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Received: 7 June 2024 | Accepted: 20 March 2025
DOI: 10.1002/2688-8319.70044

BRITISH ECOLOGICAL SOCIETY Ecological Solutions and Evidence

REVIEW

A scoping review of evidence for the effects of seven global deer species on woody vegetation

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Funding information
Natural Environment Research Council, Grant/Award Number: NE/L002604/1

Handling Editor: Holly Jones

Abstract

1. *Context*: Rapid expansion of deer (Cervidae) populations is a concern for forest ecosystems. Despite extensive reviews on how deer affect forests, variation in effects across deer species has received less attention. A lack of focus on species-specific effects may lead to oversights and failure to achieve desired management outcomes.
2. *Methodology*: We used a systematic approach to compile data on the extent to which the effects of seven deer species on woody vegetation have been studied. We focused on the six deer species present in Britain and Ireland, and elk (*Cervus canadensis*).
3. *Results*: A total of 455 studies were included from across the globe. Red deer (*Cervus elaphus*) ($n = 163$) and elk ($n = 158$) were the most studied species, while Reeve's muntjac (*Muntiacus reevesi*) ($n = 18$) and Chinese water deer (*Hydropotes inermis*) ($n = 5$) were the least researched. Fifty-four per cent of studies ($n = 245$) used fenced exclosures to assess deer impacts. Research mainly focused on defoliation via browsing and grazing ($n = 424$), while debarking ($n = 44$), defecation ($n = 8$) and trampling ($n = 5$) were less frequently studied. Vegetation density ($n = 235$), height ($n = 189$) and diversity ($n = 135$) were the most common metrics used, while fewer studies focused on vegetation mortality ($n = 74$), structural variability ($n = 28$) and condition ($n = 15$).
4. *Practical implication*: While previous studies have often focused on the probability or severity of deer damage to woody vegetation, we identified key knowledge gaps on the ecological influence of such damage, with a species-specific focus. Researchers should treat deer species as distinct entities and appreciate the differences in their body size, sociality, physiology and behaviour when studying their ecological effects. Where multiple deer species co-occur, identifying relative local species abundance and differences among species foraging behaviours

will help to determine how their interactions—whether additive, synergistic or antagonistic—affect ecosystem processes and vegetation dynamics.

KEYWORDS
Cervidae, deer, foraging, forest, herbivory, invasive species, scoping review, ungulate, wildlife management, woodland

1 | INTRODUCTION

Deer (Cervidae) populations are growing across the temperate zone (Reimoser & Putman, 2011). Stricter hunting laws, changing land management practices and non-native species introductions have contributed to this rapid population growth (Côté et al., 2004; Martin et al., 2020). Increases in native populations are arguably a conservation success story (Linnell et al., 2020), in contrast to many other large herbivore populations declining globally (Ripple et al., 2015). Deer are important components of ecosystems: they can mediate competitive interactions between plant species through herbivory (Bernard et al., 2017; Newman et al., 2014), alter soil nutrient content (Stephan et al., 2017), disperse seeds (Eycott et al., 2007) and maintain open habitats (Carranza & Mateos-Quesada, 2001). These effects can improve ecosystem resilience through increased habitat heterogeneity, supporting greater biodiversity (Lilleeng et al., 2016). However, unchecked deer population growth can present environmental challenges (Putman, Langbein, et al., 2011; Putman, Watson, et al., 2011). There is a motivation to plant more trees in the temperate zone to enhance commercial forestry, promote carbon sequestration and conserve woodland biodiversity. Increased herbivory pressure from growing deer populations can interfere with these aims. Selective, intense deer herbivory can reduce the diversity of the canopy, understory and ground flora by favouring herbivory-tolerant or unpalatable plant species (Bernes et al., 2018; Boulanger et al., 2015). This can lead to homogenisation of plant communities and forest structure (Eichhorn et al., 2017; Martin et al., 2010), with detrimental consequences for animal species that rely on dense, complex vegetation, such as small mammals, birds and invertebrates (Bush et al., 2012; Phillips & Cristol, 2024).

The effects of deer on forests have been broadly reviewed (Côté et al., 2004; Davis et al., 2016; Gill, 1992; Ramirez, 2021; Reimoser & Putman, 2011). However, differences in effects among deer species have rarely been outlined, often because of limited data (Spake et al., 2020). There is a recognised need to understand how introduced and native deer species may differ in their impacts on ecosystems (Dolman & Wäber, 2008). For instance, there has been increased interest in how growing populations of native and introduced deer species are affecting European trees (Brabec et al., 2024; Hardalau et al., 2024). A systematic review found livestock positively affected plant species richness, while the abundance of woody understory vegetation was negatively affected by both livestock and non-native wild ungulates, but not native ungulates (Bernes et al., 2018). Ramirez (2021) showed that the strongest ecological impacts of deer–forest interactions emerged under two conditions: very high deer densities or the co-existence of small- and large-bodied species.

Six species of free-ranging deer inhabit Britain, five of which also inhabit Ireland (Table 1): Red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), fallow deer (*Dama dama*), Japanese sika deer (*Cervus nippon*, hereafter sika deer), Reeve's muntjac (*Muntiacus reevesi*, hereafter muntjac) and the Chinese water deer (*Hydropotes inermis*, hereafter water deer). The populations of all six species are expanding in size and range (Croft et al., 2019). These species exhibit marked differences in their morphology, foraging behaviour, home range size, sociality and reproductive strategies (summarised in Table 1). This variation leads to differences in resource selection and likely their relative effects on vegetation (Dolman & Wäber, 2008).

The Irish, United Kingdom, Scottish and Welsh governments have all recognised a need for deer management plans that consider the potential impacts of the individual species. In 2023, the Irish Deer Management Strategy Group published a report on developing a deer management strategy for Ireland, with a call to classify fallow and sika deer as invasive species (Government of Ireland, 2023). The UK Government conducted a public consultation in 2022 to inform the upcoming Deer Management Strategy, which included questions on how best to control range expansion and impacts of invasive muntjac and expressed concern regarding sika and water deer range expansions (DEFRA, 2022). Established in 2021, Scotland's Deer Management Strategic Board has been monitoring the progress of legislation to improve deer management. NatureScot is currently piloting incentive schemes to target roe, red and sika deer in different regions of Scotland (NatureScot, 2024). Welsh Government continues this pattern of species-specific management interest, publishing a 2017–2022 action plan for wild deer management, stating the need for individual action plans for non-native sika deer and muntjac (Welsh Government, 2017). These government reports demonstrate a consistent recognition of the need for species-specific deer management, and yet lack concrete strategies for achieving this, likely due to persistent knowledge gaps.

Our study aimed to scope the current extent of knowledge of the ecological effects of seven deer on woody vegetation. Six of the selected species co-occur within a relatively small geographic area in Britain and yet differ markedly in their morphology, ecology, behaviour and origins of introduction, making them an ideal test case. The extent of this review was global, as the six species all exist outside of Britain and Ireland. The elk (*Cervus canadensis*) was also included. Red deer and elk have been classified as the same species

TABLE 1 Characteristics of the six deer species present in Britain and Ireland, and elk (British Deer Society, 2022; Yellowstone National Park Service (US), 2022).

Deer species	Geographic origin	Body size	Mode of foraging	Sociality	Reproduction	Habitat
Elk (*Cervus canadensis*) 	*Not* present in the wild in Britain or Ireland. Close relative of the red deer. Native to North America, central and eastern Asia.	Adult males ~318 kg, females ~226 kg	Large bulk-roughage grazer but may browse on woody vegetation in winter	Herding animals, older males are often solitary	Annual rut mid-September to mid-October. Calving May–June	Meadows, prairies, forest, aspen parkland, sagebrush
Red deer (*Cervus elaphus*) 	Native to Britain and Ireland (since last glacial maximum)	Adult male 90–190 kg, females 63–120 kg	Large bulk-roughage grazer with some opportunistic browsing	Solitary or mother and calf groups in woodland environments. Large single-sex social groups persist in open habitats	Annual rut late September to early November. Calving mid-May to mid-July	Woodland, shrubland, grassland, heather moorlands, mountains
Roe deer (*Capreolus capreolus*) 	Native to Britain (since last glacial maximum). Introduced to Ireland in the 19th century	Adult 10–25 kg	Medium-sized concentrate selector for browse, forbs and herbs	Solitary, small social groups in winter. Can form larger social groups in open habitats	Annual rut mid-July to mid-August, 2–3 kids born May–June. Capable of delayed fertilisation	Woodland, shrubland, grassland, freshwater wetlands
Sika deer (*Cervus nippon*) 	Introduced to Britain and Ireland around 1860 from deer parks. Native to Japan	Adult males 40–70 kg, females 30–45 kg	Large bulk-roughage grazer. Grazes on high cellulose-content graminoids with some opportunistic browsing	Solitary, small social groups in winter. Sexes strongly segregated outside of the rut	Annual rut late September to early November, calving May–June	Woodland, shrubland, grassland
Fallow deer (*Dama dama*) 	Naturalised in Britain and Ireland (introduced 12th Century). Native to southern Europe	Adult males 36–93 kg, females 35–56 kg	Intermediate grazer. Grazes on high cellulose-content graminoids with some opportunistic browsing	Single-sex social groups in woodland, large mixed-sex herds in open habitats. Group size highly variable, can reach >50 individuals in open habitat	Annual rut late September to early November, calving June–July	Woodland, shrubland, grassland
Reeve's muntjac (*Muntiacus reevesi*) 	Introduced as an escapee from wildlife parks in 20th century, with subsequent introduction to Ireland. Classified as invasive (Ward et al., 2021). Native to eastern Asia	Adult males 10–18 kg, females 9–16 kg	Small concentrate selector for browse, forbs and herbs	Solitary or in pairs	Reproduce year-round, can form high densities very quickly	Woodland, shrubland, grassland
Chinese water deer (*Hydropotes inermis*) 	Not present in Ireland. Introduced to Britain in 1929 as a zoo escapee. Native to eastern Asia	Adult 11–18 kg	Small concentrate selector for browse, forbs and herbs	Solitary or in pairs	Breeding pairs defend territories November–April, calving May–July	Woodland, shrubland, grassland, freshwater and intertidal wetlands

until mitochondrial DNA analysis resulted in their taxonomic separation (Ludt et al., 2004). Nonetheless, *Cervus elaphus is still sometimes used to describe elk* in the literature (Corkery et al., 2024). By collating available literature reporting how different deer species influence woody vegetation, this can inform targeted, species-specific deer management in Britain, Ireland and globally.

2 | METHODS

2.1 | Systematic search strategy

Peer-reviewed journal articles were obtained by searching the Web of Science (WoS) Core Collection for articles published between 1970 and 2024. The searches were restricted to the six deer species present in Britain and Ireland and elk, including any subspecies. No geographic limits were imposed. We also searched the online thesis database Opengrey and the UK government website GOV.UK, which includes literature from Natural England, the Department for Environment, Food and Rural Affairs and the Forestry Commission.

Initially, scoping searches were conducted to assess the quantity and relevance of articles (Mak & Thomas, 2022). When selecting Outcome search terms (Table S1), each potential term was first entered into the Web of Science (WoS) Core Collection along with the Population terms. Each Outcome search term was recorded with the date, the total number of hits and whether relevant hits were returned. Outcome search terms were selected for the final search when they gave relevant results that were not already being generated by other terms. Search terms were put together in one additive search. Search terms were discussed among the authors to ensure the search encompassed everything the review aimed to address. Some terms that generated many irrelevant sources were excluded (Table S1).

Study relevance was sequentially assessed using our finalised inclusion criteria (Box S1) and the ROSES flowchart (Haddaway et al., 2017; Figure S1). Studies were first assessed based on title, abstract and keywords. The second screening stage involved reading the full text. Any articles not entirely published in English were excluded. Reviews identified by the WoS search published from 2010 onwards were screened for relevant articles through bibliographical back-searching. Following the final search at the end of 2021, a WoS weekly search alert was used to monitor for new publications until the end of 2024. The GOV.UK website was revisited in December 2024 to search for final updates to the literature. The same could not be completed for Opengrey, as the database had since been closed.

2.2 | Data collection

Data were extracted on the study location, deer species present, any additional herbivores reported, whether the study focused on captive or wild deer, use of exclosures, population monitoring methods—if any—used to assess relative deer species abundance or density, effect mechanism studied (browsing, grazing, bark removal, trampling), and effects(s) of deer activity for forest, woodland or woody vegetation. Some inconsistencies in terminology made it difficult to classify these effects. For example, the terms 'regeneration' and 'recruitment' are often used interchangeably in the literature. Furthermore, in measuring tree recruitment rate, some studies defined the minimum size of a tree by height, and others by stem diameter. In addition, numerical thresholds that defined a 'tree', 'sapling' or 'seedling' were inconsistent across studies. To investigate the spread of studied effects on woody vegetation across the focal deer species while accounting for this diverse terminology, effects were classified into broad categories similar to those previously used to describe canopy structure (Atkins et al., 2018; Table S2).

To assess the global distribution of studies relative to species distributions, we produced a hexagonal binned global grid using the *dggridR* package (Barnes & Sahr, 2017). The binned data were overlaid upon a global species distribution map, which was produced by combining the IUCN species range maps with maps from the DAMA alien mammal's database (a full list of data sources is available in Table S3). All plots were compiled using R version 4.3.1 (R Core Team, 2023).

3 | RESULTS

A total of 455 articles were selected for inclusion. The Opengrey search identified three relevant PhD theses. Searching the GOV.UK website did not identify any relevant literature.

3.1 | Deer species coverage

Of the 455 studies, the majority investigated the effects of red deer (36%) or elk (35%) (Figure 1). Roe (26%), sika (23%) and fallow (13%) deer received moderate coverage, while muntjac (4%) and water deer (1%) received the least attention. Excluding elk, sika deer were the most frequently studied species in isolation from other focal species. In contrast, red deer and roe deer were predominantly examined in studies where they co-occurred. Fallow deer were studied independently in only eight cases.

3.2 | Geographic extent

The geographic extent of the studies revealed a skew towards North America for elk (Figure 2), with 147 studies in the United States and 11 in Canada. Eighty-seven studies were conducted in Japan, all of which contained sika deer. Further, sika deer co-occurred with other focal species in introduced ranges: New Zealand ($n=5$), the United Kingdom ($n=4$), the Czech Republic ($n=4$), Ireland ($n=3$) and China ($n=1$). Three sika deer studies in the University of Tokyo Chiba Forest reported introduced muntjac in the area but deemed the species an insignificant contributor to the effects observed (Harada et al., 2020; Suzuki et al., 2021; Suzuki & Ito, 2014). The

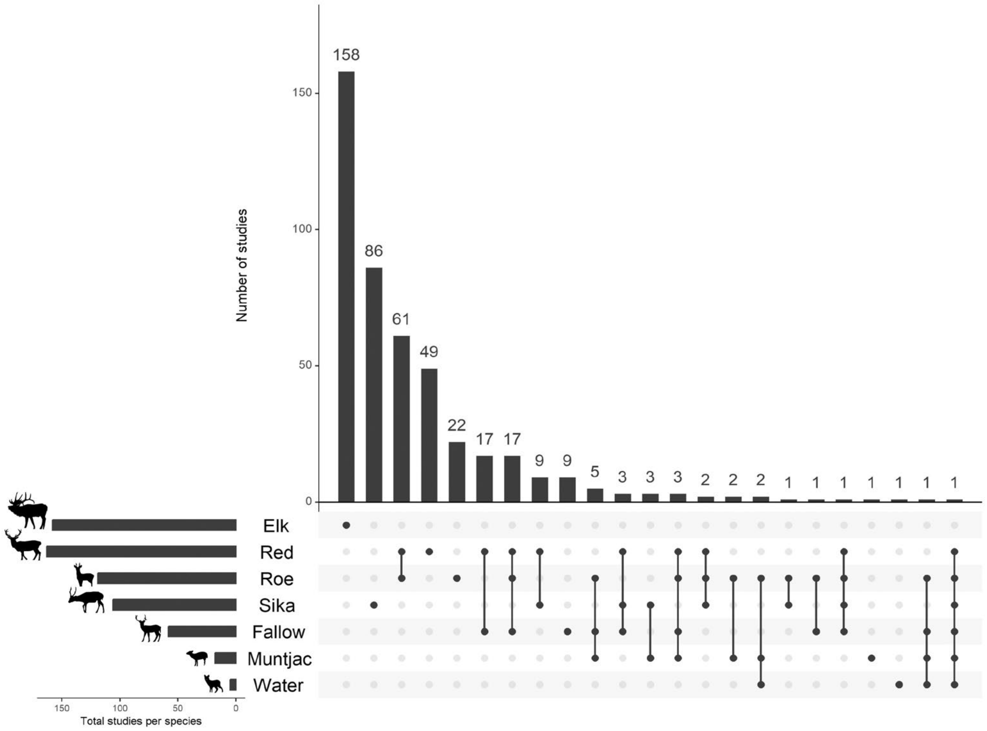

FIGURE 1 Frequency of studies where each focal species was present (horizontal bars) and the frequency of research within co-occurrence or single occurrence context of each focal species (vertical bars). Single dots show occurrence of one species, while two or more joined dots indicate co-occurrence of deer species reported in studies.

remaining studies containing muntjac all took place in south and east England (UK). There were no studies on muntjac in their native range (Figure 2). Four studies including water deer were in southern England and one in South Korea. Table S4 gives examples of recurring study sites.

Of the 119 studies on roe deer, 118 were in Europe, with one study investigating plant dispersal by red and roe deer in Iran (Karimi et al., 2018). Of the 163 studies including red deer, 139 (85%) were in Europe, 16 in New Zealand, six in Argentina and one in China. Of the 59 studies including fallow deer, 48 (81%) were in Europe, five in New Zealand, five in Argentina and one in Australia. Where fallow and red deer co-occurred ($n=42$), four studies were on Isla Victoria (Argentina) and two in New Zealand, with the rest in Europe. Studies with the combination of fallow, roe and red deer ($n=17$) were all found in Europe.

3.3 | Mechanisms of effect on vegetation

Browsing and grazing were the most studied modes of impact on vegetation (contained in $n=424$: 93% of studies). Forty-four studies (10%) contained investigations of the effects of bark removal, including fraying, rubbing or bark-stripping. All these studies included one or more of the larger-bodied focal species (red, sika, elk and fallow deer), which are known to strip bark for food. Five studies investigated the effects of trampling, all involving at least one of the larger-bodied focal species, which typically herd in greater numbers compared to the smaller species (roe, muntjac and water deer). Eight studies investigated the effects of defecation.

3.4 | Deer numbers or activity

The use of exclosures accounted for 54% of studies ($n=245$) investigating deer effects upon vegetation. Most studies (95%) were focused on wild deer populations. Twenty-eight studies utilised deer farms or game enclosures with known deer densities, with some utilising a density 'gradient' between farmed and wild deer populations (e.g. Hegland & Rydgren, 2016; Lilleeng et al., 2021).

Methods for estimating wild deer population size, such as abundance or density, included bag counts from culling efforts, aerial census, terrestrial count census, camera traps and sign surveys such as trackway counts (Figure 3; Table S5). Density was the most common population metric, with 186 studies (41%) including densities of wild deer. Some studies assessed deer habitat use ($n=31$), relative activity ($n=5$) or herbivory rates ($n=15$) rather than deer numbers or density. In addition, 18% of studies sourced landscape-scale, long-term data from game management records, while 16% used previously published literature to gain a population size or density estimate for the area surveyed.

Of the 455 identified studies, 112 (25%) did not give any information on deer numbers or activity. Fifty per cent of these studies used fenced exclosures, while the remaining 50% did not. Of those studies that did not use exclosures, several examined long-term changes

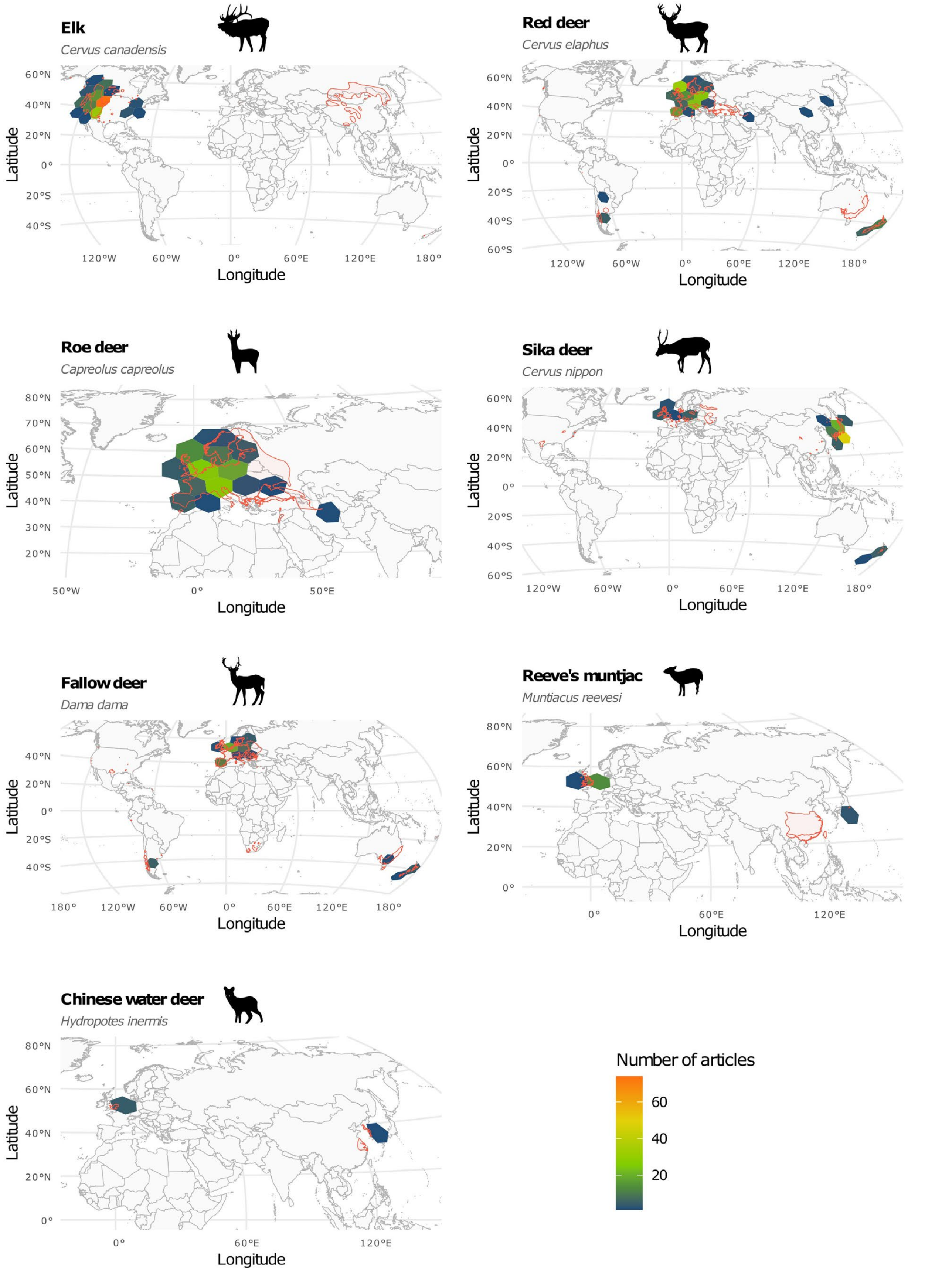

FIGURE 2 Global distributions of the 455 articles included in the review, faceted by deer species. Coloured hexagons indicate the areas where studies took place. The colour hue indicates the number of studies in each area. The red outlines show the global distribution of each species according to the IUCN and DAMA alien mammals database.

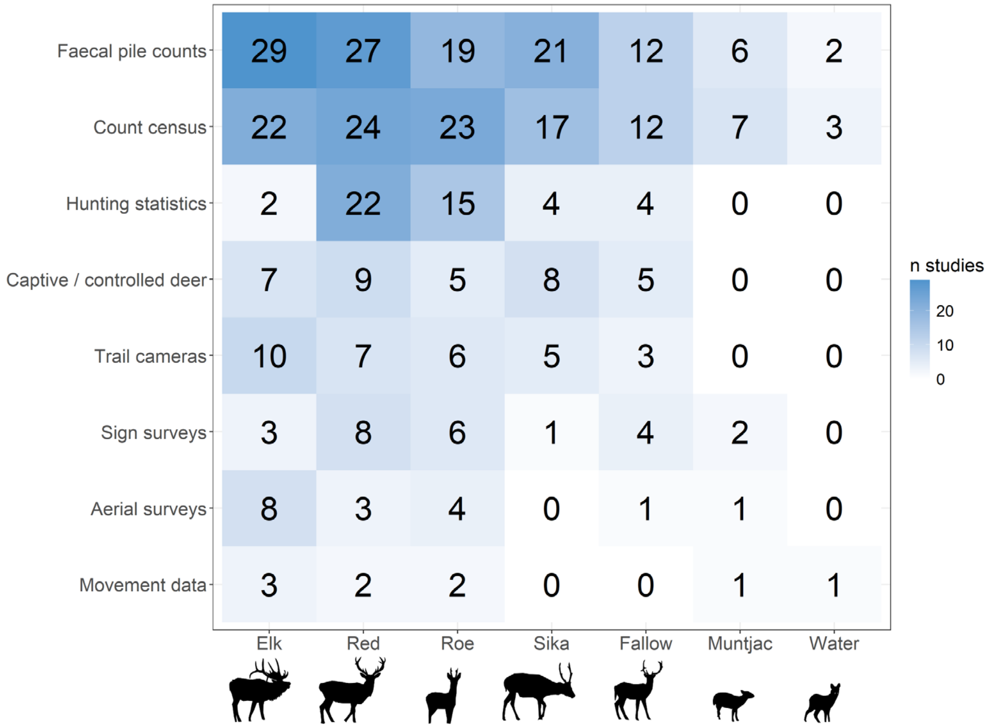

FIGURE 3 The number of studies reporting the occurrence of each focal deer species and the methods used to quantify their presence. Note that several studies included more than one deer species and/or more than one method, while others did not report a metric of deer numbers. Some studies included in this matrix did not use these methodologies directly but reported their use in external surveys from which data were obtained.

in forest dynamics, such as plant species composition or tree cover. This was often in the context of a significant event, such as the introduction of an invasive deer species or the re-establishment of large predators.

A total of 275 studies (60%) reported whether other ungulate herbivores were present in the study system (examples in Table S6), while 181 did not (40%). Only 6% confirmed the absence of species that may have otherwise been expected ($n=28$).

3.5 | Effects on woody vegetation across deer species

A wide range of effects on woody vegetation were reported from deer activity or herbivory, often including more than one effect type (Figure 4; Table S2). *Area and density* of woody vegetation was the most researched category for all seven deer species ($n=235$; Figure 4), principally via stem density, diameter or volume, as these are useful metrics to gauge impacts on forest dynamics and timber production. Effects on vegetation *height* were also commonly researched ($n=189$), again primarily relating to impacts on tree sapling growth but also understory vegetation height, including shrubs and herbaceous vegetation.

Vegetation *diversity and composition* ($n=135$) received moderate coverage across elk, sika, roe and fallow deer studies, but was more common for red deer (Figure 4). *Cover and openness* ($n=96$) was frequently measured alongside *diversity and composition*, as cover is a useful metric to assess the relative tolerance of different plant species to herbivory (Meier et al., 2017). Exclosures were commonly used in studies of vegetation diversity ($n=87$), as shifts in plant community structure are typically medium- to long-term processes (Klopcic et al., 2010; Stohlgren et al., 1997).

The *productivity* category received moderate coverage across the focal species ($n=87$; Figure 4). The most frequently assessed metric was plant biomass. Other *productivity* metrics included reproductive outputs such as flowering success, production of cones and fruits and resource allocation metrics such as foliage nutrient content and primary productivity.

Plant *mortality* ($n=74$) received a similar level of attention as *productivity* (Figure 4). Sixty-four studies (14%) focused on mortality rates due to foliage browsing, mostly on seedlings or saplings. Sixteen studies addressed the effects of debarking by elk ($n=4$), red ($n=4$), sika ($n=7$) and fallow ($n=1$) deer on tree *mortality*.

Across all deer species, few studies addressed the effects on *plant form* ($n=28$), *condition* ($n=15$) or *dispersal* ($n=6$).

4 | DISCUSSION

This scoping review summarises global research on the effects of seven deer species on woody vegetation. For all included studies, we identified the deer species present (Figure 1) and whether the

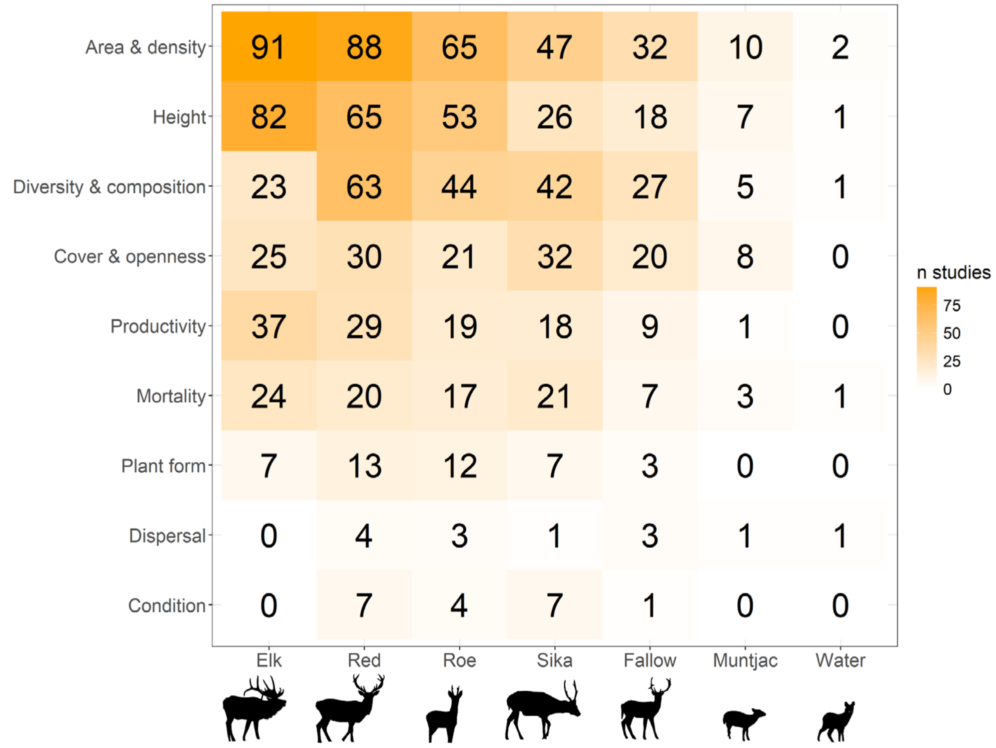

FIGURE 4 The number of studies reporting the occurrence of each deer species, together with the different effects on woody vegetation that were studied. Note that the numbers in this matrix add up to more than the total number of studies (n = 455), as many studies reported more than one deer species present and more than one effect category.

study reported the presence of other ungulate herbivores. We assessed the geographic locations of studies and compared these to known species distributions (Figure 2). We also identified what methods—if any—were used to assess deer numbers or activity in the study area (Figure 3) and the ecological effects on woody vegetation that were studied (Figure 4). By collating this existing knowledge base, we can begin to identify where future research focus may be most beneficial to inform management of deer populations and forest ecosystems.

The distribution and focus of research on the effects of deer species on woody vegetation reveal distinct patterns across species and regions. Although roe deer and red deer share a large extent of their European range, red deer have been more extensively studied. This is perhaps because red deer are herding bulk-foragers with a tendency to bark-strip for food; therefore, they may generally be a greater concern for production forests compared to the smaller, more solitary roe deer (Latham et al., 1996). In addition, red deer have been studied in their invasive ranges, such as Argentina (e.g. Relva et al., 2010) and New Zealand (e.g. Wilson et al., 2006) due to concerns for native vegetation. Aside from elk, sika deer were the most studied species in isolation from the other focal taxa, primarily in their native range in Japan. Only 20 studies (4.4%) researched sika deer in co-existence with any other focal deer species, indicating limited evidence of how sika deer are influencing vegetation as part of ungulate communities in their introduced ranges. Although fallow deer are a growing concern in British and Irish forests due to high-density herds (Ferretti & Lovari, 2014), their effects on woody vegetation have received limited study compared to red, roe and sika deer on a global scale. Similarly, despite rapidly expanding populations in Britain and Ireland, and emerging populations in continental Europe (Ward et al., 2021), the impacts of muntjac on vegetation remain understudied outside of England (United Kingdom). These disparities in research effort underscore the need for a more balanced and comprehensive understanding of the diverse impacts of deer species on woody ecosystems globally.

A lack of evidence on how co-occurring deer species influence vegetation can result in observed effects being attributed to whole herbivore communities equally, with limited information on how to improve species-specific management. Red and roe deer were the most common focal species combination due to their significant range overlap across Europe. However, less than 5% of studies reported co-occurrence of roe and fallow deer or that of red, roe and fallow deer, with less than 2% of studies reporting the occurrence of any other species combination. While studies may report the deer species and additional herbivores present in an area, they often do not report which herbivores are likely to be the stronger drivers of any perceived damage or ecological effects, mainly because this is difficult to achieve. For example, Valdés-Correcher et al. (2018) compared the impacts of bison and cattle with roe deer, fallow deer and rabbits; however, wild herbivore densities were too variable to separate their effects. Deer browsing results in characteristic rough cuts on browsed twigs, which can indicate herbivory levels relative to other groups, such as lagomorph grazing (Chauchard et al., 2018) or wild boar rooting (Perea & Gil, 2014). Browse height can indicate the most likely deer species responsible (Chauchard et al., 2018), but this usually remains speculative, especially if browsing heights overlap. For instance, competition with fallow deer can mask the impacts of muntjac, making it more difficult to distinguish the impacts of each species (Cooke, 2021). Furthermore, when attempting to quantify the relative local abundance of deer species, faecal counts can be unreliable in distinguishing between deer species of a similar size (Hegland et al., 2005; Vuorinen et al., 2020).

Methods are now available that can help to distinguish the foraging behaviour and ecological effects of different deer species. For example, environmental DNA in saliva on browsed twigs can be used to identify the species responsible (Nichols et al., 2015; Nichols & Spong, 2014). In addition, deer diet components can be identified through microscopy of partially digested plant material (Borkowski & Obidziński, 2003; Ismaili et al., 2018). Molecular approaches such as DNA metabarcoding can identify plants present in herbivore faeces to a high taxonomic resolution (Gresham, Pillay, et al., 2025; Nichols et al., 2016), while the identification of herbivore species from faecal DNA could improve the accuracy of species density estimates using faecal counts (Spitzer et al., 2019).

While information on relative species abundance may help to inform local management efforts, short-term assessments of deer numbers are often not strongly correlated with herbivory pressure experienced in the medium- to long-term, leading to misleading conclusions concerning deer impacts (Putman, Langbein, et al., 2011). There is potential for long-term movement studies to improve understanding of how different deer species influence forest ecology; however, we identified just six studies utilising movement data to understand spatial and temporal variation in deer browsing pressure (e.g. Beschta & Ripple, 2013; Riesch et al., 2020). Tracking multiple deer species in a landscape across seasons may highlight how interspecific interactions influence browsing pressure and allow resource selection to be compared across spatiotemporal scales. In addition, trail cameras can provide detailed population-level activity and distribution data across the landscape, with reliable species identification (Ramirez, Jansen, Den Ouden, Li, et al., 2021; Ramirez, Jansen, den Ouden, Moktan, et al., 2021) but have rarely been used for studying deer herbivory. This can be achieved, for example, through behavioural assays using videos of species foraging bouts (Kupferschmid et al., 2015) or using camera hits to assess differences in species habitat use (Zitzmann & Reich, 2022) or relative abundance (Smith et al., 2022). Further, advances in Terrestrial Laser Scanning (TLS) technology have facilitated studies of how variation in forest structure may influence deer species habitat use (Gresham et al., 2023) and how deer themselves influence vegetation structure (Eichhorn et al., 2017). Utilising remote sensing technology can help to quantify how habitat use and population trends of deer species drive changes in vegetation.

Fenced deer exclosures were used in 55% of studies to assess the effects of deer absence on vegetation, by comparison with simultaneous monitoring of herbivory in unfenced control areas. This can be especially important when studying the effects of invasive deer species, such as muntjac in England (United Kingdom) (Cooke, 2006) or red deer in New Zealand (Forsyth et al., 2015). Exclosures can also help to separate the effects of deer and other herbivores, such as livestock (Durham, 2010; Endress et al., 2016) and rodents (Itô & Hino, 2008; Lyly et al., 2014) in multifactorial fencing experiments. However, exclusion studies represent a binary presence/absence comparison, therefore we recommend that exclosures should be used in combination with one or more species-specific monitoring methods. This will ensure a better understanding of how different deer species are concurrently influencing the vegetation in a study system.

Relatively few studies addressed the effects of deer species on *plant form* ($n=28$), *condition* ($n=15$) or *dispersal* ($n=6$). These categories cover the wider ecological effects of deer on vegetation beyond the number, size or cover of plants. *Plant form* concerns structural heterogeneity of vegetation, such as multi-trunking (Scott et al., 2009; Welch et al., 2013), number of branch junctions (Lyly et al., 2014), height distribution (Tamura & Nakajima, 2017) and structural diversity (Kurzel et al., 2007; Tinsley-Marshall, 2010). The methods used to measure plant size and density are often straightforward to implement and can be used for both short-term snapshot studies and long-term monitoring of vegetation responses to deer activity. However, the less-studied metrics can indicate how deer activity might influence plant fitness, bridging the gap in understanding how effects on plant area and density may lead to changes in community diversity and composition through differential impacts on the competitive ability of plant species.

In addition to inter-species variation, foraging behaviours vary within deer species according to environmental conditions, especially across large geographic areas (Putman & Flueck, 2011). Deer respond to perceived risk from anthropogenic disturbance or natural predators through changes in activity patterns, habitat selection and feeding rates (Kuijper et al., 2013; Mols et al., 2022). They also react to adverse weather conditions (Conradt et al., 2000) and competition for resources (Bartos et al., 2002). Behaviour also varies according to reproductive status, age and sex (Bartolomé et al., 2012; Pecorella et al., 2019). Therefore, the most informative assessment of deer effects on vegetation may in fact focus on variation within deer species, not only between them.

4.1 | Study limitations

Due to linguistic limitations of the authors, any sources not published in English were rejected from the final list. In addition, the searches were limited to Web of Science, Opengrey and the UK Government website. Other databases such as Scopus, Google Scholar, or resources from the Scottish Government, Welsh Government, Government of Northern Ireland and Government of Ireland were not consulted. Furthermore, the inclusion of elk biased the search results towards North American studies from a relatively low diversity of authors and study locations. While studies looking at the effects of defecation were reported, some were likely missed, as defecation and seed dispersal were not specified as search terms.

5 | CONCLUSIONS

To stem the global biodiversity and climate crises, countries are adopting reforestation policies to increase forest cover for biodiversity conservation and boost carbon sequestration. Growing populations of native and introduced deer species in the temperate zone can be a significant barrier to these objectives, with the potential to cause significant ecological impacts. As herbivore communities develop with non-native species introductions and expanding global ranges, sustainable and successful management strategies will need to be informed by species- and context-specific ecological knowledge. We should seek to prioritise research efforts to study the lesser-known effects of deer on ecosystems that are most relevant to management and, where possible, identify how co-occurring deer species differ and interact in their effects. Fortunately, there exists a strong foundation of high-quality deer research to build upon, which, combined with rapid advances in remote sensing techniques that resolve habitat use and dietary patterns with increasing precision, means we are able to address these complex ecological and societal challenges.

AUTHOR CONTRIBUTIONS

Amy Gresham led conceptualisation, data curation, formal analysis, investigation, methodology, project administration, visualisation and writing of the original draft. Graeme Shannon was the lead supervisor for this work and contributed to conceptualisation, formal analysis and methodology. Markus P. Eichhorn and John R. Healey were co-supervisors on this work and contributed to conceptualisation, formal analysis and methodology. Graeme Shannon, Markus P. Eichhorn and John R. Healey co-led funding acquisition. Peter J. Lawrence contributed to data curation, visualisation and methodology. All authors contributed critically to the manuscript and gave approval for publication.

ACKNOWLEDGEMENTS

This research was funded by the Natural Environment Research Council through the Envision Doctoral Training Partnership (funding code: NE/L002604/1). We would like to acknowledge the valuable input of Dr. Owain Barton, Will Justus and Dr. Rebecca Spake for their advice on this manuscript, and the reviewers and editors at Ecological Solution & Evidence for a constructive peer review process which greatly improved the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70044.

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.b5mkkwhn7 (Gresham, Healey, et al., 2025).

RELEVANT GREY LITERATURE

You can find related grey literature on the topics below on Applied Ecology Resources: Deer, Herbivory, Foraging, Invasive species, Wildlife management, Forest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1: Structure of the final systematic search entered into the Web of Science Core Collection including the different components of the main research question, detail on each component and the search terms used to satisfy each component.

Table S2: The nine categories of effects on vegetation used to classify the 455 studies identified in the systematic search, with examples of metrics and sources included in each category.

Table S3: Data sources used to produce the global deer species distributions featured in the global hexagonal binned maps (Figure 2 in main text).

Table S4: Recurring study sites noted in the included articles.

Table S5: Methodologies used to assess or manipulate deer numbers, with example papers from the systematic search.

Table S6: Examples of additional herbivore species that were reported in included studies.

Figure S1: Flow diagram for acquisition and filtering of articles for the scoping review.

Box S1: Inclusion criteria.

How to cite this article: Gresham, A., Healey, J. R., Lawrence, P. J., Eichhorn, M. P., & Shannon, G. (2025). A scoping review of evidence for the effects of seven global deer species on woody vegetation. *Ecological Solutions and Evidence*, *6*, e70044. https://doi.org/10.1002/2688-8319.70044