Polish Journal of Veterinary Sciences Vol. 29, No. 2 (2026), 203–

DOI

Review paper

How toxic environments influence well-being of cervids, and further perspectives for cervid monitoring in Europe

A.J. Korzekwa[1], M.K. Kowalik[2], G. Boztepe[1,4], J. Gogola-Mruk[3], A. Ptak[3]

[1] Biodiversity Protection Research Group, InLife Institute of Animal Reproduction
and Food Research of Polish Academy of Sciences (IAR&FR PAS), Trylińskiego 18, 10-683 Olsztyn, Poland
[2] Physiology and Toxicology Research Group, IAR&FR PAS, Trylińskiego 18, 10-683 Olsztyn, Poland
[3] Laboratory of Physiology and Toxicology of Reproduction, Institute of Zoology and Biomedical Research,
Faculty of Biology, Jagiellonian University, Gronostajowa 9, 30-387 Kraków, Poland
[4] University of Agriculture in Kraków, Poland

Correspondence to: a.korzewka@pan.olsztyn.pl

Abstract

This review provides an exhaustive overview of the main cervid species in Europe, including the red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), fallow deer (*Dama dama*), moose (*Alces alces*) and reindeer (*Rangifer tarandus*) regarding the geographic distribution of the species, population trends, habitat preferences, and key biological traits. The review focuses on the environmental factors that influence the well-being of cervids, such as habitat quality, competition, food availability, climate change, contamination and anthropopression. Cervids are considered effective bioindicators of ecosystem stability and environmental contamination due to their status as large herbivores with wide-ranging territories and sensitivity to biotope changes. In addition, the impact of perfluoroalkyl and polyfluoroalkyl substances (PFAS) and polychlorinated biphenyls (PCBs) on the well-being of this taxonomic family is characterized. It is imperative to emphasize the significance of incorporating prey, predators, and humans as a comprehensive ecosystem within which cervids reside. The significance of habitat sharing is well documented, particularly in regard to the definition of predator – prey mechanisms. The insights derived from this research are of particular relevance when seeking to define solutions that optimize human-wildlife coexistence, especially within the context of European highly anthropogenic systems. The review concludes with a view on future perspectives for cervid well-being in Europe and emphasizes the necessity of sustainable land use, pollution mitigation, and the establishment of conservation programs for cervid populations and the ecosystems they represent. Effective management requires long-term monitoring, including significant fluctuations and behaviour of the species.

Keywords: cervids, environment, monitoring, toxins

Introduction

Cervids play a crucial role in maintaining Europe's biodiversity, forest dynamics, and wildlife management. Populations of roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*), fallow deer (*Dama dama*), moose (*Alces alces*), and reindeer (*Rangifer tarandus*) have expanded across the continent in recent decades due to changes in land use, and regulated hunting. Deer management involves culling and the use of quotas to maintain populations at desired levels. However, the stability of deer populations is connected with exposure to environmental stressors and pollutants resulting from urbanisation, industrialisation and agricultural intensification.

Environmental contaminants such as polychlorinated biphenyls (PCBs), per- and polyfluoroalkyl substances (PFASs), and other endocrine-disrupting chemicals (EDCs) persist in ecosystems, accumulating in soil, vegetation and animal tissues. Because cervids inhabit varied habitats and have distinct feeding and behavioural patterns, they are particularly susceptible to bioaccumulation of toxic compounds.

Evaluating the effects of such toxic environments on cervid physiology and immune status is essential within the One Health framework, which recognises the interdependence of human, animal and environmental health. This review describes the status of European cervid species, highlights key environmental and toxicological threats, and discusses their potential as bioindicators. It also outlines perspectives for improved monitoring and sustainable management to safeguard the well-being of cervids in Europe's changing environments.

Volume profile of main species of cervids in Europe

Europe is inhabited by several cervid species, which play a vital role in maintaining biodiversity, regulating forest dynamics and contributing to game management. The most widespread species is the roe deer (*Capreolus capreolus*), which has demonstrated a remarkable capacity for adaptation to diverse habitats (van Beeck Calkoen et al. 2023). The roe deer is also the most abundant species, followed by the red deer. Other notable species include the moose (*Alces alces*), which is primarily found in Northern and Eastern Europe, where habitat fragmentation and road mortality pose significant threats (Balciauskas et al. 2023). Additionally, the fallow deer (*Dama dama*) and sika deer (*Cervus nippon*) have established populations in various regions, while the Eurasian reindeer (*Rangifer tarandus*) remains restricted to the northern areas of the continent. The regulation of cervids is predominantly achieved through hunting, which plays a pivotal role in the management of cervid populations and the conservation of their habitats. However, regulatory frameworks vary across different countries. European countries implement specific hunting seasons, designated zones and culling limits with a view to preventing overhunting, promoting sustainable wildlife management and upholding ethical hunting practices. Furthermore, conservation strategies aim to mitigate overpopulation and habitat degradation, ensuring the long-term ecological balance of cervid populations and their habitats (Apollonio et al. 2010, Myronenko 2015).

Roe deer

The European roe deer population has experienced a substantial increase, from 6.2 million individuals in 1984 to an estimated 15 million in 2015 (https://www.iucnredlist.org/species/42395/22161386). Furthermore, the population density across Europe also increased, from 1.55 to 2.22 animals per km² between 1984 and 2005. Since 2015, the population has continued to grow. The highest increases in population have been recorded in France (277%), Latvia (219%), Italy (201%), Finland (200%) and Denmark (167%), along with Luxembourg, Austria and Germany. In Germany, the population has reached 3 million, followed by France with 1.2 million, Austria with 750,000, Poland with approximately 878,000 (according to the Polish Central Statistical Office in 2025) and Sweden with 600,000 individuals. In the UK, the roe deer population has surpassed half a million, with approximately 324,000 individuals spread across England's southern and midland counties, including Cornwall, Essex, Gloucestershire, Suffolk and Norfolk (https://www.gwct.org.uk/research/long-term-monitoring/national-gamebag-census/mammal-bags-comprehensive-overviews/roe-deer/). In Norway, the roe deer population is estimated to be approximately 150,000.

Roe deer populations are shaped by a variety of environmental factors, such as habitat quality, climate and predation. In less productive habitats, predation exerts a more significant influence on population dynamics. Additionally, climate change can affect roe deer through shifts in temperature, precipitation and snow cover, influencing their physiology, behaviour and habitat use. Human activities, including agriculture, urbanisation and hunting, have been identified as significant factors that play a role in shaping roe deer populations. The expansion of agricultural areas and the intensification of farming practices have had a significant impact on the availability of food and cover for roe deer, also influencing their behaviour and population dynamics (Carpentier et al. 2024).

Pielowski (1984) demonstrated different ecotypes of this highly territorial species in Europe, including forest, field and mosaic. It has been suggested that such behaviour exerts a significant influence on the condition and immune potential of the organism, with consequential effects on its phenotype. Roe deer population trends across Europe are, overall, undergoing a period of sustained growth, characterised by considerable increases in both their density and distribution. This phenomenon is particularly evident in the regions of Western and Central Europe. However, recent reports from nearby areas suggest that certain populations may be experiencing stress, attributable to various factors, including predation, hunting pressure, habitat degradation and demographic change. If these pressures are not effectively addressed through informed management, there is a risk of decline in these populations.

Red deer

The red deer is largely absent from northern Fennoscandia and the majority of European Russia. In Europe, excluding Russia, its population grew from approximately 1.25 million individuals in 1985 to 2.4 million by 2005. The density of red deer in different regions generally ranges from 1 to 5 individuals per km², although some areas have densities as high as 15 individuals per km² (Burbaitė and Csányi 2010; https://www.iucnredlist.org/species/55997072/142404453). The population in Poland is approximately 270,000, with the total area available for hunting being 25.2 million ha (according to the Central Statistical Office 2024). In Hungary, the population has exhibited a marked increase, growing from 93,000 in 2010 to 128,000 in 2024, and reaching 364,000 individuals in 2023. In the Czech Republic, the population increased from 27,666 in 2014 to 32,839 in 2023.

In the *Mammals of the British Isles: Handbook* (2008), a review of population estimates was conducted, the results indicating that the number of red deer in major populations across the British Isles ranges from 335,350 to 366,110. In England, the red deer population increased from 12,500 in 1995 to 56,000 in 2023 (Harris and Yalden 2008; https://www.donnees.statistiques.developpement-durable.gouv.fr/lesessentiels/essentiels/faune-flore-cervides.html?form=MG0AV3). The French red deer population was over 68,000 in 2019, which has established it as one of the most frequently hunted species in the country, after wild boar and roe deer (Kuba et al. 2015).

The practice of selective breeding for specific traits, as it is understood in the present day, emerged the 1970s, with pioneers in New Zealand and Scotland. In modern Europe, red deer breeding often involves the cross-breeding of diverse genetic lines, including those originating from the UK. The primary objectives of the programme are the production of venison, the cultivation of large antlers and the–breeding of high-quality animals. Poland exemplifies this modern approach. Influenced by EU regulations, since 199~~5~~7, Polish law has classed red and fallow deer as farm animals, thus allowing commercial breeding for meat and hides without special permits. These farms are regarded as ecological enterprises, using pastures for the production of diverse products (meat, hides, antlers) and placing significant emphasis on animal welfare. The regulations governing this practice are stringent, covering housing, stocking density (maximum of 7 deer/ha) and mandatory veterinary oversight, including disease notification (Mattiello 2009, Kuba et al. 2015).

Fallow deer

The fallow deer is native to southern Anatolia, Sicily, southern Italy and the southern Balkan Peninsula. Over the last four decades, their populations have expanded across much of Europe, into which they have been introduced. There are 634,075 fallow deer in Europe, although corrected figures indicate a population of 951, 521 (Bijl and Csanyi 2022, Esattore et al. 2022).

In Poland, the population has increased fourfold from approximately 6,500 in 2000 to over 23,000 by 2010, with 35,540 individuals recorded in 2022 (Kalen et al. 2022). There are 18 game breeding centres located throughout Poland according to the Polish Hunting Association, which specialises in the breeding of fallow deer for the purpose of enriching their genetic pool. These centres also facilitate hunting activities. In other countries as Bijl and Csanyi (2022) reported, from 2015/2016 to 2020/2021 the fallow deer population has shown the least growth, with declines observed in Serbia and Ukraine. A decline in harvest numbers has been reported from Portugal, Sweden and the United Kingdom during this period. The average growth factors were the lowest during this interval, at 1.51 for population size and 1.49 for harvest (Esattore et al. 2022).

Moose

In 2010, the estimated moose occupancy was 16,712,600 km² in Eurasia, with primary range areas (≥0.11 moose per km²) accounting for only 18% of its range while supporting over 66% of the estimated 1.2 million moose. The total circumpolar moose population has been estimated at over 2.2 million, occupying an area of 26,205,000 km². As demonstrated by the harvest data from 2010, 149,860 moose, representing 47% of the total harvest, were taken from a mere 10%

(1,722,660 km²) of the occupied range. Moose populations in Fennoscandia (comprising Norway, Sweden and Finland) have been among the most productive and heavily harvested in the world, with a growth trend since the 1960s. In the early 20th century, annual harvests were below 10,000, but by 2000, they had increased to approximately 200,000. The European moose population has undergone a substantial increase over the past five decades, reaching a minimum of 440,000 individuals, of which approximately 50% are harvested annually (Lavsund et al. 2003, Jensen et al. 2020, Bobek et al. 2024).

Sweden has the highest moose population density, among the three Scandinavian countries, particularly in 2020, when the population was estimated around 311,000 individuals. Norway has the lowest population density, 120,000 in 2009 and 107,000 in 2010, followed by a steady decline in harvest numbers over the the following years. Finland has more stable population numbers, with 115,000 recorded in 2009 and 110,000 in 2015.

Since the implementation of a nationwide hunting ban in Poland in 2001, there has been a substantial increase in the moose population. The presence of moose has become increasingly prevalent in the eastern Polish provinces of Podlaskie and Lubelskie, where it is found in abundance in areas of dense woodlands. There is evidence to suggest that the species has also established itself in Central Poland. However, there is a degree of concern that these population estimates may be excessively high. The increased population has deleterious effects, including damage to forests and crops and an increase in road accidents. Discussions regarding the potential resumption of hunting activities are currently underway, with the government disbursing substantial compensation for damage. However, the hunting ban remains in effect.

Reindeer

Reindeer populations in Europe are predominantly located in the northern regions (Pokharel et al. 2023). Overall, the global reindeer population has undergone a significant decrease over the last two decades (Uboni et al. 2016, Bargmann et al. 2020). The most recent Report Card, issued by the National Oceanic and Atmospheric Administration, indicates a precipitous decline in reindeer populations. The estimated decline – from approximately 5 million in the mid-1990s to a mere 2.1 million in 2018, – is reported to be 56% (Valente et al. 2020). This decline is indicative of broader ecological changes affecting the species, including changes in their habitat. The observed trend may indicate a complex interplay of ecological changes and human impacts, leading to both a growth and decline in reindeer densities across different regions. The decline in reindeer populations across many Arctic and subarctic regions is multifactorial, resulting from the combined effects of environmental and anthropogenic pressures. Climate change plays a key role, increasing the frequency of “rain-on-snow” events that limit access to winter forage (lichens), as well as altering vegetation structure and reducing reproductive success.

Factors influencing the condition of wild cervids

Anthropopression

It is evident that the fluctuations in deer numbers are closely linked to human activities. A number of factors can be identified as contributing to migratory behaviours – the search for more favourable feeding grounds, the migration of individuals during their reproductive cycles in pursuit of a mate, population overcrowding and the need to move due to the impacts of human activities. Populations of large ungulates are considered overabundant in many regions of Europe due to the rapid growth in numbers experienced in recent years (Apollonio et al. 2010, Valente et al. 2020). Although large ungulates had been driven close to extinction in many regions of Europe by the nineteenth century, their recovery has been favoured by a combination of factors since the mid-twentieth century. These included large-scale processes of rural – urban migration, natural afforestation, mild winters, a lack of natural predators and legislative changes to their management (Martin et al. 2020).

In Europe, recreational hunting is the primary source of mortality and the principal management tool used to control large ungulate populations. However, despite the escalating levels of hunting pressure, populations of large ungulates have exhibited a consistent and sustained increase (Apollonio et al. 2017, Quirós-Fernández et al. 2017).

Competition in the habitat

Vegetation patterns, including those related to plant growth, dispersion and the weather, influence resource availability and thereby determine the potential for competitive interactions between herbivores (Arsenault and Owen-Smith 2002). Among mammalian herbivores, environmental conditions (e.g. habitat quality, food availability, weather) in spring and summer, during the nursing and weaning of offspring, are crucial determinants of population dynamics (Pettorelli et al. 2007). Thus, species can be affected by interspecific competition, even under favourable environmental conditions. Alternatively, the positive effects of weather on resource availability could offset the negative effects of interspecific competition (Arsenault and Owen-Smith 2002). The response of species to competition pressure may differ across habitats, the response being expected to be stronger in habitats characterised by a lower availability of suitable resources (Anderwald et al. 2016).

Observations of Cervidae species in their natural habitats have shown that the duration of grazing activity by white-tailed, fallow and roe deer has remained unaffected by factors such as pasture harvesting and the presence of other deer when the focal animal entered the area (Bartos et al. 2002). The tendency of red deer to graze was found to be related to the numbers of white-tails or female fallow deer visible before red deer entered the pasture. The grazing time of white-tailed and fallow deer was found to increase if the focal deer was joined by another animal. In the context of white-tailed and fallow deer, the anti-predatory strategy of joining a group may have been balanced by avoiding the most competitive classes of animals. Bartos et al. (2002) suggested that interspecific cooperative behaviour, rather than interspecific competition, is the predominant form of social behaviour among these sympatric cervids.

The presence of predators has been demonstrated to exert a regulatory effect on the population density of large herbivorous species (Kuijper 2011, Ripple and Beschta 2012). The role of wolves and other predators is important in mitigating the multifaceted issue of overabundant ungulates, although this has to be deeply considered having in mind the increase in the predator population in Europe. This is because most of the environmental changes that have facilitated the increases in large ungulate numbers, such as mild winters, will not revert in the short term. In contemporary shared environments, the interactions among different species have become increasingly complex, contingent on the allocation of shared resources. Human activities have been demonstrated to exert a significant influence on these dynamics, thereby affecting both the abundance and distribution of wildlife populations. It is imperative to acknowledge the pivotal function that habitat stability plays in the dynamics of predator – prey and herbivore – predator interactions, particularly in the context of human-modified environments. The sharing of habitat is a significant factor in defining predator – prey mechanisms, and this should be taken into consideration when formulating solutions to optimise human – wildlife coexistence, especially in a highly anthropogenic system such as Europe (Rolle et al. 2025).

Kubala et al. (2024) described variations in range size for the Eurasian lynx in roe deer habitat based on GPS telemetry in the Western Carpathians. The authors explained how intrinsic and environmental factors have shaped the lynx's spatial behaviour when facing anthropogenic pressures. The implementation of an evaluation would facilitate the acquisition of knowledge pertaining to the interactions between predators and ungulates in other habitats. Understanding the spatial requirements of wildlife, particularly of elusive species, such as large carnivores, is essential for the strategic planning of conservation initiatives in human-dominated landscapes. This understanding is crucial for the selection of optimal locations and dimensions for protected areas and/or management units, which are necessary to cover the home ranges of multiple individuals. Moreover, estimates of home-range sizes are crucial for population size estimations, whether through the implementation of formal distance rules or when extrapolating from local surveys to the population level.

Feeding base

In 1972, Hofmann and Stewart (1972) proposed a classification system for cervids based on the chemical characteristics of their feed. This system divided cervids into three groups: concentrate feeders (i.e. browsers), grazers (consumers of grass and other roughage), and intermediate feeders (which both graze *and* browse). This traditional concept posits that approximately 40% of ruminants (moose and roe deer) are concentrate feeders, 25% (sheep and cattle) are grazers, and the remaining 35% (red deer) are intermediate feeders. The discovery that the lining of the rumen can alter its morphology (i.e. its structure and appearance) in accordance with the quality of the diet has allowed subsequent authors to modify this division (Clauss et al. 2011, Redjadj et al. 2014).

In the context of wild ruminants, the seasonality of their diet is indicative of both rumen morphology and digestion efficiency. The microbiota in the rumen also assume a pivotal function in not only the process of digestion, but also in maintaining the overall health of the individual. A comparison has been made of the rumen contents of red deer kept in both farm and wild environments. The prevalence of *Campylobacter* spp. and total anaerobic bacteria was found to be highest in the farmed deer, with the lowest levels observed in the wild animals. Conversely, *Clostridium* spp. levels were lowest in the farmed deer and highest in the wild animals. A decline in Diplodininae protozoa in the farmed deer was also identified, and the presence of holotrichs was recorded, these which were not observed in the wild animals. The rumen digesta of the farmed animals had lower amounts of dry matter and acid-detergent fibre compared to that of their wild counterparts. The impact of feeding on the papillation of the rumen was observed, with the farmed animals having the shortest papillae in the atrium ruminis, reflecting their immune condition (Mason et al. 2019).

In the wild red deer rumen, grasses constituted between 30% and 70% of the total contents in summer, with rushes, sedges, heathland vegetation, forbs, deciduous browse and conifers comprising the remainder, ranging from 5% to 20%. During the winter months, the volume in the rumen was dominated by heaths, with blueberry and heather comprising the majority of this vegetation. Sedges and rushes constituted a further 30% of the vegetation (Gebert and Verheyden 2001).

The feeding base of roe deer is characterised by a greater abundance of forage than that of red deer. This dietary disparity has a significant influence on the evolution of three distinct ecotypes of the roe deer species across Europe: field, forest and mosaic (Pielowski 1984). The impact of roe deer on woody plants in this habitat has depended mainly on its population density (Barancekova 2004). It has been suggested that different ecotypes of roe deer may exhibit divergent immune profiles. It is also evident that moose have developed specific digestive strategies and foraging behaviours that are adapted to seasonality. This adaptation is based on specific morphological variations in the digestive system (Nygren and Hoffman 1990). The efficacy of the feeding base for cervids has been thoroughly evaluated (Redjadj et al. 2014). This review aims to identify plants from this base that may potentially negatively influence wild herbivores though the accumulation of toxins.

Pleijel et al. (2022) showed that evergreen conifers accumulate larger amounts of polycyclic aromatic hydrocarbons (PAHs) and dibenzothiophenes (DBTs) than broadleaved trees. This accumulation has been observed to occur under both using leaf mass- and area-based concentrations. The highest accumulations of H-PAH occur in some of the most common European forest trees, including larch (*Larix* spp.), fir (*Abies* spp.), pine (*Pinus* spp.) and birch (*Betula* spp.). The highest concentrations of DBTs have been noted in fir and larch. The proportion of tree and shrub shoots in the diet relative to herbaceous matter varies seasonally in cervids, and additionally depends on sex and age (Homolka 1990).

Of the dicotyledonous flora consumed by cervids, the most prevalent species include pinswort, hare sorrel, anemone, strawberry, oakleaf, lily of the valley, sorrel, woodruff and starflower. Among the grass and sedge species are *Calamagrostis arundinacea*, *Luzula pilosa*, *Carex digitata*, *Agrostis vulgaris*, *Agrostis canina* and *Calamagrostis epigejos* (Dzięciołowski 1967, Pielowski 1984). High accumulations of environmental pollutants have been reported from sorrel, sare sorrel and borage (starflower), with oakleaf containing less. *Agrostis* spp. (bentgrasses) have been a focus of study for mine spoil remediation, since they tolerate acidic, metal-rich soils as they do. *Carex* spp. in wetlands and riparian zones help trap and absorb runoff pollutants, including nitrates, phosphates and metals (Redjadj et al. 2014).

Recently, environmental pollution has become a significant concern for human, animal and environmental health, recognised as part of the One Health framework. Many wildlife species may be exposed to biologically active concentrations of endocrine-disrupting chemicals. There is strong evidence, obtained from laboratory studies, showing the potential for several environmental chemicals to cause endocrine disruption at environmentally realistic exposure levels. The observed abnormalities vary from subtle changes to permanent alterations, including disturbed sex differentiation with sex organs being feminised or masculinised, changed sexual behaviour and altered immune function. For most of the effects reported in wildlife, however, the evidence for a causal link with endocrine disruption is weak or non-existent.

Environmental contaminants

As of February 2024, the United States Environmental Protection Agency's (EPA's) Toxic Substances Control Act Chemical Substance Inventory contains 86,741 potentially hazardous chemicals, with 42,293 being currently commercially active (Federal Register 2024). Of these, special attention has been given to those contaminants that enter the environment, accidentally or deliberately, often as a result of human activities. Some of these contaminants are manufactured for industrial use, and because they are highly stable, they do not break down easily. Other environmental contaminants come from natural events, such as volcanic eruptions. Environmental contaminants can appear through various pathways, such as industrial discharge, agricultural runoff and improper waste disposal, leading to air, water, soil and food contamination. Some of those that are detected in the environment and are potentially hazardous, or have recently been determined to be hazardous to humans and ecosystems, are referred to as contaminants of emerging concern (CEC). They include pharmaceuticals and personal care products, per- and poly-fluoroalkyl substances (PFASs) and other industrial chemicals, micro/nanoplastics, nanomaterials and other exogenous substances (EPA 2025).

Many of these pollutants have been characterised as endocrine-disrupting chemicals (EDCs). According to the definition adopted by the Endocrine Society's Scientific Statement, an EDC is "a compound, either natural or synthetic, which, through environmental or inappropriate developmental exposures, alters the hormonal and homeostatic systems that enable the organism to communicate with and respond to its environment". Examples of well-known EDCs include bisphenol A (BPA), dioxins, polychlorinated biphenyls (PCBs) and pesticides (Diamanti-Kandarakis et al. 2009).

Introducing pollutants into ecosystems can significantly reduce species diversity, particularly affecting sensitive species that struggle to survive and reproduce in polluted conditions. Prolonged exposure to environmental contamination may cause genetic alterations, diminishing genetic diversity and weakening population resilience (Reid et al. 2019). Possible CEC and EDC exposure routes for terrestrial animals are food, water and the atmosphere. For these reasons, monitoring the presence of EDCs in the environment is of critical importance. However, monitoring only the presence of these xenobiotics in the environment may not be sufficient to determine the real biotic exposure. As described by Rendón-Lugo et al. (2017) and Zhou et al. (2008), the use of biomonitoring could be more useful than monitoring alone. Adopting a One Health perspective recognises the interconnectedness of human health, animal health and the health of the environment, emphasising the need for collaborative efforts to address CEC and EDC issues.

Accumulation of toxins from environment

PFASs as contaminants of emerging concern

As part of a large family of man-made fluorinated chemicals, PFASs are ubiquitous environmental toxicants. Some of the most well-known PFASs include perfluorooctanesulfonic acid (PFOS), perfluorohexane sulfonate (PFHxS), perfluorooctanoic acid (PFOA), GenX chemicals, perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA) and perfluorobutane sulfonate (PFBS) (Fan et al. 2022). Due to their chemical stability and resistance to degradation, PFASs are used as polymers and surfactants in a variety of industrial and commercial applications. Specifically, PFASs are used as stain- and water-resistant coatings for clothing, non-stick cookware, food packaging materials, personal care products and cosmetics, and fire-fighting foams (Dickman et al. 2022). They are a collection of chemicals with varying lengths of carbon chains containing a perfluoroalkyl moiety. Long-chain, legacy PFASs contain eight or more carbons, have long half-lives and tend to persist in the environment. These long-chain PFASs were phased out in the 2000s, leading to the increased use of short-chain PFAS containing seven or less carbons along with other replacement PFAS (Dickman et al. 2022). Management and regulatory actions relating to PFASs have been implemented to reduce exposure, but the effectiveness of these measures is still under evaluation (Badry et al. 2025).

Numerous studies have documented that PFASs are ubiquitous in environmental matrices, such as water, soil and sewage sludge (Naile et al. 2010, Clarke and Smith 2011, Sun et al. 2011). Their concentration in soil ranges from <0.001 to 237 µg/kg (Brusseau et al. 2020). Irrigation water and soil conditioners are the main sources of PFASs in field soils (Ghisi et al. 2019). Common irrigation water includes effluents from wastewater treatment plants, surface water, rain/snow and groundwater, which contain maximum reported ΣPFAS values of up to 1,000 µg/l (Vo et al. 2020), 1,860 µg/l (Liu et al. 2016), 327 ng/l (Murakami et al. 2009) and 7,090 µg/l (Moody and Field 1999), respectively.

Root uptake is the primary pathway for PFAS translocation from environment to plant. Plants are apparently capable of taking them up from the soil (Stahl et al. 2009) from where they can enter various food chains. In general, previous studies have shown that the short-chain PFASs accumulate in aboveground plant parts (leaves, seeds, fruits and florets) while the long-chain PFASs become concentrated in the roots. This is influenced by the higher water solubility and smaller molecule size of the short-chain PFASs. Therefore, short-chain PFASs are more easily transported from the soil pore water through the roots to the leaves (Felizeter et al. 2012, Brandsma et al. 2019). The physicochemical properties of PFASs result in a very low potential for excretion, which leads to bioaccumulation and biomagnification in humans (Calafat et al. 2019) and wildlife (Vestergren et al. 2013, Zhao et al. 2013, Miranda et al. 2021).

Although PFASs have been detected in various locations worldwide – even in remote areas such as the Arctic – in reindeer samples, PFOS, PFNA, PFOA and PFPeA have been only sporadically detected, showing no clear pattern. Of these, PFOA and PFOS were detected in 33% of the muscle samples, at maximum concentrations of 2.56 and 1.02 ng/g w/w, respectively; PFPeA was detected in 20% of the fat and mixed muscle and fat samples, at a maximum concentration of 3.54 ng/g w/w in the fat; and PFNA was detected in a single mixed muscle and fat sample at a concentration of 9.85 ng/g w/w (Byrne et al. 2022).

In the contrast, roe deer can be bioindicators of PFAS (per- and polyfluoroalkyl substances) contamination in the environment due to their territorial behaviour and limited home range. Studies have shown that PFAS concentrations in roe deer tissues, particularly the liver and muscle, are higher in urbanised areas (2.141 µg/kg

Table 1. Comparison concentrations of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in the liver and muscle roe deer between urbanized and rural area (Draghi et al. 2024a)

		Area					
		Urbanized (U)			Rural (R)		
Compound	Organs	Concentration (µg/kg)		% Samples > LOQ	Concentration (µg/kg)		% Samples > LOQ
		Mean	Median		Mean	Median	
PFOA	liver	0.380	0.156	60	0.164	0.018	75
	muscle	0.095	0.039	25	0.048	0	55
PFOS	liver	0.786	0.535	100	0.596	0.549	100
	muscle	0.522	0	50	0.077	0.003	45
PFBA	liver	0.025	0	15	0.013	0	35
	muscle	0.07	0	35	0.034	0	45
PFBS	liver	0.119	0	20	0.048	0	40
	muscle	0.096	0	30	0.038	0	35
PFDA	liver	0.006	0	20	0.005	0	20
	muscle	0.011	0	15	0.005	0	35
PFHxS	liver	0.128	0	20	0.066	0	40
	muscle	0.091	0	15	0.034	0	35
PFHpA	liver	0.123	0	25	0.038	0	45
	muscle	0.095	0	15	0.039	0	35
PFNA	liver	0.445	0.383	100	0.387	0.379	85
	muscle	0.166	0.004	55	0.063	0.00084	65
PFPeA	liver	0.022	0	15	0.01	0	35
	muscle	0.036	0	35	0.021	0	45
6-2 FTS	liver	0.042	0.007	45	0.028	0	50
	muscle	0.055	0	40	0.025	0	45
8-2 FTS	liver	0.065	0.017	50	0.039	0.035	50
	muscle	0.061	0.034	50	0.032	0.00007	50
∑	***liver***	***2.141***			***1.394***		
	muscle	***1.303***			***0.418***		

Abbreviations: PFOA – Perfluorooctanoic acid, PFOS – Perfluorooctanesulfonic acid, PFBA – Perfluorobutanoic acid, PFBS – Perfluorobutanesulfonic acid, PFDA – Perfluorodecanoic acid, PFDoDA – Perfluorododecanoic acid, PFHxA – Perfluorohexanoic acid, PFHxS – Perfluorohexanesulfonic acid, PFHpA – Perfluoroheptanoic acid, PFNA – Perfluorononanoic acid, PFPeA – Perfluoropentanoic acid, Perfluorooctanesulfonamide, 6-2FTS – 6:2 fluorotelomer sulfonate, 8-2FTS – 8:2 fluorotelomer sulfonate, LOQ – limit of quantification, n.d. – not detected, ∑ – sum of mean concentrations of all PFAS.

in the liver and 1.303 µg/kg in the muscle) compared to less-urbanised areas (1.394 µg/kg in the liver and 0.418 µg/kg in the muscle) (Table 1), suggesting that roe deer can reflect the presence of PFASs in their environment (Tables 1 and 2). In addition, the liver and muscle are considered important bioaccumulation sites for PFASs in roe deer, with studies showing higher concentrations in the liver than in the muscle (Draghi et al. 2024a). Age can also be a factor, older animals tending to have higher PFAS concentrations in their tissues due to their longer exposure times (Draghi et al. 2024a). Additionally, roe deer are often found to have higher PFAS concentrations in female individuals, which may be related to hormonal factors or differences in body composition, although the reasons for this are not yet fully understood (Draghi et al. 2024a).

PCBs as endocrine-disrupting chemicals

Due to their environmental persistence and potential health impacts on wildlife and humans, PCBs have been widely studied (James et al. 1993). The historical use of PCBs in industrial applications, such as transformers, capacitors and other electrical equipment, has left a legacy of contamination (James et al. 1993, Montano et al. 2022). Additionally, agricultural practices involving pesticides and other chemicals have contributed to environmental PCB levels (Szymczyk-

Table 2. Concentrations of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in roe deer 1989-2010 (n=110).

Component	Mean	Median	% Samples > LOQ	Organs	Country	References
6-2FTS	0.033	0	47.5	liver	Italy	Draghi et al. 2024ab
	0.003	0	22.5	muscle		
	0.037	0	42.5	muscle		
	0.043	0.0000705	50	muscle		
PFOA	0.7	0.5	83.6	liver	Germany	Falk et al. 2012
	0.156	0.073	70		Italy	Draghi et al. 2024ab
bPFOS	7.0	6.3	100	liver	Germany	Falk et al. 2012
	0.666	0.526	100		Italy	Draghi et al. 2024ab
PFBA	0.7	< LOQ	46.4	liver	Germany	Falk et al. 2012
	0.018	0	25		Italy	Draghi et al. 2024ab
PFBS	< LOQ	< LOQ	0.9	liver	Germany	Falk et al. 2012
	0.081	0	27.5		Italy	Draghi et al. 2024ab
PFDA	0.4	0.3	75.5	liver	Germany	Falk et al. 2012
	0.006	0	20		Italy	Draghi et al. 2024ab
PFDoDA	< LOQ	< LOQ	12.7	liver	Germany	Falk et al. 2012
PFHxA	< LOQ	< LOQ	5.5	liver	Germany	Falk et al. 2012
	0	0	2.5			Draghi et al. 2024a
bPFHxS	< LOQ	< LOQ	20.9	liver	Germany	Falk et al. 2012
	0.09445	0	30		Italy	Draghi et al. 2024ab
bbPFHpA	< LOQ	< LOQ	0.9	liver	Germany	Falk et al. 2012
	0.079	0	35		Italy	Draghi et al. 2024ab
PFNA	1.3	1.2	100	liver	Germany	Falk et al. 2012
	0.366	0.373	95		Italy	Draghi et al. 2024ab
PFPeA	< LOQ	< LOQ	4.5	liver	Germany	Falk et al. 2012
	0.015	0	25		Italy	Draghi et al. 2024ab
	0.016	0	25			
	0.026	0	42.5	muscle		
	0.026	0	42.5			

Abbreviations: FOSA – Perfluorooctanesulfonamide, 6-2FTS – 6:2 fluorotelomer sulfonate, 8-2FTS – 8:2 fluorotelomer sulfonate, PFOA – Perfluorooctanoic acid, PFOS – Perfluorooctanesulfonic acid, PFBA – Perfluorobutanoic acid, PFBS – Perfluorobutanesulfonic acid, PFDA – Perfluorodecanoic acid, PFDoDA – Perfluorododecanoic acid, PFHxA – Perfluorohexanoic acid, PFHxS – Perfluorohexanesulfonic acid, PFHpA – Perfluoroheptanoic acid, PFNA – Perfluorononanoic acid, PFPeA – Perfluoropentanoic acid, LOQ – limit of quantification.

-Kobrzyńska and Zalewski 2023). The production of PCBs was banned or restricted in many industrial countries in the 1970s to 1980s (Danse et al. 1997). Despite this ban, these compounds continue to pose a threat due to their long-lasting presence in the environment. They can be found in soil and water due to past industrial activities and the improper disposal of PCB-containing materials (Kodavanti and Loganathan 2017, Montano et al. 2022). These contaminants can enter the food chain and accumulate in the tissues of wildlife. In a study comparing red deer, roe deer and wild boar, red deer showed the highest toxic equivalent levels in the muscles, adipose tissue and liver, indicating a higher bioaccumulation of PCBs and related compounds (Warenik-Bany et al. 2016). This pattern is consistent across different regions and types of tissues analysed. Red deer have been found to accumulate significant levels of PCBs in their liver, primarily exposed through their diet. They consume plants and other vegetation that may have absorbed PCBs from contaminated soil and water (Kodavanti and Loganathan 2017 et al. 2017).

The mean concentration of ΣPCBs in red deer liver samples from north-western Poland was 60.13 ng/g lipid weight, which is higher than in roe deer (Tomza-Marciniak et al. 2011). The most frequently detected PCB congeners in red deer include PCB-28, PCB-138, PCB-153, PCB-180 and PCB-118 (Romanić et al. 2012, Niewiadowska et al. 2013), whereas, PCB congeners such as PCB-138, PCB-153 and PCB-180 are dominant in roe deer tissues (Tomza-Marciniak et al. 2011, Warenik-Bany et al. 2016). Studies have shown that roe deer from industrial regions have higher PCB concentrations than those from less polluted areas (Romanić et al. 2012, Niewiadowska et al. 2013). However, the PCB levels in roe deer are lower than in other game animals, such as red deer and wild boar, but are still significant enough to warrant monitoring. The long-term persistence of PCBs in the environment means that, even though their production has been restricted, they continue to impact wildlife. Efforts to clean up contaminated sites, such as those in the United States, have shown some success in restoring marine ecosystems, but global action is still needed to address the remaining PCB stocks.

Naturally occurring removal mechanisms are only marginally effective in eliminating these compounds. As a result, these pollutants accumulate in certain parts of the environment, such as sediments and soils, which then act as secondary sources. Therefore, they can still be found in all of the biotic and abiotic parts of the environment._The Stockholm Convention was aimed at eliminating PCBs, but enforcement remains a challenge, with an estimated 80% of existing PCB stocks still needing safe disposal.

Cervids as bioindicators

Cervids are considered to be a game species. Some species are characterised by migratory behaviour (e.g. moose), others are strictly territorial (e.g. roe deer). The European roe deer is a suitable bioindicator among wild mammals due to its unique behavioural characteristics, such as its small home range (16-80 ha), which allows it to live in a broad range of habitats, including those extensively used for human activities (Draghi et al. 2024a). The roe deer is a herbivore species that consumes a wide variety of plant materials. They tend to browse rather than graze, selecting only those plants they deem nutritious. These plants include herbs, young shoots and berries. Their diet varies seasonally, with a higher proportion of herbs and grasses in spring and early summer, and a greater reliance on woody plants and fungi during autumn and winter (Jackon 1980). These species typically consume easily digestible foodstuffs. Roe deer are valuable bioindicators for human health assessment because their limited home range allows contaminant levels measured in their tissues to be closely linked to local environmental conditions. As herbivores, they integrate exposure from multiple environmental compartments, including plants, soil, and water, leading to the accumulation of substances such as PFAS and PCBs in their tissues over time. Moreover, in peri-urban and urbanizing landscapes where wildlife habitats increasingly overlap with human living spaces, roe deer share environmental resources with people. Consequently, contaminant burdens detected in roe deer can provide meaningful insight into potential human exposure in the same areas. Research findings have indicated that the concentration of pollutants in their muscles is contingent upon their diet (Cygan-Szczegielniak et al. 2022, Pavlovic et al. 2024). Fur has been considered a valuable material for the non-invasive biomonitoring of wild animals, including roe deer, because it can provide insights into their exposure to certain environmental contaminants (Draghi et al 2024b). However, despite the relative ease of sampling and storing fur, it exhibits significant variability in its PFAS levels, with different detection frequencies observed when compared to muscle and liver tissue. Poly-fluoroalkyl substances, such as PFHxA, have been detected more frequently in fur than in liver and muscle tissues, whereas compounds such as PFBA, PFPeA, PFHpA, PFDA, PFHxS, 6-2 FTS and 8-2 FTS have been found at lower levels in fur (Draghi et al. 2024a, 2024b).

Another notable characteristic of roe deer is their propensity to cohabit with livestock in pastures (Varela-Castro et al. 2021). The capacity to detect environmental pollutants in the tissues of grazing animals could facilitate the evaluation of pasture quality. Furthermore, because wild mammals often share ecosystems and food resources with humans, they can serve as indicators of potential health effects on humans. Therefore, roe deer are considered a suitable bioindicator for the accumulation of organic xenobiotics.

Perspectives on cervid well-being in Europe

The population dynamics of cervids throughout Europe may be influenced by a combination of ecological, anthropogenic and management-related factors. The factors contributing to their growth include changes in land use, reduced hunting pressure, high reproductive rates and habitat modifications. However, challenges, such as habitat loss, road mortality and climate change, particularly for reindeer and moose, pose significant threats. The implementation of effective management strategies, encompassing regulated hunting, habitat restoration and the mitigation of human – wildlife conflicts, is imperative to achieve a balance between ecological benefits while addressing the issue of overabundance, ecological imbalance and human – wildlife conflicts. The overabundance of the species, the fragmentation of its habitat, the mortality of individuals at roadside locations, and climate change all serve

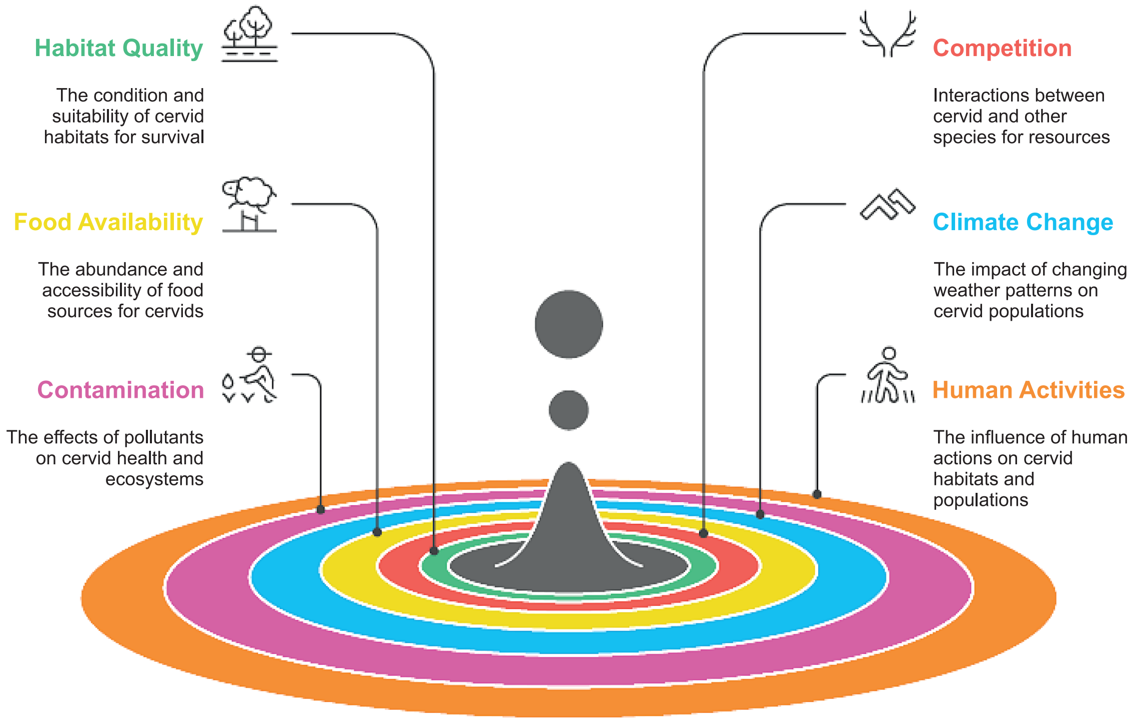

Fig. 1. Cervid well-being in Europe.

to emphasise the need for efficacious management strategies. Such strategies must include regulated hunting, the restoration of the species' habitat and genetic monitoring in order to ensure ecological balance and long-term sustainability. However, reliable data concerning specific countries and particular years remains limited due to inconsistencies in monitoring and reporting that hinder comprehensive assessment. This underscores the necessity for more comprehensive and consistent data collection to support future conservation and management initiatives throughout Europe.

Cervid species are experiencing a combination of opportunities and challenges across Europe. Due to its digestive system anatomy and foraging strategy, red deer is considered an intermediate feeder, depending on food availability. In contrast, roe deer and moose are classified as concentrate selectors (commonly referred to as "browsers"), also depending on food availability. Based on the feeding base and habitat type, different ecotypes have been identified within species, for example in roe deer. The well-being of such wild cervids is influenced by a multitude of ecological, environmental, social and policy factors (Fig. 1). A comprehensive overview of the key perspectives that will shape the future of cervid well-being in Europe is required. The positive aspects of the situation under consideration include the fact that reforestation and land abandonment in some regions of Europe have resulted in an increase in available habitat for cervids. Furthermore, the existence of ecological corridors (e.g. the Natura 2000 network) has been demonstrated to support the movement and gene flow of cervids. The challenges associated with urban sprawl, infrastructure and fencing (for roads and agriculture) are well-documented. Such practices have been shown to fragment habitats, leading to genetic isolation.

Intensive agriculture has been demonstrated to reduce natural forage and increase exposure to environmental contaminants. The overpopulation of certain regions has been found to exert pressure on forest ecosystems, result in crop damage and elevate the risk of disease transmission (e.g. tuberculosis or chronic wasting disease in reindeer). It is imperative to acknowledge that certain species, such as sika deer, are invasive. Their ability to interbreed with native red deer poses a significant threat to the genetic integrity of the species. Some European countries have forbidden the release of alien species such as sika deer in the natural habitats of red deer. Consequently, comprehensive monitoring of these species in their natural habitats is of paramount importance. This is particularly crucial in light of the potential competition that may arise with native deer species.

Toxic environments significantly affect the well-being of European cervids by impairing key physiological and ecological parameters, including reproductive success, immune function, and long-term survival. Persistent pollutants such as PFAS and PCBs accumulate in liver, muscle, and other tissues, leading to bioaccumulation and potential endocrine disruption. Exposure to these contaminants, together with habitat fragmentation and anthropogenic pressure, may reduce fitness and increase vulnerability to disease. Because cervids integrate contaminants from soil, water, and vegetation, they serve as effective bioindicators of local environmental quality. Establishing standardized, long-term monitoring programs across Europe under a One Health framework would enhance continent-wide assessment of ecological health and support sustainable wildlife and environmental management.

Author Declaration

Ethics approval

Ethical approval was not required for this study. This work is a review article that summarizes previously published research. No new experimental procedures involving live animals were conducted, and no primary data collection from live subjects occurred.

Use of generative artificial intelligence

No generative artificial intelligence (AI) tools were used in the preparation of this manuscript. All content was produced by the authors.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgements

Financed by basic statutory funds of the Research Team of Biodiversity Protection IAR&FR PAS (FBW/2025/ZOB_1) and the Polish National Science Centre grant: Opus Lap 2021/43/I/NZ9/01077.

We conducted a literature search in PubMed (https://www.ncbi.nlm.nih.gov/pubmed, accessed on 15 October 2024), Google Scholar (https://scholar.google.com, accessed on 15 November 2025), Web of Science (https://www.webofscience.com, accessed on 15 November 2025), Scopus (https://www.scopus.com, accessed on 15 November 2025), and ScienceDirect (https://www.sciencedirect.com, accessed on 15 November 2024). To write each section, the following keywords were used in combination with each cervid: ‘europe’, ‘main species’, ‘volume profile’, ‘anthropopression’, ‘competition’, ‘feeding base’, ‘environmental contamination’, ‘environmental toxin accumulation’, ‘endocrine disrupting chemicals’, ‘contamination of emerging concern’, and ‘bioindicators’. We included studies that assessed the association between the well-being of cervides and toxic environments and studies that explained the further perspective for cervids monitoring in Europe. The selected articles were published between 1997 and 2025 (with two exceptions). The exclusion criteria were nonoriginal reports, pilot studies, conference abstracts, commentaries, editorials, and articles applied to non-cervids. Additionally, review articles were also screened to refine and consolidate relevant information. The findings were limited to those published in English.

References

Anderwald P, Haller RM, Filli F **(2016)** Heterogeneity in Primary Productivity Influences Competitive Interactions between Red Deer and Alpine Chamois. PLoS One 11: e0146458.

Apollonio M, Andersen R, Putman R (eds) **(2010)** European ungulates and their management in the 21th century. Cambridge University Press, Cambridge.

Apollonio M, Belkin VV, Borkowski J, Borodin OI, Borowik T, Cagnacci F, Danilkin AA, Danilov PI, Faybich A, Ferretti F, Gaillard JM, Hayward M, Heshtaut P, Heurich M, Hurynovich A, Kashtalyan A, Kerley GI, Kjellander P, Kowalczyk R, Yanuta G **(2017)** Challenges and science-based implications for modern management and conservation of European ungulate populations. Mamm Res 62: 209-217.

Arsenault R, Owen-Smith N **(2002)** Facilitation versus competition in grazing herbivore assemblages. Oikos 97: 313-318.

Badry A, Lämmer R, Göckener B, Koschorreck J **(2025)** Pre-regulatory actions as a driver for reduced PFAS emissions? Long-term trends and change points for human and environmental samples from Germany. Environ Sci Eur 37: 84.

Balčiauskas L, Kučas A, Balčiauskienė L **(2023)** The impact of roadkill on cervid populations in Lithuania. Forests 14: 1224.

Barančeková M **(2004)** The roe deer diet: is floodplain forest optimal habitat. Folia Zool 53: 285-292.

Bargmann T, Wheatcroft E, Imperio S, Vetaas OR **(2020)** Effects of weather and hunting on wild reindeer population dynamics in Hardangervidda National Park. Pop Ecol 62: 91-104.

Bartos L, Vankova D, Miller KV, Siler J (**2002**) Interspecific competition between white-tailed, fallow, red, and roe deer. J Wild Manag 66: 522-527.

Bijl H, Csányi S (**2022**) Fallow deer (Dama dama) population and harvest changes in Europe since the early 1980s. Sustainability 14: 12198.

Bobek B, Furtek J, Merta D, Wojciuch-Ploskonka M (**2024**) Number, density and sex-age of the moose Alces alces population in north-eastern Poland after 20 years of hunting ban. Sylwan 168: 287-295.

Brandsma SH, Koekkoek JC, Van Velzen MJ, de Boer J (**2019**) The PFOA substitute GenX detected in the environment near a fluoropolymer manufacturing plant in the Netherlands. Chemosphere 220: 493-500.

Brusseau ML, Anderson RH, Guo B (**2020**) PFAS concentrations in soils: Background levels versus contaminated sites. Sci Total Environ 740: 140017.

Burbaitė L, Csányi S (**2010**) Red deer population and harvest changes in Europe. Acta Zool Lituanica 20: 179-188.

Byrne S, Seguinot-Medina S, Waghiyi V, Apatiki E, Immingan T, Miller P, von Hippel FA, Carpenter DO (**2022**) PFAS and PBDEs in traditional subsistence foods from Sivuqaq, Alaska. Environ Sci Pollut Res 29: 77145-77156.

Calafat AM, Kato K, Hubbard K, Jia T, Botelho JC, Wong LY (**2019**) Legacy and alternative per- and polyfluoroalkyl substances in the U.S. general population: paired serum-urine data from the 2013–2014 National Health and Nutrition Examination Survey. Environ Int 131: 105048.

Carpentier CA, Heurich M, Gimenez O, Devineau O, Linnell JD (**2024**) Cumulative mortality effects on roe deer population dynamics in the boreal forest: Searching for pathways of population persistence. Global Ecol Conserv 56: e03318.

Clarke BO, Smith SR (**2011**) Review of 'emerging' organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids. Environ Int 37: 226-247.

Clauss M, Lechner I, Barboza P, Collins W, Tervoort TA, Südekum KH, Cordon D, Hummel J (**2011**) The effect of size and density on the mean retention time of particles in the reticulorumen of cattle (Bos primigenius f. taurus), muskoxen (Ovibos moschatus) and moose (Alces alces). Br J Nutr 105: 634-644.

Cygan-Szczegielniak D, Stasiak K (**2022**) Effects of age and sex on the content of heavy metals in the hair, liver and the longissimus lumborum muscle of roe deer Capreolus capreolus L. Environ Sci Pollut Res 29: 10782-10790.

Danse IR, Jaeger RJ, Kava R, Kroger M, London WM, Lu FC, Maickel RP, McKetta JJ, Newell GW, Shindell S, Stare FJ, Whelan EM (**1997**) Position paper of the American Council on Science and Health: public health concerns about environmental polychlorinated biphenyls (PCBs). Ecotoxicol Environ Saf 38: 71-84.

Diamanti-Kandarakis E, Bourguignon JP, Giudice LC, Hauser R, Prins GS, Soto AM, Zoeller T, Gore AC (**2009**) Endocrine-disrupting chemicals: an Endocrine Society scientific statement. Endocr Rev 30: 293-342.

Dickman RA, Aga DS (**2022**) A review of recent studies on toxicity, sequestration, and degradation of per- and polyfluoroalkyl substances (PFAS). J Hazard Mater 436: 129120.

Draghi S, Curone G, Risoluti R, Materazzi S, Gullifa G, Amoresano A, Spinelli M, Fontanarosa C, Pavlovic R, Pellegrini A, Fidani M, Cagnardi P, Di Cesare F, Arioli F (**2024a**) Comparative analysis of PFASs concentrations in fur, muscle, and liver of wild roe deer as biomonitoring matrices. Front Vet Sci 11: 1500651.

Draghi S, Curone G, Pavlovic R, Di Cesare F, Cagnardi P, Fornesi Silva C, Pellegrini A, Riva F, Arioli F, Fidani M (**2024b**) Influence of area, age and sex on per- and polyfluorinated alkyl substances detected in roe deer muscle and liver from selected areas of northern Italy. Animals 14 (4): 529.

Dzięciołowski R (**1967**) Food of the Red Deer in Annual Cycle. Acta Theriol 12: 503-520.

Esattore B, Saggiomo L, Sensi M, Francia V, Cherin M (**2022**) Tell me what you eat and I'll tell you… where you live: an updated review of the worldwide distribution and foraging ecology of the fallow deer (Dama dama). Mammal Biol 102: 321-338.

Falk S, Brunn H, Schröter-Kermani C, Failing K, Georgii S, Tarricone K, Stahl T (**2012**) Temporal and spatial trends of perfluoroalkyl substances in liver of roe deer (Capreolus capreolus), Environmen Pollut 171: 1-8.

Fan X, Tang S, Wang Y, Fan W, Ben Y, Naidu R, Dong Z (**2022**) Global exposure to per- and polyfluoroalkyl substances and associated burden of low birthweight. Environ Sci Technol 56: 4282-4294.

Felizeter S, McLachlan MS, De Voogt P. (**2012**) Uptake of perfluorinated alkyl acids by hydroponically grown lettuce (Lactuca sativa). Environ Sci Technol 46(21): 11735-11743.

Gebert C, Verheyden-Tixier H (**2001**) Variations of diet composition of red deer (Cervus elaphus L.) in Europe. Mammal Rev 31: 189-201.

Ghisi R, Vamerali T, Manzetti S (**2019**) Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: a review. Environ Res 169: 326-341.

Harris S, Yalden D (**2008**) Mammals of the British Isles: handbook. Mammal society.

Hofmann RR, Stewart DR (**1972**) Grazer or browser: a classification based on the stomach structure and feeding habits of East African ruminants. Mammalia 36: 226-240.

Homolka M (**1990**) Food of Cervus elaphus in the course of the year in the mixed forest habitat of the Drahanská vrchovina Highlands. Folia Zool (Brno) 39: 1-13.

James RC, Busch H, Tamburro CH, Roberts SM, Schell JD, Harbison RD (**1993**) Polychlorinated biphenyl exposure and human disease. J Occup Med 35: 136-148.

Jensen W, Rea RV, Penner C E, Smith J, Bragina E, Razenkova E, Balčiauskas L, Bao H, Bystiansky S, Csányi S, Chovanová Z, Done G, Hackländer K, Heurich M, Jiang G, Kazarez A, Pusenius J, Solberg E, Veeroja R, Widemo F (**2020**) A review of circumpolar moose populations with emphasis on Eurasian moose distributions and densities. Alces 56: 63-78.

Kalen C, Andrén H, Månsson J, Sand H (**2022**) Using citizen data in a population model to estimate population size of moose (Alces alces). Ecol Modell 471: 110066.

Kodavanti PR, Loganathan BG (**2017**) Organohalogen pollutants and human health. In: Quah SR, Cockerham WC (eds) The international encyclopedia of public health. Academic Press, San Diego: 359-366.

Kuba J, Landete-Castillejos T, Udala J (**2015**) Red deer farming: breeding practice, trends and potential in Poland – a review. Ann Anim Sci 15: 591-599.

Kubala J, Signer J, Fin̆o S, Dul'a M, Krojerová-Prokešová J, Mysłajek RW, Smolko P (**2024**) Factors shaping home ranges of Eurasian lynx (Lynx lynx) in the Western Carpathians. Sci Rep 14: 21600.

Kuijper DP (**2011**) Lack of natural control mechanisms increases wildlife – forestry conflict in managed temperate European forest systems. Europ J Forest Res 130: 895-909.

Lavsund S, Nygrén T, Solberg EJ (**2003**) Status of moose populations and challenges to moose management in Fennoscandia. Alces 39: 109-130.

Liu Z, Lu Y, Wang T, Wang P, Li Q, Johnson AC, Sarvajayakesavalu S, Sweetman AJ (**2016**) Risk assessment and source identification of perfluoroalkyl acids in surface and ground water: spatial distribution around a mega-fluorochemical industrial park, China. Environ Int 91: 69-77.

Martin M, Boucher Y, Fenton NJ, Marchand P, Morin H (**2020**) Forest management has reduced the structural diversity of residual boreal old-growth forest landscapes in Eastern Canada. Forest Ecol Manag 458: 117765.

Mason F, Fotschki B, Di Rosso A, Korzekwa A (**2019**) Influence of farming conditions on the rumen of red deer (Cervus elaphus). Animals (9) 9: 601.

Mattiello S (**2009**) Welfare issues of modern deer farming. Ital J Anim Sci 8: 205-217.

Miranda DA, Benskin JP, Awad R, Lepoint G, Leonel J, Hatje V (**2021**) Bioaccumulation of per- and polyfluoroalkyl substances (PFASs) in a tropical estuarine food web. Sci Total Environ 754: 142146.

Montano L, Pironti C, Pinto G, Ricciardi M, Buono A, Brogna C, Venier M, Piscopo M, Amoresano A, Motta O (**2022**) Polychlorinated biphenyls (PCBs) in the environment: occupational and exposure events, effects on human health and fertility. Toxics 10: 365.

Moody CA, Field JA (**1999**) Determination of perfluorocarboxylates in groundwater impacted by fire-fighting activity. Environ Sci Technol 33: 2800-2806.

Murakami M, Shinohara H, Takada H (**2009**) Evaluation of wastewater and street runoff as sources of perfluorinated surfactants (PFSs). Chemosphere 74: 487-493.

Myronenko M (**2015**) Analysis of legislation and practice of hunting in some EU countries.ENPI: 1-91.

Naile JE, Khim JS, Wang T, Chen C, Luo W, Kwon BO, Park J, Koh C, Jones PD, Lu Y, Giesy JP (**2010**) Perfluorinated compounds in water, sediment, soil and biota from estuarine and coastal areas of Korea. Environ Pollut 158: 1237-1244.

Niewiadowska A, Kiljanek T, Semeniuk S, Żmudzki J (**2013**) Organochlorine pesticides and polychlorinated biphenyls in game animals from Poland. Bull Vet Inst Pulawy 57: 197-201.

Nygren K, Hofmann RR (**1990**) Seasonal variations of food particle size in moose. Alces 26: 44-50.

Pavlovic R, Draghi S, Pellegrini A, Fornesi Silva C, Di Cesare F, Curone G, Fidani M (**2024**) High-resolution mass spectrometry non-targeted detection of per- and polyfluoroalkyl substances in roe deer (Capreolus Capreolus). Molecules 29: 617.

Pettorelli N, Pelletier F, von Hardenberg A, Festa-Bianchet M, Côté SD (**2007**) Early onset of vegetation growth vs. rapid green-up: Impacts on juvenile mountain ungulates. Ecology 88: 381-390.

Pielowski Z (**1984**) Roe deer. State Agricultural and Forestry Publishing, Warsaw.

Pleijel H, Klingberg J, Strandberg B, Sjöman H, Tarvainen L, Wallin G (**2022**) Differences in accumulation of polycyclic aromatic compounds (PACs) among eleven broadleaved and conifer tree species. Ecol Indic 145: 109681.

Pokharel K, Weldenegodguad M, Dudeck S, Honkatukia M, Lindeberg H, Mazzullo N, Paasivaara A, Paippo J, Soppela P, Stammler F, Kantanen J (**2023**) Whole-genome sequencing provides novel insights into the evolutionary history and genetic adaptation of reindeer populations in northern Eurasia. Sci Rep 13: 23019.

Quirós-Fernández F, Marcos J, Acevedo P, Gortázar C (**2017**) Hunters serving the ecosystem: the contribution of recreational hunting to wild boar population control. Eur J Wild Res 63: 57.

Redjadj C, Darmon G, Maillard D, Chevrier T, Bastianelli D, Verheyden H, Loison A, Saïd S (**2014**) Intra- and interspecific differences in diet quality and composition in a large herbivore community. PloS One 9: e84756.

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (**2019**) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol Rev 94: 849-873.

Rendón-Lugo AN, Santiago P, Puente-Lee I, León-Paniagua L (**2017**) Permeability of hair to cadmium, copper and lead in five species of terrestrial mammals and implications in biomonitoring. Environ Monit Assess 189: 640.

Ripple WJ, Beschta RL (**2012**) Trophic cascades in Yellowstone: the first 15 years after wolf reintroduction. Biol Conserv 145: 205-213.

Rolle F, Boiani MV, Fardone L, Gaydou F, Macario M, Parentela F, Ruco V, Sigaudo D, Marucco F (**2025**) Integrating Human and Wildlife Dynamics in Co-Occurrence Modelling. Ecol Evol 15: e70984.

Stahl T, Heyn J, Thiele H, Hüther J, Failing K, Georgii S, Brunn H (**2009**) Carryover of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from soil to plants. Arch environ Contam Toxicol 57: 289-298.

Sun H, Gerecke AC, Giger W, Alder AC (**2011**) Long-chain perfluorinated chemicals in digested sewage sludges in Switzerland. Environ Pollut 159: 654-662.

Tomza-Marciniak A, Pilarczyk B, Wieczorek-Dąbrowska M, Bąkowska M, Witczak A, Hendzel D (**2011**) Polychlorinated biphenyl (PCB) residues in European roe deer (Capreolus capreolus) and red deer (Cervus elaphus) from north-western Poland. Chem Ecol 27: 493-501.

Uboni A, Horstkotte T, Kaarlejärvi E, Sévêque A, Stammler F, Olofsson J, Forbes BC, Moen J (**2016**) Long-term trends and role of climate in the population dynamics of Eurasian reindeer. PloS One 11: e0158359.

Valente AM, Acevedo P, Figueiredo AM, Fonseca C, Torres RT (**2020**) Overabundant wild ungulate populations in Europe: management with consideration of socio-ecological consequences. Mamm Rev 50: 353-366.

van Beeck Calkoen ST, Kuijper DP, Apollonio M, Blondel L, Dormann CF, Storch I, Heurich M (**2023**) Numerical top-down effects on red deer (Cervus elaphus) are mainly shaped by humans rather than large carnivores across Europe. J Appl Ecol 60: 2625-2635.

Varela-Castro L, Sevilla IA, Payne A, Gilot-Fromont E, Barral M (**2021**) Interaction patterns between wildlife and cattle reveal opportunities for mycobacteria transmission in farms from North-Eastern Atlantic Iberian Peninsula. Animals 11 (8): 2364.

Vestergren R, Orata F, Berger U, Cousins IT (**2013**) Bioaccumulation of perfluoroalkyl acids in dairy cows in a naturally contaminated environment. Environ Sci Poll Res 20(11): 7959-7969.

Vo P, Ngo HH, Guo W, Nguyen H, Li J, Liang H, Hen LD, Nguyen H (**2020**) Poly-and perfluoroalkyl substances in water and wastewater: a comprehensive review from sources to remediation. J Water Proc Engin 36: 101393.

Warenik-Bany M, Strucinski P, Piskorska-Pliszczynska J (**2016**) Dioxins and PCBs in game animals: interspecies comparison and related consumer exposure. Environ Int 89-90: 21-29.

Zhao S, Zhu L, Liu L, Liu Z, Zhang Y (**2013**) Bioaccumulation of perfluoroalkyl carboxylates (PFCAs) and perfluoroalkane sulfonates (PFSAs) by earthworms (Eisenia fetida) in soil. Environ Pollut 179: 45-52.

Zhou Q, Zhang J, Fu J, Shi J, Jiang G (**2008**) Biomonitoring: an appealing tool for assessment of metal pollution in the aquatic ecosystem. Anal Chim Acta 606: 135-150.