

# Demographic Patterns and Harvest Vulnerability of Chronic Wasting Disease Infected White-Tailed Deer in Wisconsin

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## Abstract

Chronic wasting disease (CWD) is a fatal disease of white-tailed deer (*Odocoileus virginianus*) caused by transmissible protease-resistant prions. Since the discovery of CWD in southern Wisconsin in 2001, more than 20,000 deer have been removed from a >2,500-km<sup>2</sup> disease eradication zone surrounding the three initial cases. Nearly all deer removed were tested for CWD infection and sex, age, and harvest location were recorded. Our analysis used data from a 310-km<sup>2</sup> core study area where disease prevalence was higher than surrounding areas. We found no difference in harvest rates between CWD infected and noninfected deer. Our results show that the probability of infection increased with age and that adult males were more likely to be infected than adult females. Six fawns tested positive for CWD, five fawns from the core study area, including the youngest (5 months) free-ranging cervid to test positive. The increase in male prevalence with age is nearly twice the increase found in females. We concluded that CWD is not randomly distributed among deer and that differential transmission among sex and age classes is likely driving the observed patterns in disease prevalence. We discuss alternative hypotheses for CWD transmission and spread and, in addition, discuss several possible nonlinear relationships between prevalence and age. Understanding CWD transmission in free-ranging cervid populations will be essential to the development of strategies to manage this disease in areas where CWD is found, as well as for surveillance strategies in areas where CWD threatens to spread. (JOURNAL OF WILDLIFE MANAGEMENT 70(2):546–553; 2006)

## Key words

Chronic wasting disease (CWD), disease prevalence, epidemiology, harvest vulnerability, *Odocoileus virginianus*, prion, transmissible spongiform encephalopathy (TSE), white-tailed deer, Wisconsin.

The discovery of chronic wasting disease (CWD) in high-density white-tailed deer (*Odocoileus virginianus*) populations in the midwestern and eastern United States has increased the interest of wildlife managers in understanding the epizootiology of this disease, its potential long-term impacts on deer populations, and development of potential management strategies. The spread of CWD threatens areas where deer hunting is an important cultural and economic institution and is an essential management tool for controlling high-density deer populations. Chronic wasting disease (Williams and Young 1980) belongs to a family of diseases known as transmissible spongiform encephalopathies (TSEs), which affect both animals (sheep scrapie, bovine spongiform encephalopathy, transmissible mink encephalopathy) and humans (Creutzfeldt–Jakob disease and kuru). The causative agent of TSEs is likely an abnormal prion protein that is consistently associated with the disease (Prusiner 1991). Chronic wasting disease is the only infectious TSE that affects free-ranging cervid species including elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), and white-tailed deer (Miller et al. 2000). The disease was first recognized in captive cervids in the 1960s, and since 1981 in free-ranging cervids, but the actual length of time that the condition has been present in North American cervids is unknown. Distribution of the disease in North America is largely unknown because adequate sampling and surveillance have not been conducted in most areas of the continent (Samuel et al. 2003). Until 2003, CWD was found in free-ranging cervids in

portions of Colorado, Nebraska, South Dakota, Wyoming, Saskatchewan, New Mexico, Illinois, Utah, and Wisconsin (Williams and Miller 2003). Clinical signs develop at  $\geq 1.5$  years after infection in wild mule deer (Williams et al. 2002) and include changes in behavior, excessive salivation, periods of somnolence, and loss of body condition. Microscopic spongiform lesions and detection of abnormal prion protein in the brain accompany clinical signs. No captive or wild cervid has ever recovered once clinical signs develop (Williams et al. 2002). Similarities between lesions and epidemiology, as well as observation of interspecies transmission, indicate that the same CWD agent infects all three species (Williams et al. 2002). In addition, similar patterns of prevalence related to age and sex have been demonstrated for other cervid species affected by CWD (Miller and Conner 2005).

Chronic wasting disease was first detected in south-central Wisconsin during the 2001 fall hunting season, but the source of CWD infection in Wisconsin remains unknown (Bartelt et al. 2003; Joly et al. 2003). In 2002, the Wisconsin Department of Natural Resources (WDNR) established goals of eradicating CWD by dramatically reducing white-tailed deer density within a 1,064-km<sup>2</sup> area surrounding the initial CWD infections and of decreasing the probability of CWD spread by reducing the deer density from an estimated 15–20 deer/km<sup>2</sup> to  $\leq 4$  deer/km<sup>2</sup> in areas around this disease-eradication zone. As a key component of this control program, retropharyngeal lymph nodes and brain tissue (obex) from deer harvested in the CWD management areas were collected to identify new CWD infections, assess the

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distribution of CWD on the landscape, and provide data for research on CWD epidemiology.

The potential impacts of, and management strategies for CWD control in cervid populations remain controversial. Population models suggest that CWD could have a substantial long-term impact on affected populations (Gross and Miller 2001; J. Cary, University of Wisconsin, unpublished data). Although CWD causes direct mortality of cervids, the long-term population effects of the disease are unknown. In addition, public concerns regarding human risk of contracting CWD also decrease the perceived value of wild cervids and affect hunter participation (Petchenik 2003), which increases the difficulty of managing high-density cervid populations. Currently, there is no evidence that CWD will spontaneously disappear or be controlled without management intervention (Gross and Miller 2001, Peterson et al. 2002). In contrast, there is significant potential for expansion of the geographic range of the disease, and once established, the disease could be maintained through environmental contamination for an unknown period of time (Peterson et al. 2002, Miller et al. 2004). Current management strategies to reduce prevalence or eradicate CWD by reducing cervid densities assume that CWD transmission is density dependent (Schauber and Wolf 2003) and homogeneous among animals. Typically, these strategies involve surveillance to determine the prevalence and distribution of disease and intensive culling of animals within the affected area (Nebraska Game and Parks Commission 2002; Williams et al. 2002; Bartelt et al. 2003).

Studies on CWD transmission in captive deer and elk indicate that lateral transmission by direct contact and ingestion of abnormal prion via contaminated body fluid is a likely mechanism for infection (Williams and Young 1992; Miller et al. 1998, 2000; Miller and Williams 2003). Vertical transmission does not seem to be a major factor in transmission (Gross and Miller 2001, Miller and Williams 2003). Transmission from infected deer to the environment, then to susceptible deer, is also suspected to be a factor in transmission (Miller et al. 2004), but the mechanisms for this route of transmission and their significance in free-ranging cervids are not understood. In addition, the effect of prion dose, genetic resistance, and prion strains on transmission and disease progression is uncertain. However, recent studies on prion genetics in Wisconsin white-tailed deer indicate that >90% of the population genotypes are susceptible to disease (Johnson et al. 2003). These unknown factors associated with routes of CWD transmission and risks of disease infection related to density, demography, movement, and deer behavior have hampered the development of management strategies and public acceptance of population reduction programs to eradicate the disease.

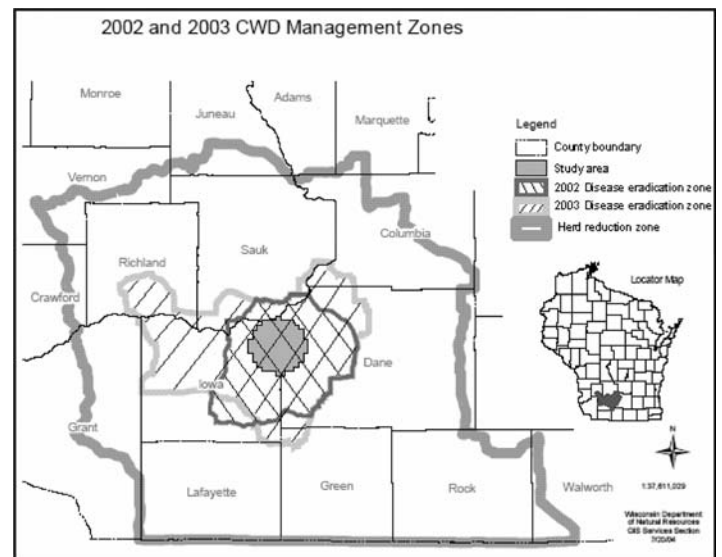
Demographic patterns of CWD infection in wild cervids can indicate when disease is transmitted among animals, which animals are likely to become infected, and how disease spreads across the landscape. However, the demographic patterns of CWD prevalence in white-tailed deer related to age and sex have not been determined. Our major objective was to characterize age and sex prevalence patterns and evaluate hypotheses about CWD transmission in free-ranging white-tailed deer. Specifically, we tested the hypothesis that mass action (or random) transmission of CWD occurs in white-tailed deer populations such that all

individuals have the same probability of becoming infected. Understanding CWD prevalence patterns may also help improve surveillance programs (Samuel et al. 2003) and disease management by identifying animals that are most likely to be infected. In addition, prevalence patterns from harvested mule deer in Colorado indicated a harvest bias, where CWD infected animals were more likely to be harvested as the harvest season progressed (Conner et al. 2000). Our secondary objective was to test for differential harvest susceptibility of infected white-tailed deer to evaluate whether harvest bias affected our prevalence estimates and to determine the potential impacts of harvest on CWD prevalence.

## Methods

### Study Area

During 2002, WDNR conducted spring and summer culls of approximately 500 deer to obtain a preliminary assessment of the distribution of CWD infection. Based on this initial surveillance, the WDNR established a 1,064-km<sup>2</sup> CWD eradication zone encompassing all positive animals. In 2003, this eradication zone was expanded to cover 2,507 km<sup>2</sup> as new positive animals were detected outside the 2002 area (Fig. 1). For our analyses, we selected a 310-km<sup>2</sup> core study area within the disease eradication zone where the highest disease prevalence was observed (Joly et al. 2003, fig. 1). The landscape in this high-prevalence area is characterized by rolling hills and small stream valleys with a mixture of dairy farms and oak-hickory woodlots, almost exclusively in private ownership. Prior to CWD management efforts (posthant 2001) deer density in our core study area was estimated at 13.5–15.5 deer/km<sup>2</sup> (Rolley 2002). As a result of



**Figure 1.** Location of chronic wasting disease (CWD) management areas and core study area in southern Wisconsin, USA. The core study area (310 km<sup>2</sup>) is the area where disease prevalence was greatest (6.7%) in 2002 (Joly et al. 2003). The Wisconsin Department of Natural Resources set a goal of eradicating CWD by reducing white-tailed deer density in the disease eradication zone. The disease-eradication zone increased in size from 1,064 to 2,507 km<sup>2</sup> because new CWD positives were found to the west and south, outside of the 2002 area. The herd-reduction zone was established for intensive disease surveillance and to reduce deer densities to prevent CWD from spreading outside of the infected areas.

generally temperate climate and abundant resources, white-tailed deer in this area have high fecundity and exhibit very little seasonal movement (Larson et al. 1978, Ishmael 1984).

### Data Collection

Deer were removed by hunter harvest and limited culling by government sharpshooters from the core study area during April 2002–April 2003 and July 2003–January 2004. Hunters were required to register every harvested deer. At registration, age, sex, and kill location to the quarter section (0.65 km<sup>2</sup>) were recorded for each deer. Age was determined by tooth replacement and wear (Severinghaus 1949). Heads were removed from harvested deer and sent to a tissue extraction center where a portion of the brain stem (obex) and retropharyngeal lymph nodes (RPLN) were collected for CWD diagnosis. Tissues from all deer harvested within the core study area were collected from the 2002 harvest, but primarily adult tissues (>1 year old) were collected from the 2003 harvest. At dissection, a portion of the obex and 1 RPLN were immediately fixed in 10% buffered formalin and the remaining tissues were frozen. Retropharyngeal lymph nodes and obex tissues were sent to the Wisconsin Veterinary Diagnostic Lab for CWD testing by immunohistochemistry (IHC) (Miller and Williams 2002) or plate ELISA (IDEXX Laboratories Inc, Westbrook, Me.; D. Keane, Wisconsin Veterinary Diagnostic Laboratory, personal communication). Fixed RPLN tissues for all deer from the 2002 harvest were tested with the use of IHC. If the RPLN tested positive, the fixed obex tissue was also tested with the use of IHC. Frozen RPLN tissues from a majority of deer harvested during 2003 were screened with the IDEXX test, and suspect positives were confirmed with the use of IHC by testing RPLN and obex. A small number of deer harvested in 2003 had only RPLN and obex tissue tested by IHC (D. Keane, Wisconsin Veterinary Diagnostic Laboratory, personal communication). For disease reporting and demographic analysis, tests showing positive IHC reactions in the RPLN or the obex were classified as positive for CWD.

### Statistical Analysis

We assessed harvest vulnerability of CWD infected deer by dividing the year into 5 periods that roughly corresponded to different harvest methods. Period 1 (1 Apr–15 May) corresponded to the initial surveillance, Period 2 (16 May–23 Oct) corresponded to summer culls targeted at high-prevalence areas and early archery season, Period 3 (24 Oct–15 Nov) corresponded to early-season gun harvest, Period 4 (16–30 Nov) corresponded to the traditional gun harvest, and Period 5 (1 Dec–31 Mar) corresponded to extended gun harvest and sharpshooter culls. There was no spring surveillance in 2003. We used  $\chi^2$  analysis (function `chisq`, R-project 2004) to test for homogeneity in prevalence between periods within the harvest season, and we used a Mantel–Haenszel test for trends in prevalence during the harvest season (Schlessman 1982; Freeman 1987). We performed separate analyses for all deer, as well as on bucks and does. Conner et al. (2000) hypothesized that behavioral change due to CWD infection may affect vulnerability to harvest. Therefore, for the harvest-vulnerability analysis, we considered individuals to be positive only if the obex was infected because behavioral changes have not been observed prior to this stage of disease. However, for

analysis of disease-prevalence patterns based on age and sex, we considered a deer positive if either the lymph node or obex was infected.

We used a Cochran–Mantel–Haenszel  $\chi^2$  test to evaluate year-to-year change in prevalence stratified by age class (function `mantelhaen.test`, R-project 2004) and found no difference in prevalence between harvest years. As a result, we combined prevalence data across years for the remainder of the analyses. We examined sex, age, and year as possible factors that affected CWD prevalence with the use of logistic regression analysis (function `glm`, R-project 2004). The logistic regression model for predicting prevalence is

$$y = \exp(\mu) / (1 + \exp(\mu))$$

where  $y$  is the prevalence and

$$\mu = b_0 + b_1x_1 + b_2x_2 + \dots + b_kx_k$$

is the usual linear regression that includes the factors that affect prevalence. A preliminary analysis indicated an interaction between the effect of sex and age on prevalence, so we conducted separate analyses for each sex. For each sex, we used age and  $\ln(\text{age})$  to evaluate potential linear and nonlinear trends in prevalence with age. We used a Hosmer and Lemeshow goodness-of-fit test (Cox and Snell 1989) to assess whether our models were a good fit to the data and compared alternative logistic regression models with the use of Akaike's Information Criteria (AIC; Burnham and Anderson 1998). To attempt clarification of the nonlinear patterns with age, we also tested for a decline in prevalence in older age classes by using a  $\chi^2$  test that compared the prevalence in peak age classes to all older deer. To compare differences in prevalence between years, ages, and sexes we calculated the odds ratio (OR) and 95% confidence interval (Selvin 1991) of a deer testing positive for CWD.

## Results

### Harvest Summary

Between April 2002 and January 2004, 21,285 deer were sampled from the disease-eradication zone and 316 (1.5%) tested positive. In our core study area, 4,510 deer were sampled: 2,967 adults, 1,346 fawns, and 197 deer of unknown age or sex. In 2002, 3,171 were sampled from the core study area consisting of 1,978 adults, 1,021 fawns, and 172 deer of unknown age or sex. In 2003, 1,339 deer were sampled, including 989 adults, 325 fawns, and 25 deer of unknown age or sex. Estimated prevalence was 6.3% (95% CI: 5.5–7.2%) for adults and 0.5% (95% CI: 0.1–0.9%) for fawns. Estimated adult prevalence was 6.7% in 2002 and 5.3% in 2003. Testing results were also categorized by RPLN only or obex and RPLN positive for each individual. Harvest-vulnerability analysis was performed with the same data set as the analysis of demographic patterns, but this analysis considered only individuals with an obex positive test as infected. In 2002, 18 of 139 positive tests were RPLN positive only, including 15 of 134 positive adults and 3 of 5 positive fawns testing RPLN only positive. In 2003, 14 of 53 positive tests were RPLN only positive.

### Harvest Vulnerability

Sixty-three percent of deer were harvested during the early and traditional hunting seasons in October and November. A small

**Table 1.** Number of deer harvested and prevalence of obex-positive individuals by sex in 5 periods during 2002 and 2003 from the chronic wasting disease (CWD) high-prevalence area in southern Wisconsin, USA. Initial CWD surveillance was conducted in spring 2002 but was not repeated in spring 2003.

Period	2002		Males		Females		2003		Males		Females	
	n	Prevalence	n	Prevalence	n	Prevalence	n	Prevalence	n	Prevalence	n	Prevalence
Spring (1 Mar–15 May)	193	0.052	39	0.051	154	0.052	0	0	0	0	0	0
Summer (1 Jun–23 Oct)	388	0.069	124	0.081	264	0.064	59	0.068	23	0.043	36	0.083
Early fall (24 Oct–15 Nov)	679	0.059	385	0.068	294	0.048	563	0.036	353	0.045	210	0.019
Late fall (15 Nov–30 Nov)	395	0.035	166	0.042	229	0.031	228	0.044	101	0.050	127	0.040
Winter (1 Dec–28 Feb)	323	0.087	114	0.105	209	0.077	139	0.036	55	0.055	84	0.024
Total	1978	0.060	828	0.069	1150	0.054	989	0.039	532	0.047	457	0.031

fraction of the total harvest was taken during spring surveillance in 2002, about 15% of the harvest was taken during summer, and 15% during the late winter periods (Table 1). For harvest vulnerability, we only considered animals with positive CWD test in their obex to be CWD positive; thus, prevalence shown in our analysis (Table 1) is slightly lower than prevalence based on lymph-node or brain infection. We found no evidence that CWD-positive deer were harvested differentially than CWD-negative deer. Homogeneity tests indicated that adult prevalence did not vary among harvest periods during 2002 ( $\chi^2 = 8.40$ ,  $df = 4$ ,  $P = 0.16$ ) and 2003 ( $\chi^2 = 1.58$ ,  $df = 3$ ,  $P = 0.67$ ), for adult males during 2002 ( $\chi^2 = 4.35$ ,  $df = 4$ ,  $P = 0.72$ ) and 2003 ( $\chi^2 = 0.11$ ,  $df = 3$ ,  $P = 0.99$ ), or for adult females during 2002 ( $\chi^2 = 4.63$ ,  $df = 4$ ,  $P = 0.40$ ) and 2003 ( $\chi^2 = 5.21$ ,  $df = 3$ ,  $P = 0.53$ ). We found no significant difference between the odds of infection during the early gun season (24 Oct–15 Nov) and traditional gun season (16 Nov–30 Nov) in either year (2002: OR = 1.616, 95% CI = 0.70–2.18,  $\chi^2 = 2.60$ , 2-sided  $P = 0.21$   $df = 1$ ; 2003: OR = 0.91, 95% CI = 0.48–1.93,  $\chi^2 = 0.72$ , 2-sided  $P = 0.42$   $df = 1$ ). We also tested for a linear trend in prevalence through the harvest periods using a Mantel–Haenszel test but found no apparent trends in prevalence for adults during 2002 ( $\chi^2 = 0.41$ ,  $df = 1$ ,  $P = 0.52$ ) and 2003 ( $\chi^2 = 0.11$ ,  $df = 1$ ,  $P = 0.74$ ), for adult males during 2002 ( $\chi^2 = 0.26$ ,  $df = 1$ ,  $P = 0.61$ ) and 2003 ( $\chi^2 = 0.11$ ,  $df = 1$ ,  $P = 0.74$ ), or for adult females during 2002 ( $\chi^2 = 0.09$ ,  $df = 1$ ,  $P = 0.76$ ) and 2003 ( $\chi^2 = 0.36$ ,  $df = 1$ ,  $P = 0.55$ ).

### Demographic Patterns

Five of 1,021 (0.5%) fawns tested positive in 2002 and zero of 325 tested positive in 2003 in the core study area (1 additional fawn in the surrounding lower prevalence area also tested positive). Three of these fawns, approximately 5 months old (2 animals) and 9 months old, tested positive in RPLN only. The remaining 2 fawns, approximately 9 and 10 months old, tested positive in RPLN and obex. For all the following prevalence data and analyses, we defined positive cases as having CWD infection in the RPLN or obex. Adult prevalence in 2002 (6.8%) was similar to 2003 (5.4%; OR = 1.26, 95% CI = 0.91–1.75) and prevalence in fawns was lower than in adults (OR = 0.0523, 95% CI = 0.022–0.127). We excluded fawns from further demographic analysis because their prevalence was so much lower than adult deer. Adult males had a higher overall prevalence (7.4%) than

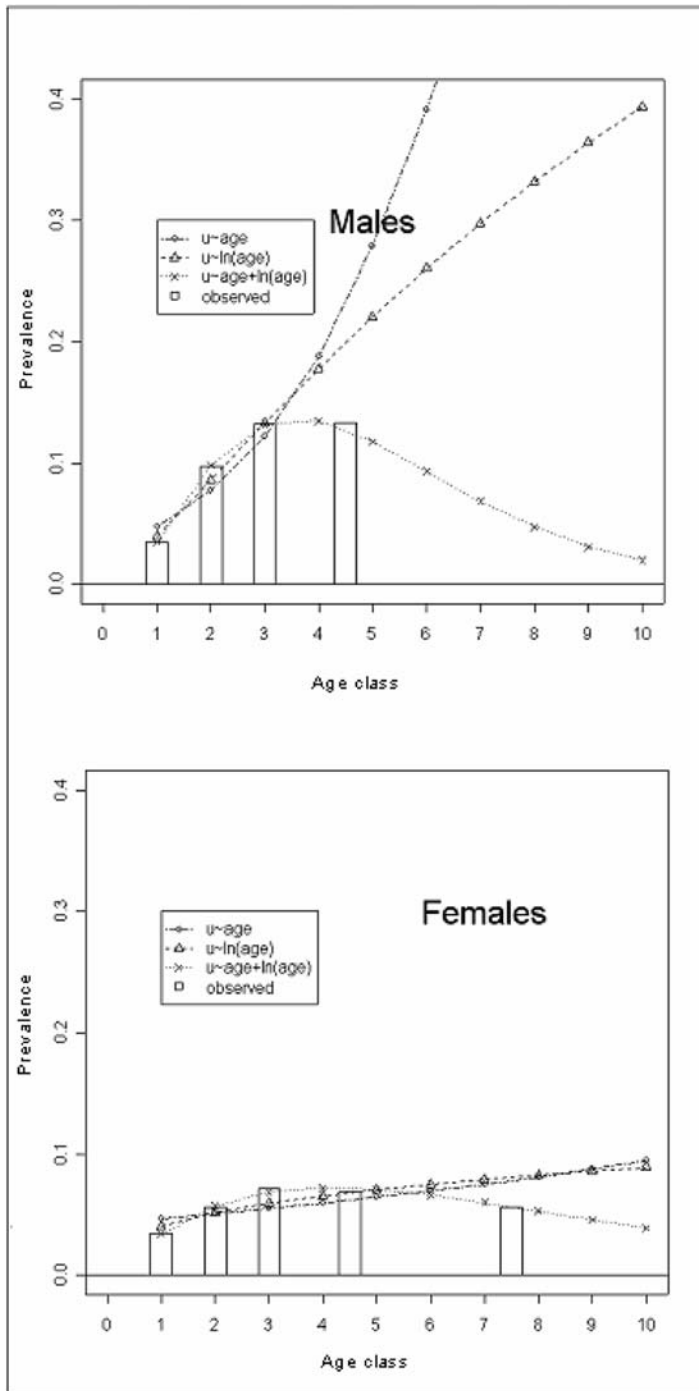
females (5.4%; OR = 1.43, 95% CI = 1.07–1.91; Table 1). Adult male prevalence in 2002 (8.1%) was similar to 2003 (6.4%) (OR = 1.29, 95% CI = 0.84–1.97). Adult female prevalence was also similar between 2002 (5.8%) and 2003 (4.2%; OR = 1.09, 95% CI = 0.65–1.82). Prevalence between years did not differ when stratified by age in males (Cochran–Mantel–Haenszel  $\chi^2 = 0.734$ ,  $df = 1$ ,  $P = 0.39$ ) or females (Cochran–Mantel–Haenszel  $\chi^2 = 1.10$ ,  $df = 1$ ,  $P = 0.29$ ).

Sex-specific logistic regression models of prevalence show that age has a nonlinear relationship with prevalence. Our regression models with asymptotic or declining trend in prevalence at older ages fit better than regression models with a linear trend in prevalence with age (Fig. 2). However, we found little support ( $\Delta AIC < 2.0$ ) for distinguishing between an asymptotic and declining relationship between prevalence and older age classes for either males (Table 2) or females (Table 3). In addition, there was no evidence that peak prevalence in the 3-year-old age class was different from prevalence in older age classes for males ( $\chi^2 = 0.003$ ,  $df = 1$ ,  $P = 0.95$ ) or females ( $\chi^2 = 0.144$ ,  $df = 1$ ,  $P = 0.70$ ).

## Discussion

### Demographic Patterns

Our results showed that the risk of CWD infection does not follow a random transmission process, which predicts homogeneous rates of infection among age and sex classes. We found a significant increase in prevalence with age for both male and female white-tailed deer. This pattern is characteristic of a chronic disease, like CWD, where the cumulative risk of infection increases with length of potential exposure (age). We found that CWD prevalence was 3–4% for yearling males and females, but increased to peak prevalence in 3-year-olds of both genders. However, peak prevalence in 3-year-old males (13%) was nearly twice that for females (7%), illustrating the dramatic increase in risk of infection for males after the yearling class. We believe these infection patterns reflect heterogeneous rates and/or pathways of disease transmission in Wisconsin based on the social behavior of white-tailed deer. Miller and Conner (2005) observed similar age and sex patterns in a separate CWD epidemic in Colorado mule deer, and O'Brien et al. (2002) observed similar epidemiology in Michigan in white-tailed deer infected with bovine tuberculosis (TB; a chronic bacterial infection). Both studies hypothesized that social behavior is a strong explanation for these infection patterns.



**Figure 2.** Observed chronic wasting disease (CWD) prevalence and estimated prevalence from alternative logistic regression models based on age in male and female adult white-tailed deer from southern Wisconsin, USA, Apr 2002–Feb 2004.

We believe that different social structure and behavior of bucks and does may be important factors causing differential CWD infection. Females form matrilineal social units comprised of an older female, her daughters, and up to 4 generations of closely related females (Hawkins and Klimstra 1970). These groups are highly philopatric to summer and winter ranges and to related members of the group (Mathews and Porter 1993, Aycrigg and Porter 1997, Nelson and Mech 1999). In southern Wisconsin, females use relatively small home ranges (1.5–2.5 km<sup>2</sup>) and move

**Table 2.** Alternative logistic regression models of chronic wasting disease (CWD) prevalence in adult male white-tailed deer ( $n = 1360$ ) from southern Wisconsin, USA, Mar 2002–Jan 2004.

Model	df	$\chi^2$ <sup>a</sup>	$p$ <sup>b</sup>	$\Delta$ AIC	$\omega_i$ <sup>c</sup>
Age + ln(age)	2	0.068	0.99	0	0.58
ln(age)	3	1.417	0.23	0.74	0.4
Age	3	5.334	0.15	6.95	0.03

<sup>a</sup>  $\chi^2$  is the Hosmer and Lemeshow ratio goodness-of-fit test statistic.

<sup>b</sup>  $p$  is the significance of the goodness-of-fit test.

<sup>c</sup>  $\omega_i$  refers to the relative probability that the model is the best model given the data.

little throughout the year (Larson et al. 1978, Ishmael 1984). In contrast to does, bucks have larger home ranges (2–4 km<sup>2</sup>), form smaller male social units that are seasonally dynamic, seldom philopatric, and have little contact with females for most of the year (Hirth 1976, Wozencraft 1978, Nixon et al. 1991). The composition of buck groups varies from larger groups in late winter and early spring to individual males with increased movement and contact with competing bucks and females during the breeding season (Hirth 1976, Nixon 1991).

Based on differences in male social behavior and movement, we suggest several hypotheses to explain the increased risk of CWD infection in males compared to females. First, direct transmission may occur among males in buck groups from late winter through summer. Second, transmission may occur during the breeding season when susceptible bucks contact many infected females or when bucks visit scent stations (rubs and scrapes) used by infected bucks. Third, bucks have a greater chance to contact CWD in the environment than susceptible females due to their larger home range size and breeding season movements. Fourth, females may be more susceptible to disease mortality and/or males may have a longer preclinical period than females. Behavioral evidence supports the rationale for the first 3 hypotheses (Hirth 1976, Nixon 1991), whereas there is no evidence to suggest that males or females have different susceptibility to CWD.

Prevalence of CWD in adult white-tailed deer appears to approach an asymptote or potentially decline in older age classes (Fig. 2), but we were unable to distinguish between these alternative patterns. We believe the trends in prevalence for older deer provide important epidemiological information about the disease progression and the potential effects of CWD on cervid populations. For chronic diseases, age-specific prevalence will generally be determined by the infection rate and the disease mortality rate. Increasing prevalence typically occurs with age because infection rate exceeds disease mortality rate. But for older individuals, the number dying from the disease can reach equilibrium with the number of new infections, resulting in a constant prevalence in the older age classes. If mortality rates exceed infection rates, the result would be decreasing prevalence in older age classes. Declining prevalence in older age classes may indicate that infection rates are decreasing or disease mortality rates are increasing.

Studies on prion diseases in sheep (Redman et al. 2002), humans (Bacchetti 2003), and mule deer (Miller et al. 2000, Miller and

**Table 3.** Alternative logistic regression models of chronic wasting disease (CWD) prevalence in adult female white-tailed deer ( $n = 1607$ ) from southern Wisconsin, USA, Mar 2002–Jan 2004.

Model	df	$\chi^2$ <sup>a</sup>	$p$ <sup>b</sup>	$\Delta$ AIC	$\omega_i$ <sup>c</sup>
Age + ln(age)	2	0.072	0.99	0	0.51
ln(age)	3	2.621	0.45	0.63	0.37
Age	3	4.861	0.18	2.9	0.12

<sup>a</sup>  $\chi^2$  is the Hosmer and Lemeshow goodness-of-fit test statistic.

<sup>b</sup>  $p$  is the significance of the goodness-of-fit test.

<sup>c</sup>  $\omega_i$  refers to the relative probability that the model is the best model given the data.

Conner 2005) have shown that prevalence peaks and then declines with age. Heisey and Joly (2004) proposed that one explanation for this pattern for prion diseases could be decreased immune function in older individuals. They postulated that healthy immune function may facilitate the progression of infectious prions through lymphatic tissues, whereas immune system senescence may provide resistance. This hypothesis predicts that decreased infection rates in older individuals would produce lower observed prevalence. Alternatively, if disease mortality rates increased in older age classes, prevalence would also decline. Although this is a typical pattern for a conventional infectious disease due to reduced immunity in older individuals, CWD does not initiate an immune response like a typical infectious agent (Williams et al. 2002).

We suggest that spatial heterogeneity of CWD infection (or temporal heterogeneity of sample collection) also could produce declining prevalence patterns in older animals because disease mortality in infected landscape patches may result in a declining age structure, whereas an older age structure could persist in uninfected patches. Because the white-tailed deer population in southern Wisconsin has a relatively young age structure, it is difficult for us to determine exactly what pattern may be occurring in older age classes. More research is necessary to determine whether heterogeneity, infection, or mortality rates are involved in these patterns.

### Harvest Vulnerability

Conner et al. (2000) reported that CWD prevalence in hunter-harvested mule deer in Colorado increased during the hunting season. They considered seasonal movement of deer from areas with less hunter harvest to areas with more harvest as a likely cause for this bias. They also concluded that differential harvest vulnerability of infected animals due to behavioral changes caused by disease was a less likely cause for the bias. In contrast, we detected no seasonal trends in our analyses of harvested Wisconsin white-tailed deer. Because the deer herd in southern Wisconsin showed little or no seasonal movement, our results were not confounded by seasonal migration patterns like those found in western mule deer. In addition, Spraker et al. (1997) reported there was little evidence that disease progression or behavioral changes due to CWD infection were different for mule deer than white-tailed deer. Thus, it seems unlikely that CWD infection causes substantial differential susceptibility of white-tailed or mule deer to hunter harvest. These results indicate that harvest can be

used as effective tool for collecting cervids for estimating CWD prevalence rates, transmission rates, and other epidemiological parameters.

### Fawns and Yearlings

Infection in Wisconsin white-tailed deer fawns between 5 and 10 months of age represented the youngest free-ranging cervids to test positive for CWD. In disease-progression studies CWD can be detected in RPLN tissue of captive mule deer fawns by 2 months postinoculation (Sigurdson et al. 1999). These results suggest that the 5-month-old deer were likely infected prior to weaning. This could indicate transmission in utero or transmission within several months of birth. However, pen studies on CWD indicate that transmission in utero is not a likely route of infection (Williams and Miller 2003). White-tailed deer fawns use very small ranges and engage in intense grooming and nursing exclusively with their mother for the first 6 weeks postparturition (Schwede et al. 1993). Therefore, it is likely that transmission within 2–3 months following birth is from contact with the mother or from contact with CWD-contaminated surroundings in the mother's home range.

Because CWD prevalence in fawns (0.5%) was low compared to the prevalence in adult does (5.4%), our data indicated a low probability of CWD being transmitted from infected does to their fawns early in life. If mother-to-offspring transmission was common, especially prior to weaning, we would expect higher prevalence in fawns. Alternatively, if we failed to detect early stages of infection in some fawns, we would expect increased infection in yearlings following an additional year of disease progression and exposure. However, yearling prevalence was also much lower than adult female prevalence. Our results for free-ranging white-tailed deer support research by Miller and Williams (2003) in captive mule deer that maternal (dam to young) transmission is not an important route for CWD infection. Based on their low prevalence rates, fawns are unlikely to play an important role in maintaining and spreading CWD.

Difference in movement and dispersal between white-tailed bucks and does may also be a significant component of CWD distribution across the landscape, especially in areas where animals do not show seasonal migration. Yearling male dispersal rates are 50% to >80% with dispersal distances between 10 and 30 km, compared with female dispersal rates of <20% (Hawkins and Klimstra 1970, Nixon et al. 1991, Nelson 1993, Rosenberry et al. 1999). Infected yearling males have the potential to spread the disease over a large geographic area. Fortunately, prevalence in yearling males and females is similar, 3.4% and 3.3%, respectively, and considerably lower than adult males.

### Management Implications

An understanding of processes that drive transmission of CWD among free-ranging deer and cause the geographic spread of disease will aid in developing effective strategies for CWD management in white-tailed deer and other cervid populations. Our results provide biologically based hypotheses about the mechanisms of CWD transmission, but do not provide sufficient information to distinguish the relative importance of direct CWD transmission by animal-to-animal contact and indirect (environmental) routes of transmission. We recommend further research

regarding how contact among animals or accumulation of environmental sources of infectious prions influence transmission. In addition, we note that most challenge studies in cervids have been conducted with young animals, and we suggest that similar studies using older animals would provide a useful comparison given the apparent higher risk of infection in older deer in the wild.

Given the low observed prevalence in fawns, we recommend that surveillance programs with the goal of detecting disease where it has not been previously found should focus testing on animals >12–18 months of age. Surveillance, with the goal of detecting geographic spread of CWD from an infected area, should focus on yearling and adult bucks, as these animals are the most likely to disperse the disease by natural means. Finally, we recommend that in areas where disease is present and the goal is to estimate prevalence, testing should focus on adult deer of both sexes.

We suggest a strategy that focuses on removing CWD-positive animals, along with density reduction, in situations where controlling CWD is the goal. Adult bucks with larger home ranges are much more likely to be infected than either young dispersing bucks or adult does, and thus create the greatest potential for local disease spread as well as the highest probability for removal of infected animals. Although does have a lower disease prevalence, they are likely to be more abundant than adult bucks, due to higher hunting pressure on large bucks, hunting

traditions, and regulations that tend to protect does. As a result of these competing implications and in the absence of clear information about the routes of CWD transmission, management strategies need to strike a balance among efforts to reduce deer population density by increasing antlerless harvests, reducing prevalence and density of infected animals in highly affected areas by removing older females and males, and eliminating the spread of disease to new areas by removing males of all ages. In the long term, further research, preferably integrated with management actions, will be needed to develop a better knowledge of the factors affecting the transmission of CWD in free-ranging cervids and to develop appropriate management strategies.

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## Literature Cited

- Aycrigg, J. L., and W. F. Porter. 1997. Sociospatial dynamics of white-tailed deer in the central Adirondack Mountains, New York. *Journal of Mammalogy* 78:468–482.
- Bacchetti, P. 2003. Age and variant Creutzfeldt–Jakob disease. *Emerging Infectious Diseases* 9:1611–1612.
- Bartelt, G., J. Pardee, and K. Thiede. 2003. Environmental impact statement on rules to eradicate chronic wasting disease in Wisconsin's free-ranging white-tailed deer herd. Wisconsin Department of Natural Resources, Madison, USA.
- Burnham, K. P., and D. R. Anderson. 1998. *Model selection and inference: a practical information-theoretic approach*. Springer-Verlag, New York, New York, USA.
- Conner, M. M., C. W. McCarty, and M. W. Miller. 2000. Detection of bias in harvest-based estimates of chronic wasting disease prevalence in mule deer. *Journal of Wildlife Diseases* 36:691–699.
- Cox, D. R., and E. J. Snell. 1989. *Analysis of binary data*. Second edition. Chapman and Hall, New York, New York, USA.
- Freeman, D. H. 1987. *Applied categorical data analysis*. Marcel Dekker, New York, New York, USA.
- Gross, J. E., and M. W. Miller. 2001. Chronic wasting disease in mule deer: disease dynamics and control. *Journal of Wildlife Management* 65:205–215.
- Hawkins, R. E., and W. D. Klimstra. 1970. A preliminary study of the social organization of white-tailed deer. *Journal of Wildlife Management* 34:407–419.
- Heisey, D. M., and D. O. Joly. 2004. Age and transmissible spongiform encephalopathies. *Emerging Infectious Diseases* 10:1164–1165.
- Hirth, D.H. 1976. Social behavior of white-tailed deer in relation to habitat. *Wildlife Monographs* 53.
- Ishmael, W. E. 1984. *White-tailed deer ecology and management in Southern Wisconsin*. Thesis, University of Wisconsin, Madison, USA.
- Johnson, C., J. Johnson, M. Clayton, D. McKenzie, and J. Aiken. 2003. Prion protein gene heterogeneity in free-ranging white-tailed deer within the chronic wasting disease affected region of Wisconsin. *Journal of Wildlife Diseases* 39:576–581.
- Joly, D. O., C. A. Ribic, J. A. Langenberg, K. Beheler, C. A. Batha, B. J. Dhuey, R. E. Rolley, G. Bartelt, T. R. Van Deelen, and M. D. Samuel. 2003. Chronic wasting disease in free-ranging Wisconsin white-tailed deer. *Emerging Infectious Diseases* 9:599–601.
- Larson, T. J., O. J. Rongstad, and F. W. Tebelcox. 1978. Movement and habitat use of white-tailed deer in south central Wisconsin. *Journal of Wildlife Management* 42:113–117.
- Mathews, N. E., and W. F. Porter. 1993. Effect of social structure on genetic structure of free-ranging white-tailed deer in the Adirondack Mountains. *Journal of Mammalogy* 74:33–43.
- Miller, M. W., M. A. Wild, and E. S. Williams. 1998. Epidemiology of chronic wasting disease in Rocky Mountain elk. *Journal of Wildlife Diseases* 34:532–538.
- Miller, M. W., E. S. Williams, C. W. McCarty, T. R. Spraker, T. J. Kreeger, C. T. Larsen, and E. T. Thorne. 2000. Epizootiology of chronic wasting disease in free-ranging cervids in Colorado and Wyoming. *Journal of Wildlife Diseases* 36:676–690.
- Miller, M. W., and E. S. Williams. 2002. Detection of PrP<sup>CWD</sup> in mule deer by immunohistochemistry of lymphoid tissues. *Veterinary Record*: 610–612.
- Miller, M. W., and E. S. Williams. 2003. Horizontal prion transfer in mule deer. *Nature* 425:35–36.
- Miller, M. W., E. S. Williams, N. T. Hobbs, and L. L. Wolfe. 2004. Environmental sources of prion transmission in mule deer. *Emerging Infectious Diseases* 10:1003–1006.
- Miller, M. W., and M. M. Conner. 2005. Epidemiology of chronic wasting disease in free-ranging mule deer: spatial, temporal, and demographic influences on observed prevalence. *Journal of Wildlife Diseases* 41:275–290.
- Nebraska Game and Parks Commission. 2002. CWD test results, northern Sioux County, NE. Sampling periods: November 2001 and January/February 2002. <http://www.ngpc.state.ne.us/wildlife/cwd/cwdFAQ.html>. Accessed 2002 Nov 12.
- Nelson, M. E. 1993. Natal dispersal and gene flow in white-tailed deer in northeastern Minnesota. *Journal of Mammalogy* 74:316–322.
- Nelson, M. E., and L. D. Mech. 1999. Twenty-year home range dynamics of a white-tailed deer matriline. *Canadian Journal of Zoology* 77:1128–1135.
- Nixon, C. M., L. P. Hansen, P. A. Brewer, and J. E. Chelvig. 1991. Ecology of white-tailed deer in an intensively farmed region of Illinois. *Wildlife Monographs* No. 118.
- O'Brien, D. J., S. M. Schmitt, J. S. Fierke, S. A. Hogle, S. R. Winterstein, T. M. Cooley, W. E. Moritz, K. L. Diegel, S. D. Fitzgerald, D. E. Berry, and J. B. Kaneene. 2002. Epidemiology of *Mycobacterium bovis* in free ranging white-

- tailed deer, Michigan, USA, 1995–2000. *Preventive Veterinary Medicine* 54: 47–63.
- Petchenik, J. 2003. Chronic wasting disease in Wisconsin and the 2002 hunting season: gun deer hunters' first response. Wisconsin Department of Natural Resources: Bureau of Integrated Science Services. Miscellaneous publication PUB-SS-982 2003. Madison, Wisconsin, USA.
- Peterson, M. J., M. D. Samuel, V. F. Nettles, Jr., G. Wobeser, and W. D. Hueston. 2002. Review of chronic wasting disease management policies and programs in Colorado. Colorado Wildlife Commission, Denver, USA.
- Prusiner, S. B. 1991. Molecular biology of prion diseases. *Science* 252:1515–1522.
- Redman, C. A., P. G. Coen, L. Matthews, R. M. Lewis, W. S. Dingwall, J. D. Foster, M. E. Chase-Topping, N. Hunter, and M. E. J. Woolhouse. 2002. Comparative epidemiology of scrapie outbreaks in individual sheep flocks. *Epidemiology and Infection* 128:513–521.
- Rolley, R. 2002. White-tailed deer population status 2001. In: Wisconsin Wildlife Surveys. Compiled by B. Dhuey and H. Arrowood. Wisconsin Department of Natural Resources. Bureau of Integrated Science Services. Miscellaneous Publication PUB-SS-970 04/2002. Madison, Wisconsin, USA.
- Rosenberry, C. S., R. A. Lancia, and M. C. Conner. 1999. Population effects of white-tailed deer dispersal. *Wildlife Society Bulletin* 27:858–864.
- [R-project] The R project for statistical computing. 2004 Nov 28. R-project home page: <<http://www.r-project.org>>. Accessed 2004 Nov 28.
- Samuel, M. D., D. O. Joly, M. A. Wild, S. D. Wright, D. L. Otis, R. W. Werge, and M. W. Miller. 2003. Surveillance strategies for detecting chronic wasting disease in free-ranging deer and elk. USGS–National Wildlife Health Center, Madison, Wisconsin.
- Schauber, E. M., and A. Woolf. 2003. Chronic wasting disease in deer and elk: A critique of current models and their application. *Wildlife Society Bulletin* 31: 610–616.
- Schlessman, J. J. 1982. *Case-control studies*. Oxford University Press, New York, USA.
- Schwede, G., H. Hendrichs, and W. McShea. 1993. Social and spatial organization of female white-tailed deer, *Odocoileus virginianus*, during the fawning season. *Animal Behaviour* 45:1007–1017.
- Selvin, S. 1991. *Statistical analysis of epidemiological data*. Oxford University Press, New York, USA.
- Severinghaus, C. W. 1949. Tooth development and wear as criteria of age in white-tailed deer. *Journal of Wildlife Management* 13:195–216.
- Sigurdson, C. J., E. S. Williams, M. W. Miller, T. I. Spraker, K. L. O'Rourke, and E. A. Hoover. 1999. Oral transmission and early lymphoid tropism of chronic wasting disease PrP<sup>Sc</sup> in mule deer fawns (*Odocoileus hemionus*). *Journal of General Virology* 80:2757–2764.
- Spraker, T. R., M. W. Miller, E. S. Williams, D. M. Getzy, W. J. Adrian, G. G. Schoonveld, R. A. Spowart, K. I. O'Rourke, J. M. Miller, and P. A. Merz. 1997. Spongiform encephalopathy in free-ranging mule deer (*Odocoileus hemionus*), white-tailed deer (*Odocoileus virginianus*) and Rocky Mountain elk (*Cervus elaphus nelsoni*) in Northcentral Colorado. *Journal of Wildlife Diseases* 33:1–6.
- Williams, E. S., and S. Young. 1980. Chronic wasting disease of captive mule deer: a spongiform encephalopathy. *Journal of Wildlife Diseases* 16:89–98.
- Williams, E. S., and S. Young. 1992. Spongiform encephalopathies of Cervidae. *Revue Scientifique et Technique* 11:551–567.
- Williams, E. S., M. W. Miller, T. J. Kreeger, K. R. H. Kahn, and E. T. Thorne. 2002. Chronic wasting disease of deer and elk: a review with recommendations for management. *Journal of Wildlife Management* 66:551–563.
- Williams, E. S., and M. W. Miller. 2003. Transmissible spongiform encephalopathies in non-domestic animals: origin, transmission and risk factors. Vol. 22, pp. 145–156 in Bengis, R. G., editor. *Risk analysis of prion diseases in animals*. *Revue scientifique et technique*. International Office of Epizootics, Paris, France.
- Wozencraft, W. C. 1978. Investigations concerning a high-density white-tailed deer population in south central Wisconsin. Thesis, University of Wisconsin, Madison, USA.

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