograms and have palmate antlers, while females, or does, are somewhat smaller, weighing between 29 and 65 kilograms (Ueckemann & Hansen, 2002).

The roe deer (*Capreolus capreolus* L.) (Figure 1.5) is the smallest native ungulate in Europe and is known for its high adaptability to diverse habitats. Typically weighing between 20 and 35 kilograms, roe deer are characterized by their slender bodies, short legs, and distinctive reddish-brown coat, which changes to a grayer hue in winter. Males, referred to as bucks or roebucks, are recognized by their medium-sized antlers, while the does are smaller. The kids, or fawns, weigh between 1.25 and 1.60 kg at birth.

1.3.3. Data collection

For the evaluation of the spread and impact caused by ungulate browsing, all scientific studies from 1900 to 2002 were retrieved and analyzed. At the state level, the browsing situation was developed based on the country, browser species, browsed species, browsing proportion (%), and ungulate density (ind./100 ha) (Hardalau et al., 2024).

To assess the growth trends of red deer, roe deer, and fallow deer, hunting bag and sex data were obtained from national statistics and official reports from the Baltics, Central, and Eastern Europe for the period from 2012 to 2022 (Ionescu et al., 2025)

To assess the browsing impact in the main study area, a sample grid consisting of 42 plots, each measuring 100 m², was established in late winter of 2023 (Hardalau et al., 2025). For artificial regeneration, a rectangular plot measuring 10 meters on each side was used, featuring five rows of saplings in accordance with the adopted planting scheme of 2 × 1 meters for all stands (Hardalau et al., 2025). In contrast, for natural regeneration, where sapling distribution was random, a circular plot with a radius of 5.64 meters was utilized (Hardalau et al., 2025). The data collection approach (Ruprecht et al., 2012, 2013; Vacik et al., 2017) included recording the occurrence of browsing, the root collar diameter (mm), the height of saplings below 1.3 m, and the vigor of the saplings. Additionally, characteristics of the forest stand and wildlife parameters were recorded.

To assess the abundance of red deer, roe deer, and fallow deer, the Sustainable Population Threshold (SPT) was developed based on biotic, abiotic, management, and anthropogenic factors Ionescu et al., 2025. Using a Stock Unit Equivalent, a parameter to assess the abundance of deer units was developed, where red deer were assigned a value of 1, fallow deer a value of 0.56, and roe deer a value of 0.2 (Ionescu et al., 2025). The real population size of the three species was used as a reference.

1.3.4. Statistical analysis

For the evaluation of the spread and impact caused by ungulate browsing, a database was developed using Microsoft Excel 16.91. Furthermore, visualizations based on the data from each study were created to characterize browsing trends in Europe and the frequency of tree species.

For the assessment of the growth trends of red deer, roe deer, and fallow deer in the Baltics, Central, and Eastern Europe, the database and visualizations were developed using Microsoft Excel 16.91, while the statistical analysis was performed using IBM SPSS Statistics 29.0.2.0. To assess the hunting bag trend, the relative growth for each species was calculated based on the reference year of 2012. Additionally, for the assessment of the sex ratio's influence on growth trends, annual growth was computed.

To examine the influence of spatial and environmental factors affecting browsing occurrence, a regression model was developed using R, incorporating the following packages: MASS (Hadley, 2016), ggplot2 (Venable & Ripley, 2002), and jtools (Long, 2022). For all analyses and visualizations, the data was carefully checked for outliers, collinearity, and other types of errors.

1.4. Outline of the research

The Doctoral thesis is presented in manuscript-style chapters. The focus of these chapters is as follows:

Chapter 2. The expanding thread of ungulate browsing—A review of forest ecosystem effects and management approaches in europe

In recent decades, ungulates have expanded in number and range in Europe. This review aims to analyze the impact of ungulate browsing in different forest ecosystems and identify the main driving factors and trends. In total, 155 studies were analyzed in preparing this review, across 19 European countries. In Europe, the main browsers are represented by roe deer (*Capreolus capreolus* L.), red deer (*Cervus elaphus* L.), moose (*Alces alces* L.), chamois (*Rupicapra rupicapra* L.), and fallow deer (*Dama dama* L.). Regarding browsing severity, they frequently exceeded 50%, meaning that over half of the saplings were browsed. Ungulate density was the main driving factor of browsing severity, with areas exhibiting high browsing pressure often having more than ten individuals per square kilometer. The type of silvicultural system used played a vital role in the severity of browsing, and trends in foraging for preferred tree species were identified. Fencing was the most common non-harmful protection method used, while hunting management was the most efficient method for controlling deer numbers and browsing intensity. Large carnivores were missing in most study areas, but in the areas where they were present, they played a significant role in creating a chain reaction of ecological impacts. Considering the significant impact of ungulate browsing on forest ecosystems, there is a pressing need for more research to comprehend and effectively mitigate the effects of deer presence comprehensively.

Chapter 3: Tracking population trends: insights from deer hunting harvests in the Baltics, Central, and Eastern Europe

Understanding the dynamics of ungulates is crucial for proper wildlife management and conservation efforts. Where high densities of ungulates are present and exceed the carrying capacity, damage occurs in both the forestry and agriculture sectors, moreover human safety is endangered through road accidents. This study explores the evolution of deer populations in the Baltics, Central, and Eastern Europe through the analysis of hunting bag data, which represents the total number of specimens harvested annually. By utilizing hunting bag statistics reported by wildlife managers and hunters, this research aims to provide a more reliable indicator for population trends compared to traditional wildlife monitoring techniques, which may suffer from issues such as double counting, underreporting, or different estimation methods. The study focuses on the evolution of hunting bag numbers for red deer (Cervus elaphus L.), roe deer (Capreolus capreolus L.), and fallow deer (Dama dama L.) between 2012 to 2022. The primary metrics used in the description of growth and statistical analyses were the hunting bags and population parameters such as the sex ratio. The findings of this study indicate that hunting bag data have shown an increasing trend during the study period. The sex ratio of the harvested specimens seems to play a role in annual growth only in the case of roe deer. Based on different harvesting rates, the population estimates for the year 2022 were projected. This research confirms similar trends in population growth for the studied species and also indicates an increase in damage caused by high densities of ungulates. The study underscores the significance of integrated approaches in assessing ungulates populations and their ecological roles, contributing to future wildlife management practices.

Chapter 4: Insights in managing ungulates population and forest sustainability in Romania

Improved forage and living conditions in certain parts of Europe over the past few decades have led to alarming levels of ungulate densities. Consequently, the overabundance of red deer, roe deer, and fallow deer in the Western Plains of Romania has begun to generate issues in the development of young oak stands. In addition to causing damage to the agricultural sector and increasing the risk of vehicle collisions, ungulates are increasing pressure on the forestry sector, mainly through the browsing of young saplings. This study quantifies the levels of ungulate browsing in oak stands using a permanent sample grid of 42 plots in both natural and artificial regeneration areas. A total of 3223 individual saplings were measured, revealing browsing intensities of 49.65% in clearcut systems and 12.8% in continuous forest cover systems. With high ungulate densities identified as the main cause, the Sustainable Population Threshold was calculated using a complex set of indices and compared to the actual numbers of ungulates, both of which were translated into stock unit equivalents. A logistic regression model was developed based on silvicultural and wildlife indices to identify other factors influencing browsing occurrence. The findings indicate that the proportion of forested areas in the hunting ground and the type of silvicultural system are significant factors in the occurrence of browsing. The problem of ungulate overabundance clearly influences forest development, and new solutions should be identified in terms of both forestry and wildlife management.

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CHAPTER 2. THE EXPANDING THREAD OF UNGULATE BROWSING—A REVIEW OF FOREST ECOSYSTEM EFFECTS AND MANAGEMENT APPROACHES IN EUROPE

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2.1. Introduction

The main goals of wildlife management related to population size are to increase, decrease or harvest for a continuing yield (Fryxell & Caughley 2006). In the history of wildlife conservation, game species have experienced significant population declines until effective wildlife management techniques were introduced to keep their numbers stable (Mahoney and Jackson 2013). The most affected group of animals were the large predators, which disappeared partially or totally in most of Europe (Fernandez-Gil et al. 2018). The decline of the Brown bear (*Ursus arctos* L.), grey wolf (*Canis lupus* L.) and Eurasian lynx (*Lynx lynx* L.) during the 18th and 19th centuries were mainly due to human expansion, environmental changes and especially direct persecution by humans (Breitenmoser 1998). Due to the expansion of human activities, settlements, and agriculture, coupled with deforestation and the decline of wild ungulate populations, the pressure on large carnivores escalated as they were perceived as significant threats to both livestock and human safety (Jakubiec 1993; Kratochvil et al. 1968; Zimen E. 1978). In 21st century, the large carnivores' populations have only recovered in a few European countries (e.g., Eastern Europe, Scandinavia, and Northern Spain), while the rest still have unstable populations (Chapron et al. 2014). After the middle of the 20th century, as a result of regulated silviculture practices, modern game management, controlled hunting laws, and designated hunting seasons, the population of wild ungulates, particularly in the Cervidae family, experienced an increase in numbers (Côté et al. 2004). However, because the predator populations have not grown in tandem with ungulate populations, the main predator-prey stabilizing factor has not occurred, resulting in uncontrolled growth of ungulates (Ripple et al. 2014; Ripple & Beschta 2012).

High densities of ungulates can be considered the result of proper wildlife management, which has both negative and positive effects on ecosystems. However, when populations exceed the carrying capacity, it can also lead to various types of damage that impact human activities, agriculture, and the forestry sector. The agricultural sector is one of the most affected by high ungulate population, causing material damage to both large- and small-scale agriculture (Anthony & Fisher 1973; Apollonio & Putman 2010; Putman et al. 2013). As the agricultural crops offer a better alternative food source than the natural ecosystem, in some periods of the year, the ungulates are using them as both feeding and resting zones (Apollonio et al. 2011; Szemethy et al. 2003). In some countries, such as Austria, Croatia, and the Czech Republic, supplementary winter feeding of game species to prevent damages to crops is a legal obligation for hunters to prevent mortality and overwintering in areas where their presence is undesirable, which leads to an increase in ungulate numbers. In contrast, in other countries such as the Netherlands and Switzerland, the practice is prohibited (Katona et al. 2014; Linnell et al. 2015; Putman et al. 2004).

Understanding the feeding ecology and feeding strategies of ungulates is crucial for revealing the dynamics of plant-herbivore interactions, ecosystem functioning, and the preservation of biodiversity in ecosystems (Janis 2008). Plant characteristics such as traits, nutritional quality, and the spatial distribution of food resources impact herbivores' foraging choices and patch perceptions, underscoring the intricate interplay between herbivore feeding behavior and plant attributes (Skarpe & Hester 2008). The selective feeding behavior, preferences for browsing height, and reactions to plant defenses highlight the varied feeding strategies utilized by herbivores to maximize nutrient intake and navigate their foraging habitats (Janis 2008; Skarpe & Hester 2008). Additionally, the horizontal structure of the vegetation plays a role in protecting the ungulates from predation threats (Potash et al. 2019).

This study focused only on the effects of browsing in forest ecosystems and on woody plants. The damage caused by ungulates to the forestry sector are numerous. Therefore, they can result in severe depreciation of commercial forests and as well a decrease of the protection functions of a forest, by altering the forest structure and composition and by possibly removing protected species (Côté et al. 2004; Putman 1996). The ungulates can alter the growth of trees, depreciate the quality of the timber, change the forest composition, or remove certain tree species through actions like browsing, bark stripping, fraying, trampling of saplings, and others (Gill 1992b; Radu 1989a).

Ungulate browsing refers to all forms of feeding damage other than bark stripping: removal of twigs, shoots, leaves, needles, buds, or flowers (Gill 1992a). These tree parts are typically located at a height within the reach of the ungulates, making forest plantations, both natural and artificial, the most susceptible to ungulate browsing (Kupferschmid et al. 2022). The height that can be reached by ungulate is related to the animal's size. Moose (*Alces alces* L.) affect saplings and young trees between 0.5 to 3.5 m in height (Borkowska A and Konopko A 1994), red deer (*Cervus elaphus* L.) can reach heights up to 2.4 m, fallow deer (*Dama dama* L.) can reach 1.7 m, roe deer (*Capreolus capreolus* L.) usually up to 1.4 m (Nichols et al. 2015). At the same time, chamois (*Rupicapra rupicapra* L.) can consume shoots at heights less than 1.3 m, but usually prefers saplings that are between 10 and 40 cm tall (Kupferschmid & Bugmann 2005).

The main gap that of this review is represented by analyzing the impact of ungulate browsing, considering not only ecological aspects but also silvicultural practices, the applicability of hunting, and the presence and role of large carnivores. This study aims to comprehensively investigate the impact of ungulate browsing on tree species in Europe. Specifically, it seeks to identify the main browsers, the most preferred tree species, and any common browsing trends. Additionally, the study aims to analyze the effectiveness of different forestry management strategies, with a focus on hunting and on the presence of large carnivores. Overall, this research seeks to provide a systematized general overview, which can be accessible to researchers, but also to forest owners and managers, aiming to inform effective forest and wildlife management practices.

2.2. Material and methods

Two databases, the Web of Science and Google Scholar, were mainly used for information retrieval. A set of keywords was used in order to identify possible articles: "ungulate", "deer", "moose", "chamois", "browsing", "effect", "impact" and "tree damage" in different combinations using Boolean operators. After conducting a preliminary search, the countries from Europe were included as an additional keyword to enhance the scope of the findings. The search was conducted with the restriction of publication year, ranging from 1900 to 2022. The search included only peer-reviewed papers written in English. The investigations concluded in April 2023. Prior to analyzing the full text, a preliminary check of inclusion was performed, utilizing the following criteria: (1) title, (2) abstract, and (3) keywords, which served as the initial sorting of the database. Following an initial screening of the complete text, additional sources were identified and incorporated as a result of examining the bibliography of the initial batch of papers.

As a final step, inclusion and exclusion criteria were applied to sort the selected studies. The inclusion criteria were as follows: (a) Studies that focused explicitly on browsing of ungulates on tree species, (b) Studies conducted in Europe as the study areas, (c) Studies that measured ungulate browsing using browsing indicators (browsing proportion, browsing intensity, browsing level, browsing pressure and others) (d) Studies with significant results/recommendations for developing a good workflow for future, (e) Studies that measured the browsing intensity of ungulates, even if their primary objectives were broader, (f) Studies that analyzed the browsing on forest ecosystems, g) Studies employing natural or field experimental approaches. On the other hand, the exclusion criteria were as follows: (A) Studies focused solely on browsing on plant species other than tree species, (B) Studies where the browsers were species other than ungulates (e.g., marsupials, rodents, hares or livestock), (C) Studies conducted in fields other than wildlife research, forestry or other ecology science, (D) Studies utilizing repetitive datasets with no significant improvements, (E) Studies lacking descriptions of the ungulate species or tree species studied, (F) Studies utilizing laboratory experimental approaches. By applying these inclusion and exclusion criteria, the selected studies were carefully filtered to ensure their relevance and suitability for the research on ungulate browsing.

After filtering, 155 papers from 21 countries were relevant for full-text screening. Studies have been carried out on one, two, or more ungulate species since their range often overlaps and they tend to browse the same tree species. The earliest study included dates from 1964, while the latest dated from 2022. Most of the studies were conducted between 1999 and 2020 period. The main browsers and their frequency in reviewed papers are presented in Table 2.1, with the most commonly studied species in Europe being Roe deer (n=95) and red deer (n=93).

Table 2.1. The frequency of ungulates in the reviewed papers

Europe							
Species	Roe deer	Red deer	Moose	Chamois	Fallow deer	European bison	Muntjac deer
N	95	93	32	19	12	4	3

2.3. Results

In order to create a general view of the ungulate browsing magnitude from each paper, the (1) Study area, (2) Ungulate species, (3) Browsing proportion, and (4) Ungulate density were extracted and compiled in Table 2. "Browsing proportion" is defined as the percentage of browsed saplings divided by the total number of saplings in the area. This parameter was chosen due to its widespread use in the reviewed literature as the most commonly employed metric. Both browsing proportion and ungulate density do not aim to reflect the general situation of the mentioned country; instead, they showcase the range and diversity of situations identified. The wide range of values can be attributed to the various silvicultural aspects (such as treatment, planting scheme, composition) and wildlife density. For instance, at the same ungulate density (e.g., red deer 10 ind./km^2), different browsing intensities can be observed based on sapling density (e.g., in an artificial plantation of broadleaves with a density of 3500 saplings/ha, the intensity will be significantly higher than in a natural regeneration of broadleaves from a shelterwood). On the other hand, the same regeneration area (e.g., mixed broadleaves and coniferous plantation with a planting scheme of 5000 saplings/ha) may experience varying browsing intensities depending on the ungulate species and density (e.g., 4 roe deer ind./km^2 or 13 red deer ind./km^2). Therefore, the range of the mentioned values is influenced by local situations but can also serve as a descriptor for specific regions or countries (e.g., mixed deciduous-coniferous mountainous stands with silver fir and Norway spruce).

For a better understanding of its scale, the papers have been organized according to the United Nations geoscheme system for a better representation (United Nations 2023). Lithuania, Norway, and Spain were not included in Table 2.2, as neither the Browsing proportion nor the Ungulate density provided useful quantitative values.

Table 2.2. Browsing situation as retrieved from reviewed literature

No.	Country	Ungulate species	Browsing Proportion (%)	Ungulate density (ind./100ha)
Europe				
Eastern Europe				
1	Czech Republic	Roe deer, red deer, Fallow deer	5-85	0.8-56
2	Poland	Roe deer, red deer, Chamois, Moose	12.8-58	0.5-10.4

		Bison	n.m.*	0.7
		Moose	n.m.*	0.31-0.5
3	Romania	Red deer, Roe deer	3-88	1.8-8.6
4	Russia	Moose	79.5-80	1-5
5	Slovakia	Roe deer, red deer	n.m.*	21
Northern Europe				
6	Denmark	Roe deer	49-57	0.8-9.8
7	Finland	Roe deer	51	4-4.5
		Moose	8-75	0.4-3
8	Latvia	Red deer, roe deer	10-12	n.m.*
11	Sweden	Roe deer, red deer, fallow deer	5-85	1-20 (32.7)
		Moose	4-84	0.45-2.4
12	UK	Red deer, roe deer, fallow deer, Muntjac deer	5-81 (96)	4-60 (75)
Southern Europe				
13	Italy	Roe deer, red deer, fallow deer, chamois,	7-61	4.5-25
14	Slovenia	Red deer, roe deer	8.2	1-12
16	Portugal	Red deer	10	10
Western Europe				
17	Austria	Roe deer, red deer, chamois	5-67	3.6-25 (46)

18	France	Roe deer, red deer, chamois	7-100	10-15
19	Germany	Roe deer, red deer, fallow deer, Chamois,	5-79	5.3-20
20	Netherlands	Red deer, roe deer	6-85	4-14
21	Switzerland	Roe deer, red deer, chamois	3.3-67.5 (92.5)	10-27.5

2.3.1. Ungulate browsing in Europe

Based on our established criteria, relevant studies related to ungulate browsing were found only in 21 countries out of the 50 countries in Europe. The countries with the highest number of included studies were Sweden with 35 studies, United Kingdom with 24 studies, Germany with 14 studies, France, Poland, Czech Republic and Romania each with 9 studies, Switzerland, Italy and Austria with 8 studies and Finland with 7 studies. In contrast, the remaining countries had a relatively low number of studies included: Russia with 3 studies, Slovakia, Norway, Slovenia and Netherlands with 2 studies and the rest of the countries had only one study included. The number of studies included do not reflect the real situation of ungulate browsing in the specific countries, it relatively reflects the interest of researchers studying this phenomenon.

2.3.1.1. Ungulate browsing in Eastern Europe

The Eastern Europe region, which includes the Czech Republic, Poland, Romania, Russia, and Slovakia, has been the subject of numerous studies on red deer, roe deer and moose browsing (n=31). Red deer and roe deer were identified as the primary browsers, with 26 and 19 studies including these species, respectively. The density of these species varied widely across the studies, ranging from 2.2 to 90 ind./km^2, with the highest densities observed in the Czech Republic and Slovakia. Moose were found in 6 studies, located in Poland and Russia, with densities up to 5 ind./km^2. The authors declared the presence of large carnivores in the study area in 14 out of the 31 studies, except Slovakia and the Czech Republic (11 studies). The ungulate density in the study areas with the presence of carnivores does not exceed 10 ind./$km^{2,}$ and only in two studies the browsing level exceeds 50% (Kuijper et al. 2013; Radu V and Popa I 2007). In the Czech Republic, the browsing levels are between 5% and 85%.

A study from Northern Czech Republic found that the most frequently browsed tree species by red and roe deer are sycamore maple (*Acer pseudoplatanus L.*), black alder (*Alnus glutinosa L.*), rowan (*Sorbus aucuparia L.*), European beech (*Fagus sylvatica L.*), silver birch (*Betula pendula Roth*), sessile oak (*Quercus petraea Matt.*), and Norway spruce (*Picea abies L.*) (Fuchs et al. 2021). In the Czech Republic, even in floodplains, where biomass production is very high, the damage caused by browsing can be barely compensated, while in artificial regenerated areas, a successful regeneration cannnot be possible without fencing (Barančeková et al. 2007). In unfenced areas, the ungulates significantly affect the development of silver fir, with a higher mortality and suppressed growth in height than in fenced areas (Bulušek & Bílek 2015). During hard winters, in cases of high ungulate concentration and lack of supplementary food, the red deer feeds on all the available food, even on less preferred species like Norway spruce (up to 68% of the available saplings) (Čermák & Grundmann 2006). Due to intense and repeated browsing by roe deer and mainly fallow deer, the sycamore maple cannot develop properly in the mixed stand, and it is overwhelmed by other species like European ash (*Fraxinus excelsior L.*), or field maple (*Acer campestre L.*) (Cermak P. and Mikva R 2006).

In Poland, Białowieża National Park represents a core area for studying the behavior and the impact of ungulates on the forest, including the effects of browsing. The area represents one of Europe's least disturbed temperate, lowland forest ecosystems (Kuijper et al. 2010). This ecosystem, which has no human activities and has a stable population of large carnivores, provides evidence that areas with sufficient predator numbers experience lower browsing intensity in core areas. The observed reduction in browsing intensity is attributed to a combination of direct (lethal) and indirect (non-lethal) predator effects, the density-mediated effects of wolves on red deer being the most likely explanation (Kuijper et al. 2013). In Roztocze National Park, a protected area in central-eastern Poland where natural predators are present, browsing intensity remained below significant thresholds. The only study specifically focused on moose in Poland showed that the highest preferences of moose are downy birch (*Betula pubescens Ehrh.*), silver birch (*Betula pendula Roth*), alder buckthorn (*Frangula alnus Mill.*) and rowan (*Sorbus aucuparia L.*) (Borkowska & Konopko 1994). In Poland, natural predators have helped to keep browsing damages below critical levels. In the Tatra National Park, browsing damages were generally low, with damages on Norway spruce remaining under 5%. (Bodziarczyk et al. 2017).

The European bison (*Bison bonasus L.*) is a Near Threatened (Plumb et al. 2020) mammal native to Europe that primarily grazes but can also browse on shrubs and trees in the forest (Caboń-Raczyńska et al. 1987; Krasińska & Krasiński 2013). In the Białowieża Primeval Forest (Poland), the European bison's tree species diet consisted of European hornbeam (*Carpinus betulus L.*)/Common hazel (*Coryllus avellana L.*) (33.0%), Silver birch (*Betula pendula Roth.*) (15.6%), willow (*Salix sp*). (10.6%), Scots pine (*Pinus sylvestris L.*) (9.7%) and English oak (*Quercus robur L.*) (8.3%) (Kowalczyk et al. 2011). However, trees and shrubs only comprise 5-33% of the European bison diet (Borowski and Kossak 1972; Caboń-Raczyńska et al. 1987). Compared to the other ungulate species in the

Białowieża Primeval Forest, the bison is the species that has browsed the least and has the smallest browsing impact on tree species (Kuijper et al. 2009, 2010, 2013).

Most browsing studies in Romania have been carried out in the Northern Carpathians. The most susceptible stands of Norway spruce monocultures are those that extend beyond the spruce's naturally occurring areas (Tudoran & Zotta 2020). The number of red deer has increased over the past six decades due to the establishment of monocultures in large areas and intensive control of wolf populations between 1961 and 1986, which led to better forage conditions and ceasing regulating effects of predators (Ichim Radu 1989b). During the communist regime in Romania, there was a significant focus on timber harvesting to repay the World War II debts to the Soviet Union, which amounted to 4.3 million cubic meters (Turnock 2006). The harvested areas were predominantly replanted with Norway spruce. This choice was preferred due to its ease of cultivation in nurseries, higher yield and financial value, and lower ecological demands compared to other species such as silver fir and European larch. As most of the area is represented by large spruce monocultures, the shortage of forage and game concentration in winter caused the deer to consume the Norway spruce saplings (Radu 1964, 1971). The reduction of wolf populations in the Northern Carpathians during the communist era increased the density of roe and red deer, which, in turn, indirectly caused high browsing pressure (Radu 1987). These past hunting management practices led to an explosion in the damage caused by deer in Norway spruce stands, which is reflected in stands aged between 21-80 years old and also in recently planted stands (Vlad et al. 2011), as well as in the economic pressure on forest restoration (Vlad 2007; Vlad & Cuciurean 2009). In contrast, in other areas of Romania, where a stable population of deer and predators such as lynx, wolf, and bear are present, browsing damage is negligible compared to similar stands in Germany without a predator population. In Romania, only 3 to 6% were affected, while in Germany, the impact ranged from 17 to 39% in the same site conditions (Schulze et al. 2014).

In European Russia, around Moscow region, the impact of moose on forest regeneration was correlated with density: 0.2-0.3 ind./km^2 does not noticeably affect reforestation, 0.3-0.5 individuals/km^2 significantly suppress the growth of aspen (*Populus tremuloides L.*), rowan (*Sorbus aucuparia L.)*, and oak (*Quercus sp.)*, and 0.8-1.0 ind./km^2 severely repress aspen and birch (*Betula sp.)* resulting in grassy glades on clear-cuts (Abaturov & Smirnov 1992). A similar correlation was also established for roe deer in mixed pine-spruce forests of the Ural Mountains. The study found that at a density of 1.01 ind./km^2, 80% of the saplings were browsed. At a density of 0.58 ind./km^2, 58% of the trees were damaged, and at a density of 0.42 ind./km^2, 39% of the trees were affected (Savin et al. 2017). In the eastern Ural Mountains, damages caused by roe deer in commercial forests can reach up to 100%, with Scots pine and aspen being the most targeted species (Belov 2008).

In Northern Slovakia, particularly in Tatra National Park, it has been observed that rowan represents one of the most chosen tree species for browsing in post disturbance stands, as its ecological requirements facilitate its growth in open areas and it possesses a high nutritional content in the shoots, buds and fruits (Konôpka et al. 2018). In the northernmost part of Slovakia, over a period of 10 years, the exclusion of ungulates increased tree species richness and diversity by reducing the dominance of Norway spruce in terms of biomass and future composition (Konôpka et al. 2021).

2.3.1.2. Ungulate browsing in Northern Europe

The region of Northern Europe was divided into the insular and mainland parts to highlight the different wildlife management practices and geographical differences. The insular part included the United Kingdom, where red deer is the main ungulate species causing browsing damage, observed in 16 out of 24 studies. Alongside the red deer, roe deer (present in 8 studies) is also present as a secondary species that contribute to browsing, with overall damage ranging between 5% and 82%, accordingly to the silvicultural practices, the density of planting scheme and the hunting management. In some studies, the densities of ungulates were up to 60 ind./km^2 (Gill and Fuller 2007; Miller, Kinnaird, and Cummins 1982). No presence of any large carnivores was declared in the studies.

The damage caused by red and roe deer species can be found in pure Sitka spruce (*Picea sitchensis* Bong.) and Scots pine (*Pinus sylvestris* L.) plantations, where the damage levels rarely exceed 50% (Baines et al. 1994; Welch et al. 1991). In Kielder Forest, the winter browsing on Sitka spruce depends on the availability of shrubs, herbs and grasses (Jong et al. 1995). Additionally, the two deer species were attracted to mixed plantations and natural regenerations that contain rowan (*Sorbus aucuparia* L.), Silver birch (*Betula pendula* Roth), wild cherry (*Prunus avium* L.), and oaks (Quercus sp.), where the diversity of forage is higher (Harmer 2002; Harrison & Bardgett 2004; Hester et al. 2004; Joys et al. 2004; Miller et al. 1982). On the other hand, fallow deer have been documented in 5 out of the 24 studies. In the surrounding Suffolk areas, they are responsible for causing some form of browsing damage in almost (96% of cases) of all the mixed plantations of pedunculate oak (*Quercus robur* L.), chestnut (*Castanea sativa* Mill.), wild cherry (*Prunus avium* L.), and ash (*Fraxinus excelsior* L.) (Moore et al. 1999, 2000). The muntjac deer (*Muntiacus reevesi Ogilby*) is an introduced species that, since 1975, has grown in numbers and affected mainly coppices in Eastern England through browsing (Cooke 1998; Cooke & Farrell 2001a, 2001b; Cooke & Lakhani 1996).

The mainland part of Northern Europe consists of Denmark, Finland, Latvia, Lithuania, Norway, and Sweden. The primary browsers of the region are the moose and the roe deer (Kaien 2006). In the current review, the moose was identified in 34 studies and roe deer in 17 studies out of the 43 conducted in the region. The red deer is found in just 7 studies as a secondary species, and fallow deer in 3 studies. The moose densities are usually between 0.5-1.5 ind./km^2, with a few exceptions where the density exceeds 2.4 ind./km^2 (Hörnberg 2001b; Lyly & Saksa 1992). The roe deer density is usually higher than 4 ind./km2 and has a maximum of 24 ind./km^2, depending on the silvicultural practices, planting scheme and hunting management (Olesen & Madsen 2008). The damage intensity caused by ungulate browsing was between 5-81%, depending on the species and location.

In Sweden, moose browsing represents the biggest hindrance to the development of forests, both for commercial (especially on Scots pine and Norway spruce stands) and for protection purposes forests (Andrén & Angelstam 1993; Beest et al. 2010; Bergqvist et al. 2014; Bergström & Bergqvist 1997, 1999; Edenius et al. 1993; Edenius & Ericsson 2015; Jarnemo et al. 2014). A possible reason for the browsing issue could be the increasing moose population over the past four decades, as revealed also by National Forest Inventories. (Hörnberg 2001a, 2001b). A study based on data from the Swedish National Forest Inventory (1969-1972 and 1983-1987 cycles) revealed that the most common browsing species, which made up 91% of the browsing vegetation consumed by moose, were, in order: birch (*Betula sp.*), willow (*Salix sp.*), pine (*Pinus sp.*), juniper (*Juniperus sp.*), rowan (*Sorbus aucuparia L.*), and aspen (*Populus tremula L.*) (Hörnberg 2001b). The current study found that the most browsed species by moose were the Scots pine, Norway spruce, and aspen, which can be related to changes in preferences in the last four decades. In coastal northern Sweden, the browsing occurred mainly in stand that contains both aspen and pine (Danell et al. 1991; Ericsson et al. 2001). In the same area, the Scots pine represented 75% of the diet of 41 free-ranging moose (Shipley et al. 1998), while in Central Sweden, 73.7% of browsing on Scots Pine was caused by moose (Nichols & Spong 2014). Even though Norway spruce is a less preferred woody species for moose, they consume it when their density exceeds the ecosystem's optimum supportability (Faber' and Pehrson 2000). It was found that the practice of fertilization only increases browsing intensity (Ball et al. 2000; Edenius 1993).

A study done in Southern Sweden revealed that the most browsed tree species by roe deer are: pedunculate oak (*Quercus robur L.*), common alder (*Alnus glutinosa L.*), European beech (*Fagus sylvatica L.*), small-leaved lime (*Tilia cordata Mill.*), wild cherry (*Prunus avium L.*), Silver birch (*Betula pendula Roth.*), Norway spruce (*Picea abies L.*) and European ash (*Fraxinus excelsior L.*) (Kullberg & Bergström 2001). The studies included in the review primarily centered on the browsing behavior of roe deer in Norway spruce and Scots pine stands, given the significant economic implications associated with their browsing in these particular forest types. The silvicultural treatment seems not to have any influence on roe deer browsing on Norway spruce (Bergquist et al. 1999; Bergquist et al. 2001) and the stand characteristics did not influence the frequencies and pattern of browsing (Bergström & Bergqvist 1997). Plant vigour represents the parameter that controls the selectivity of red deer, with a higher attraction to the higher classes of vigour (Bergquist et al. 2003; Bergquist & Orlander 1998; Bergström & Bergqvist 1999). Deterrents slightly reduce the intensity of Norway spruce and pine sapling browsing but has not shown any significant impact (Bergquist & Örlander 1996).

The only study where fallow deer is the principal species and causes browsing issues is conducted in the Koberg estate in Västergötland region, where the management type promotes high game densities for hunting purposes, and the damages caused by browsing are considered secondary damages (Garrido et al. 2014).

In Finland, in both natural and artificial regeneration, Scots pine was highly browsed over Norway spruce, with moose density being the only variable influencing the damage's severity (Bianchi et al. 2021). Moose damage is significantly greater in Southern Finland in pine stands with low sapling density, while in planting schemes of 2000-3000 stems per hectare, the damages were lower (Lyly & Saksa 1992). Seedling densities and the proportion of browsed seedlings varies greatly between tree species and the silvicultural treatment (thinnnings, clear-cuts), the browsing intensity being correlated with tree density (Atte et al. 2020). In central Finland, moderate browsing by moose may be beneficial by releasing conifers from competition among tree species, especially rowan, aspen, and birch. At the same time, a higher pressure represents the main threat to aspen, affecting its regeneration and population structure, with a clear gap in the middle-sized aspens.

In Denmark, Latvia, Lithuania, and Norway, less than 2 studies related to ungulate browsing were identified in each of the countries. The study conducted in Denmark reported that after 8 years, the natural beech (*Fagus sylvatica L.*) regeneration, under the most favourable treatment and conditions in the unfenced areas, did not exceed 130 cm due to the high density (24 ind./km^2) of roe deer (Olesen & Madsen 2008). In Latvia, browsing damages caused by red and roe deer accounted for 66.5% of all tree damage and 75% of the total damage to Norway spruce (*Picea abies L.*) (Šņepsts et al. 2018), as the red deer population had exponentially increased over the past two decades (Balčiauskas & Kawata 2022). The study conducted in Lithuania characterized the browsing pressure of red deer and moose during different winter conditions and found that browsing can increase up to 2.1 times during a harsher winter due to the unavailability of food (Padaiga 1998). In Norway, the conservation of the English yew (*Taxus baccata L.*) in natural forest reserves has been affected by roe deer (Mysterud & Østbye 2004). In contradiction to the majority of the studies, in central and southern Norway, the moose was found to promote the economically important coniferous trees in commercial forests (Kolstad et al. 2018).

2.3.1.3. Ungulate browsing in Southern Europe

The Southern Europe region, which included Italy, Slovenia, Spain and Portugal, was the focus of 12 studies. Red or roe deer were identified as the primary browsers in all nine studies, while chamois were found in three studies. The damage was mainly observed in mountainous mixed forests, which primarily were not used for timber production.

In the Graie Alps, the impact of browsing on post-disturbance forest dynamics was significant, as the regeneration was scarce, and the development conditions were harsher (Bottero et al. 2013).

Browsing pressure is usually more severe on regeneration farther away from the deadwood, as the lying deadwood may provide mechanical protection to the saplings (Bottero et al. 2013). Also, in the Paneveggio-Pale di San Martino Nature Park, the percentage of adult broadleaved trees in a plot and the relative proportion of broadleaved species in mixed deciduous-coniferous stands are factors that increased the browsing activity on young trees by ungulates (D'Aprile et al. 2020). The high densities of red and roe deer are reducing the presence of broadleaved trees in favor of Norway spruce (Rozman et al. 2015). In the western Italian Alps (Motta 1996, 1998) and in the North-West Dinaric Alps (Klopčič et al. 2017; Klopcic et al. 2010), the silver fir is the most preferred species by red deer, roe deer, and chamois, which causes a reduction in the percentage of fir in the future regeneration composition in favour of Norway spruce. The silver fir is overwhelmed by the spruce because the fir has a considerably lower growing rate and light regime (Sofletea N & Curtu L 2007). In contrast, damages of up to 60% are focused on Norway spruce and rowan in the dominant spruce layer of the eastern Italian Alps (Motta 2003). In the coastal Mediterranean area of the Lazio coast, the roe deer exhibits a generalist feeding behavior with a preference for deciduous and evergreen woody plants (especially *Quercus suber* L. and *Prunus spinosa* L.), showing adaptability to seasonal variations in food availability (Freschi et al. 2021). In Sardinia, red deer exhibited strong preferences for browsing on tree species such as *Quercus ilex* L., *Alnus glutinosa* L. and *Salix caprea* L., highlighting the significant impact of deer browsing on vegetation composition and ecosystem dynamics (Lovari et al. 2007). In Central Italy, roe and red deer have been observed to significantly reduce the volume of the coppice system of Turkey oak (*Quercus cerris* L.) and chestnut (*Castanea sativa* Mill.) by 25% at medium and high ungulate densities (Cutini et al. 2015). In the Dinaric Alps, the non-hunting mortality of large ungulates occurs mainly due to the grey wolf and Eurasian lynx. Still, only a portion of this mortality is recorded (Klopcic et al. 2010).

In South-Western Spain, the only study included showed that the maritime juniper (*Juniperus macrocarpa* Sibth. & Sm.), a species with continuous growth throughout the year, has a lower relative growth rate only during the summer when browsing by red deer significantly slows down its growth (Muñoz-Reinoso 2017). In Central Portugal, red deer browsing caused significant damage to maritime pine (*Pinus pinaster* Aiton*)* regeneration, but overall, the tree survival was not affected (Monzón, Vaz da Silva, and Manso 2012).

2.3.1.3. Ungulate browsing in Western Europe

The Western Europe region comprises Austria, France, Germany, Netherlands, and Switzerland and includes 41 studies. Roe and red deer were the most common browsers found in the studies, being present in 39 and 35 studies, followed by chamois within 13 studies. The browsing intensities ranged from 5% to 92.5%, while the ungulate densities were between 3.6 and 46 ind./km^2. Only a few large carnivores were declared as being present in the study areas, but their number can be considered negligible, and they did not have any impact on the ungulate populations (Bödeker et al. 2021; Calkoen et al. 2022).

Browsing is a substantial concern in Austria's forestry sector, posing a significant economic challenge (Apollonio et al. 2010; Putman et al. 2013). In Tyrol, the browsing leads to the disappearance of silver fir (*Abies alba* Mill.) and Scots pine (*Pinus sylvestris* L.), ultimately favouring the dominance of Norway spruce (Meier et al. 2017). In Lower Austria, while Norway spruce has not been affected by browsing, the oaks and beech were highly preferred by roe deer, which significantly impacted the restoration efforts (Partl et al. 2002). In the Northern Calcareous Alps, natural regeneration is highly affected by browsing in post-disturbance and marginal stands, with forest establishment being delayed significantly due to the intense browsing of red and roe deer (Pröll et al. 2015). It was found that to reduce the browsing impact, a more close-to-nature felling treatment (e.g., shelterwood, group selection) is needed. This is mainly due to the low predisposition to overall damage, as a slower transition of the forest using natural regeneration decreases the game pressure (Reimoser et al. 1999; Reimoser & Gossow 1996; Vospernik et al. 2008). In Austria, planting is done using a low density of saplings per ha (e.g., 5000-6000 saplings/ha), which creates a shortage of food selection and forces the game to be less selective. At the same time, the shelterwood treatment offers a considerably higher amount of regeneration which provides the game species enough food, the browsed saplings being counted as "compensatory mortality" (Reimoser 2003; Reimoser & Gossow ' 1996).

In the Vosges Mountains in North-Eastern France, the red and roe deer intensive browsing is causing a significant loss of silver fir regeneration in favor of Norway spruce (Bernard et al. 2017; Heuze et al. 2005a, 2005b). In French Alps, in mixed uneven-aged mountain forest stands, additionally to a decrease in water availability and rising temperature, red deer, roe deer, and chamois browsing on fir and beech could jeopardize the renewal of these species in the future (Unkule et al. 2022). In the North-Eastern of France, the roe deer browsing on sessile oak saplings are drastically delaying the reach of the closed canopy stage (Drexhage & Colin 2003). Based on a 10-year study in Grand East Region, the oak browsing index had been successfully used to estimate roe deer density (Chevrier et al. 2012). Without ungulate browsing, sessile oak stumps maintain a moderate sprouting capacity up to 80 years old (Mårell et al. 2018). In the Haute-Marne administrative area, the red and roe deer population dynamics were the main driver of changes in plant and tree assemblages for over 30 years (Boulanger et al. 2009, 2015).

In the Bavarian Alps, the browsing preference of red and roe deer was the following: rowan, European beech, silver fir, and Norway spruce (Calkoen et al. 2022). In the same geographic area, red deer, roe deer, and chamois browsing drastically reduces the survival rate of silver fir (Amrner 1996). Additionally, ungulates influence the growth rate and species composition of natural regeneration. The total removal of browsing allows unhindered growth for all tree and plant species. In North-East Germany, the height of Scots pine saplings was considerably lower when browsing occurred (Tschöpe et al. 2011). In Northern Germany, the browsing on beech saplings is positively influenced by the availability of birch and blueberry (*Vaccinium myrtillus L.*). In contrast, for Norway spruce, the presence of blueberry had a negative impact (Bobrowski et al. 2015). In Germany, proper hunting management is needed to control the high numbers of ungulates, which can easily reach up to 20 ind./km^2 (with exceptions in game units where it can reach 100 ind./km^2). A hypothesis claims that the only solution to control ungulate density in Germany and to allow successful forest regeneration can be achieved through hunting (Heinze et al. 2011a). In different regions of the country, the hypothesis has been proven to be the only realistic solution to control browsing, both in protected areas (such as Bavarian Forest National Park) and in commercial forests (Calkoen et al. 2022; Heinrichs et al. 2012; Hothorn & Müller 2010a; Möst et al. 2015). The population of large predators found in Germany is scarce, and the impact on the ungulate is relatively inexistent (Bödeker et al. 2021; Calkoen et al. 2022).

In the Netherlands, in the forest heathlands (Heinze E et al, 2011) and other forest types (Van Hees et al. 1996), mainly beech and Scots pine were able to successfully regenerate, as oak, birch, and rowan were suppressed by red and roe deer.

The silver fir in the Central European Alps (Switzerland) has suffered a decline over the past two decades, being the most heavily browsed among commercially important tree species, primarily due to red deer, roe deer, and chamois (Häsler & Senn 2012; Kupferschmid et al. 2013; Senn & Suter 2003). However, in contrast, the lightly browsed saplings of silver fir tended to grow better than the untouched ones (Kupferschmid 2018). At higher altitudes, below the subalpine level, the Norway spruce is also affected by browsing, but the damage scale is much lower than in silver fir (Kupferschmid & Bugmann 2005). Between altitudes of 1600 and 2000 m, the browsing of Norway spruce significantly decreases to 3.3% (Cunningham et al. 2006). In the lowlands of Northern Switzerland, the only notable browser is the roe deer, which causes damage to deciduous forest regeneration, especially in sites with lower amounts of alternative food resources (Moser et al. 2006).

2.3.2. Browsing trends in Europe

As seen from the preceding sub-chapters, ungulates exert a significant impact on tree regeneration, and the extent of damage is influenced by various factors such as silvicultural practices (e.g. planting schemes, composition, consistency, treatment and others.), ungulate species, wildlife or hunting management, and the presence of large carnivores. The primary trends concerning the issues caused by browsing, the underlying causes, the protective (preventing) and controlling measures implemented, as well as the presence and potential impact of large carnivores, can be observed in Table 2.3. The development of commercial forests poses a problem as valuable timber depreciates at harvesting age due to browsing, leading to the apical shoot being browsed and resulting in a multi-stem trunk (Bergeron et al. 2011; Weigand et al. 1993). Another common issue is the shift in species composition, where broadleaved tree species are more palatable than coniferous species.

Additionally, it has been proven that silver fir is preferred over Norway spruce in the majority of mixed artificial regenerations (Bernard et al. 2017; Diaci 2001; Heuze et al. 2005b). The root cause of issues stemming from ungulate browsing is the high density that often surpasses accepted levels. However, in some cases, other management practices have exacerbated the situation (e.g., monocultures over large areas, introduction of exotic species, among others). Depending mainly on the severity of the phenomenon, protective (preventive) and population control measures are implemented on varying scales. The most common approach involves reducing or controlling ungulate populations through hunting (Boer 1991; Simard et al. 2013), followed by fencing or the use of deterrents. Large carnivores are adequately present in only a few instances (such as Poland, Romania, Finland, Sweden, and Slovenia), while in other countries, their numbers are considered negligible, with no discernible impact on ungulate populations.

Table 2.3. Browsing trends in Europe

Country	Ungulate species	Problems	Causes	Protective measures	Large carnivores
Czech Republic	Red deer, Roe deer	Development of commercial forests	Δ	***	/
Poland	Red deer, Roe deer, Chamois, Moose	Development of protection forests	Δ	¦	+++
Romania	Red deer, Roe deer	Development of commercial forests	Δ, Monocultures on large areas	**	++
Russia	Moose	Unwanted changes in tree composition	Δ	¦	+
	Roe deer	Development of commercial forests	Δ	¦	+
Slovakia	Red deer	Favoring Picea abies L., Exclusion of broadleaved species	Δ	*	/
United Kingdom	Red deer, Roe deer	Risk of plantation failure	Δ	*	/
	Fallow deer	Risk of plantation failure	Δ	*	/
	Muntjac deer	Reduction of vegetative regeneration	Δ, Exotic species	*	/
Sweden	Moose	Development of commercial forests, Exclusion of broadleaved species	Δ	**	+

	Roe deer	Development of commercial forests, Exclusion of broadleaved species	∆	***	/
	Fallow deer	Tree survival severely reduced	∆, Hunting reserve	¦	/
Finland	Moose	Development of commercial forests	∆, Low-density planting scheme	**	+
Denmark	Roe deer	Diminished growth in height	∆	**	/
Latvia	Red deer, Roe deer	Development of commercial forests	∆	*	/
Lithuania	Red deer, Moose	Development of commercial forests	Harsh winters	*	/
Norway	Roe deer	Conservation of a protected species (Taxus baccata L.)	∆	¦	/
Italy	Red deer, Roe deer, chamois	Unwanted changes in tree composition, Reduction of broadleaved species and Abies alba Mill.	∆	¦	/
Slovenia					+
Austria	Red deer, Roe deer, Chamois	Development of commercial forests, High financial losses	∆	****	/
France	Red deer, Roe deer	Development of commercial forests	∆	**	/

Germany	Red deer, Roe deer	Development of commercial forests High financial losses	∆	***	/
Netherlands	Red deer, roe deer	Suppression of broadleaves	∆	*	/
Switzerland	Red deer, roe deer, chamois	Unwanted changes in tree composition, Reduction of broadleaved species and Abies alba Mill.	∆	*	/

∆- high ungulate density, *-only one measure is applied, mainly hunting, **- two protective measures are applied, mainly fencing and hunting, ***, **** - a multitude of efforts are implemented, including intensive culling, ¦ - no protective measure is applied, + - large carnivores are present, ++ - large carnivores are present and have an impact on ungulates, +++ - large carnivores are controlling the ungulate densities, /- large carnivores are not present or their number is insignificant

2.3.3. Frequency of tree species in the literature reviewed

In the context of this review, only the studies that included tree species of silvicultural interest were considered, both in terms of timber production and in terms of their protective and biodiversity aspects. The frequency of tree species included in studies, either as an individual species or as a part of a composition scheme are present in Figure 2.1. The frequency of these tree species in studies does not necessarily reflect the preferences of ungulates but rather their silvicultural importance, mainly determined by their value at harvesting age, the share in the planting scheme and their production in nurseries.

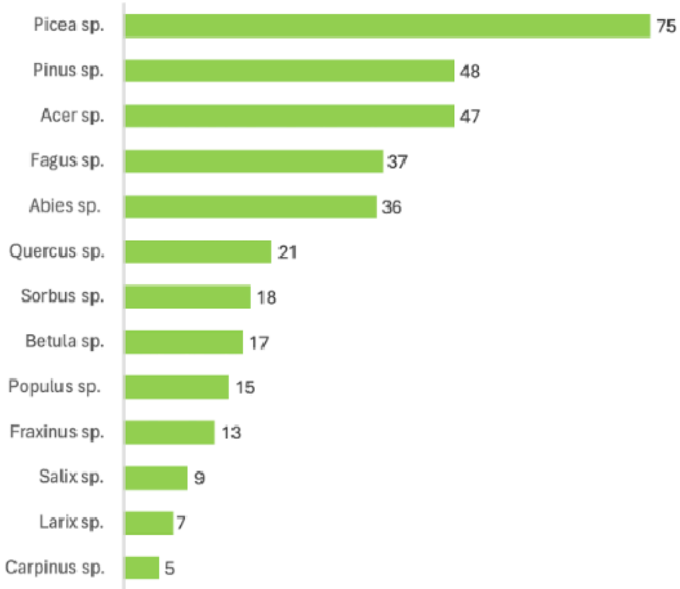

Figure 2.1. Frequency of tree species analyzed in the reviewed studies

Despite Norway spruce being one of the species with low palatability, it is one of the most common species in Europe, which has been extended beyond its natural range (Sofletea & Curtu 2007; Tudoran & Zotta 2020), and is indirectly the subject of many browsing studies (n=75), whether as a species affected or favoured. Pine species, known for their ecological plasticity, have been included in numerous composition schemes at the European level. In this case, pine (n=48) has higher palatability than spruce but, in some instances, it is favoured over deciduous species. Species from *Aceraceae* family (n=47) exhibit both high ecological plasticity and silvicultural interest (Sofletea & Curtu 2007), but they are highly palatable and are often the first species browsed. One of the most important silvicultural species in the mountainous region is the silver fir (n=36), which is frequently overwhelmed by ungulates to the detriment of Norway spruce (Bernard et al. 2017; Diaci 2001; Klopčič et al. 2017). Species from the genera *Quercus, Sorbus, Betula, Populus, Fraxinus,* and *Salix* are considered the most consumed by ungulates, leading to their suppression and reduced growth, potentially being overtaken by species that have not been browsed (Borkowska & Konopko 1994; Fuchs et al. 2021; Harmer 1999; Harrison & Bardgett 2004; Kowalczyk et al. 2011).

2.4. Discussion

The repercussions of ungulate browsing are diverse and far-reaching in natural ecosystems, encompassing hindrance to tree regeneration, alteration of forest composition through selective feeding, reduction in overall biodiversity, economic losses stemming from the reconstruction of plantations, degradation of soil quality and increased erosion, and disruption of the natural regeneration process, affecting the long-term resilience of ecosystems.

The high densities of ungulate species is the primary factor contributing to the adverse impact of ungulate browsing on forest ecosystems, with ungulate populations significantly increasing in numbers and expanding their geographical range in Europe (Apollonio et al. 2010; Barton et al. 2022a; Côté et al. 2004; Coulson 1999; Healy, deCalesta, & Stout 1997; Ramirez et al. 2018; Valente et al. 2020), resulting in substantial economic and ecological consequences in forestry (Apollonio et al. 2010; Clasen et al. 2011; Putman et al. 2013). Browsing damages have intensified in the past few decades, as the number of studies on the topic has grown since 1999. According to the results of this review, the populations of roe deer, red deer and moose, as native species, have significantly increased in number and range, and their density can be used as an indicator of their browsing. These ungulates have extended their range and started occupying new ecosystems as they adapted to their requirements.

The other species mentioned in this review can be considered of secondary interest in various ways, such as having a lower browsing impact, overlapping ranges with the main species, occupying specific regions only (e.g., Chamois, European bison), or being introduced species (e.g. Muntjac deer in the UK). The chamois was found mainly in mountainous and alpine areas of Poland, Austria, France, Germany, Switzerland, Slovenia, and Italy and was reported as a secondary species with the roe and red deer, with no study focused only on the sole impact of the chamois (Amrner 1996; Bodziarczyk et al. 2017; D'Aprile et al. 2020; Häsler & Senn 2012; Hothorn & Müller 2010a; Klopcic et al. 2010; Kupferschmid 2018; Kupferschmid et al. 2013, 2020; Kupferschmid and Bugmann 2005; Meier et al. 2017; Motta 1996, 1998; Pröll et al. 2015; Reimoser & Gossow ' 1996; Rüegg & Nigg 2003; Senn & Suter 2003; Szwagrzyk et al. 2020; Unkule et al. 2022). In most cases, fallow deer were reported as secondary browsers, except in Sweden and the UK, where they are managed as a main game species, resulting in higher densities than those found in other studies (Garrido et al. 2014; Moore et al. 1999, 2000). The Muntjac deer from the UK is an introduced species that have overbred in the absence of natural predators, significantly damaging tree regeneration (Cooke A. 1998; Cooke & Farrell 2001a; Cooke & Lakhani 1996; Joys et al. 2004; Kay 1993). All research on the European bison has been conducted in the Białowieża Primeval Forest in Poland, and conservation efforts are focused on increasing their population, as the browsing is seen as a natural phenomenon (Kowalczyk et al. 2011; Kuijper et al. 2009, 2010, 2013).

As shown in the review, the ungulate preferences focus, when available, on broadleaves over coniferous due to their high forage quality, taste and palatability, digestibility, and other phenological factors (Linnel et al. 2015; Kupferschmid et al. 2005; Chantal et al. 2007, Dannell et al. 1991; Duncan et al. 1998; Gill & Fuller 2007; Marrel et al. 2018; Kittredge et al. 1995; DeGraaf et al. 1991). One of the most favored broadleaved species in Europe is the rowan (Sorbus aucuparia L.), but this tree species acts more like an attractant for the deer in freshly cut forests, as it does not have any commercial importance (Berguist et al. 2003; Bottero et al. 2013) . From the category of commercial species, which are designated for future crop trees all of the oak species (*Quercus sp*.) are highly consumed in both continents, with the exception of the higher latitudes' (Abaturov & Smirnov 1992; Castleberry et al. 2000; Cretaz & Kelty 2002; DeGraaf et al. 1991; Drexhage & Colin 2003; Fuchs et al. 2021; Van Hees et al. 1996; Kittredge & Ashton 1995; Mårell et al. 2018; Partl et al. 2002). Higher latitude birch is affected mainly by moose browsing, as it is a highly prolific species and it is often used in the plantation schemes in Scandinavia (Abaturov & Smirnov 1992; Bergqvist et al. 2014; Heikkilä et al. 2003; Hörnberg 2001b, 2001a; Rea 2011). A general trend for browsing preference can be seen in the case of the Abies genera, which has seen a drastic reduction in number and height in mixed plantations, both natural and artificial. In Central, Southern Europe and the Czech Republic the silver fir (Abies alba Mill.) has seen a decline in the recent decades which is related to the browsing damages, and its presence in future composition is replaced by other less palatable species such as the Norway spruce (Picea abies L.). Studies conducted in Northern Europe and Eastern Europe have shown that pines are preferred over spruces within the coniferous group. Mainly in Sweden, Scotland, and Finland, where the Scots pine is a principal species in composition schemes, it is highly preferred over the Norway spruce due to its chemical composition and nutritional properties (Ball et al. 2000; Beest et al. 2010; Bergquist, Löf, and Örlander 2009; Bergqvist et al. 2014; Bianchi et al. 2021; Danell, Niemelä, et al. 1991; Franklin et al. 2020; Heikkilä et al. 2003; Nichols and Spong 2014; Pfeffer et al. 2021). Even if the Norway spruce does not represent an important forage species in mixed natural regenerations, due to the practice of large-scale of monocultures, the ungulates adapted and consumed the spruce over acceptable limits (Radu 1964, 1971, 1989b, 1989a; Vlad 2007; Vlad et al. 2011).

The silvicultural systems identified in the review play a vital role on the damage levels and can be divided as follows: clearcuts where all the crop trees are harvested at once, on the whole area, repeated treatments such as shelterwood, continuous cover system with selection cuttings and coppice systems. The silvicultural system type is designated for artificial and natural regeneration, which, together with the planting scheme and the regeneration composition, acts as variables that influence the browsing phenomena. The forest predisposition to browsing damages strictly correlates to the silvicultural system and regeneration method. The clearcut system has the highest susceptibility to browsing due to the creation of a suitable habitat for most ungulates. The browsing impact is particularly high because of the limited availability of artificial regeneration (planting density), leading to a shortage of food resources (Bergquist & Orlander 1996; Kuiters et al. 2002). The shelterwood and selection systems have been proven to be the less affected by browsing, as these treatments offer a considerably higher amount of natural regeneration, which satisfies the food requirements of ungulates, and the browsed saplings can be counted as "compensatory mortality" (Putman 1996; Snepsts et al. 2018; Motta 1998). Silvicultural aspects such as planting schemes, sapling density, composition, forest treatments, and tending operations play a crucial role in shaping ecosystems and influencing browsing behaviour. Factors like release cutting and respacing periodicity, thinning intensity and type, as well as disturbances, can impact the availability of plants, shrubs, and young trees for browsers.

Besides the negative effects of ungulate browsing, this phenomenon also has some positive effects on the forest ecosystem, even though most of the literature focuses only on the negative impact. Browsing itself, as a natural phenomenon, does not significantly affect the ecosystem; rather, the altered high densities of ungulates create problems. Selective browsing on competitive dominant plants enhances the diversity of both seedling survival and growth (Cook-Patton et al. 2014). Under normal densities of ungulates, plant communities can increase in cover and richness, as normal levels of browsing create favorable scenarios for plant growth (Chollet et al. 2016). Ungulates have an important role in maintaining plant diversity in forest ecosystems in the absence of episodic artificial or natural disturbances (fire or mechanical tending) (Pekin et al. 2014).

A general overview of preventing and controlling browsing methods was split into two categories: techniques that promote non-harmful/banishment of ungulates and procedures that promote the extraction of ungulates. The first category represents short-term solutions that prevent young trees from being affected by ungulates until they reach a particular stage of development or height (Burņeviča et al. 2022). The most commonly used method was fencing, which was typically installed across the entire target area and by using electric fences or different types of steel wire (Barančeková et al. 2007; Bergquist et al. 2009; Bulušek & Bílek 2015; Cooke & Lakhani 1996; Löf et al. 2010). Other methods, such as tree guards, repellents, and natural obstacles (such as repellents, slash, mounds, stumps barriers, and others) have proven to be even shorter-term solutions with highly fluctuating results (Bergquist et al. 1999; Grisez 1960; Van Lerberghe 2014; Redick & Jacobs 2020). While these short-term prevention measures can be effective, they do not fully solve the problem and move it to another area. Additionally, these measures create additional economic pressure on forest owners and managers and do not provide any immediate financial revenue.

The other category of measures, which promotes the extraction of ungulates, is represented by hunting and natural predator-prey interactions. Hunting is practiced in all of the countries mentioned in the study but in only a few countries, such as Austria, Germany, France, Sweden, and UK (Berger et al. 2001; Hothorn & Müller 2010b; Putman et al. 2013; Schulze et al. 2014), hunting management plans focus on the reduction of ungulates number for browsing related issues. The intervention of the hunter is needed as the ungulates breed uncontrollably and prevent the regeneration from reaching the canopy stage, inflicting higher financial pressure on the forest owners. Compared to the non-harmful methods for preventing and controlling the browsing, hunting generates revenues through selling licenses, trade of meat and trophies and other revenues gained through hunting (Arnett & Southwick 2015; Cotta V. 1956). In some areas of Germany, the overabundance of ungulates has reached such a high rate that hunting is seen as the only viable solution (Calkoen et al. 2022; Heinrichs et al. 2012; Hothorn & Müller 2010a, 2010b; Möst et al. 2015). A controlled culling has to be adopted in the regions where browsing has gotten out of control. Also, alternative measure such as fertility control has to be taken into account as future measures (Warren & Warnell, 2000).

Out of the 153 studies included in the review, only 15 declared the presence of predators in the study area. Out of the 15 studies, only 6 of them showed a stable population of predators that can impact the numbers of ungulates, while the other 4 had in their study area a deficient number of predators (Bödeker et al., 2021; Calkoen et al., 2022; S van Beeck Calkoen et al., 2018). In Poland, Romania, Russia, and Slovenia, the presence of large predators such as the grey wolf, European lynx and brown bear has been shown to impact the ungulate population and behavior. Areas with higher predator densities have lowered the browsing intensity, and the ungulate density has been balanced with the ecosystem carrying capacity (Abaturov B.D. & Smirnov K.A., 1992; Bodziarczyk et al., 2017; Borowski et al., 2021; Ichim, 1987; Kuijper et al., 2009, 2010, 2013). A study comparing the browsing impact on similar forest stands and ungulate density in Germany and Romania showed that the presence of stable populations of large carnivores reduces browsing intensity (to less than 5%) (Schulze et al., 2014). The reintroduction of natural predator-prey interactions can have a beneficial effect not only on the browsing issue but also on the overall balance of the ecosystem (Brown et al., 1999; Fortin et al., 2005; Kuijper et al., 2013; Padaiga, 1998; Ripple et al., 2001; Ripple & Beschta, 2003, 2012b). Studies have provided evidence that the ungulates actively avoid areas where predators and hunting activities are prevalent, preferring locations with lower risks to their safety (Jedrzejewski et al., 2000; Theuerkauf & Rouys, 2008). In areas with high densities of predators, the feeding and resting behavior of ungulates changes, as they tend to be more cautious and avoid high predation risk areas (e.g., large clearcuts with no refugees) (Gervasi et al., 2013; McCullough et al., 2000; Sand et al., 2006). This suggests that the reduction in browsing damages may not only be due to predation of the ungulates themselves but also by the changes in behavior caused by the presence of carnivores. As the natural reoccupation of large carnivores of their former habitats can be a slow process, relocation procedures from countries with high densities of carnivores have to be carried out to countries with low populations (Linnel et al., 1997). For this purpose, not only will the relocation action be challenging, but also the education of local communities and changes in the perception of the locals (Franchini et al., 2021).

In this branch of wildlife studies, it is crucial to acknowledge several limitations that affect a uniform analyzis of the impact of ungulates. The lack of clear standardization in data collection methods affects the ability to compare different studies, even within the same country. This review found both quantitative and qualitative parameters used to assess browsing intensity, which can lead to an improper assessment of the severity of the phenomenon and create unfair comparisons between study areas. The density of ungulates is an important parameter as it explains the primary cause of browsing. In certain instances, the forest ecosystem has been altered in recent decades due to the high densities of ungulates. It is therefore logical to establish thresholds for acceptable ungulate densities based on different forest scenarios (Putman et al., 2011). This approach can help in managing ungulate populations effectively and maintaining a balanced ecosystem. It is important to acknowledge that browsing by ungulates not only changes the forest ecosystem but also influences the behavior and ecology of the ungulates themselves. The interaction between ungulates and their forest habitat is dynamic, with both sides adapting to each other's presence and characteristics (Putman, 1996). Understanding how ungulate behavior is influenced by the forest ecosystem is essential for effective management and conservation strategies. In some cases, counting and determining the number of ungulates can be challenging due to habitat diversity, sensitivity to disturbance, the risk of overcounting, and other factors. As shown in Table 1, some of the data were not clearly mentioned, and qualitative terms such as "high" or "severe" were often used to describe the browsing intensity or ungulate density.

Regarding future research directions for studying ungulate browsing, it is essential to standardize the measurement units used in studies to enable proper comparison and assessment. Additionally, study areas should extend to regions where browsing phenomena is not causing significant damage to identify the variables that keep damages under control. Future studies should focus on analyzing browsing in different geographic regions with varying carnivore densities, hunting management, and forest management practices. By doing so, a better understanding of the impact of ungulate browsing on the environment can be gained, and an effective management strategy can be developed to mitigate its effects.

2.5. Conclusions

This research confirms that ungulate browsing represents a critical issue to the development of young forests in Europe, as their numbers have reached alarming numbers in the past decades. The results provided valuable insights on local and regional aspects of the dynamics of ungulate herbivory in vastly different ecosystems. The results revealed that the overpopulation of ungulate represents the main cause of the damage, followed by silvicultural systems, lack of natural predators and hunting management. High levels of browsing can explain why some palatable species decrease in density while promoting the growth of other unpalatable tree species. Effective forest management practices, including proper hunting management and predator presence, are essential for controlling ungulate populations and promoting successful forest regeneration. This review highlights that the ungulates expanded in numbers and range in the past decades and ungulate browsing is a real issue.

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CHAPTER 3: TRACKING POPULATION TRENDS: INSIGHTS FROM DEER HUNTING HARVESTS IN THE BALTICS, CENTRAL, AND EASTERN EUROPE

The results presented in this chapter were published in Central European Forestry Journal (Ionescu, O., Hardalau, D., Bakševičius, M., Manton, M., Popovici, D.-C., Codrean, C., Ionescu, G., & Iordache, D. (2025). Tracking population trends: Insights from deer hunting harvests in the Baltics, Central, and Eastern Europe. *Cent. Eur. For. J*, *71*,)

3.1. Introduction

Ungulates population dynamics and distribution are vital for maintaining ecological integrity and balancing human activities such as forestry, agriculture, and wildlife management. Species like red deer (Cervus elaphus L.), roe deer (Capreolus capreolus L.) and fallow deer (Dama dama L.) represent not only important game species but also play key roles in shaping vegetation (Cook-Patton et al., 2014; Pekin et al., 2014), influencing biodiversity (Adhikari et al., 2021; Coulson, 1999; Vavra et al., 2007), and serving as prey for large carnivores (Clark & Hebblewhite, 2021; Linnel et al., 1997). The three ungulate species are among the most common deer species in Europe, characterized by their extensive range and substantial population numbers.

Red deer has one of the largest distributions, being found not only in Europe but also in Africa, Asia, North and South America. This species is only absent from northern Scandinavia and most of European Russia, being found even in the British Isles and Sardinia (Burbaite & Csányi, 2010; Lovari et al., 2019). Out of the studied species, red deer has the biggest body weight and their habitat covers a bigger altitudinal range, being found from the alpine meadows down to the low-land agricultural fields (Cotta et al., 2001; Szemethy L et al., 1998). As a polygynous ungulate, (Clutton-Brock & Lonergan, 1994) red deer populations not exposed to predation or culling tend to have an adult sex ratio that favors females, typically ranging from 1.5 to 2 females for each male.

Roe deer can be considered the most abundant and widespread species in Europe, except for southern Greece, parts of southern Italy and the Iberian Peninsula, Ireland, Iceland, and some Mediterranean islands such as Corsica, Sardinia, and Sicily (Sommer et al., 2009; Torres et al., 2015). The roe deer is the smallest species, but it is the one best represented by numbers, which often overlaps with red deer (Cotta et al., 2001; Lovari et al., 2017). There is a high inconsistency and variation in the roe deer sex ratio, influenced by various intra- and inter-specific factors, predation, and habitat conditions (Hewison et al., 1999; Macdonald & Johnson, 2008; Vreugdenhil et al., 2007).

Fallow deer, originate from Minor Asia, southern Anatolia, Sicily, southern Italy, and the southern Balkan peninsula. It is now one of the most widespread cervid species in Europe, having been introduced to the majority of the continent (Chapman & Chapman, 1980; De Marinis et al., 2022; Ludwig et al., 2012). With a body weight in between to other studied species, fallow deer are more social than the others (Cotta et al., 2001). In terms of habitat range, fallow deer prefer lower altitude zones and typically do not overlap with roe and red deer, often pushing them outside their habitat (Ferretti et al., 2011). The sex ratio of males to females at birth is about 1:1, with very small fluctuations (Ueckemann & Hansen, 2002).

Cervids are influential herbivores that directly affect positively and negatively forest dynamics and plant communities through their browsing activities (Pellerin et al., 2010). Their role as prey species is also critical. Large carnivores like wolves (Canis lupus L.) and lynx (Lynx lynx L.) depend on cervid populations for sustenance (Sunde P et al., 2000). In regions where predator populations are low or absent due to human intervention, cervid populations have increased, leading to more significant herbivory pressures on ecosystems (Ripple & Beschta, 2012a; van Beeck Calkoen et al., 2023)

The interaction between cervid populations and forest regeneration is a central concern for forestry (Ramirez et al., 2018). In many regions, cervids limit the regeneration of commercially important tree species, such as oak species (Cutini et al., 2015; Drexhage & Colin, 2003; Partl et al., 2002), Aceraceae species (Cermak P. & Mikva R, 2006; Fuchs et al., 2021), and especially broadleaved species (Cermák & Mrkva, 2000). In the case of coniferous species, a common issue identified in the literature is the tendency of Silver fir replacement with Norway spruce through browsing. (Bernard et al., 2017; Heuze et al., 2005b). Besides browsing, other types of damage, such as bark stripping (Konôpka et al., 2024), fraying, and trampling, are problematic in areas with high ungulate densities.To mitigate ungulate impact, forest managers often employ measures such as controlled hunting. Ungulate are an integral part of hunting culture and the rural economy in many parts of Europe (Mysterud et al., 2020). Significant importance should be placed on culling and maintaining an appropriate sex ratio within the adult population. At times, the sex ratio is not well maintained, with the number of females exceeding the number of males, deviating from the ideal ratio of 1:1 (Clutton-Brock T.H. et al., 2002). The ideal sex ratio for the red, roe and fallow deer is considered to be 1:1 (50:50), value at which generations do not overlap and mating is strictly at random (Sinclair et al., 2006). Hunting provides a source of income through game tourism, meat production and also serves as a tool for population control (Apollonio et al., 2010) However, because females are often considered less valuable than males and as the hunters are reluctant to harvest them, there is greater pressure on males in certain populations (Festa-Bianchet, 2003). The selection of ungulates should not be based solely on male harvest; the harvesting of females is equally important. Over time, ungulate populations can become unmanageable, and cervid overabundance can lead to conflicts with human activities, including forest and crop damages and increased vehicle collisions (Delahay et al., 2007). Thus, understanding the population dynamics and distribution of cervids is essential for the sustainability of both ecosystems and human livelihoods.

This calls for integrated approaches that assess trends in cervid populations and their distribution. Traditionally, cervid populations are estimated using various surveying methods conducted by hunters, wildlife managers, and relevant ministries, which are then reported at regional or national scales (Done et al., 2024). However, these methods of evaluating large populations can be time-consuming and costly and inaccurate, as the survey area and population numbers may be too large to count efficiently (Amos et al., 2014; Daniels, 2006; Davis et al., 2020; Forsyth et al., 2022).Whereas the hunting bag method has been proposed and somewhat developed as a timelier and cost-efficient method (Burbaitė & Csányi, 2009; Burbaite & Csányi, 2010; Milner et al., 2006). By using real data shared by hunters and wildlife managers through different reporting systems based on game tags or licenses, the information can be considered more trustworthy and it can be used even to project the population number estimates. As modern wildlife management is applied, the number of annually harvested game is managed to avoid over-exploitation and to maintain an equilibrium in game populations.

The aim of this study is to evaluate and describe the trends of three European cervid populations (red deer, roe deer, and fallow deer) for the period from 2012 to 2022, using hunting bag numbers and sex ratios. Firstly, the growth trends of the three ungulate species will be calculated, with 2012 serving as the reference year. Secondly, population numbers for the three species for 2022 will be projected based on three different harvest rate scenarios.

3.2. Material and methods

3.2.1. Study area

This study focused on 14 countries from Baltics, Central and Eastern Europe countries.

In the Baltics, data were found for all of the three countries: Estonia, Latvia and Lithuania. In the Central Europe region, data were gathered from Germany, Switzerland, Austria, Slovenia, Slovakia, the Czech Republic, Poland, and Hungary; however, data from Liechtenstein were not available. In Eastern Europe, data were collected from Belarus, Romania, Moldova, Serbia and Ukraine, while data from European Russia were not identified. Due to inconsistencies in the data from Moldova, Serbia and Ukraine, these countries were excluded from the study. In the case of Moldova, the numbers were briefly described only for 'hoofed' animals. For Serbia, hunting bag data were reported biennially rather than continuously, and for Ukraine, data were available only for the period from 2018 to 2020. Out of the 14 countries included, sufficient data were available for red and roe deer in all of them. However, Belarus, Slovenia, and Switzerland lacked data for fallow deer. Other areas of Europe were not included in the study due to inconsistent data or because data was not publicly available for all the years analyzed. Including countries where these species are less common or where different subspecies are more prevalent would diminish the focus and relevance of the findings. The selected ungulate species are either the most abundant or have experienced significant population increases in recent decades in Baltics, Central and Eastern Europe. Moose were not selected for the study due to their more northern distribution range, and sika deer were excluded because of their reduced range.

3.2.2. Data collection

This paper proposes an alternative approach to understanding the evolution of deer populations by utilizing the hunting bag. The hunting bag is a parameter that represents the total number of specimens harvested from a species, as reported annually by wildlife managers and hunters. This indicator can be more reliable, as the numbers are reported under specific regulations rather than estimated through various wildlife monitoring techniques (Marrocoli et al., 2019). Although monitoring methods can provide a good statistical representation, they may lead to double counting or the omission of individuals (e.g. in remote mountainous areas lacking proper infrastructure) (Apollonio et al. 2017). Even though factors such as mortalities caused by deer-vehicle collisions, poaching (Eliason 1999), and predation (Ballard 2003) are important, this paper will focus solely on the hunting bag.

Hunting bag numbers for red, roe, and fallow deer were sourced from national statistical databases and relevant ministries (Table 3.1). While the accuracy of hunting bag data varies between countries due to differing reporting systems, it is considered more reliable than population estimates. Consequently, hunting bag data provide a more dependable basis for analyzing trends (Carvalho et al., 2024). The study period spanned a decade, from 2012 to 2022, to provide a comprehensive timeline The final year of investigation was set as 2022, as data for 2023 and 2024 had not been updated for all countries.

Table 3.1. Sources of hunting bags in selected countries of the Baltics, Central and Europe

Country	Data Source	Comments
Austria	STAT Cube – statistical database of statistics Austria https://www.statistik.at/en/statistics/agriculture-and-forestry/animals-animal-production/hunting	*
Belarus	National Statistical Committee of the Republic of Belarus https://dataportal.belstat.gov.by/osids/rubric-info/1063239	No sufficient data for fallow deer
Czech Republic	Czech Statistical Office	*

	https://data.csu.gov.cz/datastat/data/	
Croatia	Croatian Bureau of Statistics https://web.dzs.hr/default_e.htm	
Estonia	Statistics Estonia https://www.stat.ee/en/find-statistics/statistics-theme/environment	No data for fallow deer
Germany	German Hunter Association (Deutscher Jagdschutzverband) https://www.jagdverband.de/zahlen-fakten/zahlen-zu-jagd-und-jaegern	
Hungary	STADAT- system of Central Statistical Office Hungary https://www.ksh.hu/stadat?lang=hu&theme=kor	
Latvia	Official statistics of Latvia https://stat.gov.lv/en/statistics-themes/environment	No data for fallow deer
Lithuania	Ministry of Environment of the Republic of Lithuania https://am.lrv.lt/lt/	
Poland	Forestry Statistical Yearbook 2022 https://stat.gov.pl/en/topics/agriculture-forestry/	
Romania	Ministry of Environment, Waters and Forests https://www.mmediu.ro/categorie/vanatoare/26	No data for 2012 and 2013 *
Slovakia	Statistical Office of the Slovak Republic https://datacube.statistics.sk/	
Slovenia	Slovenian Forest Service https://pxweb.stat.si/SiStat/en/Podrocja/Index/99/environment	No data for fallow deer
Switzerland	Federal Office for the Environment https://www.bafu.admin.ch/bafu/de/home.html	No data for fallow deer *

*-Sex and age class data were identified

3.2.3. Statistical analysis

All analysis will be based solely on the hunting bag and related parameters in order to emphasize its importance and reliability. The database and the visualization were created using Microsoft Execell 16.91. All statiscal analysis were performeed using IBM SPSS Statistics 29.0.2.0. Firstly, to assess the trend in hunting bag growth for each country, a relative growth trend was calculated based on the provided numbers, with 2012 designated as the reference year. After assessing each country, a map illustrating the overall trend was created, and a general growth trend was established based on the average growth. For the relative growth trend, the difference between the refference year and the following year was divided by the value of the following year (Formula 1):

Formula 1

$$RG1 = \frac{y2013 - y2012}{y2012} \ldots RG10 = \frac{y2022 - y2012}{y2012},$$

where RG=Relative growth

y2012= the refference of the hunting bag value

y2022= the value of the hunting bag for the specific year

Secondly, based on studies by (Bijl & Csányi, 2022; Cotta et al., 2001), the hunting bag was used as an indicator of population estimates. In this matter, a projection of population size for each country was calculated at different harvest rates. It is believed that the harvest rate accounts for 20% to 30% of the total population size; values exceeding 30% can lead to over-exploitation of deer species and hinder natural population growth. For this study, the projection was done also using 40% harvest rate, as some countries are using even a higher rate in order to keep the ungulate number under control (Burbaitė & Csányi, 2009; Burbaite & Csányi, 2010).

3.3. Results

3.3.1. Relative growth of deer hunting bag in Baltics, Central and Eastern Europe

For red deer, the highest relative growth in hunting bags was recorded in Belarus and Lithuania, with an increase of 645.5% and respectively 639.9%. This was followed by Latvia at 330.0%, Estonia at 134.9%, Romania at 129.8%, Slovakia at 122.83%, Croatia at 95.7%, Hungary at 70.0%, Slovenia at 63.8%, Switzerland at 47.6%, and the Czech Republic at 42.4%. In contrast, a decreasing trend was observed in both Austria and Germany, with declines of -2.2% and -2.0%, respectively. Among three of the studied countries - Estonia, Lithuania, and Romania - the relative value of red deer harvested specimens in 2012 was approximately 1,650. Notably, by 2022, the relative growth rates were 134.9% for Estonia, 129.8% for Romania, and an impressive 639.9% for Lithuania.

Regarding roe deer, Estonia had an impressive growth of 1232.4%, followed by Latvia with 668.4% and Belarus with 302.7%. Romania and Slovakia also showed impressive increases, with values of 102.45% and 122.8%, respectively, while Lithuania recorded a growth of 56.9%. Slovenia experienced a decreasing trend of -7.6%, while Switzerland maintained a stable trend at 0.3%. The remaining countries recorded growth values ranging from 3.3% to 25.8%.

Data on fallow deer hunting bags were unavailable for Belarus, Estonia, Latvia, Slovenia, and Switzerland, so relative growth was calculated only for the remaining countries. Aside from Germany, which showed a decreasing trend of -6.2%, all other countries demonstrated an increase in hunting bag numbers. The smallest increase was recorded in Poland at 38.2%, while the other countries reported growth rates above 65%. The highest increase was observed in Lithuania at 1138.7%, followed by Slovakia at 389.9%, Czech Republic at 135.6%, Romania at 113.4%, Croatia at 111.2%, Hungary at 103.4%, and Austria at 65.7%. The relative growth trend for all of the 3 cases is presented in Figure 3.1.

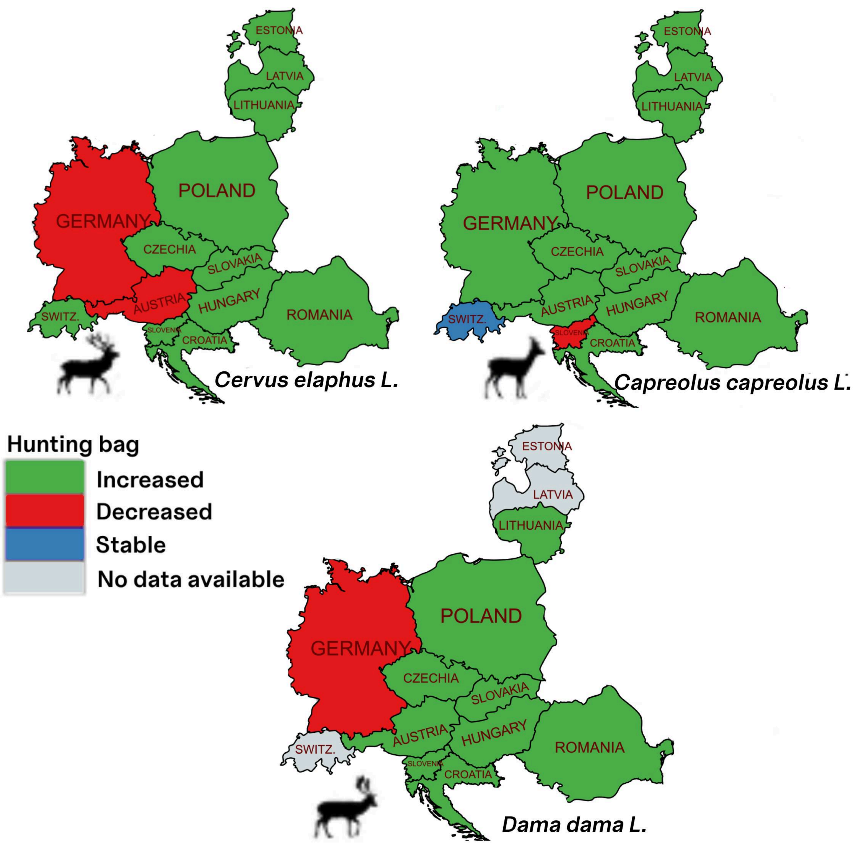

Figure 3.1. Changes in deer hunting bags in selected countries of the Baltics, Central and Eastern Europe between 2012 and 2022.

Overall, the population trends of the three species have increased throughout the study area. At Baltics, Central and Eastern Europe level, the highest relative growth in hunting bag values was registered for the fallow deer population (54.1%), followed by red deer with a rise of 50.2% and roe deer with 15.7% (Figure 3.2).

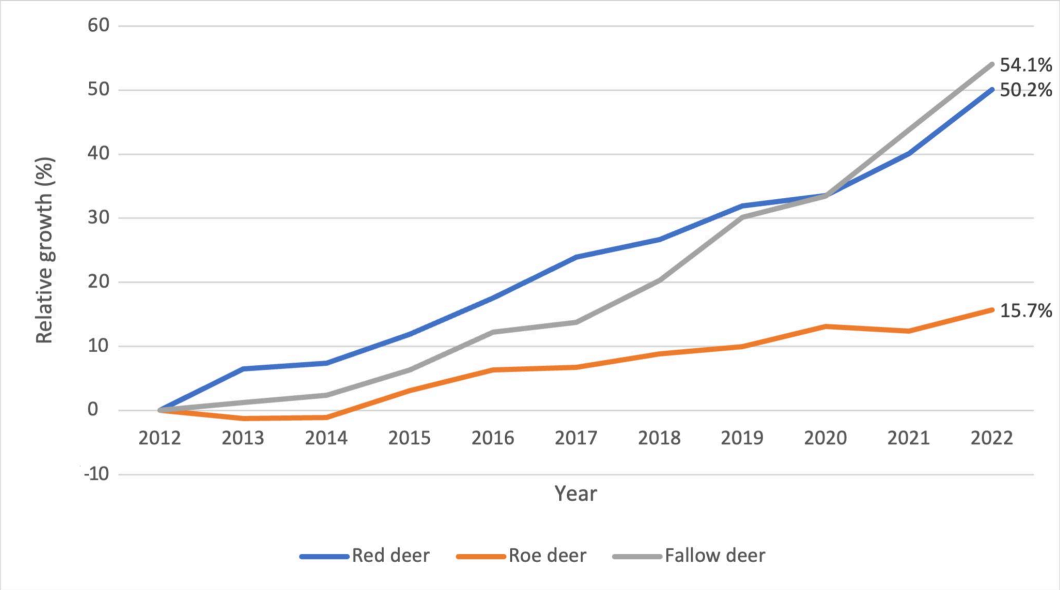

Figure 3.2. Relative growth in hunting bags in selected countries from Baltics, Central and Eastern Europe.

3.3.2. Deer population in Baltics, Central and Eastern Europe based on the hunting bag

Based on the theoreticaly projected population size for 2022 across 14 European countries, 3 harvest rates were used: 40%, 30% and 20%. Based on these projections, the estimated number of red deer ranges from 1,242,600 to 2,485,200 individuals, roe deer population estimate ranges between 5,828,700 to 11,148,000 individuals, while fallow deer population is estimated ranges between 422,700 and 845,300 individuals.

Table 3.2. Population estimation based on adjusted values from hunting bag (thousands) in selected countries from Baltics, Central and Eastern Europe in 2022

Country	Species								
	Red deer			Roe deer			Fallow deer		
Harvest rate	40%	30%	20%	40%	30%	20%	40%	30%	20%

Austria	144	191	289	728	961	1456	3	4	6
Belarus	15	20	31	67	88	133	0	0	0
Estonia	82	109	164	285	377	571	0	0	0
Czech Republic	14	18	27	45	59	89	97	128	193
Croatia	16	22	33	103	136	206	4	5	8
Germany	187	247	374	3264	4309	6529	162	214	323
Hungary	203	268	406	274	361	547	52	68	103
Latvia	60	79	120	88	117	177	0	0	0
Lithuania	37	49	74	63	83	126	2	3	5
Poland	269	356	539	505	667	1010	27	36	54
Romania	12	15	23	71	94	142	4	5	8
Slovakia	146	193	293	146	193	293	75	99	150
Slovenia	22	29	45	77	102	154	0	0	0
Switzerland	34	45	69	113	149	225	0	0	0
TOTAL	1243	1640	2485	5829	7694	11657	423	558	845

3.3. Discussion

Based on the findings of this study, all three species have shown an increasing trend in hunting bag growth. This increase in harvest suggests a corresponding growth in population. In Romania, all three species have demonstrated an upward trend during the studied period. primarily attributed to the adoption of a modern wildlife management plan that emphasizes normalizing both population numbers and sex ratios. Since the 2010s. the management of hunting grounds has been assigned to private managers, forest administrators, and county associations, following strict regulations, harvesting plans, and monitoring techniques. Additionally, due to the high density of large carnivores, red deer and roe deer have migrated to lower altitudes and in the proximity of agricultural crops, where they have begun to reach abundant densities (Hardalau et al., 2025).

The highest overall growth has been recorded for the fallow deer, with an increase of 54.1%. This species has been anthropogenically influenced in its distribution and is one of the world's most widely naturalized animals, aside from domesticated or feral livestock (Esattore et al., 2022). The highest growth was identified in Lithuania with an increasse of 1138.7%. This growth can be explained by the efforts of creating a stable population of fallow deer in Lithuania. The second highest growth was identified in Slovakia, with an increase of 389.9%, followed by the Czech Republic with 164.9%. These increases are primarily attributed to management efforts driven by the popularity of fallow deer as a game species in these countries, as well as the escape of fallow deer from farms.

Red deer become one of the most proficient species in recent decades, with an overall growth of 50,2% in hunting bags, as their populations have increased in most of the studied countries, except for Austria and Germany. Particularly in Germany, the population of red deer is already oversaturated, and efforts to reduce their numbers have been a long-standing concern for hunters in order to prevent damage to forestry and agriculture (Gerner et al., 2011; Heinze et al., 2011b; Hothorn & Müller, 2010b). As the trend in Germany and Austria shows a decrease in red deer populations, it can be admitted that these countries are managing the issue effectively. In both Belarus and Lithuania the hunting bag increased drastically, with more than 600% in the studied period. In the case of Belarus, with the adoption of modern hunting management and a proper monitoring method, made the red deer and roe deer population to explode (Shumski et al., 2017). In Lithuania, the growth and high densities of red deer are primarily due to immigration and relocations following World War II, particularly after the adoption of proper management plans in the 2000s and the increase in final forest harvesting resulting in a greater availabity of young stands for foraging (Balčiauskas & Kawata, 2022). In the last five years, the red deer population in Lithuania has doubled, leading to increased damage to agricultural crops and forests, which resulted in the lifting of the hunting quota for red deer (Bakševičius, unpublished). The 330% growth of the red deer population in Latvia can be primarily attributed to reintroduction efforts in the 19th century and forest management (Baumanis J et al., 2018). Since then, the red deer population has undergone impressive changes, allowing it to occupy nearly 90% of the country's territory and follow a normal population development pattern.

Among the three studied species, the roe deer recorded the lowest relative growth value in hunting bags; however, the overall harvest numbers are nearly five times higher than those of red deer (see Table 3.4, Appendix). During the decade from 2012 to 2022, the highest growth rates were observed in Estonia and Latvia, with impressive increases of 1232.3% and 668.4%, respectively. The newly adopted hunting regulations and quotas, along with milder winters, lower predatory pressure, and an increase in agricultural crops, have created more favorable conditions for the roe deer population to thrive (Burbaitė & Csányi, 2009). The growth of roe deer in Lithuania over the past two decades has made it the most abundant cervid species, outnumbering moose by 8 to 12 times and red deer by 2 to 4 times (Balčiauskas, 2024).

Not only have hunting bag numbers increased in the past decades, but population numbers have also risen exponentially. Based on the population projections made in this study, a similarity was identified in the same countries compared to other studies conducted prior to this one. In the case of red deer, considering the lowest population estimate of 1,243,000 individuals, these figures are approximately three times higher than those reported by (Burbaite & Csányi, 2010) for the year 1984 and 2.2 times higher than the values from the 2010s for the same countries. For roe deer, compared to a similar study conducted by (Burbaitė & Csányi, 2009), the lowest estimate of 5,829,000 individuals is 1.82 times higher than the value reported in 1984 and 1.31 times higher than the value from the 2000s. For fallow deer, the lowest estimate from the projection is 423,000 individuals, which is only 15% higher than the population reported by (Bijl & Csányi, 2022) at the beginning of the 2020s, corresponding to a growth of around 7.5% each year in fallow deer numbers.

Based on the correlation analysis, it was found that only in the case of roe deer does the sex ratio of harvested specimens impact annual growth, while for the other studied species, these parameters did not show any correlation. In many deer populations, the main goal of management is to optimize the annual harvest of mature males, which requires a high culling rate of females to prevent their numbers from increasing to a point that negatively impacts male survival and skews the adult sex ratio in favor of females (Clutton-Brock & Lonergan, 1994). These findings may be explained by the ethology of the species and the age at which they reach adulthood and are able to reproduce (Cotta et al., 2001). As the roe deer is the smallest of the studied species and has the lowest age of reaching adulthood, it might explain the existing correlation. However, other studies have shown that at high densities of red deer, the tendency of dominant females to give birth predominantly to males disappears, resulting in a ratio that favors females (Kruuk L et al., 1999). The significant increases in all three deer populations may be influenced more by other factors than the sex ratio of harvested animals. These factors include advancements in agricultural and forestry technology, improvements in crop genetics, greater forage availability in forested areas and low large carnivores densities. (Apollonio et al.. 2010; Bijl & Csányi. 2022; Kaczensky et al.. 2013; Reimoser & Reimoser. 2016). In some cases, such as in Poland and Romania, where a large and stable population of large carnivores is present, it must be acknowledged that, in addition to the hunting bag, a considerable number of deer are naturally removed by carnivores (Chapron et al., 2014; Kaczensky et al., 2013).

Ungulates overabundance is affecting the forestry, agricultural and the human safety itself. High ungulate densities can lead to over-browsing, which reduces tree seedling survival, alters species composition, and impedes tree recruitment (Angelstam et al., 2017; Gill, 1992c). Over-browsing often impacts overall plant diversity and habitat quality which results in a shift towards less palatable species (Bernes et al., 2018), which are not always the species desired by forest managers. Timber depreciation caused by browsing, bark stripping, and fraying also impacts the financial gains of forest managers (Gill, 1992c; Ichim, 1989b), particularly in areas where timber production is a key industry (Suzuki et al., 2021). A study from Slovakia have shown that artificially regenerated tree stands are more susceptible to browsing than naturally regenerated ones (Šebeň & Konôpka, 2024). In the case of the stands with natural regeneration, the sapling density is considerable higher and the damaged saplings are considered "compensatory mortality" (F. Reimoser & Gossow ', 1996). Additionally, the opening of new forest gaps allows invasive species to install, such as rowan (*Sorbus aucuparia L.),* aspen (*Populus tremula L.*) or blackberries (*Rubus hirtus Waldst. & Kit.*) (Edenius & Ericsson, 2015; Konôpka et al., 2018). In some cases, such as Austria, the damages caused by ungulates to the forestry sector reached up to 218 million euros annually between 1990 and 1999 (F. Reimoser & Reimoser, 2010). In the case of damages in agricultural fields, ungulates primarily affect corn and wheat crops, reducing their yield per hectare (Bleier et al., 2017). Additionally, by trampling, they decrease the height of the plants and indirectly the productivity of the plant (Drimaj et al., 2023). In the case of road accidents involving ungulates, the number of incidents has surpassed millions worldwide, with damages exceeding billions of euros through various compensation methods (Langbein et al., 2011).

Currently, the focus of wildlife management is not on increasing population sizes but rather on maintaining and reducing the numbers (Barton et al.. 2022). The carrying capacity is a crucial indicator that should be highly respected (del Monte-Luna et al., 2004). Three main aspects of this parameter (ecosystem, economy and social acceptance), which influence the coexistence between ungulates and humans, should be considered for effective wildlife management (Linnell et al., 2020). Wildlife managers should maintain ungulate populations at levels that do not exceed the ecosystem support capacity, as excessive populations can negatively alter the ecosystem (Apollonio et al., 2017). Ungulates and other game animals must be maintained at levels that do not cause more damage than forest managers, wildlife managers, or ministries can support (R. Putman, Apollonio, et al., 2011). Social acceptance must be considered, as a high number of ungulates can create problems for local communities and farmers that they may not be willing to tolerate (Carpio et al., 2024). In response, these communities might resort to alternative methods to reduce ungulate populations on their own.

The countries involved in this study employ various methods to establish the limits of game that can be supported by the ecosystem, the economy, humans, or a combination of these factors. In the case of Romania, the Ministry of Environment, Waters, and Forests (Law 407/2006) has established an optimal population number for game that should be maintained based on the characteristics of certain areas. According to (Almasan H., 1989), the method establishes the limits that can be supported by 1,000 hectares of forest, depending on various bonity types. Additionally, based on the body mass of the ungulates and on the consumption level, the study proposed that the stock unit equivalents for deer are as follows: for every 5 roe deer, the equivalent is 1 red deer, and for every 1.78 fallow deer, the equivalent is also 1 red deer. Similarly, Ministry of Environment of the Republic of Lithuania , has set limits of animals per 1,000 ha based on the forest type. In this case, for every 4 roe deer, the equivalent is 1 red deer. In both of the cases, the stock unit equivalent should not exceed the limits of the carrying capacity. As most ungulates coexist in the same areas, a stock unit equivalent based on the carrying capacity should be proposed throughout Europe to ensure that ungulate populations remain under control. By reducing the number of ungulates to levels that can be supported ecologically, economically, and socially, the damages they cause can also be kept at acceptable levels. In order to control the increasing growth of ungulate populations, new management practices that promote culling and the reintroduction of large carnivores should be implemented. At the European level, a uniform method for game estimation and a hunting bag reporting system should be established. Additionally, there is a need for the harmonization of the interests of hunters, foresters, and farmers, which requires a coordinated approach across EU countries.

While this study utilized harmonized data, it does have limitations stemming from the variations in wildlife management practices across Europe. Our conceptual model was applied solely to the hunting bag and related parameters. Wildlife management varies significantly among the selected countries, with the size of hunting grounds being a key issue (Mesinger & Ocieczek, 2021). These grounds can range from private properties of just a few hectares to leased hunting areas as large as 30,000 hectares, and data on this variability were not available. Additionally, the terrain's orography plays an important role; some hunting grounds are located in remote mountainous areas, which cannot be managed as effectively as those situated in flat regions. The densities of large carnivores and the effects of natural selection were not taken into account (Linnell et al., 2001). Future studies should also focus on the impact of both large and small carnivores, as well as the losses due to mortality and competition with livestock. Additionally, similar studies should be developed on moose, sika deer, wild boar and other species of interest. The impact of ungulates is a significant issue for ecosystems, economics, and human safety, and more emphasis should be placed on this subject.

3.4. Conclusions

This study focused on the growing of the ungulates population across 14 countries from Baltics, Central and Eastern Europe, a phenomenom a o high interest for practitioners and academics. The approach of quantifiying the growth was the use of hunting bags as a primary parameter. Evidence from previous studies confirms the robust growth of ungulate numbers population based on hunting bags in the 2012-2022 period. Despite the harmonized data used in the study, limitations exist due to varying wildlife management practices across different countries, as well as the influrence of terrain and large carnivores presence. Future studies should focus on these factors to develop a more nuanced understanding of ungulate dynamics.

3.5. References

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CHAPTER 4: INSIGHTS IN MANAGING UNGULATES POPULATION AND FOREST SUSTAINABILITY IN ROMANIA

The results presented in this chapter were published in Diversity Journal (Hardalau, D.; Fedorca, M.; Popovici, D.-C.; Ionescu, G.; Fedorca, A.; Mirea, I.; Daniel, I.; Ionescu, O. Insights in Managing Ungulates Population and Forest Sustainability in Romania. *Diversity* 2025, *17*, 194. Q2, Impact Factor - 2.1. https://doi.org/10.3390/d17030194)

4.1. Introduction

The interactions between wildlife and forest ecosystems are essential for preserving biodiversity and maintaining ecosystem health. They support the sustainable management of natural resources—both game and timber—by enhancing biodiversity through seed dispersal, pollination, and species diversity; regulating ecosystem processes via predation, herbivory, and nutrient recycling; and maintaining habitat structure for forest resilience (Brockerhoff et al., 2017; Hunault-Fontbonne & Eyvindson, 2023; Sample, 2006). In some temperate areas in Europe, ungulates have increased in numbers in the past decades, creating imbalances between conservationists, ecologists, farmers, wildlife managers and forest managers (Apollonio et al., 2010; Carpio et al., 2021; R. Putman et al., 2011, 2013; R. J. Putman, 1996).

Noticeable shifts in ungulate populations have coincided with climate change and advances in agricultural practices, which have improved forage conditions. As a result, there have been significant increases in both the populations and the range of these species (Malpeli, n.d.; Mysterud & Sæther, 2011). Throughout Europe, the overabundance of ungulates has resulted in damage to the agricultural sector through reduced yields of several crops, damage to the forestry sector due to browsing, fraying, and trampling, and human safety concerns stemming from vehicle collisions (Gill, 1992c, 1992a). This study specifically focuses on the damage within the forestry sector caused by browsing. Ungulate browsing is represented by the consumption of vegetal material other than bark from young saplings which interfere with the normal development of the plant.

Browsing is a well-researched topic in the literature, with over 155 research papers published in Europe, of which roe deer (*Capreolus capreolus L.)* is the focus of 95 studies and red deer (*Cervus elaphus L.)* is the subject of 93 studies (Hardalau et al., 2024). One trend in the study of browsing focuses on the damage inflicted on coniferous species, particularly the replacement of more palatable species like silver fir (*Abies alba Mill.*) with less palatable ones such as Scots pine (*Pinus silvestris L.*) and Norway spruce (*Picea abies L.*) in Central and Southern Europe (Bernard et al., 2017; Diaci, 2001; Heuze et al., 2005; Motta, 1998; R. J. Putman, 1996; Reimoser et al., 2022; Unkule et al., 2022).. Another trend is the preference for broadleaved species over coniferous species in mixed plantations, as their palatability is much higher (D'Aprile et al., 2020; Rozman et al., 2015). This is the case for oak species (Drexhage & Colin, 2003; Shifley et al., 2006; Vacik et al., 2009), which are part of mixed regeneration with less valuable species; however, oak typically serves as a future crop tree (Clasen et al., 2011). Therefore, the loss experienced is not only ecological but also economic. Even if the browsed saplings survive, it has been shown that the future timber depreciates due to the development of multi-stem trunks and the onset of additional diseases that affect timber quality (Weigand et al., 1993).

This is particularly evident in the Western Plains of Romania, where populations of red deer (*Cervus elaphus L.*), fallow deer (*Dama dama L.*), and roe deer (*Capreolus capreolus L.*) have increased in numbers. The study area is characterized by large-scale, intensive agriculture on flat terrains, bordered by forests, similarly to areas found in the Hungarian Great Plain (Katona et al., 2013). Ungulates utilize the agricultural fields as both feeding and resting zones (Cimino & Lovari, 2003; Lande et al., 2014) almost year-around, with the exception of late winter and early spring when the crops are harvested and no abundant food is available. During their refuge period in the forests, the overabundant ungulates exploit all available resources. However, due to intensive browsing, the tree species struggle to develop adequately or survive in order to reach the canopy stage (Holzer et al., 2024).

The aim of wildlife managers is to maintain a population level at a level which the ecosystem can support, while preventing the loss of genetic diversity, enhancing the long-term survival and reduce the damages caused to the other sectors (Saltz & White, 2013). In most of the cases, the economical compesantion has to be covered by widllife managers(Gren et al., 2018), however, in some situations, the legislation does not provide enough flexibility to manage the population effectively, as the behavior of ungulate species has significantly changed, resulting in an increased natural annual growth (Carpio et al., 2021; König et al., 2020). Similarly, forest manager have to assure that the forest will develop properly and to use preventive measures against ungulate browsing, such as fencing or the use of repellents (Barančeková et al., 2007). Some silvicultural practices are also influencing the levels of damages, as silvicultural system use different regeneration techniques with highly different sapling density(F. Reimoser & Gossow ', 1996).

This study provides the first assessment of ungulate browsing in young oak stands in Romania and evaluates ungulate occupancy in forests with high unugulate densities. Analyzing browsing from both forestry and wildlife management perspectives, it aims to clarify the primary impact of high ungulate density—exacerbated by intensive agriculture—and to identify secondary factors based on local silvicultural practices. A comparison between actual and optimal ungulate populations, using Sustanaible Population Threshold (SPT), offers a clear visualization of density discrepancies. The findings will equip wildlife and forestry managers with crucial insights to mitigate browsing damage.

4.2. Materials and Methods

4.2.1. Study area

The study area was conducted in northwestern Romania, in the Western Plains, within forests managed by the Forest Administration Tinca. The location of the study is at 46° 46' N latitude and 21° 55' E longitude. The study encompasses five hunting grounds (HG): HG 25 Boboștea, HG 26 Păușa, HG 30 Peri, HG 31 Goroniște, and HG 35 Oșand (Figure 4.1), all under the jurisdiction of the Forest Guard Bihor. These hunting grounds cover a productive area of 43,282 ha, of which 13,562 ha are represented by forested areas, representing 31.33% ot the total area of the hunting grounds.

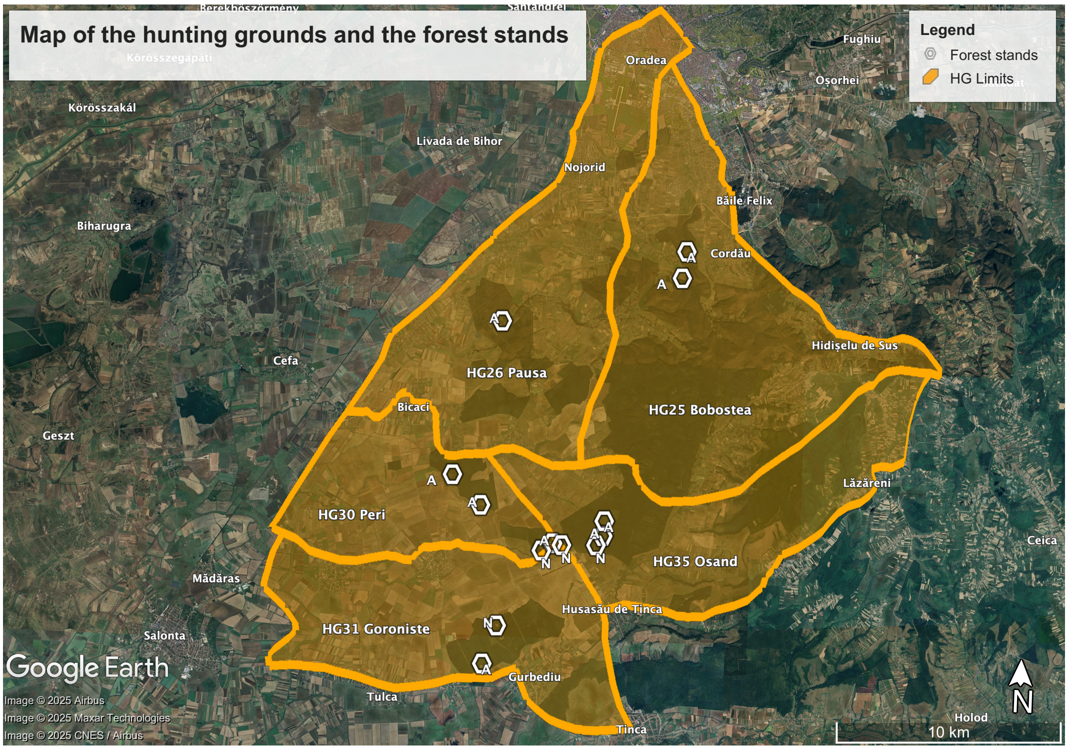

Figure 4.1. Map of the hunting grounds and forest stand included in the study

The forest included in the study are primarily dominated by oak species: Turkey oak (*Quercus cerris L.*), pedunculate oak (*Quercus robur L.*), Hungarian oak (*Quercus frainetto Ten.*), sessile oak (*Quercus petraea L.)* and northern red oak (*Quercus rubra L.).* Other tree species of forestry interest that can be found in the study area include European ash (*Fraxinus excelsior L.),* hornbeam (*Carpinus betulus L.),* black locust (*Robinia pseudoacacia L.)* and wild cherry (*Prunus avium L.).* The area is characterized by mostly flat terrain with altitudes below 200 m.a.s.l. The primary regeneration method implemented in the management plan is natural regeneration, as most silvicultural systems are continuous (shelterwood cutting). In forest-type substitutions, ecological reconstruction, and clearcuts, artificial regeneration is employed.

13 forest stands with abundant regeneration were selected, consisting of stands in the removal cut stage of shelterwood silvicultural systems or artificially regenerated stands within the first three years after planting. The selected forest stands covered a total area of 78.57 ha, of which nine stands were artificially regenerated (15.71 ha) and four stands were naturally regenerated (62.86 ha). All the studied stands were characterized by inadequate exclusion of ungulates, including inappropriate fencing or partial use of slash, which did not keep wildlife away. The area is characterized by a high density of the following ungulates roe deer (*Capreolus capreolus L.)*, fallow deer *(Dama dama L.)* and red deer (*Cervus elaphus L.).* The presence of large carnivores in the study area is limited, with infrequent sightings of gray wolves (*Canis lupus L*.) reported. The forested area is bordered by agricultural fields (54.3%) and meadows (23.9%), which provide wildlife with essential resting and feeding zones during the vegetation season. However, in winter and early spring, most wildlife (except for a portion of the roe deer population) migrates into the forest as the agricultural fields are harvested and meadows are heavily occupied by livestock.

4.2.2. Sampling design and data collection

For this study, a sample grid consisting of 42 plots, each covering an area of 100 m², was established in late winter of 2023. For artificial regeneration, a rectangular plot measuring 10 m on each side was utilized of asses five rows of saplings, in line with the adopted planting scheme of 2x1 m for all stands. In contrast, for natural regeneration, where sapling distribution was randomized, a circular plot with a radius of 5.64 m was employed. This method facilitates measurements and obtains minimal errors, ensuring that the collected data can be effectively compared. (Packalen et al., 2023).

The data collection protocol was adopted based on similar approaches (Ruprecht et al., 2012; Vacik et al., 2017) conducted in Central Europe. The main parameters during the measurements and used were represented by the presence of browsing on the sapling, whether it was on the terminal or lateral bud or shoots, the type of species, the root collar diameter (mm), the height of the saplings (cm) and the sapling vigour (3 classes). Only saplings of forestry interest species were recorded, while shrubs were not considered. The maximum height measurement for the saplings was 1.3 m. Besides the data recorded from the terrain, stand characteristics data were gathered from forest and wildlife management plans.

Secondly, using a concept developed in 1989 (Almasan, 1989) and in accordance with the methodology from Order 393/2002 (Ministry of Enviroments, 2002), the Sustainable Population Threshold (SPT) was calculated for the study area. The SPT is defined as the maximum density of individuals per 1000 hectares for a given species, considering economic, ecological, and social acceptance based on the best and worst conditions identified throughout the natural habitats in Romania.

The calculation is based on a four-category scoring system: biotic, abiotic, management and anthropogenic factors. These indicators consider climate factors, orographic factors, silvicultural practices, predation, agricultural impact and includes the particularities of the ecoregions. Based on these factors, the optimal number of each specimen for an area of 1,000 hectares was determined. Additionally, the stock unit equivalents for game species were calculated based on the largest ungulate in the study, the red deer.

4.2.3. Statistical analysis

The database and parts of the visualization and descriptive statistics were created using Microsoft Excel 16.91. All statistical analyses were performed using R, incorporating the following packages: MASS (Venable & Ripley, 2002), ggplot2 (Hadley, 2016), and jtools (Long, 2024). Box plots were developed to better visualize sapling density in both artificial and natural regeneration cases, as well as browsing occurrence.

A regression model was utilized to examine the spatial patterns and environmental factors affecting browsing incidence. Before fitting any models, the dataset was carefully checked for outliers and collinearity among the predictor variables (Table 4.1). To ensure comparability, all continuous variables were standardized and harmonized. The density of the ungulates was not included in the model, as the premise of the model is to identify the secondary variables that influence the browsing occurrence. The presence of browsing was treated as the dependent variable, encoded with 1 for its presence and 0 for its absence.

Table 4.1. Variables used to model the browsing occurrence, with encoding, type of variable and parametric

Variable	Code	Type	Min.	Max.	Mean
Dependent variable					
Browsing occurrence	BO	Categorical (2 levels): 0 or 1			
Independent variables					
Sapling characteristics					
Species	SP	Categorical (8 levels)			
Sapling vigour	VI	Categorical (3 levels)			

Root collar diameter	RD	Continuous	16	346	83.89
Height	HE	Continuous	10	130	53.70
Environmental characteristics					
Soil	SO	Categorical (10 levels)			
Forest share	DW	Continuous	0.12	0.41	0.33
Forest treatment	RT	Categorical (2 levels): Natural or Artificial			

4.3. Results

4.3.1. Regeneration and browsing characteristics

3,223 individual saplings were recorded from both natural and artificial regeneration. Regeneration was observed in all 42 sapling plots. In the artificial regeneration plots, 1,041 saplings were recorded, of which 62.4% were Pedunculate oak, 17.3% were European ash, 11.5% were Turkey oak, and 8.8% were red oak. In the natural regeneration plots, 2,182 saplings were recorded, with 79.8% being Turkey oak, 12.8% Pedunculate oak, and 7.3% European ash. Overall, the species composition of saplings for both types of regeneration was as follows: 57.3% Turkey oak, 28.6% pedunculate oak, 5.5% European ash, 4.9% Hungarian oak, and 2.8% northern red oak (Figure 2).

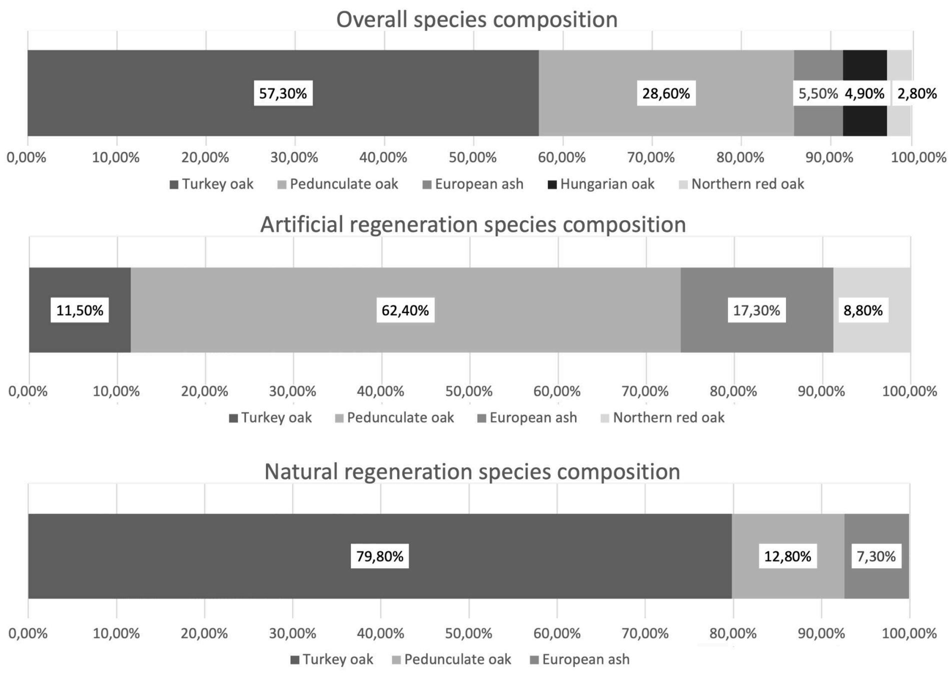

Figure 4.2. Species composition in the study area based on the 3,223 saplings recorded

In the case of clearcut forest treatment with artificial regeneration, the maximum density was 5,500 saplings per hectare, while the minimum was 4,200 saplings per hectare (Figure 3). The densities for artificial regeneration primarily fluctuated between 4,825 and 5,150 saplings per hectare, with an average of 4,980 saplings per hectare. In contrast, for continuous forest cover treatment with natural regeneration, the maximum density reached 17,100 saplings per hectare, while the minimum density was 8,400 saplings per hectare. The densities for natural regeneration mainly fluctuated between 9,600 and 15,650 saplings per hectare, with an average of 12,830 saplings per hectare.

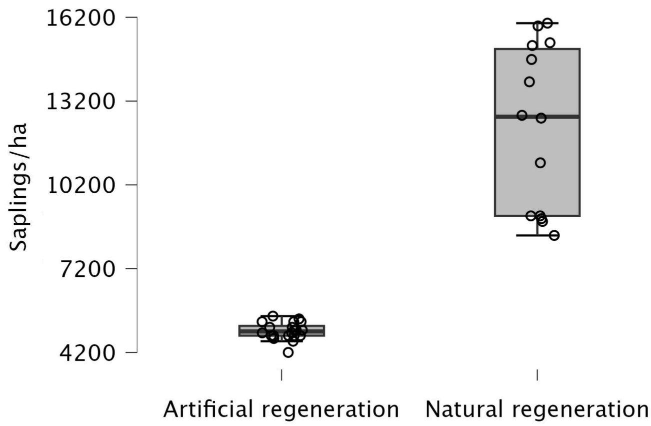

Figure 4.3. Sapling density per ha for artificial and natural regeneration in 2023 based on 3223 saplings recorded

The occurrence of browsing in study area varies according to the type of forest treatment (Figure 4). In the case of clearcut fellings with artificial regeneration, browsing occurrence ranged from 42% to 55%, with an average of 49.65%. In contrast, for continuous cover forestry with natural regeneration, the occurrence ranged from 8% to 17%, with an average of 12.8%.

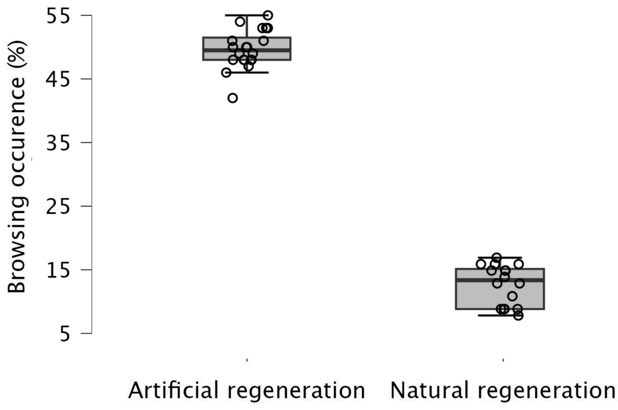

Figure 4.4. Browsing occurrence in artificial and natural regeneration in 2023 based on 3223 saplings recorded

4.3.2. Occurrence of ungulate browsing

Out of the seven independent variables used in the regression model, only two were found to be significant: forest area share ($p < 0.01$) and forest treatment ($p < 0.01$). It was determined that a lower percentage of forest in the hunting ground increases the probability of browsing occurrence, as a greater proportion of agriculture results in considerably better feeding conditions. Regarding the silvicultural system, it was observed that clearcut fellings, which utilize an artificial regeneration scheme with a predetermined sapling density per hectare, have a considerably higher probability of browsing occurrence compared to continuous cover forestry, which employs natural regeneration at a significantly higher density.

4.3.3. Ecosystem supportability

All of the indicators and values resulting from the calculations of the optimum and actual numbers are presented in Table 2. Based on the four categories of factors, it was determined that the ecosystem can support the following numbers in the study area: 195 red deer, 95 fallow deer, and 820 roe deer. The ungulate population numbers in the study area were as follows: 755 red deer, 380 fallow deer, and 1,422 roe deer. According to the stock unit equivalent theory, where the base unit in this study is considered to be the red deer with a value of 1, the fallow deer is equivalent to 0.56 of a red deer, while the roe deer is equivalent to 0.2 of a red deer.

After converting the stock unit equivalents and calculating the density of ungulates per 1,000 hectares, it was found that the total loading of deer equivalents in the study area was 25.39 stock unit equivalents, while the actual number of ungulates was 93.38 stock unit equivalents, exceeding the supportability by approximately 3.67 times. The highest excess of stock unit equivalents was found in the case of red deer, with 40.55 units above the limit, followed by 14.63 units for roe deer and 11.81 units for fallow deer (Table 4.2).

Table 4.2. Sustainable population threshold (SPT) and real number of ungulates in the study area

Indicator	Red deer	Fallow deer	Roe deer	Total
Deer number/total area	755	380	1422	-
SPT number/ total area	195	95	820	-
Stock unit equivalent	1	0,56	0,2	-

SPT equivalent/1000ha	15.12	3.94	6.34	25.39
Real deer unit equivalent/1000ha	55.67	15.74	20.97	92.38
Deer unit equivalent excedent/1000ha	40.55	11.81	14.63	66.99

4.4. Discussion

This study presents the first assessment of the impact of ungulate browsing in oak-dominated forests in Romania, as previous studies have primarily focused on coniferous species such as Norway spruce and Scots pine (Radu V & Popa I, 2007; Vlad, 2007; Vlad et al., 2011). It includes the first quantification of the overabundance of red deer, fallow deer, and roe deer, based on scientific calculations of the Sustainable Population Threshold, which simultaneously considers economic, social, and ecosystem sustainability. The findings of this study are particularly significant from a wildlife management perspective, as they quantify the SPT and actual densities of ungulates, providing evidence for the need for new hunting regulations that can be applied in similar scenarios.

Ungulates typically exhibit a preference for certain tree species and browse them in a particular order [47–49]. However, in this study, the tree species did not influence the selection process, as ungulate density was so high during the refuge period that a shortage of forage occurred, leading to non-selective consumption. The same lack of selectivity under high densities was also identified in a study conducted in Italy (Motta, 1998). The vigor of the sapling influences the browsing selection process (Bergquist et al., 2003; Bergquist & Orlanderä Orlander, 1998), but in this study, this factor appears to be insignificant, further demonstrating that overabundance leads to non-selective consumption. The only factors found to be significant in this study, with ungulate densities 3.7 times higher than the SPT, are forest cover and the silvicultural system. The five hunting grounds that overlapped with the study area had varying proportions of forests and agricultural fields. When the share of forest area in the total hunting ground was below 20%, browsing probability was found to be significantly higher. This can be attributed to a reduced refuge area during critical periods of the year, as many more animals moved into the forests after crop harvesting. Silvicultural treatment plays a vital role in ungulate browsing phenomena, with the probability of browsing occurrence being significantly higher in clearcut systems that employ artificial regeneration with low planting density (Motta, 1998; R. J. Putman, 1996; F. Reimoser & Gossow ', 1996; Šņepsts et al., 2018) In clearcut fellings, not only the planting scheme is considerably lower, but also a light gap is created, facilitating the appearance of grasses and shrubs (Kuijper et al., 2009). In the shelterwood system, natural regeneration is prioritized, and the gaps created through the removal cuts are significantly smaller than those produced by the clearcut system. The removal cuts are executed after prior establishment cuts, which are performed following fruiting years to promote the establishment of a continuous cover of saplings (Mason et al., 1999). Also, the planting scheme is not established by foresters and depends on the fructification and germination capacity, which in some cases, such as the European beech can reach in the seedling phase up to a million seedlings/ha (Sofletea N & Curtu L, 2007). While in the clearcut fellings the planting schemes are adopted based on the future crop trees technique and to facilitate the silviculture works in the tending phases, in the natural regeneration case, the density is regulated through natural competition and through tending operations (Peura et al., 2018; Tremblay et al., 2007). In a similar study situation in Austria, it was found that the browsing predisposition is lower in shelterwood systems and higher in clearcut systems (F. Reimoser & Gossow ', 1996). The same study admits that in Austria, Liechstein and Switzerland a more "close-to-nature" silvicultural can reduce the risk of browsing damage by decreasing habitat attraction for ungulates and favoring abundant regeneration (Beguin et al., 2009b). It needs to be pointed that a continuous silvicultural system with natural regeneration is not excepted from the browsing phenomena, but due to a much higher sapling density, the impact is not as visible and economically harmful as in the case of artificial regeneration. In this study, the browsing occurred in the clearcut fellings at an average of 49.65% browsed saplings in an average density of 4980 saplings/ha, while in the shelterwood system at an average of 12.8% browsed saplings in a average density of 12.830 saplings/ha. Even if the proportion of browsed species is quite different in the two cases, the number of browsed saplings is higher in both cases, with an average of 2472 saplings/ha browsed in artificial regeneration and 1642 saplings/ha browsed in the natural regeneration.

To mitigate damages caused by ungulate browsing on long term, forest managers should adapt their management process to adapt to the situations caused by the climate change and the impressive growth of ungulate number (Loosen et al., 2021), adopting silvicultural system with higher regeneration density and with mixed composition (Bolibok et al., 2021). Measure such as fencing [61–63], tree guards (Van Lerberghe, 2014), repellents (Bergquist & Örlander, 1996) and natural obstacles (Bergquist et al., 1999; Grisez T, 1960) are solutions to prevent damage from browsing, fraying, and trampling; however, they are costly and require continuous maintenance, which can place a burden on forest managers (Ersson et al., 2023).

The biggest emphasis should be put in the management of the wildlife species to control the number of ungulates. The current legislation (*Legea 407/2006*, 2024) in Romania heavily regulates hunting processes, with quotas determined by annual evaluations of game species. In the study area, ungulate populations have reached alarming levels, suggesting that the existing legislation may not be appropriate for this situation. At densities 3.7 times higher than the SPT, the densities of ungulates should be considered in an overabundance. Similarly, in Lithuania, the hunting law (Ministry of Environment of the Republic of Lithuania, 2005) establishes a maximum limit of 28.75 red deer equivalents per 1000 ha of deciduous and mixed stands of deciduous trees with coniferous species. However, the legislation allows for the culling of red deer, fallow deer, and roe deer without a designated hunting season or quota. In Italy, a similar equivalent system was used in the elaboration of the Ungulate Density Index (UDI), where the UDI was employed to quantify the magnitude of ungulate abundance (Motta, 1998). In commercial forests in Scotland, the tolerable threshold of red deer was considered to be 4 deer per 100ha (Ratcliffe, 1987). In Germany, the tolerable densities for roe deer depending on habitat quality have been suggested at between 4 to 12 roe deer per 100 ha (Raesfeld et al., 1985). Relying on the current quota system from Romania' hunting law (*Legea 407/2006*, 2024) may be considered outdated in this case, indicating that special regulations might be needed greater flexibility should be granted to wildlife managers, and higher quotas should be adopted. Similar cases were identified in Germany (Heinze et al., 2011b), where non-selective culling has been adopted to control game numbers. An additional hunting season should also be implemented for red deer, allowing the harvesting of two-year-old specimens that are not participating in reproduction by professional hunters. In high-density populations, particularly among cervid species, individuals experience a reduction in body weight (Jerina, 2013; Vetter & Arnold, 2018). To effectively control the damage caused by ungulates to forest ecosystems, a comprehensive set of hunting regulations and practices should be implemented in critical areas of overabundance. These measures should aim to reduce the populations of both males and females to optimal levels while preserving genetic diversity and maintaining the overall health of the game.

In terms of combined wildlife and forest management, this study can be viewed as an interdisciplinary effort that addresses both sectors simultaneously. Future research on ungulate browsing should not only present actual ungulate densities but also calculate an SPT. Since the term "overabundance" can sometimes be ambiguous, it is essential to establish a clear threshold between actual and optimal numbers to determine if an area is experiencing ungulate overabundance. Future studies should focus on viable solutions to reduce damage levels in areas with high ungulate densities while also identifying effective methods for controlling ungulate populations.

4.5. Conclusion

This study provides a valuable first assessment of ungulate browsing on oak stands in the plain region of Western Romania, a region lacking a normal density of large carnivores to control ungulate numbers through natural selection. The overabundance of ungulates is identified as the primary factor contributing to the damage, while the study also highlights secondary factors influencing the occurrence of browsing.

The results underscore the importance of a collaborative approach between wildlife and forest management to understand the extent of the damage caused by ungulates. These findings can inform foresters, hunters, and conservationists, serving as scientific evidence for reforms in hunting legislation. Furthermore, this study demonstrates that humans and wildlife can coexist, and it is essential to adopt appropriate measures to prevent conflicts between them.

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CHAPTER 5. CONCLUSIONS. ORIGINAL CONTRIBUTIONS. DISSEMINATION OF RESULTS

5.1. Conclusions

The presented PhD thesis focuses on the impact of ungulate browsing on forest ecosystems, examining the causes and characteristics of browsing as well as the growth of ungulate populations in specific scenarios, with the aim of investigating their growth and expansion and the resulting effects through browsing, revealing a notable growth trend in ungulate numbers over the past decade and an increased intensity of browsing occurrences throughout Europe and within the primary study area. The main results are outlined below:

1. Ungulate browsing is a phenomenon that has been extensively researched in 21 European countries, with the high density of ungulates identified as the main cause of the damage. Particularly in countries from Northern, Central, and Eastern Europe, the intensity of this phenomenon is relatively high under similar scenarios: stands with artificial regeneration and a lack of large carnivores. Although the palatability of Norway spruce is reduced compared to other broadleaved species, it has been found to be the most consumed species in Europe, as it is the most common species used in artificial regeneration. In Romania, the main causes of browsing are the silvicultural practices, predominantly the spread of monocultures over large areas and the reduction of gray wolf populations.

2. The overall trend in the Baltics, Central, and Eastern Europe shows an increasing growth in ungulate populations based on the analysis of hunting bag data. While the rise for red and fallow deer is around 50%, for roe deer it is approximately 15%. These findings confirm the same growth trends identified in similar prior studies. However, in cases where there is a lack of predators and new, modern wildlife management practices have been implemented, the increase in numbers has multiplied by as much as 8 to 13 times.

3. In the main study area, due to the high density of ungulates, browsing occurs without selectivity, indicating that the forest ecosystem is at risk. Among the different silvicultural systems, the one that uses artificial regeneration through planting at a low density is the most susceptible. In this system, browsing reached an average of 49.65% at a sapling density of around 4,900 saplings per hectare. In contrast, in the natural regeneration system, although the browsing value is relatively lower at 12.8%, the sapling density is around 13,000 saplings per hectare. This indicates that while browsing in the main study area is high, the availability of different sapling densities makes this phenomenon more or less acceptable for silviculture practices.

4. By using the Sustainable Population Threshold and the Stock Unit Equivalent, it has been found that the main study area has a population that is 3.7 times higher than the calculated optimum number. With values around four times higher than threshold , it can be concluded that the ungulate population is overabundant.

5.2. Orgininal contributions

- Evaluation of the impact of ungulate browsing and its expansion across Western, Northern, Central, Eastern, and Southern Europe for the most representative ungulate species;

- Presentation of a detailed assessment of ungulate browsing characteristics, along with proposed management solutions;

- Elaboration of an updated overview of the numerical expansion of red deer, roe deer, and fallow deer in the Baltics, Central, and Eastern Europe, utilizing hunting bag data as an indicator of growth;

- Explaination of the effects of an improper sex ratio in harvests, reflecting excessive annual growth in ungulate populations;

- The projection of ungulate population in the Baltics, Central, and Eastern Europe based on various harvest rates;

- The first assessment of ungulate browsing on oak species in the Western Plain, as well as in Romania;

- The quantification of ungulate abundance is calculated based on the Sustainable Population Threshold and Stock Unit Equivalent.

5.3. Dissemination of results

The results of the research carried out within this doctoral thesis were disseminated through three scientific articles and presented at three international conferences

Scientific publications based on the material of the thesis:

- **Hardalau, D.**; Codrean, C.; Iordache, D.; Fedorca, M.; Ionescu, O. The Expanding Thread of Ungulate Browsing—A Review of Forest Ecosystem Effects and Management Approaches in Europe. Forests 2024, 15, 1311. Q1, Impact Factor – 2.4

- Ionescu, O., **Hardalau, D.***, Bakševičius, M., Manton, M., Popovici, D.-C., Codrean, C., Ionescu, G., & Iordache, D. (2025). Tracking population trends: Insights from deer hunting harvests in the Baltics, Central, and Eastern Europe. *Cent. Eur. For. J*, *71*, Q2, Impact factor – 1.4 .
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- **Hardalau, D.**; Fedorca, M.; Popovici, D.-C.; Ionescu, G.; Fedorca, A.; Mirea, I.; Daniel, I.; Ionescu, O. Insights in Managing Ungulates Population and Forest Sustainability in Romania. *Diversity* 2025, *17*, 194. Q2, Impact Factor - 2.1.

Participation in international scientific conferences:

- **Hardalau D.**; The Expanding Thread of Ungulate Browsing - A Review of Forest Ecosystem Effects and Management Approaches in Europe; DoCo2024, 25-26 June 2024, Brasov Romania
- **Hardalau D.**, Ionescu O.; Ungulate browsing impact in western Romania; 11th International Symposium Forest and Sustainable Development 2024, 17-18 October 2024, Brasov, Romania
- Bakševičius M., **Hardalau D.**, Manton M., Brazaitis G., Šimkevičius K., Kibiša A.; 13th International Conference Of Young Scientists. The Young Scientists For Advance Of Agriculture. Agrisci2024, Vilnius, Lithuania