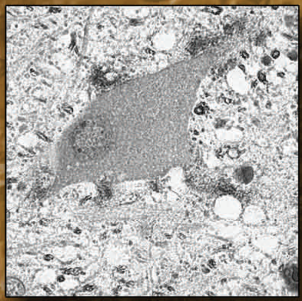
Scale-dependent approaches to modeling spatial epidemiology of chronic wasting disease



$$P_i(x_i, t_0 + s_i) = \int_{-\infty}^{+\infty} G_i(x_i - x_0, s_i) P(x_0, t_0)\, dx_0$$

$$= \int_{-\infty}^{+\infty} \frac{\exp\left[\frac{-(x_i - x_0 - \beta_i s_i)^2}{4D_i s_i}\right]}{\sqrt{4\pi D_i s_i}} P(x_0, t_0)\, dx_0$$

Special Report 2007

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- Utah Division of Wildlife Resources
- United States Geological Survey
- Association of Fish & Wildlife Agencies

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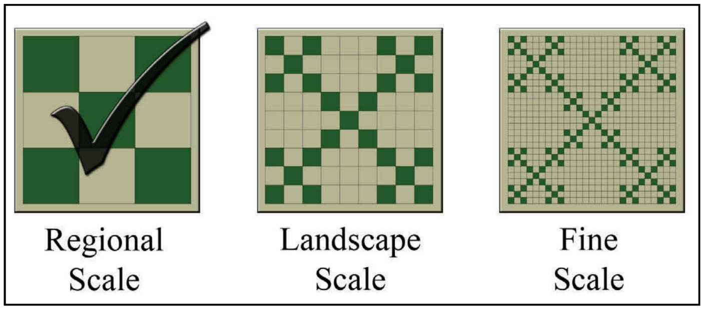
Executive Summary

This e-book is the product of a second workshop that was funded and promoted by the United States Geological Survey to enhance cooperation between states for the management of chronic wasting disease (CWD). The first workshop addressed issues surrounding the statistical design and collection of surveillance data for CWD. The second workshop, from which this document arose, followed logically from the first workshop and focused on appropriate methods for analysis, interpretation, and use of CWD surveillance and related epidemiology data. Consequently, the emphasis of this e-book is on modeling approaches to describe and gain insight of the spatial epidemiology of CWD.

We designed this e-book for wildlife managers and biologists who are responsible for the surveillance of CWD in their state or agency. We chose spatial methods that are popular or common in the spatial epidemiology literature and evaluated them for their relevance to modeling CWD. Our opinion of the usefulness and relevance of each method was based on the type of field data commonly collected as part of CWD surveillance programs and what we know about CWD biology, ecology, and epidemiology. Specifically, we expected the field data to consist primarily of the infection status of a harvested or culled sample along with its date of collection (not date of infection), location, and demographic status. We evaluated methods in light of the fact that CWD does not appear to spread rapidly through wild populations, relative to more highly contagious viruses, and can be spread directly from animal to animal or indirectly through environmental contamination. We discovered that many of the well-published methods were developed for fast-spreading human diseases, such as influenza and measles. While these methods are applicable to fast spreading wildlife diseases, such as foot-and-mouth disease or West Nile virus, many are not likely to work well for CWD. Only limited data exist to evaluate geographic and spatial spread because many locations where we find CWD tend to be locations where samples have just been taken or sample sizes have just become large enough to have a high probability of detecting a low prevalence. Consequently, methods that work well to describe or predict the spread of foot-and-mouth disease throughout England, which occurred within a year, do not work well for describing or predicting CWD spread. We did not exclude methods that we regarded as inappropriate; rather, we included methods that are commonly used for disease epidemiology and then discussed their applicability for modeling the spatial epidemiology of CWD. We hope including inappropriate methods with an explanation of why they are ill-suited for CWD will make it easier to drop them from consideration and explain to others why they were not recommended for spatial modeling of CWD.

We organized the three chapters by scale and extent for which each method was developed or best suited. The first chapter covers methods appropriate to multi-jurisdictional or multi-state modeling, which we call "regional" scale. The second chapter covers methods appropriate for within state areas such as wildlife management units or metapopulations, which we call "landscape" scale. The third chapter covers methods appropriate for population or individual-based modeling, which we call "fine" scale. We know this rubric is somewhat artificial because many methods work at multiple scales. We hope, however, that this structure addresses some of the challenges faced by managers that work at local, regional, state, and national scales. Further, the resolution of empirical data often changes with spatial scale, which affects the utility of different modeling approaches. For example, individual-based models work best at modeling spread within populations, while risk analysis is most useful for summarizing data over larger scales such as a region. Because some methods are applicable at several scales, however, we included a graphic at the beginning of each method that indicates the range of scales for which it applies. For example, the graphic to the right indicates that the method is most applicable for regional-scale modeling.



An example of the scale graphic which is found at the beginning of each method in the text. The most applicable scales are indicated by the presence of a check mark, which is the regional scale in this example.

There is also a question of resolution as well as scale and extent for each method. CWD surveillance data have been collected over large areas, such as a wildlife management unit or state, but the resolution of the data may be fine scale with GPS locations for many samples. For each method, we described the required resolution of the data and describe the type of data required, as well as what questions the method could answer and how useful the method is, given typical CWD data.

For each scale, we presented a focal approach that would be useful for understanding the spatial pattern and epidemiology of CWD, as well as being a useful tool for CWD management. The focal approaches include risk analysis and micromaps for the regional scale, cluster analysis for the landscape scale, and individual based modeling for the fine scale of within population. For each of these methods, we used simulated data and walked through the method step by step to fully illustrate the "how to", with specifics about what is input and output, as well as what questions the method addresses. We also provided a summary table to, at a glance, describe the scale, questions that can be addressed, and general data required for each method described in this e-book. We hope that this review will be helpful to biologists and managers by increasing the utility of their surveillance data, and ultimately be useful for increasing our understanding of CWD and allowing wildlife biologists and managers to move beyond retroactive fire-fighting to proactive preventative action.

Summary Table of Methods

Model	Scale	Usefulness	CWD Usefulness	Data Required	Potential Output
Risk Analysis	Broad Scale (Regional/ Multi-State)	Non-infectious or slow epidemics	CWD Modeling and management	• Spatial coordinates • Sample date • Factor of interest co-variate data	• Estimation of spatial variation of disease prevalence • Statistics for factors affecting disease prevalence • Model statistics and variable weights
Micromaps	Broad Scale (Regional/ Multi-State)	Facilitates data visualization and analysis of discrete regions	Useful for presenting data from multiple regions	• Positive/negative samples by polygon • Polygon identification	• Linked time/space prevalence maps • Linked time/space statistics
Cluster Analysis	Broad Scale (Regional/ Multi-State)	Identification of ”hot spots” with presence/ absence data	Descriptive tool for CWD surveillance	• Positive/negative samples by polygon	• Assignment of positives to clusters
Snapshot Approach	Broad Scale (Regional/ Multi-State) and/or Local/Fine-Scale	Infection spread is independent of temporary barriers	Assumptions about host distribution limits the utility for CWD modeling	• Area disease status • Centroid coordinates of area • Modeling assumptions	• Identify likely site of future infection. • Estimates of rate of spread
Occupancy Analysis	Broad Scale (Regional/ Multi-State)	Monitor disease status over large spatial scales	First cut at multi-state/ regional scales	• Area disease status • 2-years of data for each area	• Probability of disease presence • Evaluation of covariate data importance to presence/detection
Epidemic Trees	Broad Scale to Fine Scale depending on the unit of analysis (individual or management unit)	Highly infectious, rapid spreading diseases	Inability to link positive cases to original source hinders CWD use	• Location of infections • Some case-tracking data • Dates of when infections began and were reported • Rule set tying subsequent cases to origin	• Rate of spread estimates through time/space • Generation time estimates • Reporting time estimates • Rate and routes of spread
Cluster Analysis	Landscape Level (Statewide)	Depict and describe spatial patterns of disease and identify hotspots of prevalence and estimate risk surface	Descriptive tool for CWD surveillance	• Spatial coordinates • Covariates (if necessary)	• Assignments of positives to cluster • Potential spatial covariates tied to disease pattern • Identification of high-risk areas and cluster maps

Summary Table of Methods

Model	Scale	Usefulness	CWD Usefulness	Data Required	Potential Output
Geostatistical Analysis	Landscape Level (Statewide)	Depict and describe purely spatial relationships (autocorrelations) between positive and negative disease samples	Better evaluation of environmental and ecological covariates after accounting for the spatial structure of the data	• Spatial coordinates of samples or centroid of small areas if data are grouped • Covariates (if necessary)	• Autocorrelation of disease related to distance and/or direction • Spatial prevalence estimates • Potential spatial covariates tied to disease pattern after accounting for spatial autocorrelation
Cellular Automata Models	Landscape Level (Statewide)	Understanding how factors affect spatial spread/ distribution of a disease at various scales	General tool useful for various purposes, such as evaluating various locales as CWD origin point. Often assumes homogeneous environment and distribution of hosts.	• Application dependent	• Application dependent
Metapopulation Models	Landscape Level (Statewide)	Evaluation of prediction of management strategies in spatially structured populations	Accounts for the herd structure of deer and elk, but requires one to define the patches or subpopulations	• Dispersal/migration routes and probabilities among patches • Vital rates of population and transmission dynamics	• Spread of disease through a patchy distribution of hosts.
Diffusion Models	Landscape Level (Statewide)	Evaluations in diseases that do not present themselves or slow moving diseases	Hypothesis of CWD spread and potential origin point. Diffusion models often assume a uniform environment (e.g. no habitat heterogeneity).	• Date of first detection for spatial area • Proportion of adjacent spatial areas infected for each time step • Proportion of shared borders • Prevalence at several time steps • Proximity of area to features influencing rate of spread	• Prediction of probability an area will become infected at a given time step • Prevalence prediction in areas through time • Estimates of covariates effects
Trend Surface	Landscape Level (Statewide)	Evaluations in infectious, moderate to rapid spreading diseases presenting themselves	Not useful for CWD because date of detection is unrelated to date of disease initiation	• Infection detection date for spatial area • Centroid coordinates for spatial areas	• Contours of months to first reported case of disease • Rate of disease spread

Summary Table of Methods

Model	Scale	Usefulness	CWD Usefulness	Data Required	Potential Output
Compartment Models	Local or Fine-Scale	Wide utility in the disease ecology field.	Can be elaborated to incorporate a number of relevant CWD characteristics, but these models often do not include an environmental transmission component.	• Dependent on model structure and level of detail • Detailed models may require movement rates, sex and age composition, disease state, social contacts, effects of infection on vital rates, and resistance factors	• Minimal: number of individuals in each disease class of susceptible, infected and recovered or dead at each time step
Individual-Based Models	Local or Fine-Scale	Simulate a wide variety of situations in animal ecology and varies by model structure and level of detail	Useful to incorporate known individual heterogeneity in contact patterns.	• Dependent on model structure and level of detail • Theoretical model: existing observations of population structure and disease prevalence • Detailed models may require population age and sex composition, disease prevalence, animal movement rates, contact rates	• Minimal: population structure and disease state through time in the population by age and sex • Detailed models could produce harvest and treatment variables, location of animals, animal densities across landscape, physiological state, genetic composition, number of offspring, indices of genetic diversity, gene flow rates, etc.
Network Models	Local or Fine-Scale	Flexibility in simulating various spatial/social structures	Additional complexity and data requirements are probably unnecessary to adequately model CWD due to the environmental transmission and chronic nature of CWD	• Estimates of interconnectedness or association of individuals/groups	• Predictions of disease spread across the network. • Comparison of management scenarios that focus on particular individuals or groups.
Spatial Stochastic Models	Local or Fine-Scale	Evaluating population dynamics where spatial heterogeneity is important	Application dependent.	• Limited data often restricts the predictive capacity of these models. Potentially useful for “what-if” scenarios where the range of potential outcomes is important.	• Mean and variation in the potential outcomes for a given epidemic, location, or management strategy.

Acknowledgements

We gratefully acknowledge Rick Kearney for making the second multi-state chronic wasting disease workshop and e-book possible. Rick is the cornerstone of this work; he organized the funding, encouraged the workshop and e-book, and supported the process from its inception. We thank Anita Candelaria, who was responsible for the smooth logistics, great location, and general running of the workshop. We also thank our meeting facilitator, Steve Morey from the USFWS, without whom our discussions would have spiraled out of control into the digressions of the universe. To Dan Foster, a heartfelt thank you for putting together the summary table of the methods found in the Executive Summary - we were all stuck on how to create that sort of summary. Finally, we thank Kurt VerCauteren, Dan Foster, Bruce Morrison, Greg Wilson, and Jim Heffelfinger for their thorough and insightful reviews. The e-book was much improved thanks to their comments.

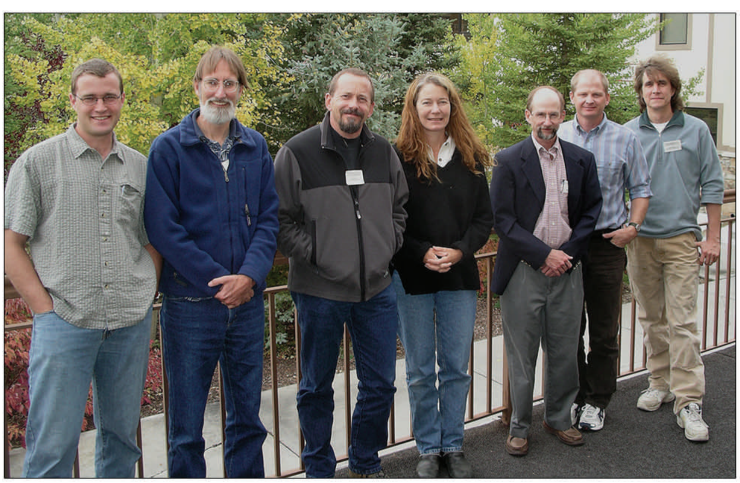
We thank Beth Williams, Mike Miller, Bruce Gill, and Gary White for most of the photographs in the e-book. Beth Williams' illustrative photos include the bottom 2 on the cover, and the top photo in the "Prion Propagation & Chronic Wasting Disease" text box. Mike Miller provided the bottom photo in the "Prion Propagation & Chronic Wasting Disease" text box. Gary White provided the group photos in the "History of CWD Workshops" text box. Finally, we are grateful to Bruce Gill (R. Bruce Gill Wildlife Reflections Nature Photography), who provided us with the mule deer group in the executive summary and the male and female busts used in Figure I.2.

HISTORY OF CWD WORKSHOPS FROM WHENCE THIS DOCUMENT ORIGINATES

In 2001, the discovery of chronic wasting disease (CWD) in Wisconsin and in other areas caused many states to initiate CWD surveillance programs. To enhance coordination between states and increase the rate of information transfer and understanding of the disease, the USGS promoted and funded the first multi-state workshop on CWD, held in Madison, Wisconsin in 2002. The workshop focused on designing, developing, and implementing CWD surveillance programs for free-ranging cervids. The main objectives were to define the surveillance goals, establish the key operational and logistical components for conducting a surveillance program, and develop prototype statistical methodologies and procedures for CWD surveillance (detection, distribution, and monitoring). Participants in the workshop included wildlife managers and biologists, epidemiologists, biostatisticians, and ecologists. A white paper reviewing the current state of knowledge on planning, conducting, and evaluating a CWD surveillance program, originated from the first workshop. The white paper from the first workshop has been well utilized by wildlife managers and biologists involved with CWD research as well as research on other wildlife diseases (see www.nwhc.usgs.gov/publications/fact_sheets/pdfs/cwd/CWD_Surveillance_Strategies.pdf).

Left to right: Julie Blanchong, Don McKinnon, Gary White (Kneeling), Matt Farnsworth, Bruce Trindle, Rob Gillies, Steve Morey, Dennis Heisey. (Missing: Dan O'Brian, Mike Samuel, Nohra Mateus-Pinnilla)

With the success of the first workshop, a second multi-state CWD workshop was held in Utah in 2004. The first workshop addressed source data and statistical guidelines to collect surveillance data for a variety of outputs. The second workshop, from which this document arose, followed logically from the first workshop and focused on analysis, interpretation, and use of CWD surveillance and related epidemiology data, with an emphasis on modeling approaches by which to gain a better understanding and describe the spatial epidemiology of CWD. Again, participants included wildlife biologists and managers, along with epidemiologists, biostatisticians, and ecologists from around the country. This document stems directly from the overarching objectives and specified outputs of the second workshop. Specifically, we addressed the goal to produce a white paper for wildlife managers and researchers that discusses the relevance of various spatial epidemiology tools and explanation of how they might be used. We hope this document, "Scale-dependent approaches to modeling spatial epidemiology of chronic wasting disease", fulfills that goal.



Left to right: Paul Cross, John Gross, Mike Miller, Mary Conner, Dennis Heisey, Steve Griffen, David Douglas. (Missing: Tim Van Deelen)

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