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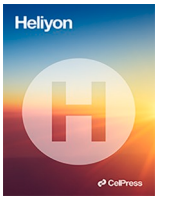

Research article

Where we stand on chronic wasting disease: A systematic literature review of its prevalence patterns, impacts, and management interventions

Sushma Bhattarai [a,*], Robert K. Grala [a], Neelam C. Poudyal [b], Shaun M. Tanger [c], Ram K. Adhikari [d]

[a] *Department of Forestry, College of Forest Resources, Forest and Wildlife Research Center, Mississippi State University, Box 9681, Mississippi State, MS, 39762-9681, USA*

[b] *School of Natural Resources, University of Tennessee, 427 Plant Biotechnology Building, 2505 E.J. Chapman Drive, Knoxville, TN, 37996-4563, USA*

[c] *Arkansas Center for Forest Business, College of Forestry, Agriculture and Natural Resources, University of Arkansas at Monticello, 346 University Drive, Monticello, AR, 71656, USA*

[d] *Department of Forestry, New Mexico Highlands University, Box 9000, Las Vegas, NM, 87701, USA*

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ABSTRACT

With high fatality and no cure, chronic wasting disease (CWD) has infected cervids in multiple regions, including the United States, Canada, Europe, and South Korea. Despite the rapid growth of literature on CWD, the full scope of its ecological, social, and economic impacts and the most effective and socially acceptable management strategies to mitigate the disease is unclear. Of 3008 initially identified published peer-reviewed papers, 134 were included in a final systematic literature review to synthesize the current knowledge on CWD transmission patterns, impacts, and the effectiveness of management interventions. The number of publications on CWD has increased steadily since 2000 with an average of six papers per year. Most papers were related to CWD prevalence (39 %), human behavior (33 %), CWD impacts (31 %), and management interventions (16 %). Environmental factors such as soil, water, and plants were identified as the most common transmission medium, with a higher prevalence rate among adult male cervids than females. Hunters showed a higher risk perception and were more likely to change hunting behavior due to CWD detection than non-hunters. Ecological impacts included the decreased survival rate accompanied by lower population growth, eventually leading to the decline of cervid populations. Culling was found to be an effective and widely implemented management strategy across countries, although it often was associated with public resistance. Despite potentially high negative economic impacts anticipated due to CWD, studies on this subject were limited. Sustained surveillance, ongoing research, and engagement of affected stakeholders will be essential for future disease control and management.

* Corresponding author.
E-mail addresses: sb3695@msstate.edu, bhattarai.sushma@gmail.com (S. Bhattarai), r.grala@msstate.edu (R.K. Grala), npoudyal@utk.edu (N.C. Poudyal), tanger@uamont.edu (S.M. Tanger), ram@nmhu.edu (R.K. Adhikari).

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1. Introduction

The emergence of chronic wasting disease (CWD) in various regions poses a threat to cervid populations, the environment, human health, and the economy around the world [1]. Since its first outbreak in Colorado's mule deer (*Odocoileus hemionus*) in 1967, the disease has been detected in free-ranging as well as captive populations of cervids in 30 states of the United States, four provinces of Canada, three Nordic countries of Europe (Norway, Finland, and Sweden), and South Korea [2,3] (Fig. 1).

CWD is caused by a misfolded protein called prion which is transmitted through saliva, urine, blood, feces, and direct contact with infected animals as well as indirectly through the soil, water, and plants as prions can survive in the environment for relatively long periods [5,6]. Infected animals show symptoms such as emaciation, stumbling, apathy, and other behavioral changes that eventually lead to their death regardless of the age group [7]. With the accelerating spread of CWD and no known cure to date, it is considered a disease of concern with the pressing need to develop more effective mitigation strategies to reduce its negative impacts on the survival of the cervid populations and hunting activity [7,8]. One example illustrating the concern about the CWD and legislative steps that have been undertaken to limit its spread is the approval of the Chronic Wasting Disease Research and Management Act by the U.S. Congress on December 23, 2022 [H.R. 5608–17th Congress (2021–2022)]. This legislation will allocate $70 million each year until 2028 to advance research and improve strategies related to the management of CWD.

Research has shown that CWD caused greater mortality of adult male cervids than young ones, negatively influenced population growth, and led to cervid population declines [9,10]. Undetected CWD outbreaks in high-prevalence areas can also lead to localized extinctions, amplifying the concern about controlling and managing the disease and mitigating its negative impacts [9]. The infected cervids are more vulnerable to predation; thus, predators are more likely to be exposed to the prions by consuming the infected meat, possibly leading to a disturbance in the natural selection of species and ecosystem imbalance [11,12]. However, no research to date has indicated CWD transmission to predators such as the mountain lion (*Puma concolor*) [13]. CWD has also shown a zoonotic potential as experimental research suggested a transmission possibility to humanized mice, squirrels, and monkeys [14–16]. Similarly, clinical trials involving an intracerebral inoculation of CWD-positive tissue to animals, such as sheep and cattle, have shown a transmission potential at different rates [17–19]. While there is no confirmed CWD transmission to humans, there is public concern over CWD's potential effects on human health [20,21], which can potentially translate to decreased hunting participation, lower venison consumption, and reduced economic contributions of deer hunting to the economy in rural areas [22].

The potential impact of CWD on hunting is particularly concerning because deer hunting is a popular outdoor tradition in many countries and generates a substantial portion of the gross domestic product (GDP) [23]. For example, about 14.4 million hunters in the United States spent $45.2 billion on hunting licenses, trips, and hunting equipment in 2022 [24]. A decrease in hunting activities due to CWD can have substantial negative impacts on the local, regional, and national economies. For example, the detection of CWD in Wisconsin, United States in 2002 led to a 10.7 % decrease in deer hunting license sales in the following year [25,26]. Although the hunting license sales returned to a pre-CWD level after several years, this reduction in hunting activity translated to a loss of $12.6 million in direct hunting expenditures and $120 million in non-market values for the years 2002 and 2003 [27]. Similarly, concerns related to a potential CWD transmission to humans can affect venison consumption and trade [28,29]. Consumption of meat from both wild and farmed cervids is popular in the United States and Canada, and it constitutes an important component of the human diet;

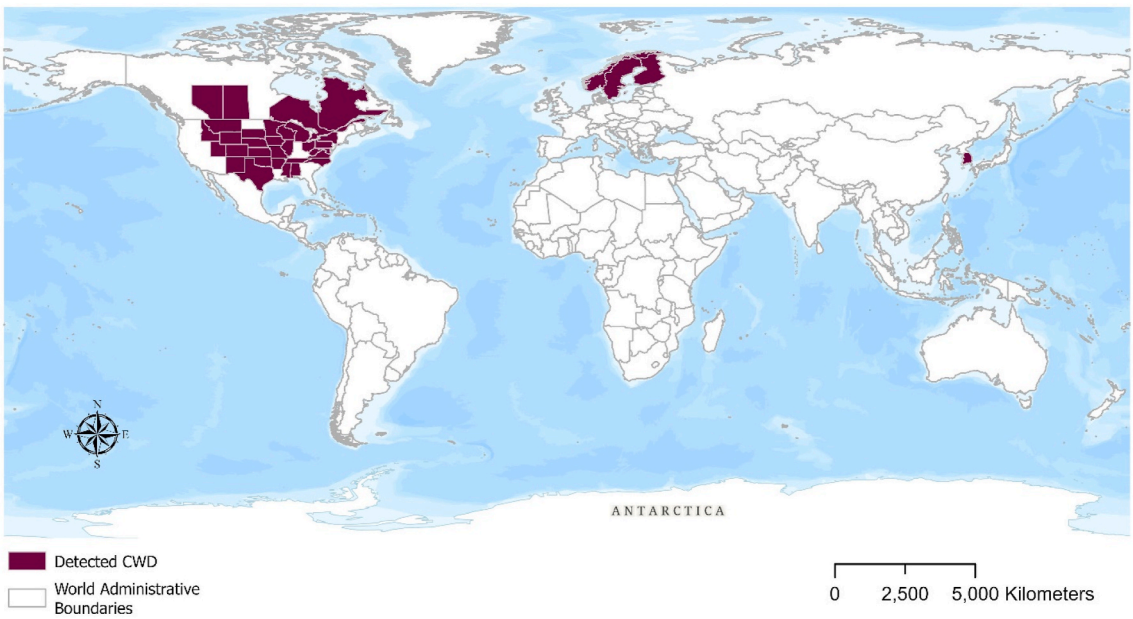

Fig. 1. Presence of chronic wasting disease (CWD) around the world based on data obtained from the U.S. Geological Survey [4].

however, it is possible that its consumption will be negatively affected by CWD because studies found that individuals have high-risk concern related to venison consumption [28,30,31]. For example [28], reported that 97 % of indigenous communities surveyed in central and northern Alberta, Canada hunted moose and deer for food, and they were concerned about the risk posed by the CWD. Overall, $284.1 million was spent to control CWD from 2000 to 2021 by the [32]. Therefore, the expansion of CWD is likely to result in negative social, cultural, ecological, and economic outcomes.

As there is no cure for CWD, it is difficult to eradicate it once the disease becomes established in an area despite the preventive measures. Surveillance and disease management are the only options to detect, manage, and reduce the transmission of prions [33–35]. The management of the disease is complex because of the nature of the disease and the wide range of stakeholders affected including deer hunters, private landowners, government agencies, and non-hunting local residents [36,37]. While some CWD management interventions seemed to be promising, they received resistance from the local stakeholders when these interventions were implemented without their involvement. One example is host culling, which is commonly practiced to contain the spread of the disease in a majority of CWD-affected areas and it includes the use of hunters and sharpshooters for selective or non-selective cervid population reduction [38,39]. After the first outbreak of CWD in Wisconsin, the Department of Natural Resources (DNR) quickly started a massive culling of all deer in the CWD eradication zone to prevent the spread of the disease, which was not welcomed by the local hunters and resulted in distrust towards the agency [25]. Studies conducted in multiple regions of the United States have also shown a great heterogeneity among stockholders in terms of CWD risk perception and behavioral response to CWD [40,41]. Furthermore, the responses of stakeholders to CWD management interventions were primarily determined by their knowledge of the disease, risk perception, and impact on human health [40,42]. Effective disease management requires a better understanding of human behavior related to CWD and the dynamics of stakeholder engagement to coordinate management interventions more effectively among them.

This study conducted a systematic review of papers published in peer-reviewed journals to better understand CWD prevalence; determine its social, health, ecological, and economic impacts; and identify management interventions implemented around the world to control its spread. The goal was to review and synthesize the existing literature on CWD to answer three research questions: 1) What factors affect CWD prevalence? 2) What are the social, health, ecological, and economic impacts posed by CWD? and 3) What methods/interventions adopted thus far have been effective in managing CWD? The study is expected to contribute to the existing knowledge on CWD, improve the comprehensive understanding of the disease, and identify the knowledge gap to outline areas where CWD research needs to be advanced. Specifically, the study identified the current and emerging issues related to CWD, outlined future CWD research priorities to address these issues, and identified the most effective and socially acceptable CWD management interventions. Results will help researchers, practitioners, policymakers, and other relevant stakeholders develop more effective disease management strategies to limit its spread and mitigate potential negative impacts.

2. Methods

2.1. Systematic literature review

This study conducted a systematic literature review (SLR) which employs a systematic, transparent, and replicable approach to identify, assess, and integrate available scientific information [43]. The systematic literature review was done by following the PSALSAR (Protocol, Search, Appraisal, Synthesis, Analysis, Report; Table 1) framework as it is recognized as a comprehensive and appropriate tool for identifying, assessing, and synthesizing scientific works relevant to methodology designed for environment-related studies [44]. The PSALSAR integrates two frameworks: SALSA (Search, Appraisal, Synthesis, and Analysis) and PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to develop a robust, complete, and consistent framework for conducting a systematic literature review related to CWD and involved the following steps [45].

2.1.1. Step 1: SLR protocol

A protocol helps maintain transparency and replicability of the research, which also minimizes biases associated with a systematic literature review such as selection and information biases [46]. The main task at this stage was to define the scope of the research

Table 1
Steps involved in the framework for conducting a systematic literature review (SLR) related to chronic wasting disease (CWD).

Steps	Outcomes	Methods
Protocol	• Research scope: CWD, prevalence, human behavior, impacts, and management	• Systematic literature review and identification of research gaps
Search	• Search strategy defined • Keywords identified	• Search of the bibliographic databases
Appraisal	• Studies selected	• Inclusion and exclusion criteria • PRISMA for the identification, screening, eligibility, and included paper [47]
Synthesis	• Data extracted • Data categorized	• Extraction template
Analysis	• Data analyzed based on the predefined categories • Result extraction, conclusion, and recommendation	• Qualitative and quantitative analysis • Display results in figures and tables, trends of prevalence, and recommend management implications
Report	• Publication and sharing of results	• PRISMA [47]

project. Initially, a literature review was conducted to gather overall information about CWD and identify research gaps from the already published scientific information. This resulted in the identification of three research questions that were essential to achieving the three research objectives:

- What factors affect CWD prevalence?
- What are the social, health, ecological, and economic impacts posed by CWD?
- What methods/interventions have been adopted thus far have been effective in managing CWD?

2.1.2. Step 2: SLR search

This step involved defining and implementing a search strategy which is one of the important steps in the SLR [46]. The first research question was related to the prevalence, transmission, and spread of CWD; therefore, the search terms involved: spread or trend or detection or mapping or presence or absence or transmission or spatial or temporal. The second research question was related to the impacts of CWD; thus, the search terms included: impact or effect or economic or financial or social or health or food system or risk or perception or behavior or attitude or norms. The third research question focused on CWD management interventions and the search terms involved: management or policy or administrative. For all these search terms, chronic wasting disease or CWD or wildlife disease or wild animal disease or deer disease were included.

The systematic literature search was conducted using four bibliographic search engines: SCOPUS, Academic Search Complete (EBSCO), CAB Abstracts, and AGRICOLA. These four bibliographic search engines were selected because SCOPUS is a global repository of peer-reviewed publications, EBSCO is an international database of scholarly research, CAB Abstracts is known for its extensive collection of research on life sciences, and AGRICOLA hosts the largest collection of research-related to agriculture and life sciences [44,48].

The search query contained: ("chronic wasting disease" OR CWD OR "wildlife disease" OR "wild animal disease" OR "deer disease") AND (norm* OR perception* OR attitude OR behavior* OR awareness OR food OR venison OR risk OR social OR economy OR finance OR money OR impact OR health OR ecology OR environment OR effect OR trend OR spread OR growth OR distribution OR transmission OR mapping OR spatial OR temporal OR time OR survival OR policy OR administrative OR management). The total list of papers received from the query search was 3008. While searching papers, inclusion criteria (I1 to I5) were taken into consideration, meaning the search was limited to the papers containing keywords and original research, being categorized as peer-reviewed papers, and in the English language (Table 2). There was no geographical limitation for paper inclusion in the review.

2.1.3. Step 3: SLR appraisal

The appraisal step involved assessing the papers obtained from the search based on the objective of the research. Publications that met the pre-defined criteria of this research were included in the analysis (Table 2). This study followed PRISMA for identifying papers, screening, eligibility checking, and inclusion of the papers [47]. The search was limited to titles, abstracts, and keywords published in peer-reviewed journals in the English language. The literature search was performed in June 2022 and included papers until the day of the literature search.

A total of 3008 papers that were obtained from the bibliographic search were downloaded from the search engines in a RIS format and exported to rayyan (www.rayyan.ai), which is a tool for conducting literature and systematic reviews. Search results from each search engine were merged into a single file in rayyan. Publications were screened using titles to identify and remove duplicate papers. A total of 1147 duplicate papers were removed using E1 criteria (duplicate papers) (Table 2) at this stage leaving 1861 papers for further screening. Similarly, 830 papers were removed using E2 (review-based papers, reports, conference papers, notes, theses, dissertations, and unpublished research papers) and E5 (papers published in a language other than English) criteria with 1031 remaining papers. A total of 856 papers were further excluded using E3 criteria (original research) where papers related to disease pathogenesis, epidemiology, and prion diagnosis were excluded because the major focus of this systematic review was CWD transmission, its impacts, and disease management. A total of 175 of the remaining papers were further reduced to 159 by excluding papers using E4 criteria (original research using data from the agency or other research). Finally, 134 papers were finalized for the review (Fig. 2).

Table 2
Inclusion and exclusion criteria used in the systematic review of peer-reviewed papers related to chronic wasting disease (CWD).

Criteria	Included/Excluded
I1 - Papers containing keywords	Papers included
I2 - Peer-reviewed papers	Papers included
I3 - Original research	Papers included
I4 - Original research using data from the agencies or other sources such as multiyear studies using data from already published reports	Papers included
I5 - Papers published in the English language	Papers included
E1 - Duplicate papers	Papers excluded
E2 - Review papers, grey literature, and conference proceedings, grey literature	Papers excluded
E3 - Papers about disease pathology, genetics, or prions	Papers excluded
E4 - Papers about one sample study or case study	Papers excluded.
E5 - papers published in a language other than English	Papers excluded

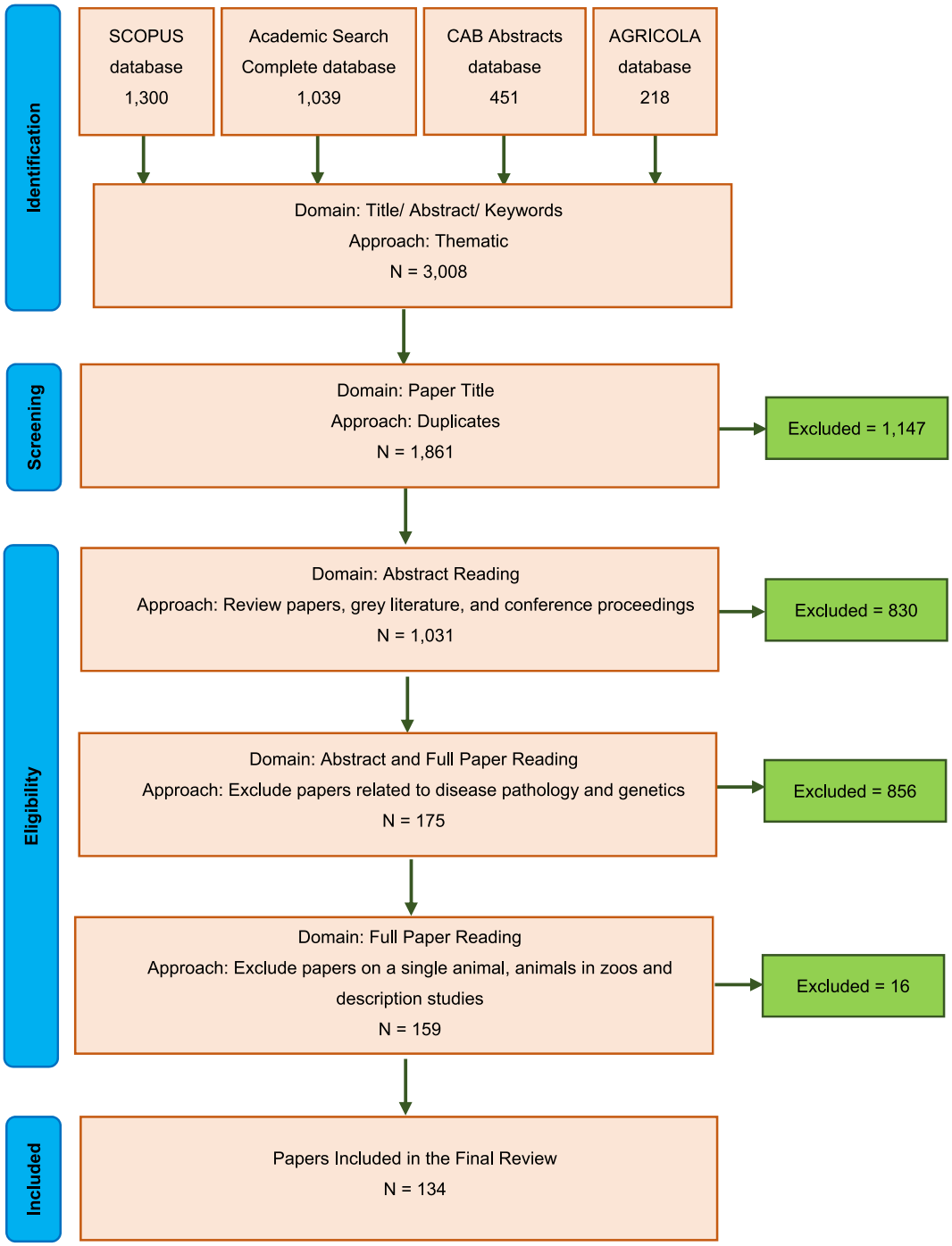

Fig. 2. The steps involved in the systematic review of peer-reviewed papers related to chronic wasting disease (CWD).

2.1.4. Step 4: SLR synthesis

A total of 134 papers were selected for data extraction. The data extraction process consisted of two stages. Firstly, the metadata of the papers was extracted, including details such as publication date, author information, research methodology, and the study period. This information was organized in a CSV format and then exported to VOSviewer and R for further analysis. In the second stage, data relevant to the research questions were extracted and compiled in a Microsoft Excel spreadsheet (the extraction spreadsheet is provided in the supplementary material). The extracted data were categorized into three thematic areas: CWD prevalence, impacts, and management.

2.1.5. Step 5: SLR analysis

A bibliometric analysis was conducted using the biblioshiny package in R studio [49]. It involved deriving general information such as the year of publication, publication trend, H-index, authors' information, and keywords. Furthermore, the extracted data were categorized into four thematic areas: CWD prevalence and transmission, human behavior, CWD impacts, and CWD management. These data were analyzed and presented in figures and tables, depicting frequencies and percentages. They were synthesized to provide an overview of each thematic area, including a summary of papers in each area, comparison among states and countries, identification of gaps, and discussion of pertinent issues. Furthermore, a CWD distribution map was prepared based on CWD presence in various countries and states, sourced from the U.S. Geological Survey [4]. The map creation process utilized ArcMap 10.8.1.

2.1.6. Step 6: Report

This step of SLR involved synthesis, communication, and dissemination of the systematic literature review findings. It consisted of describing methods used to derive the results and presenting the findings obtained from the analysis of peer-reviewed papers included in the review [50]. The manuscript was prepared at this stage.

3. Results

3.1. Publication trends with respect to chronic wasting disease

Most studies related to CWD were conducted in the United States (78 %), followed by Canada (16 %), Norway (4 %), and joint research efforts between the United States, Canada, and Japan (2 %). The papers encompassed 50 states in the United States, including some non-CWD states, five provinces in Canada, and two populations in Norway. Within the United States, Wisconsin (29 %) was the most frequently researched state where many multi-year studies were conducted, followed by Colorado (15 %) and Illinois (13 %); cumulatively, they accounted for more than half of the total CWD studies carried out around the world (Fig. 3).

A total of 134 peer-reviewed papers, fulfilling the inclusion/exclusion criteria of this study, were published between 2000 and 2022. During this timeframe, the number of papers published on the topic displayed a consistent upward trend. The minimum recorded publication count in 2000 was just one paper; however, it progressively increased to 15 papers in 2021. On average, approximately six peer-reviewed papers were published each year, with the highest number of papers published in 2021 and 2022 (Fig. 4). Leading journals that contributed significantly to the literature on CWD included *Human Dimensions of Wildlife*, accounting for 21 % of the publications, followed by the *Journal of Wildlife Management* (11 %), *Journal of Wildlife Diseases* (7 %), *PLOS ONE* (7 %), and *Wildlife Society Bulletin* (5 %) (Fig. 5). The remaining 49 % of papers were published across 39 other journals (the full list of journals is included in supplementary data). Similarly, a total of 375 authors were engaged in publishing 134 papers. Table 3 presents the number of papers published by the top 10 authors.

The reviewed papers represented three major types of studies that were categorized based on the type of data used: observational (71 %), experimental (3 %), and secondary (26 %) [51]. Papers utilized diverse types of data ranging from harvested deer data to live deer population data. Human dimensions survey data (41 %) was the most common and involved interviews with hunters, landowners, residents, and other stakeholders. Global positioning system (GPS) data, camera-trapped images, and modeling results derived from the agency data and other secondary data sources contributed 22 %, live deer population data (e.g., movement, feeding, accidents, predation) constituted 21 %, whereas deer harvest data (e.g., license, permit, and the number of deer harvested by sharpshooters) accounted for 16 % (Fig. 6).

In terms of studied species, nearly half of the papers (44 %) did not clearly mention the species, whereas the remaining 56 % focused on seven species of cervids. White-tailed deer (*Odocoileus virginianus*) was the most researched animal (22 %), followed by

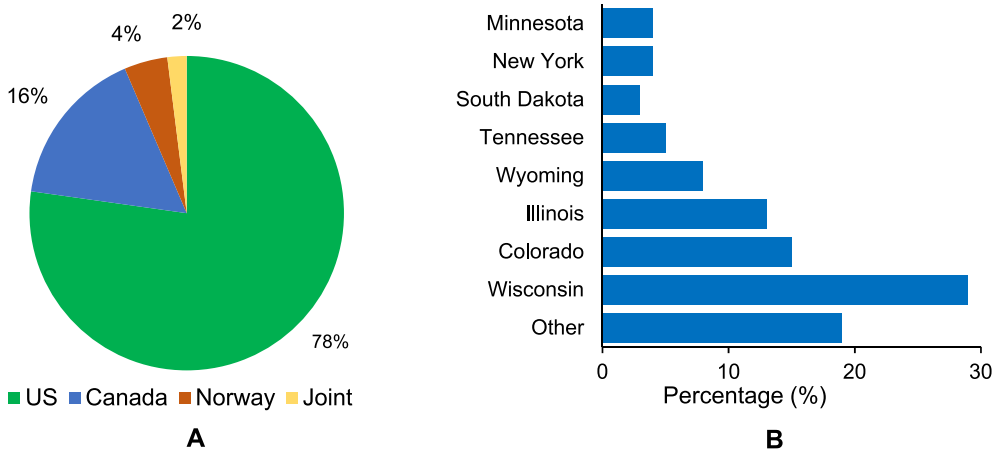

Fig. 3. Geographic distribution of the location of chronic wasting disease (CWD) studies conducted around the world (A) and in the United States (B) based on papers included in the final systematic literature review.

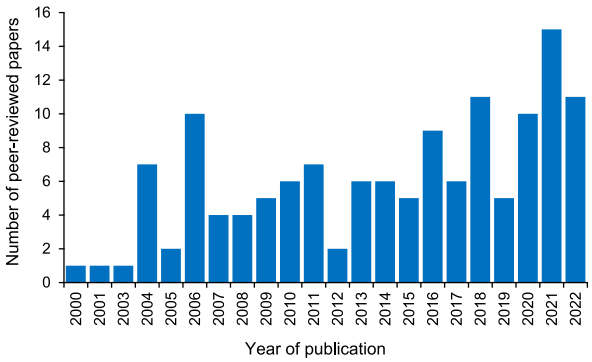

Fig. 4. The number of peer-reviewed papers published during 2000–2022 around the world in relation to chronic wasting disease (CWD) and included in the final systematic literature review.

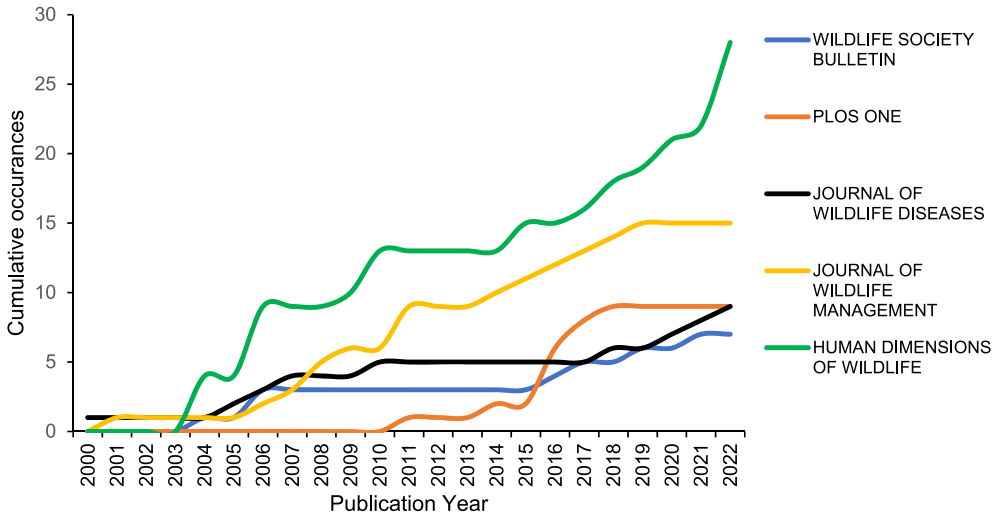

Fig. 5. Cumulative number of peer-reviewed papers related to chronic wasting disease (CWD) published during 2000–2022 in top five journals.

Table 3
The top 10 authors who published peer-reviewed papers related to chronic wasting disease (CWD) during 2000–2022.

Authors	Affiliation	Countries	Articles
Vaske, J.J.	Colorado State University	USA	18
Miller, M.W.	Colorado Division of Parks and Wildlife	USA	14
Samuel, M.D.	U.S. Geological Survey	USA	14
Needham, M.D.	Oregon State University	USA	10
Miller, C.A.	University of Illinois	USA	9
Rolley, R.E.	Wisconsin Department of natural resources	USA	8
Mysterud, A.	University of Oslo	Norway	7
Conner, M.M.	Utah State University	USA	6
Hobbs, N.T.	Colorado State University	USA	6
Shelton, P.	Illinois Department of Natural Resources	USA	6

mule deer (*Odocoileus hemionus*; 16 %), elk (*Cervus canadensis*; 4 %), reindeer (*Rangifer tarandus*; 4 %) and combination of species (54 %) such as elk and mule deer; moose, white-tailed deer, and mule deer; white-tailed and sika deer (*Cervus nippon*); and red deer (*Cervus elaphus*). In terms of the habitat, 50 % of the papers did not mention the habitat of the animals studied, whereas the other half reported three habitat types: wild, captive, and semi-domestic. The majority of the reported cervids' habitat types included free range or wild (95 %), followed by farmed or captive (4 %), and a combination of wild and captive (1 %). In terms of thematic areas, most papers focused on CWD prevalence and transmission (39 %), followed by human behavior in response to CWD detection (33 %), CWD impacts (12 %), and CWD management (16 %).

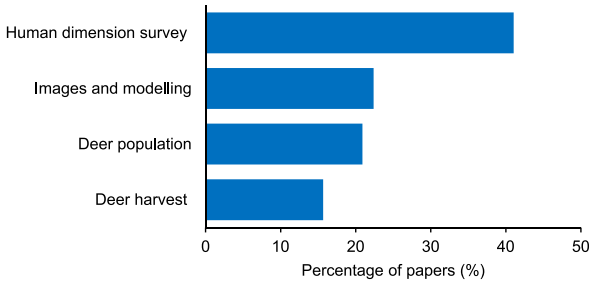

Fig. 6. Different types of data used in peer-reviewed papers related to chronic wasting disease (CWD) and included in the final systematic literature review.

3.2. CWD prevalence

The chronological data on the detection of CWD in the United States, gathered from each state wildlife agency website, revealed that the disease spread sporadically after the year 2000 with the highest detection rates taking place between 2000 and 2010 (Fig. 7). Among these 30 states, New York was the only state which claimed to be CWD-free. In terms of the cases reported, Colorado, Wyoming, Wisconsin, and Pennsylvania were the most impacted states in terms of the CWD prevalence rate. CWD was also detected in Arkansas and Montana after 2016 and its spread, measured by the prevalence rate, was higher than in other states.

A relatively large portion of papers (39 %) included in the final review studied the CWD prevalence. Studies mainly reported a horizontal transmission of prions from one animal to another (both, directly and indirectly) or through environmental repositories and their spatial and temporal distribution. Approximately 27 % of papers in this category investigated the environment as one of the major reservoirs of prions whereas 50 % of papers reported the detection of prions in soil, plants, and water; carcass (22 %); animal excreta such as saliva, feces, and blood (14 %); mineral licks (7 %); and wallow (7 %) (Fig. 8).

Approximately 42 % of papers in the prevalence category, investigated factors facilitating disease transmission. Of those, the population structure of cervids (sex and age) was found to be an important factor (59 %), followed by the movement of the animal that affected the dispersal and clustering of animals (23 %), environment-related factors such as landscape characteristics (9 %), and predation (9 %; Fig. 8). The clustering of cervids increased the likelihood of CWD transmission, which was affected by the geographic location (spatial) and time (temporal). In terms of transmission, 44 % and 17 % of papers reported spatial and temporal patterns of CWD transmission, respectively. Higher spatial clustering was observed near the home range of animals where deer spent most of their time (56 %), followed by agricultural and feeding sites (35 %), and other factors (e.g., forested areas, soil with high clay content; 9 %). The temporal clustering revealed high clustering occurrence during the pre-rut and fawning seasons. Moreover, clustering seemed to be high during the summer season and lowest during the winter season. The sex and age of animals drove the clustering and transmission patterns of prions to other animals and associated environments. Adult male deer were found to exhibit higher clustering (mainly for food, mating, and socialization) than female adults increasing the likelihood of higher disease prevalence.

3.3. Impact

Nearly half (46 %) of the papers focused on the impacts of CWD on human behavior, ecology of cervids, economy, and human health. Human behavior was the mostly researched area (72 %) followed by impact on cervids (18 %), and economic and human health impacts (10 %).

3.3.1. Human behavior

Papers on human behavior investigated peoples' attitude towards disease and its management, risk perception, and behavioral intention for hunting with respect to the CWD prevalence and its impacts in the area where respondents lived or hunted. Among the papers investigating human behavior, hunters represented a major group of stakeholders included in the human behavior studies (76 %), followed by others (landowners, local residents, and government officials; 24 %). Human behavior-related papers were clustered into three broad areas: knowledge (16 %), risk perception (80 %), and behavioral intention and changes (48 %) due to CWD[1].

Papers related to CWD risk perception reported that stakeholders (including hunters) were concerned about deer health, human health, and regulatory interventions imposed by state wildlife agencies. The level of concern was found to be higher in the case of deer health than in human health. Regulatory concerns involved concerns related to the ban on the use of bait and mineral licks, implementation of sharpshooting in the CWD zones, and disposal of infected deer parts. Hunters and landowners seemed to be more concerned about deer health than non-hunters and residents in the CWD affected areas. Very few studies found that respondents were not concerned about CWD at all, whereas some studies reported a decline in CWD risk perception over time.

Behavioral intention and change related papers referred that hunters would continue hunting (24 %) in the CWD zone and CWD did not have any significant impact on their hunting activities at low CWD prevalence rates. Hunters would decrease hunting activities if

[1] Individual percentages add to more than 100 % because some papers investigated multiple impacts.

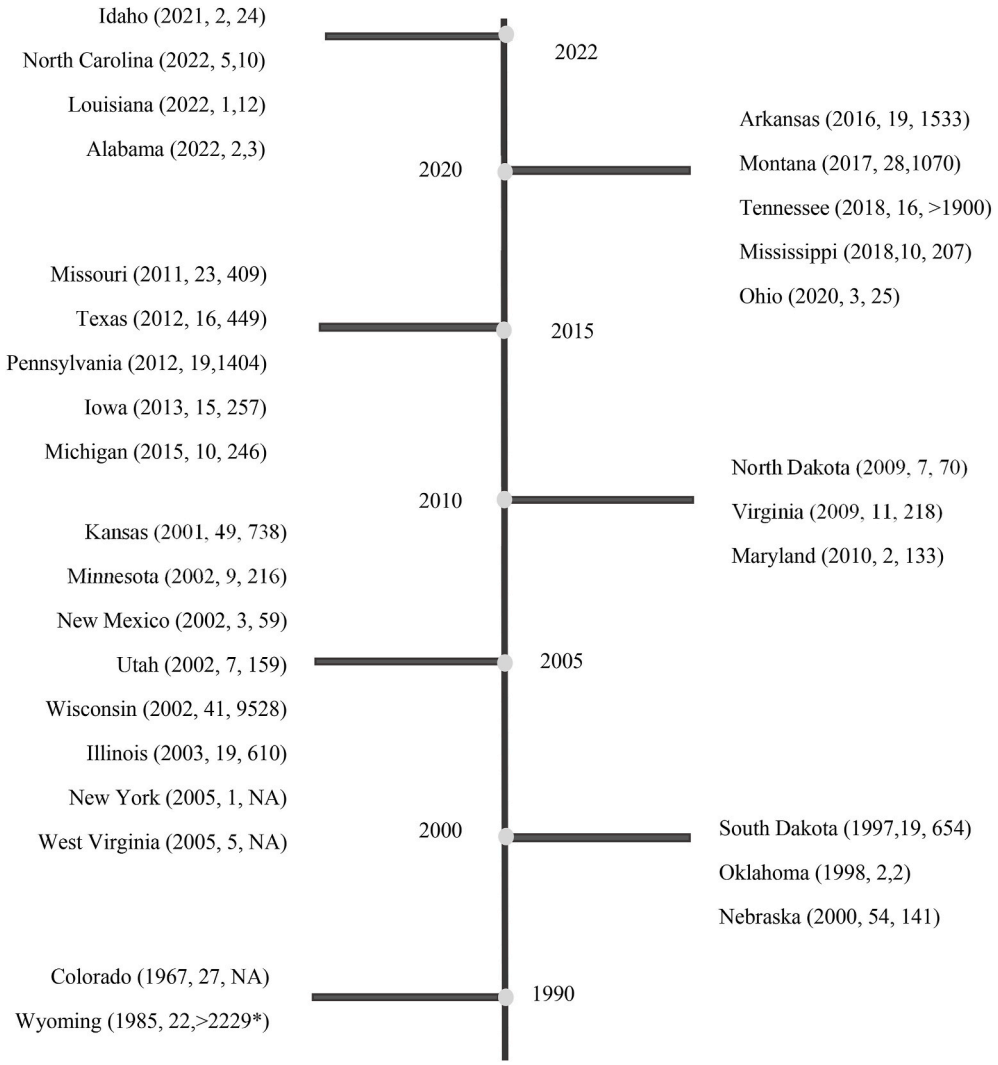

Fig. 7. Chronic wasting disease (CWD) spread in the United States during 1990–2023 (numbers in parentheses indicate the year of CWD detection in the state, number of counties affected, and the total number of cases reported, respectively; * reflects data for 2019–2021 only; source: state wildlife agency websites).

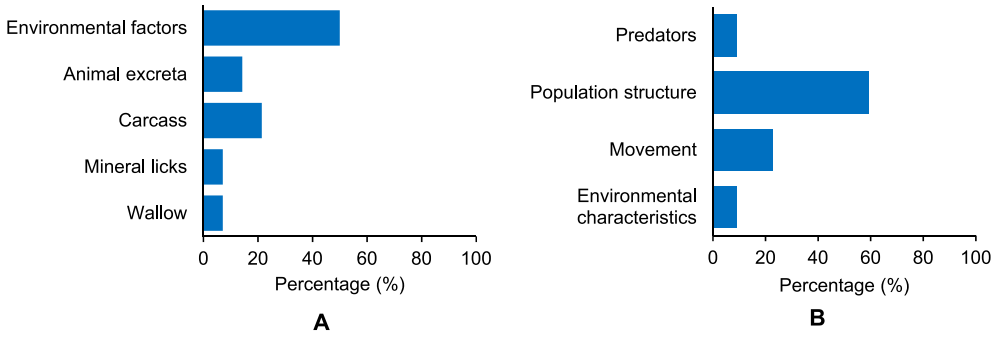

Fig. 8. Chronic wasting disease (CWD) transmission patterns: (A) CWD reservoirs and (B) factors contributing to CWD transmission, identified based on the systematic review of peer-reviewed papers published during 2000–2022.

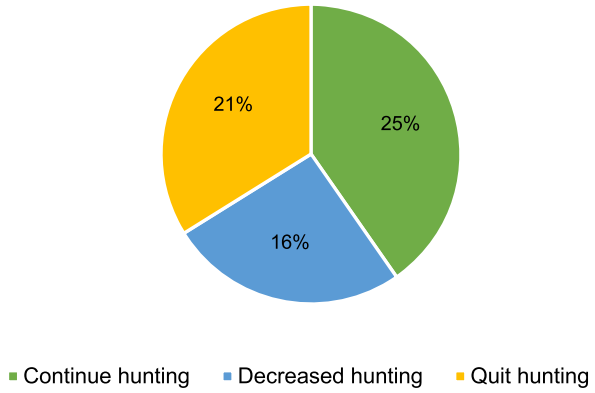

Fig. 9. Hunter's behavioral intentions and change after the detection of chronic wasting disease (CWD) in their hunting areas based on the systematic literature review.

CWD were detected (16 %), but they would quit hunting if there were a high CWD infection rate due to health concerns (Fig. 9). However, no study reported hunters quitting the hunting activity at the current CWD prevalence levels. Papers related to human behavior as a result of CWD indicated differences across countries. For example, hunters were highly concerned about the CWD risk in the United States, potentially because the country has a long history of CWD presence. However, hunters in Canada showed less concern due to a low prevalence of CWD. Regarding the source of information about CWD, the wildlife agency was found to be the major source of information. Most papers reported that respondents received enough information about CWD from the agency and they trusted the information provided to them. Relatively few respondents perceived the information as not sufficient.

Papers on knowledge related to CWD found that hunters had more knowledge of CWD than landowners and residents. Some papers indicated that while hunters were aware of CWD, they were less aware of the causes of CWD, which affected their risk perception towards the disease.

3.3.2. Deer ecology

A portion of papers (18 %) in the CWD impact category investigated the impacts of CWD on deer ecology. These papers reported changes in cervid survival rates (64 %), herd dynamics and population decline (36 %), and behavior of the CWD-infected animals (9 %)[1]. CWD impacts were found to be higher in males than females and in adults than the fawns. The CWD-infected animals were reported to often die due to predation and collisions with vehicles in addition to the disease itself.

3.3.3. Economic impact

The economic impacts of CWD were studied in 35 % of papers that examined the impacts and only 4 % of the total number of papers focused on this aspect. Papers focused on the monetary valuation related to CWD by determining stakeholder preferences towards CWD control measures and willingness to monetarily support their implementation. For example, a case study from Tennessee, United States, and Alberta, Canada reported that the majority of the surveyed respondents (hunters and landowners) were willing to pay (WTP) to avoid CWD if the agency would not do anything to control the disease and the average WTP was $20 per individual. Only 5 % of the papers investigated the CWD impacts on human health, which mainly involved the consumption of venison, and reported a decreasing trend in its consumption over the years as people preferred to test the meat prior to its consumption. Only one study examined the health of the respondents six years after they consumed meat from CWD-infected animals, but it did not find any health-related impacts due to prions.

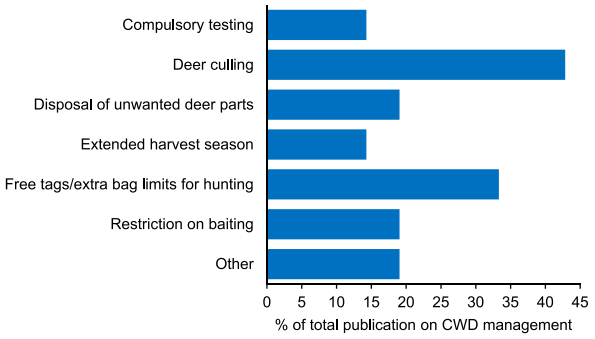

Fig. 10. Types of management interventions implemented to control chronic wasting disease (CWD) based on the systematic review of peer-reviewed papers published during 2000–2020.

3.4. Management of CWD

Papers related to the surveillance and management of CWD were categorized as management of CWD and constituted 16 % of all papers. Papers reported different types of management interventions for controlling CWD. Most common interventions included culling (43 %), disposal of unwanted parts (19 %), restrictions on baiting (19 %), free tags for hunters and increasing bag limits (33 %), extended hunting season (14 %), and other interventions (19 %; individual percentages add to more than 100 % because some papers investigated more than one CWD management intervention; Fig. 10). The management and control strategies were different for farmed and wild cervid populations. Depopulation of the diseased herds was often practiced in farmed deer settings where all animals in a specific farm were culled, whereas a population reduction was mostly practiced for free-ranging deer through selective and non-selective culling in the endemic zones.

Almost all papers related to CWD management indicated that selective/non-selective culling was essential and effective method to control the disease and reduce its spread. Culling was the most commonly implemented practice to remove the infected animals in all CWD areas across all countries and involved selective and non-selective removal of cervids either by hunters or professional sharpshooters. However, the effectiveness of cervid culling by hunters and sharpshooters as well as acceptance of this practice by the general public differed across different areas. For example, a study carried out in Norway in relation to the effectiveness of recreational hunters and sharpshooters found that sharpshooters were more efficient in terms of the number of culling done; however, the same study reported low social acceptance for sharpshooting. Of 10 papers that studied the social acceptance of CWD management interventions implemented by governmental agencies (e.g., compulsory testing, free tags for hunters, extended hunting season, ban on baiting), half reported public resistance to culling by sharpshooters, mainly expressed by hunters and landowners.

4. Discussion

The prevalence of CWD is affected by complex and interrelated factors, including the demographics of the animal (e.g., age and sex), landscape characteristics (spatial), and season (temporal) [19,52]. Studies suggested that a suite of complementary disease detection and management measures might need to be concurrently implemented to effectively control its spread. A pivotable aspect of CWD transmission highlighted by the papers was the role of the environment with soil, plants, and water serving as a reservoir of prions. These prions, shed through excreta (e.g., saliva, urine, feces) or left behind in the carcasses of infected animals, can remain infectious for long periods, posing a continuous risk to healthy cervids. The complex environmental pathway of CWD transmission and the limited understanding of indirect transmission routes, coupled with the disease dynamics, make disease management efforts challenging [53,54]. The development of advanced detection mechanisms for environmental prions is critical. Recent studies by Refs. [55,56], advocated for intensive surveillance and testing in areas involving scrapie sites, food plots, and mineral licks. Techniques such as the protein-misfolding cyclic-amplification (PMCA) assay and real-time quaking-induced conversion (RT-QuIC) have been identified as promising methods for prion detection in the environment. Moreover, understanding the relationship between CWD presence patterns and landscape characteristics, including agricultural and forest lands, as well as soil type is essential for devising targeted and effective monitoring and control strategies [57].

Studies on human behavior highlighted the significant role of risk perception of CWD among individuals. The risk perception, however, varied widely across different regions within the United States and among countries, and was frequently affected by local prevalence rate and how recent the CWD detection was. Refs [58,59] was reported that respondents in areas with a lower CWD prevalence rate tend to have less concern about the disease. In comparison, the higher risk perception was observed in the United States [26] than Canada [37], which might be because United States has a long history of CWD presence and residents and hunters were more aware about CWD and its impacts [22]. Similarly, the level of concern not only differed with geography but also the among different stakeholders. Hunters, for instance, showed higher concern about the deer's health than non-hunters. However, hunters showed less concern over human health implications of CWD [41], believing that the disease would not affect humans and thus continued hunting in CWD-affected areas [60,61]. On the contrary, non-hunters expressed concern over the spread of CWD and potential increase in the deer population if hunting had decreased in endemic areas, showing different concerns and their levels depending on the individual interests [62]. Similarly, the highest level of CWD concern was recorded after its discovery [63–65] and then it subsided over time [22,41]. This decline in CWD risk perception can be partially attributed to the education initiatives implemented by state agencies to help increase awareness about CWD [41,66]. Despite these efforts, some studies indicated that hunters might reduce or quit hunting if CWD prevalence increases significantly or poses a threat to human health [64,67,68]. Research on human dimensions of CWD mostly examined behavioral changes of hunters [42,64], whereas fewer studies have investigated the perspectives of landowners and non-hunters on CWD management [40]. Management actions implemented to control CWD affect stakeholders differently; therefore, agencies need to understand the differential behavior and perspectives of the stakeholders to earn their trust, support, and cooperation for effective CWD management [24].

The persistent prevalence of CWD has had detrimental effects on the health and ecology of cervids. The long-term negative effects on deer health were linked to a decreased survival rate and low population growth as CWD-positive animals were more likely to die than their CWD-negative animals [9,10,69]. For example [70], discovered a lower probability of fawning among infected female mule deer compared to the healthy deer in Colorado. Furthermore, the infected animals were more vulnerable to various risks, as their random and long-distance travel made them more susceptible to vehicle collisions, predators, and hunters [71]. As a prion infection shortens the lifespan of infected deer, CWD can alter deer herd dynamics in high prevalence areas [72]. Thus, CWD can not only negatively affect cervid populations but also have a negative impact on the ecosystem balance in the long term. However [73], in their decade-long study of Table Mesa mule deer herd in Colorado reported stability in terms of disease prevalence and deer abundance even

though the prion infection resulted in a change of the population age-sex ratio. The relationship between CWD and deer population health necessitates deeper explorations of deer ecology and their long-term response to the prion interaction.

Besides degrading the health of cervids, CWD has potential to negatively impact the local economies due to a decline in deer hunting, diminished recreational activities, and reduced venison consumption [74]. While a decline in hunting may be attributed to health concerns [22,26,28,75], the impact on venison consumption is unclear. Although the overall decrease in venison consumption due to CWD appears likely [28]; many individuals continue to consume deer and moose meat without testing. This is primarily because, unlike venison from commercial sources inspected by the regulatory agencies in the United States and Canada, most venison from other sources, such as hunter-harvested meat for personal use, is uninspected [28]. Addressing this concern poses a challenge because even compulsory testing in the CWD-endemic areas may not guarantee that all hunters submit harvested deer meat for testing [74]. For instance, in Wisconsin, a state with one of the highest CWD prevalence rates in North America, the hunter-harvested meat testing rate was below 7 % of total harvested animals, indicating a relatively low compliance rate [74]. While there is currently no evidence of transmission of CWD prions to humans, continuous research, monitoring, and surveillance are needed to limit the potential impact of CWD on human health [76].

Very few studies have investigated the economic impacts of CWD, resulting in a scarcity of information on potential measures to avoid or mitigate its negative economic impacts. According to Ref. [32], the federal government spent $284 million between 2000 and 2021, while state wildlife agencies spent $25.5 million in 2020 for CWD-related activities. However, the actual economic impact of CWD might be higher if actual revenue/expenditure data related to hunting (e.g., hunting license fees, hunting lease revenues, and trip and accommodation expenses) is incorporated [32]. Despite substantial potential economic impacts, there is a lack of studies investigating this aspect in relation to hunting in CWD-affected areas. In a study by Ref. [77], which surveyed hunters in Tennessee, United States, more than half of hunters expressed willingness to pay an extra amount of money to reduce CWD processing costs to facilitate testing and they were willing to pay $20 per animal. Similarly [30], reported that hunters were willing to pay $20.35 per trip, on average, to avoid CWD in the hunting area. Despite high potential economic impacts, studies focusing on the economic aspect of CWD remain relatively scarce, highlighting a substantial research gap in this area. More research is needed to comprehensively understand the extent of CWD economic impacts, compare them with the costs of implementing mitigation measures, and formulate the most effective CWD management solutions.

The implemented CWD management methods faced varied levels of acceptability across stakeholders, geographic regions, and management intervention types even when proven to be effective [78]. Moreover, the CWD management measures sometimes generated detrimental consequences, particularly in terms of public perception. This could be attributed to wildlife managers not fully recognizing and managing the diverse social values associated with cervids such as recreation, cultural significance, and economic values placed by stakeholders such as hunters, landowners, indigenous people, deer farmers, and residents. An illustrative case is the culling of CWD-infected deer in Alberta, Canada in 2008 and Wisconsin, United States in 2004 [79] which faced public resistance. However, a similar culling practice found acceptability in Illinois, the United States, Canada's Saskatchewan province, and Norway [79,80]. Similarly, while, the general public supported CWD management interventions such as reducing the infected deer population, allocating extra tags, monetary compensation for deer hunters and landowners, and deer testing, they expressed aversion to culling carried out by professional sharpshooters [81]. This disparity in acceptance might be due to differences in understanding of CWD impacts on deer populations between the general public and hunters, with hunters demonstrating greater awareness of these impacts and the necessity to maintain healthy populations. Supporting this notion [66], surveyed hunters and landowners regarding CWD management options and found greater acceptance for herd reduction than taking no action against CWD. Similarly [78], found that hunters in Tennessee, United States who were concerned about deer health were more willing to accept the CWD management actions, such as culling, than non-hunters. However [40], reported higher acceptability of selective herd reduction by non-hunters than hunters because hunters were concerned that they would not be able to find enough quality deer to hunt if it was implemented. While [37] suggested that stakeholders in Saskatchewan and Manitoba provinces in Canada had positive attitudes towards CWD management interventions and they highlighted the need education about CWD. As successful CWD management requires cooperation among many concerned stakeholder groups, wildlife agencies should consider the diversity of their attitudes and ownership goals towards CWD to design and implement the most appropriate and socially acceptable management interventions.

5. Management implications and future research

The control and management of CWD have proven to be extremely challenging due to the complexity of the disease, the different animals being infected, the diverse groups of stakeholders affected by the disease, and stakeholder attitudes towards and acceptability of various disease management activities [41,74]. As the environment was determined to be a major transmission source of prions, it is crucial to develop effective testing mechanisms for early prion detection in the environment because controlling CWD at an early stage might be more effective and require less drastic measures compared to when the disease becomes established [82]. A more comprehensive understanding and quantification of the economic impacts of CWD is essential to understand the extent to which CWD might affect stakeholders and the economy. It will also enable a comparison of the cost-effectiveness of different CWD control measures and identify and implement the most efficient and budgetarily viable disease control solutions. Wildlife agencies also must take into account stakeholders' differing behavior with respect to CWD and effectively communicate to them disease risks and the importance of disease control because it will help actively engage them in disease control and management activities on their land [37]. Moreover, education and outreach programs to address the knowledge gap are essential to increase awareness about CWD, reduce risk perception, avoid miscommunication between agencies and stakeholders in terms of disease control, and engage stakeholders in the disease management process. Further research is necessary to better understand the complexity of CWD management, including stakeholder

attitudes and behaviors, in order to develop effective strategies for monitoring and controlling the disease.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Sushma Bhattarai: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Robert K. Grala:** Writing – review & editing. **Neelam C. Poudyal:** Writing – review & editing. **Shaun M. Tanger:** Writing – review & editing. **Ram K. Adhikari:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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