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ORIGINAL ARTICLE

Evaluating the ability of a locally focused culling program in removing chronic wasting disease infected free-ranging white-tailed deer in Illinois, USA, 2003–2020

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Abstract

In northern Illinois, chronic wasting disease (CWD) was first identified in free-ranging white-tailed deer (*Odocoileus virginianus*; hereafter referred to as "deer") in 2002. To reduce CWD transmission rates in Illinois, wildlife biologists have conducted locally focussed culling of deer since 2003 in areas where CWD has been detected. We used retrospective spatial, temporal and space-time scan statistical models to identify areas and periods where culling removed higher than expected numbers of CWD-positive deer. We included 490 Public Land Survey "sections" (~2.59 km^2) from 15 northern Illinois counties in which at least one deer tested positive for CWD between 2003 and 2020. A negative binomial regression model compared the proportion of CWD positive cases removed from sections with at least one CWD case detected in the previous years, "local area 1 (L1)," to the proportion of CWD cases in adjacent sections—L2, L3, and L4—designated by their increasing distance from L1. Of the 14,661 deer removed and tested via culling, 325 (2.22 %) were CWD-positive. A single temporal CWD cluster occurred in 2020. Three spatial clusters were identified, with a primary cluster located at the border of Boone and Winnebago counties. Four space-time clusters were identified with a primary cluster in the northern portion of the study area from 2003 to 2005 that overlapped with the spatial cluster. The proportion of CWD cases removed from L1 (3.92, 95% CI, 2.56–6.01) and L2 (2.32, 95% CI, 1.50–3.59) were significantly higher compared to L3. Focussing culling efforts on accessible properties closest to L1 areas

Abbreviations: CWD, chronic wasting disease; USA, United States of America

results in more CWD-infected deer being removed, which highlights the value of collaborations among landowners, hunters, and wildlife management agencies to control CWD. Continuous evaluation and updating of the culling and surveillance programs are essential to mitigate the health burden of CWD on deer populations in Illinois.

KEYWORDS
chronic wasting disease, deer, disease management, Illinois, retrospective studies, spatio-temporal analysis

1 | INTRODUCTION

Chronic wasting disease (CWD), a prion-associated transmissible spongiform encephalopathy, infects captive and free-ranging cervids, including white-tailed deer (*Odocoileus virginianus*), mule deer (*Odocoileus hemionus*), moose (*Alces alces*), and elk (*Cervus elaphus*; Miller & Walter, 2019; Rivera et al., 2019). In the past decade, the emergence of CWD has been detected in cervid populations across North America, and currently, CWD has been detected in 26 states in the United States, and three Canadian provinces (Miller et al., 2020; Rivera et al., 2019).

In Illinois, USA, CWD was initially identified in 2002 in one free-ranging white-tailed deer in one of the northernmost counties of the state, and subsequent CWD cases have shown a westward and southward expansion. At the time of the study, CWD in wild white-tailed deer was detected in 18 northern and north-central Illinois counties (Rivera et al., 2019). Since 2003, Illinois has tested more than 132,000 deer via an annual surveillance program that collects samples each year from harvested-deer during the recreational hunting seasons (October through January), and from deer removed by other sources including deer removed under the authority of special permits (Deer Population Control Permits and Nuisance Deer Removal Permits), vehicle-killed deer on roadways in the CWD positive areas, and CWD suspect deer (i.e., showing symptoms of neurological disorders and/or emaciation). To control CWD, wildlife biologists conduct an annual adaptive disease management strategy in 15 northern Illinois counties, based on locally focussed culling of deer in areas where CWD cases have been previously identified through the Illinois CWD surveillance program (Manjerovic et al., 2014; Mateus-Pinilla et al., 2013).

The spatial and temporal scan statistic has been applied in public health research and practice to detect regions where disease prevention and control practices should be targeted to reduce the health impact of different infectious diseases. These have included salmonellosis (Paphitis et al., 2020; Varga et al., 2013, 2015, 2020a), tuberculosis (Tadesse et al., 2018), chikungunya and dengue fever (Desjardins et al., 2018). Also, wildlife disease researchers have used these methods to evaluate the clustering of diseases including haemorrhagic disease in white-tailed deer (Baygents & Bani-Yaghoub, 2018; Xu et al., 2012), *Baylisascaris procyonis* infections in raccoons (French et al., 2020), and sarcoptic mange infections in red foxes (Carricondo-Sanchez et al., 2017).

Previous research has demonstrated a spatially defined distribution of CWD cases among deer populations and identified environmental, genetic and demographic factors that impact CWD clustering in local areas. Environmental factors influencing local persistence and spread of CWD include the proportion of urban and agricultural lands (O'Hara Ruiz et al., 2013), soil clay content and pH (Dorak et al., 2017), deer habitat abundance, and deer density (Joly et al., 2006), terrain ruggedness, the extent of agriculture lands, proximity to rivers and creeks (Rees et al., 2012), the use of mineral licks (Plummer et al., 2018), fragmented habitats and large forest areas (Kelly et al., 2014; Miller et al., 2020). Demographic and genetic factors influencing host susceptibility of deer to CWD include sex (Jennelle et al., 2014), age of the deer (Mateus-Pinilla et al., 2013), genetic variability in the prion protein gene (Brandt et al., 2015; Miller & Walter, 2019; Rivera et al., 2019) and haplotypes encoding protective prion protein variants (Brandt et al., 2018; Ishida et al., 2020). Furthermore, haplotype information in cervid populations without CWD has been used to infer the risk of CWD infection in populations that did not have CWD (Perrin-Stowe et al., 2020).

As the distribution of CWD is spatially determined, localized herd reduction close to previously identified CWD positive cases is a useful strategy to mitigate the spread of CWD in local deer populations (Joly et al., 2006; Manjerovic et al., 2014; Mateus-Pinilla et al., 2013).

The CWD endemic area in Illinois is part of a larger region of neighbouring states affected by CWD (USGS National Wildlife Health Center, n.d.), including Iowa, Minnesota, Missouri and Wisconsin. However, each state's wildlife agency has adopted its unique strategies for addressing the management of CWD, and Illinois is the only state that has systematically used locally focussed culling for such an extended period.

The CWD management effort in the CWD-infected areas of Illinois is intended to decrease CWD transmission rates by decreasing deer densities, removing CWD-infected deer, and decreasing the environmental contribution of prions by infected deer (Dufford & McDonald, 2020).

Because CWD has no treatment, and is infectious and ultimately fatal, the locally focussed culling of deer in infected areas is a useful approach to decrease disease transmission with the potential to have substantial and measurable impacts to limit the emergence and spread of CWD (Manjerovic et al., 2014).

Despite the popularity of spatial epidemiology methods in human and animal health research, the scan statistic has not been used to evaluate CWD management programs. The scan statistic could be useful in identifying areas where the culling of deer was effective in removing CWD-positive deer. In this study, our first objective is to use retrospective temporal, spatial and space-time scan statistics to identify areas and periods where a higher than expected number of CWD-positive deer were removed by the locally focussed culling efforts in Illinois.

Our second objective is to compare the proportion of CWD-positive deer—removed via culling—from sections previously known to be infected with CWD to the proportion of CWD-infected deer removed in the adjacent neighbouring sections by using a negative binomial regression model. This work can guide wildlife management stakeholders in their efforts to maximize the removal of CWD-infected deer, slow the increase in the proportion of positive cases, and decrease CWD transmission rates in the Illinois deer population. We expect that our results will help wildlife conservation authorities improve the effectiveness of CWD management among deer populations in Illinois.

2 | MATERIALS AND METHODS

2.1 | Study area and setting

In the state of Illinois, a CWD surveillance and management program (locally focussed culling) was initiated after the first diagnosis of CWD in a free-ranging deer in northern Illinois during the fall of 2002 (Mateus-Pinilla et al., 2013). The Illinois Department of Natural Resources (IDNR) oversees the Illinois CWD surveillance and management program. All the deer removed by the locally focussed culling program, which is conducted during the winter months (January–March), are tested for CWD (Dufford & McDonald, 2020).

CWD surveillance sampling is stratified so that sampling intensity is much greater in CWD-area counties than in southern counties, with about 25% of all hunter-harvested deer being tested in the CWD area in recent years. In the remainder of the state, the proportion of harvested deer tested is much lower, since the goal of that surveillance is disease detection rather than monitoring spatiotemporal changes.

The locally focussed culling of free-ranging deer is an adaptive management program conducted each year by the IDNR wildlife biologists, with assistance from United States Department of Agriculture Wildlife Services personnel. The spatial-scale of CWD-positive cases was recorded at the 2.59 km^2 (1 square mile), township, range, and section referred to as sections throughout our study, as defined by the Public Lands Survey System.

During the study period, the culling effort was consistent; it was conducted in local areas in proximity to previously known CWD infected sections. Areas, where the focused culling program was conducted, generally were restricted to locations within a two-section buffer zone around each known CWD-infected section and removed as many deer as possible from the CWD-infected and adjacent sections. Furthermore, the management program was adaptive. For example, the locally focussed culling program adapted its effort based on the accessibility to areas where CWD was previously detected, if the landowners did not grant permission to their land, state agencies modified their culling approach to include areas as close as possible to the CWD-infected locations. Moreover, the program adjusted the management zone boundaries creating new management zones based on CWD cases in new locations or re-established zones where sharpshooting stopped after a 5-year absence of CWD, and another case emerged. In addition, the culling program considered local factors like deer habitat and deer census data from aerial surveys if available when selecting locations (Dufford & McDonald, 2020; Shelton & McDonald, 2016).

At the time of the culling effort, deer are removed regardless of their sex. If several deer were within shooting range at once, state biologists are instructed to remove deer by size, biggest first, and smallest last regardless of their sex. The age of each deer was evaluated using tooth development, dentition, and wear (Severinghaus, 1949) and classified as fawns (8–11 months old), yearlings (20–23 months old), or adults (>32 months old) based on the estimated age in months at the time of sampling (Green et al., 2017).

We measured the proportion of CWD cases that signified the removal of cases of CWD deer by accounting for the total number of deer removed and tested for CWD in the targeted area during the study period. Sections targeted by the culling program are evaluated and adjusted each year to include only sections within 3.2 km from and including sections with known CWD-positive cases. During 2003 through 2014, cumulative sections with known CWD-positive cases were used to delineate management areas, while in 2015, and thereafter, only cases from the previous 5 years were used to delineate targeted areas. As a result, the management area increases in size (new sections are added) when new locations of CWD-positive cases are identified in new sections in the most recent sampling year and shrinks when no cases occur. We examined CWD results for 18 years (2003—2020) from the 15 northern Illinois counties in which the culling program was conducted: Boone, Carroll, DeKalb, Grundy, Jo Daviess, Kane, Kankakee, Kendall, LaSalle, Livingston, McHenry, Ogle, Stephenson, Will, and Winnebago (Figure 1).

2.2 | Data sources

CWD diagnostic work was performed by the Illinois Department of Agriculture Animal Disease Laboratories until 2017; after the closure of these laboratories, the Veterinary Diagnostic Laboratory at the University of Illinois Urbana-Champaign continued the CWD diagnostic work.

From the fall of 2002 to June 30 of 2020, Illinois used immunohistochemistry (IHC) to evaluate the accumulation of the protein-resistant prion protein (PrP^{res}) on cellular structures of the tissues (obex and retropharyngeal lymph nodes) approved for the post mortem diagnostic testing of CWD (Peters et al., 2000) in the United States (USDA, 2019). Description of the diagnostic efforts in Illinois has been documented in previous studies (Manjerovic et al., 2014; Mateus-Pinilla et al., 2013). IHC is officially accepted as the “gold-standard” method for post mortem diagnostic testing of CWD infection in cervids (Peters et al., 2000; USDA, 2019).

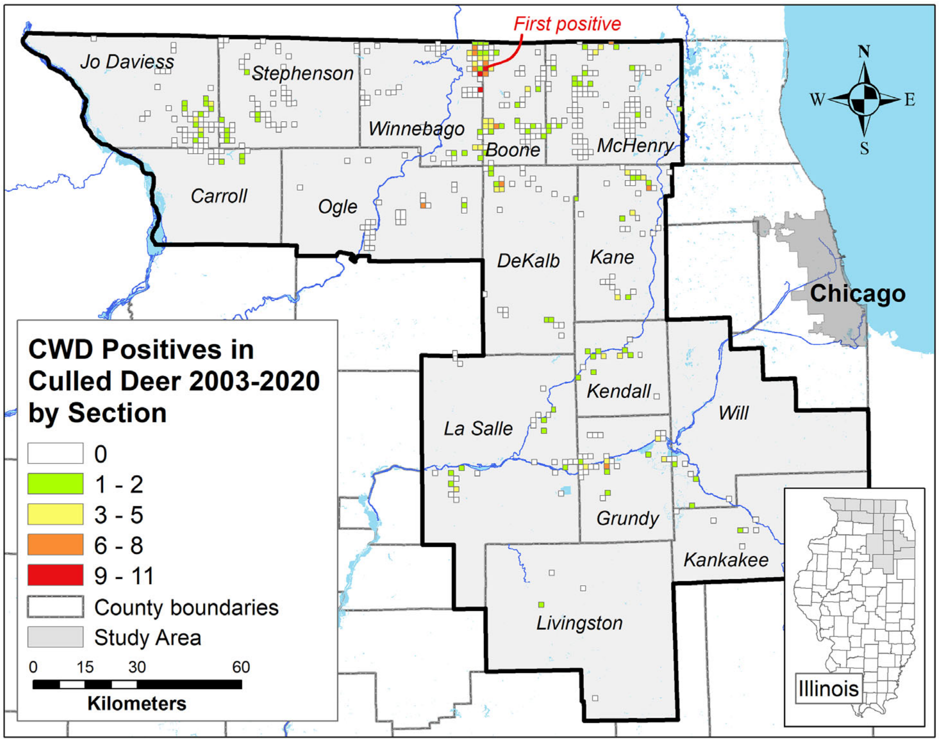

FIGURE 1 Location of the sections where the locally focussed culling program was conducted in the 15 northern Illinois counties for the 18 years (2003–2020) of the study period. The CWD positive sections with a culling event are represented on the map, with the respective number of CWD positive deer removed from the sections via the locally focussed culling

All the deer removed through the culling program were tested for CWD using IHC, and the geographic location where each deer was culled was recorded. The data used in this study included the location and year of CWD-positive deer removed via the culling program at that section in that year. We included 490 sections in our study. Consistent with prior Illinois studies (Hedman et al., 2021; Manjerovic et al., 2014; Mateus-Pinilla et al., 2013), time was documented by fiscal year, which starts on July 1 and ends on June 30 of the next calendar year. Our study period was from July 1, 2002 (the fiscal year 2003) to June 30, 2020 (the fiscal year 2020).

2.3 | Descriptive statistics

Cartesian latitude and longitude coordinates for each section were calculated in ArcGIS 10.7.1. The CWD data were entered into a spreadsheet (Microsoft Excel 2016, Microsoft Corporation, Redmond, WA), reviewed for missing values, and subsequently transferred into the SaTScan software version 9.6 for spatial statistical analysis, and into a statistical software program (STATA Intercooled, version 14.2, Stata Corporation, College Station, TX) for regression analysis.

The yearly proportion of CWD cases were calculated from the locally focussed culling program in Illinois, by dividing the total number of CWD cases culled in each year by the total number of culled deer in that year and multiplying it by 100. In addition, proportions for age categories and sex of the deer removed were calculated by dividing the age and sex-specific number of CWD cases culled by the age and sex-specific total number of culled deer during the study period and multiplying it by 100.

2.4 | Spatial, temporal and space-time clustering analysis

We conducted retrospective scan statistics using SaTScan software version 9.6 (Kulldorff, M. & Information Management Services, 2018) to detect spatial, temporal, and space-time clusters, where a higher than expected rate of CWD-positive deer was identified in deer removed by the culling program. The smallest spatial unit was represented by the section, and the smallest time unit was the year of CWD diagnosis. For the temporal scan statistic with the Poisson model, the outcome variable was represented by the number of CWD cases for each year, accounting for the number of deer tested each year. For the spatial scan statistic using the Poisson model, the outcome variable represented the section-level number of CWD cases for the whole study period, accounting for the number of deer tested from each section. For the space-time scan statistics using the permutation model (Mostashari et al., 2005), the outcome variable was represented by the number of CWD positive cases in each section each year. The scan statistic used a circular scanning window for the spatial and a cylinder with a circular spatial base and height corresponding to the time for the space–time model (Kulldorff et al., 1998; Kulldorff, 2007). The selection of the ideal scanning window size and the optimal collection of non-overlapping clusters were based on the Gini coefficient, selecting the optimal window size and cluster numbers based on the largest Gini coefficients (Han et al., 2016; Kim & Jung, 2017; Varga et al., 2021). The circular scanning window moves across space, and space and time, and the null hypothesis of no clusters within the scanning window is rejected if the number of observed cases accounting for the background population (i.e., the total number of tested deer) within the window is higher than the expected cases under the null hypothesis. Monte Carlo hypothesis testing with 999 replications and a likelihood ratio test was used to test the null hypothesis of spatial randomness, and a p-value ≤ 0.05 signified a statistically significant cluster. The cluster with the highest likelihood ratio was designated as the primary cluster. Secondary clusters were reported if they were statistically significant and were not overlapping with the primary cluster.

To avoid the assumption of similarity of relative risks among sections included in the high CWD rate spatial clusters (Desjardins et al., 2018; Varga et al., 2020b), we calculated the relative risk (RR) for each section by using Equation (1):

$$RR = \frac{c/e}{(C-c)/(C-e)} \tag{1}$$

where c was the total number of CWD cases in the section, e was the total number of expected cases in the target section, and C was the total number of observed CWD cases in all sections during the study.

The expected number of CWD cases (e) was calculated by using Equation (2):

$$e = p * \frac{C}{P} \tag{2}$$

where p was the total number of deer removed and tested for CWD in all sections during the entire study period, which accounts for the previous year's data.

The RR was computed by dividing the estimated risk within a section by the risk outside of the section. If the RR was larger than 1, the section had a greater risk of having a CWD-positive deer. Statistically significant spatial and space–time CWD clusters were illustrated using ArcGIS 10.7.1 (ESRI Inc., Redlands, CA, US).

2.5 | Regression analysis

To compare the proportion of CWD cases removed among areas targeted by the locally focussed culling program, we classified areas based on their CWD status. Local area one (L1) was signified by a 2.59 km^2 (1 square mile) area (i.e. section) where at least one CWD case was detected within the past 5 years, whereas local area two, three, and four (L2, L3, and L4) indicated potential sections based on their proximity to L1 (Figure S1). The culling program prioritized L1 sections first, and adjacent sections L2 to L4 were selected based on areas with deer habitat (i.e. forest cover), winter aerial deer survey data when available, and land access by property owners. The designation of each local area was updated each year based on the previous year's CWD positive sample results from the CWD hunter-harvest surveillance program, and the designation of local areas remained constant and changed only if no CWD case was detected during this period.

We built a Poisson regression model to compare the proportions of CWD cases originating from the four different areas (L1, L2, L3, L4). The outcome (i.e. dependent) variable signified the total number of positive CWD cases in each area (i.e. section) undergoing culling each year. The explanatory (i.e. independent) categorical variables represented the CWD status of the local area (L1, L2, L3, L4), and L3 was chosen as the reference category. The total number of deer removed and tested for CWD in each culling section in each year was used as the exposure variable to account for the culling effort. Proportion rates and their corresponding 95% confidence intervals were calculated. The proportion rate was the proportion of the category of interest compared to the proportion of the reference category. To account for the variation of samples across the years, we kept the year as a fixed effect in the final model. To account for county-level clustering, we included counties as random intercepts in the final model. The Pearson $\chi 2$ goodness-of-fit test was used to evaluate the fit of the Poisson model, and a significant test indicated a lack of model fit, and the analysis was repeated using a negative binomial regression model.

3 | RESULTS

3.1 | Descriptive results

Over the 18-year study period, culling was performed in 490 sections, and 14,661 deer were removed and tested for CWD from these areas. Overall, out of 14,661 deer removed and tested during the 18 years of the locally focussed culling program, 325 were positive for CWD (2.22%; Table 1). The proportion of CWD-positive deer removed by year ranged from 1.16% in 2011 to 3.83% in 2020 (Table 1).

The age and sex-specific proportions of CWD positive deer for the whole study period were 0.93% for female fawns (23 positive female fawns out of 2463 female fawns culled), 0.66% for male fawns (19 positive male fawns out of 2894 male fawns culled), 2.19% for female yearling (28 positive female yearlings out of 1281 female yearlings culled), 2.42% for male yearlings (36 positive male yearlings out of 1486 male yearling culled), 2.71% for female adults (130 positive female adults out of 4791 female adults culled), and 5.11% for male adults (89 positive male adults out of 1742 male adults). Although the biologists conducting the locally focussed culling program are instructed to remove deer by size, the biggest ones first, and they do not discriminate against shooting bucks, there were twice as many females removed.

3.2 | Spatial (S), temporal (T) and space-time (ST) clustering results

3.2.1 | Temporal analyses result

The retrospective temporal scan statistic using the Poisson model identified a single significant high rate CWD cluster (C1-T) occurring in 2020 (Table 2).

TABLE 1 Description of the yearly and overall proportion of chronic wasting disease positive white-tailed deer removed by the locally focussed culling program in Illinois, 2003–2020

Year	CWD-positive (n)	Samples tested (N)	Proportion CWD-positive (n/N*100)
2003	5	181	2.76
2004	21	736	2.85
2005	9	664	1.36
2006	20	747	2.68
2007	16	1203	1.33
2008	15	1101	1.36
2009	9	720	1.25
2010	17	548	3.10
2011	10	860	1.16
2012	23	704	3.27
2013	11	660	1.67
2014	18	720	2.50
2015	24	860	2.79
2016	26	888	2.93
2017	24	984	2.44
2018	15	997	1.50
2019	20	992	2.02
2020	42	1096	2.76
Total	**325**	**14,661**	**2.22**

3.2.2 | Spatial analyses result

We evaluated the Gini coefficients and identified the window size of 25% of the study area with the highest coefficient (0.27); therefore, we used this window size for our subsequent analysis.

The retrospective spatial scan statistic using the Poisson model identified three significantly high-rate CWD-positive clusters (C1-S, C2-S, C3-S) of deer removed by culling (Table 2; Figure 2).

The primary cluster (C1-S) included 134 cases from 61 sections located around the border of Boone and Winnebago counties. One secondary cluster (C2-S) included 14 cases from four sections located in the northern area of McHenry County. The other secondary cluster (C3-S) included 16 cases from seven sections located in the western area of Kendall County.

Of the 61 sections included in the primary cluster (C1-S), 28 sections had a relative risk (RR) of zero; five sections had RR ranging from 0.44 to 1; 16 sections had RR ranging from 1.22 to 3.24; 11 sections had RR ranging from 3.77 to 5.36, and one section had RR of 5.95 (Figure 2). Of the four sections included in the first secondary cluster (C2-S), one section had an RR of 3.01; two sections had an RR ranging from 4.01 to 5.06, and one section had an RR of 7.86 (Figure 2). Of the seven sections included in the other secondary cluster (C3-S), five had RR ranging from 2.45 to 3.08, and two sections had RR ranging from 6.01 to 7.55 (Figure 2).

3.2.3 | Space–time permutation model results

The retrospective space-time scan statistic using the permutation model detected four high-rate clusters (C1-ST, C2-ST, C3-ST, C4-ST) of CWD-positive deer removed by culling (Figure 3; Table 2).

The primary cluster (C1-ST) of 26 cases from 12 sections was in the northern part of the border between Boone and Winnebago counties, occurring from 2003 to 2005. One secondary cluster (C2-ST) of 32 cases from 119 sections was in the northeast part of the study region including sections of Boone, McHenry, and DeKalb counties occurring from 2006 to 2008. Another secondary cluster (C3-ST) of 35 cases from 59 sections was in the south section of the study region

TABLE 2 Spatial (S), temporal (T) and space–time (ST) clusters of chronic wasting disease positive white-tailed deer removed by locally focussed culling in Illinois, 2003–2020[a]

Cluster Type	Model Type	Cluster	Sections[b] (n)	Radius	Time Frame	Observed (O)	Expected (E)	O/E	Relative Risk	Log-Likelihood Ratio	p-Value
Temporal	Poisson	C1-T	All	NA	2020	42	24.05	1.75	1.86	6.01	0.010
Spatial	Poisson	C1-S	61	16.21 km	NA	134	71.89	1.86	2.47	29.66	<0.001
		C2-S	4	5.59 km	NA	14	2.66	5.26	5.45	12.11	0.002
		C3-S	7	6.77 km	NA	16	4.44	3.61	3.74	9.18	0.017
Space-Time	Permu-tation	C1-ST	12	4.84 km	2003 to 2005	26	5.82	4.47	NA	19.40	<0.001
		C2-ST	119	23.46 km	2006 to 2008	32	10.36	3.09	NA	15.22	<0.001
		C3-ST	59	39.40 km	2017 to 2020	35	13.67	2.56	NA	12.32	<0.001
		C4-ST	9	2.95 km	2008 to 2010	13	3.28	3.96	NA	8.33	0.019

[a]Results based on retrospective scan statistics using the SaTScan™ software.
[b]Number of sections with a culling event included in the clusters.

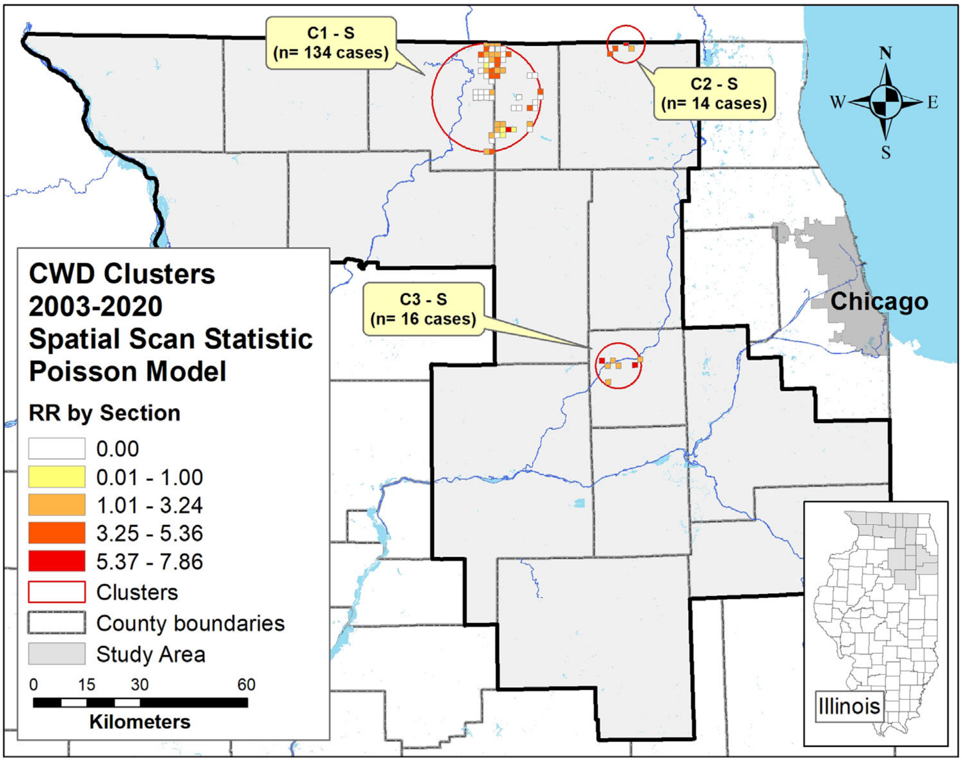

FIGURE 2 Chronic wasting disease spatial clusters (S) of higher than expected numbers of CWD-positive deer removed by locally focussed culling in Illinois, identified by the retrospective scan statistic using the Poisson model

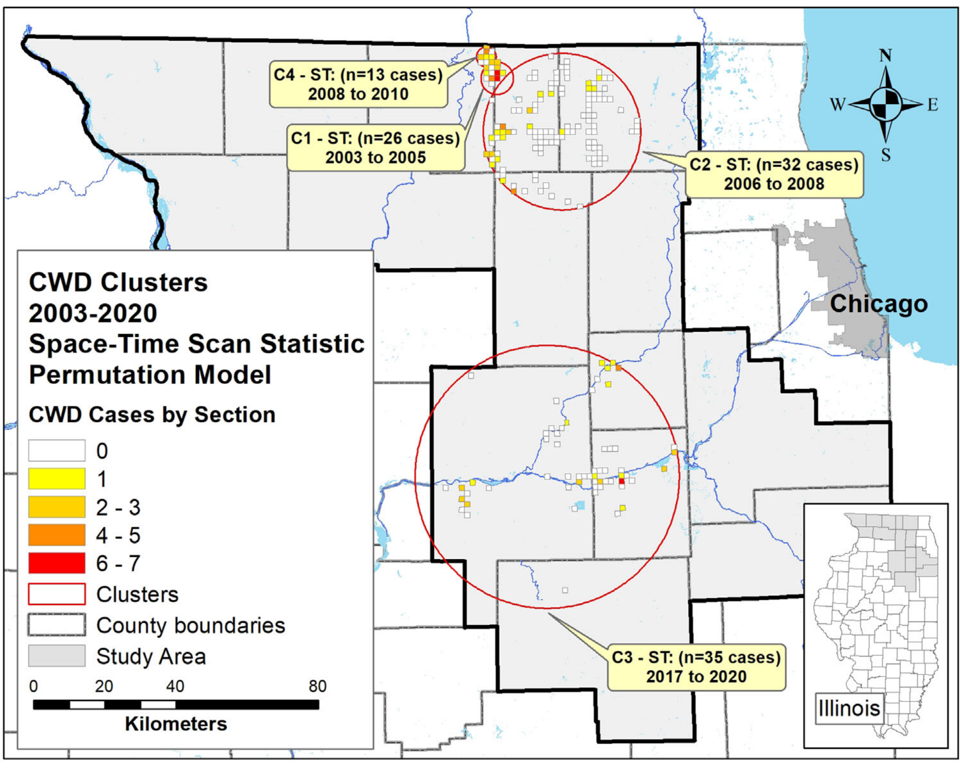

FIGURE 3 Chronic wasting disease space–time (ST) clusters of higher than expected numbers of CWD-positive deer removed by locally focussed culling in Illinois, identified by the retrospective scan statistic using the permutation model

TABLE 3 The proportion of chronic wasting disease positive deer removed at different local targeted areas in Illinois, 2003–2019 (n = 325 cases)

Locally Targeted Area	Proportion	95% CI	*p*-Value
L1	3.92	2.56–6.01	<0.001
L2	2.32	1.50–3.59	<0.001
L3	Reference	–	–
L4	0.12	0.02–0.92	0.041

including parts of Grundy, Kendall, and LaSalle counties occurring from 2017 to 2020. The third secondary cluster (C4-ST) of 13 cases from nine sections was in the northern part of the border region of Boone and Winnebago counties, occurring from 2008 to 2010.

3.2.4 | Regression analysis results

Table 3 describes the results of the negative binomial regression model comparing proportions among culling areas. Compared to culling area three (L3), the proportion of CWD-positive deer was significantly higher in culling area one (L1) and culling area two (L2). We chose L3 as the reference because in L4 only one CWD-positive case was diagnosed and choosing L4 as a reference would make the model unstable.

4 | DISCUSSION

To aid wildlife conservation authorities in mitigating CWD transmission rates, by removing prion contributions to the environment by CWD-infected deer in infected areas, we conducted a retrospective analysis of deer removed by the locally focussed culling program and tested for CWD between 2003 and 2020 from 15 northern Illinois counties. We identified areas and periods where the locally focussed culling efforts removed a higher than expected number of CWD-positive deer, and evaluated the proportion of CWD-positive deer removed via culling from sections previously known to be infected with CWD compared to the proportion of CWD-infected deer removed via culling in the adjacent neighbouring sections. This study serves as an evaluation tool to assess the effectiveness of the State of Illinois locally focussed culling program in removing CWD-infected deer via the locally focussed culling intervention program implemented in CWD-infected areas. Sustained efforts of the locally focussed deer culling in infected areas aim to decrease lingering cases, and deer density (Uehlinger et al., 2016). The Illinois locally focussed target culling does not select the deer to be removed based on signs of disease, sex, or age, the program selects areas known to be infected with CWD and removes as many deer as possible in those areas. Deer infected with CWD may be shedding prions, but not be showing signs of disease, as a result, at the time of culling it is not possible to differentiate infected from non-infected animals. Therefore, the goal of management is to decrease CWD transmission rates, by decreasing deer densities and removing prion contributions to the environment by CWD-infected deer in infected areas (Shelton & McDonald, 2016).

This study identifies areas where the locally focussed culling efforts removed a large number of CWD-positive deer and serves as a reminder that there are areas where CWD management should focus even more. We applied retrospective temporal, spatial and space–time scan statistics to identify geographic regions and periods in which the locally focussed culling program was most successful in removing a higher than expected number of CWD-positive deer. The scan statistic was used previously in Illinois to retrospectively assess deer tested for CWD from the recreational hunter-harvest surveillance program and identified high CWD rate space–time clusters among deer populations in northern Illinois counties (Hedman et al., 2021; O'Hara Ruiz et al., 2013).

In our study, using scan statistics to evaluate a large longitudinal dataset with uneven sampling across regions and periods was valuable, because the scan statistics approach does not have a prior hypothesis on the location, period, and size of CWD clusters (Kulldorff et al., 1998; Kulldorff, 2007). With the spatial scan statistics, we identified core areas where the locally focussed culling program was most successful in removing numerous CWD-positive deer. The primary spatial cluster (Figure 2) was located at the border of Winnebago and Boone counties and included 134 cases (41% of all CWD cases). This area has been identified as a CWD hot spot by previous Illinois studies analyzing the hunter–harvest CWD surveillance program (Hedman et al., 2021; O'Hara Ruiz et al., 2013). Our results confirm the persistence of CWD in local deer populations in these areas and highlight the importance of a locally focussed culling program to remove CWD-infected deer from previously infected sections. In doing so, it has the potential to have a substantial impact in mitigating the emergence and spread of CWD into new non-infected areas.

The primary spatial cluster was identified where the first case of CWD was detected in 2002 (Figure 1), suggesting a continuous CWD presence in the local deer population. Additional secondary spatial clusters were identified because the culling effort adapted to variations in CWD-infected areas. Furthermore, culling was conducted where access was allowed but as close as possible to previously identified infected CWD areas; these areas might change over time in response to the geographical spread of CWD. As such, the locally focussed culling often addresses some of the areas with the highest CWD prevalence and areas with recurrent cases of CWD. Spatial clustering of CWD in local areas was demonstrated by several previous studies that described a localized transmission pattern of CWD in deer populations (Joly et al., 2006; Miller et al., 2020; Miller & Walter, 2019) as a consequence of high deer densities that increase the direct transmission potential of CWD among infected and susceptible deer (Schauber et al., 2015), and was supported by the local accumulation of infective prion proteins as a result of the favourable local environmental conditions and reservoirs (Dorak et al., 2017; Magle et al., 2013; O'Hara Ruiz et al., 2013; Williams & Miller, 2002). Since shedding of the prions responsible for CWD increases with a rise in the number of infected deer, and as CWD in deer is spatially determined, disease management in core areas with a high proportion of CWD positive deer has the potential to reduce the emergence and spread of CWD. Also, previous studies demonstrated that local disease management was more effective than decreasing overall deer densities from a larger region without considering the local CWD status of deer populations (Jennelle et al., 2014; Joly et al., 2006).

In our study, we used a retrospective space–time scan statistic with the permutation model (Mostashari et al., 2005) to identify space–time clusters of higher than expected numbers of CWD-positive deer removed by culling. We defined space–time clusters as locations during a period where the number of CWD-positive deer that were removed through the culling program was significantly higher than expected by random chance alone. We used a space–time permutation model, which is valuable in assessing large surveillance datasets with uneven sampling across years, because it does not require information on the background population, accounts for spatial and temporal patterns, and adjusts for multiple comparisons (Mostashari et al., 2005; So et al., 2013). Moreover, compared to spatial models, the space–time scan statistic provides a time component that allows differentiating between older and more recent clusters. We identified four space–time clusters where the CWD cases among deer removed through the culling program were higher than expected (Figure 3, Table 2). Two space–time clusters (C1-ST and C4-ST) completely, and one cluster (C2-ST) partially overlapped with the spatial cluster and covered a long period (2003–2010), suggesting a continuous and localized CWD problem among deer populations, and the need for a persistent localized culling effort to control CWD. However, compared to the third space–time cluster (C3-ST), these clusters were older, suggesting their diminishing importance. On the other hand, the third space–time cluster (C3-ST) was located south of the C1-ST and C4-ST clusters, and occurred more recently (2017–2020), suggesting a new southward expansion of CWD where culling is conducted and there is a need for an increased effort to control the spread of CWD. We note that CWD surveillance of hunter–harvested deer detected an emerging CWD space–time cluster in an area of eastern Jo Daviess and western Stephenson counties (Hedman et al., 2021) where there is a considerable amount of deer habitat and deer population. However, our study did not identify this site as a cluster based on a locally focussed culling, where a greater than expected number of CWD-positive deer were culled. This study did not consider the amount of deer habitat, the deer densities in CWD-infected areas, or the lack of access of wildlife management staff to conduct culling in and around CWD-infected sections. Therefore, this emerging CWD positive area should remain under CWD management and evaluation to better understand local factors impacting the emergence of CWD and reduce CWD transmission rates.

Although we did not evaluate the impact of culling on the geographic spread of CWD, and the locally focussed culling does not claim to control the geographic spread of CWD, we showed that the proportion of CWD-positive deer removed was almost four times higher by culling deer from sections (2.59 km^2) where CWD was previously detected in deer, compared to removals of CWD-positive deer in neighbouring areas 3.22 km away. The likelihood of removing additional CWD-positive deer via culling was significantly higher when deer removals were conducted in the original positive section (L1) or the sections adjacent to L1 (e.g. L2 sections) than when culling removals were more distant from L1 (e.g. L3 and L4 sections). This finding is consistent with a previous study from Wisconsin, USA that showed a decreasing prevalence of CWD among deer as the distance increased from a central CWD hotspot location (Joly et al., 2006). Sustained locally focussed culling within and as close as possible to L1 is a powerful management tool to complement CWD control measures such as limiting the movement of infected carcasses and live cervids by people; restricting baiting and feeding of deer, and increasing harvest rates via non-selective culling (Mysterud et al., 2020, 2021; Uehlinger et al., 2016).

Culling in areas with CWD cases among deer populations, in conjunction with CWD surveillance of samples obtained through recreational hunter–harvest, can serve as important disease management tools. Both approaches have a role in limiting the increase and transmission of CWD in local deer populations (Mateus-Pinilla et al., 2013). Compared to the culling program, the surveillance of CWD of deer obtained through hunter–harvest surveillance covers a larger area and includes a higher number of samples, which increases the potential to detect emerging CWD outbreaks (Mysterud et al., 2020). Also, hunter-harvest surveillance is essential for tracking spatial and temporal changes in disease prevalence and distribution (Hedman et al., 2021; Manjerovic et al., 2014). On the other hand, culling is more focused on areas with a high number of previously identified CWD cases. It takes into consideration the size of the deer population in the target area and aims at reducing deer density and consequently the proportion of CWD positive deer to limit the spread of CWD into new non-established areas (Gagnier et al., 2020; Manjerovic et al., 2014; Mateus-Pinilla et al., 2013; Mysterud et al., 2020). Additionally, culling of deer can be conducted in locations (e.g. parks, forest preserves, and even housing developments) where public hunting is not allowed (Manjerovic et al., 2014; Mateus-Pinilla et al., 2013). However, the culling program in Illinois can only be implemented where landowners allow it. Regardless of the level of CWD positive cases or deer density, without access to private properties, the state cannot implement the CWD management program in all the CWD-infected areas. Thus, even if the highest priority for culling includes "high CWD proportion/high deer population" areas, with lesser emphasis on culling in "low CWD proportion/low deer population" areas, the locally focussed culling program may not always be able to target the desired areas.

Therefore, spatial epidemiology approaches are vital for resource allocation and can guide wildlife management agencies to focus their CWD prevention and control efforts and resources in areas where these approaches are more needed and are most effective (Hedman et al., 2021). Furthermore, given the high fecundity of white-tailed deer in Illinois, (Green et al., 2017), and their potential for rapid population growth, we recognize that there may be mechanisms of disease transmission that are both deer density and frequency-dependent (Potapov et al., 2016) in our study area; however, additional modelling approaches may be necessary to address this uncertainty.

With every study that evaluates surveillance and disease management programs, there are several limitations. First, because all areas with CWD are subject to localized focused culling, it was not possible for the effectiveness of removing CWD-positive deer to be compared against areas where the culling was not conducted. Also, the proportion of CWD-positive deer in local areas reported by our study might overestimate the true proportion of CWD-infected deer for the whole deer population in Illinois, because these areas were known as CWD-infected locations. Furthermore, our study indicates that the state agencies are adapting, expanding and moving their response to include new CWD-infected areas east, west, and south of the original cases in 2002; however, we could not assess what would have happened with the geographical spread of CWD if no culling had been implemented at all.

Another limitation is that the locally-focused culling program depends on information from all deer tested, from previous years' samples including hunter-harvest, culling, suspects, road kills, and special permits, to inform the decision to conduct a localized-focussed culling of deer in an area. Also, once the culling begins in an area, the state is more likely to identify additional positive deer as long as CWD is still present (because the locally focussed effort is designed to remove deer in infected areas), and the additional information would complement the decision for continued culling in that locale if it was necessary. Therefore, the culling effort might be uneven across years and locations, and high local variability among the number of samples that are collected and tested might occur. Also, sampling bias related to the availability of deer samples might affect the spatial and temporal patterns of CWD (Osnas et al., 2009). To account for these issues, we used a permutation model with a Monte Carlo simulation that did not have a prior hypothesis on the location and time, and extent of a significant cluster, and that accounted for multiple comparisons. Also, the removal of deer in CWD-infected areas, and the collection of deer samples via the locally-focussed culling program depends on access to private lands to conduct this effort. Unfortunately, in a few areas where CWD cases were previously detected, culling of deer was not allowed, and it had to be conducted in the next most proximate section in which culling was allowed. A partnership among wildlife conservation authorities, hunters, and landowners continues to be needed to sustain and improve the effectiveness of CWD management and to protect the health of the local deer populations in Illinois.

5 | CONCLUSION

We demonstrated the usefulness of spatial epidemiology approaches in identifying spatial, temporal and space–time clusters where and when the culling program removed a high proportion of CWD-positive deer. We also demonstrated that the closer locally focussed culling of deer occurs to a known CWD-positive section (L1), the more likely it is to remove CWD-positive deer. This effort likely reduced transmission rates and may have decreased the geographic spread of CWD in Illinois. The proportion of CWD-positive cases removed is almost four times higher if deer are removed from sections previously identified as CWD infected compared to culling 3.22 km away. Space–time clusters that were identified in the northern part of the study area (C1-ST, C2-ST and C4-ST) were older and occurred during a long period, suggesting that CWD was persistent among deer populations in the northern part of the study area. Whereas the most recent space–time cluster (C3-ST) location suggests a southward expansion of CWD. Future studies are needed in these areas to identify risk factors for CWD in local deer populations. We demonstrated the usefulness of spatial epidemiology techniques in directing and maintaining the culling of deer efforts to high-risk areas where the culling program removed higher than expected CWD-positive deer, to reduce the proportion of CWD-positive cases and limit the spread of CWD among local deer populations. Also, we detected locations where the culling effort was not removing a higher than expected number of CWD positive deer, especially concerning is an emerging CWD infected area in the northwestern part of the study area—eastern Jo Daviess and western Stephenson counties—that was identified using hunter-harvested deer surveillance (Hedman et al., 2021) suggesting that this area should be further evaluated by wildlife management authorities, to increase the removal of CWD positive deer in these underperforming areas.

Considering that CWD causes a slow but 100% mortality and the lack of treatment options, locally focussed culling of deer in partnership with CWD surveillance of hunter-harvested deer is vital to the effective implementation of the management program to limit the emergence and dissemination of CWD. Collaboration among wildlife disease management agencies, hunters, and local landowners is needed to manage, and control CWD to reduce the health impact of CWD on local deer populations.

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CONFLICT OF INTEREST

The authors have no conflict of interest to report.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available from the corresponding authors upon reasonable request following approval of the Office of Technology Management.

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ETHICAL APPROVAL

All the work was performed following University of Illinois guidelines and regulations. The authors confirm that samples originated only from state management harvested animals; therefore, no Institutional Animal Care and Use Protocol (IACUC) was needed.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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