Purpose

MO*Ov*POP*surveillance* was developed as a tool for wildlife agencies to guide collection and analysis of disease surveillance data that relies on non-probabilistic methods like harvest-based sampling. Epidemiological surveillance for important wildlife diseases mostly relies on samples obtained from hunter-harvested animals. Though this is a convenient and cost-effective strategy, samples so obtained may not be representative of the population primarily due to sampling biases associated with harvest and heterogeneities associated with the spatiotemporal distribution of a disease in the population. This model incorporates sampling biases and disease distribution heterogeneities, and provides population-specific recommendations for collection and analysis of disease surveillance data obtained from hunter-harvested animals (or other non-probabilistic sampling methods).

Currently the model is set up to represent chronic wasting disease (CWD) surveillance of white-tailed deer (*Odocoileus virginianus*) populations in Missouri, but it can be readily adapted for other disease systems and used for informed-decision making during planning and implementation stages of disease surveillance in wildlife and free-ranging species.

Chronic wasting disease (CWD) is an emerging prion disease of North American cervids, including white-tailed deer, mule deer (*Odocoileus hemtonus*), elk (*Cervus elaphus*) and moose (*Alces alces*), that represents a unique challenge for wildlife agencies in the United States. Considerable uncertainty remains about CWD

transmission dynamics in cervids, as mechanisms and factors driving transmission of this disease are poorly understood.

The basic model, **MO*Ov*POP**, simulates population dynamics of white-tailed deer and generates pre-harvest deer population (abundance, sex-age composition and distribution in the landscape) for the selected sampling region. These population data are stored as an Excel file. **MO*Ov*POP*surveillance*** is formulated to simulate hunter harvest and CWD testing under different assumptions. This model extension can be used to determine the probability of detecting an infected individual in the sample population for a specified level of population prevalence.

How to use the model:

Pre-harvest population files for Missouri Counties are available at https://github.com/anyadoc/wtdCWDSurveillance_MOprehpop for download. Use the 'Clone or download' tab and remember to unzip the folder after downloading. These files should be in the **same** folder as the NetLogo model file (**MO*Ov*POP*surveillance***). Alternatively, model **MO*Ov*POP** can be used to create a pre-harvest population of white-tailed deer for other region of interest. Model **MO*Ov*POP** is available here: https://www.openabm.org/model/5585/version/5/view.

Entities, state variables and scales

Spatial scales: MO*Ov*POP*surveillance* landscape can be set up for individual counties as well as for current or potential CWD management zones. Miles (rather than kilometers) are used as a distance and area measure in this work because of the past

and current norms of the region and its management agencies, and the related need to make the results immediately applicable to those same agencies

Temporal scale: MO*Ov*POP*surveillance* runs for one time-step (one month).

Entities: MO*Ov*POP*surveillance* has two entities: patches and deer. Irrespective of the region selected for simulation, each patch in the model landscape represents one square mile. Deer are modeled as individuals occupying the patches.

State variables: Each patch in MO*Ov*POP*surveillance* has eight patch variables (Table 1). Patch variable '*dcl* ' identifies patches in the landscape wher CWD+ deer are clustered. Patch variable '*add*' (average deer density) takes the value of average number of deer occurring on the patch and its immediate neighbors, and is used to identify patches with high deer density so as to simulate non-random sampling in the alternate version of the model. Each deer has eight state variables, which define individual characteristics like age, sex, group membership and status (Table 1).

Process overview and scheduling

MO*Ov*POP*surveillance* implements three processes: individual growth, non-hunting mortality and hunting mortality with CWD testing.

Schedule: Growth (increase age by one month) of individuals is scheduled at the beginning of the time step, and is followed by non-hunting mortality and hunting mortality. Hunting mortality also includes CWD testing.

Design concepts

Basic principles.

Processes like social organization, group dynamics, dispersal, and hunting mortality occur at an individual level and influence interactions among individuals. Such interactions underpin host heterogeneity, and thereby influence disease transmission in a host population. We incorporated these processes in the basic model so that the model-generated population reflects heterogeneity observed in real-world host populations. MO*Ov*POP-generated deer population can be used to initialize MO*Ov*CWD (model simulating CWD transmission dynamics in deer population) and MO*Ov*POP*surveillance*. Further, MO*Ov*POP*surveillance* can simulate CWD distribution heterogeneity (or clustered distribution of CWD+ deer) and sampling heterogeneity (or non-random sampling of deer) to account for real-world sampling biases.

Stochasticity: Deer mortality rates (natural and hunting) are deterministic, but individuals that die during a time step are chosen randomly. The distribution of CWD cases in the model population and selection of deer from hunter harvest are both stochastic processes.

Observation: MO*Ov*POP*surveillance* displays the total number of adult deer (male and female) in the population, number of CWD+ deer in the hunter harvest, and number of CWD+ deer in the sample (deer tested for CWD). If an alternate scenario (clustered_dist) is selected, the graphical display highlights the area where CWD cases are clustered in the model landscape. Additionally, information like number of fawns, yearlings and adults harvested (separately for both sexes), number of CWD+ deer in the

hunter harvest, and number of CWD+ deer detected is recorded in the output file *CWDsurveillanceMO*.

Initialization

MO*Ov*POP*surveillance* is initialized by importing model-generated pre-harvest deer population data (abundance, sex-age composition and distribution in the landscape) for the sampling region under consideration (using command '*import-world*').

Submodels

1. Individual growth

This submodel is executed at the beginning of the time step. All deer in the model landscape update their state variable 'aim' (age in months) by one month.

2. Non-hunting mortality

The probability of a deer dying of natural or other non-hunting related causes during every time step is determined by age- and sex- specific monthly mortality rates (Table 2). Irrespective of these rates, old deer (>240 months) have an overall high probability of dying (0.8) during a time step.

3. Hunting mortality

Deer surviving the monthly non-hunting mortality execute the hunting mortality submodel. The probability of a deer being included in the hunter harvest is specified by the age- and sex- specific hunting mortality rates (Table 2).

In MO*Ov*POP*surveillance*, patches with high average deer density (patch variable *add*) are designated as hunter-preferred patches. Deer are selected randomly for inclusion in

hunter harvest in the baseline scenario; while in the alternate scenario ~75% of deer harvest occurs on hunter-preferred patches (non-random sampling). Further, the probability of testing a harvested deer for CWD is specified by the observer using '*SampleSizeMaleHarvest'* and '*SampleSizeFemaleHarvest'* sliders. The following counters for each age class-sex category are also updated: total deer harvested, total CWD+ deer harvested, total deer tested, total CWD+ deer tested.

*Parameterization and Calibration*Population dynamics of the model deer population is defined by two sets of age-sex-specific parameters, *hunting mortality rates* and *non-hunting mortality rates*. We classify deer in four age-classes: young fawns (up to 6 months old), older fawns (7 to 12 months old), yearlings (13 to 24 months old) and adults (25 months or older). It should be noted that non-hunting mortality rates are per month rates (Table 2).

MO*Ov*POP*surveillance* has 6 additional user-specified parameters that define the distribution of CWD cases in the model landscape, the sampling intensity and the nature of sampling (random or non-random) (Table 3). With the Boolean parameter *ClusteredDistribution?*, the user indicates whether the CWD+ deer are distributed randomly (baseline version) or are clustered in the model landscape (alternate version). Parameter *%CWDlandscape* determines number of patches that constitute the cluster where 75% CWD+ deer occur. Parameter *CWD_prevalence* is used to designate a proportion of adult deer in the landscape as CWD+. Parameters *SampleSizeMaleHarvest* and *SampleSizeFemaleHarvest* determine the proportion of hunter harvest that is tested for CWD.

Table1. Agents included in MO*Ov*POP*surveillance* and their state variables. All state variables except the deer state variable '*aim*' are unitless.

Agent	Variable	Description
Patch	forest-percent	forest cover on a patch expressed as a proportion
	border	patches at the edge of the model landscape have border = 1, other patches have border = 0
	dfp	mean forest-percent calculated for a patch and its immediate neighbors
	dh	deer habitat; ≥ 1 if a patch qualifies as deer habitat, < 1 if it is not a deer habitat
	do	deer occupancy; 1 if deer occur on a patch, 0 if not
	dcl	identifies patches where CWD is clustered
	add	average deer density for a patch and its eight neighbors
Deer	sex	1 if male, 2 if female
	aim	age in months
	momid	mother's id number
	gl	1 if doe social group leader, 0 otherwise
	ml	1 if bachelor group leader, 0 otherwise
	fgroid	≥ 0 if member of a doe social group, -1 if solitary female, 0 for male deer
	gr	for doe social group leaders, gr denotes the number of group members; -1 for non-leader members of a doe social group, -2 if for solitary female deer, and 0 for all yearling and adult male deer
	mgroid	0 for all females, -2 for male fawns, -1 for male yearlings , and for bachelor group members it takes the value of group leader id
	cwd	cwd infection status (infected deer cwd = 1, uninfected deer cwd = 0)

Table 2. Age- and sex-specific mortality parameter values used in MO*Ov*POP and MO*Ov*POP*surveillance*.

Parameter	Description	Value
Non-hunting mortality		
mf6nhm	male fawns (0 - 6 months)	0.055 per month [a]
ff6nhm	female fawns (0 - 6 months)	0.055 per month [a]
mf12nhm	male fawns (7 - 12 months)	0.05 per month [b]
ff12nhm	female fawns (7 - 12 months)	0.05 per month [b]
mynhm	male yearlings (13 - 24 months)	0.01 per month [b]
fynhm	female yearlings (13 - 24 months)	0.00 per month [b]
manhm	male adults (> 25 months)	0.01 per month [b]
fanhm	female adults (> 25 months)	0.02 per month [b]
Hunting mortality		
mf6hm	male fawns (0 - 6 months)	0 [c]
ff6hm	female fawns (0 - 6 months)	0 [c]
mf12hm	male fawns (7 - 12 months)	0.05 per year [c]
ff12hm	female fawns (7 - 12 months)	0.02 per year [c]
myhm	male yearlings (13 - 24 months)	0.25 per year [c]
fyhm	male yearlings (13 - 24 months)	0.15 per year [c]
mahm	male adults (> 25 months)	0.40 per year [c]
fahm	male adults (> 25 months)	0.20 per year [c]

[a] Hiller, T.L., Campa III, H., Winterstein, S.R., Rudolph, B.A., 2008. Survival and space use of fawn white-tailed deer in southern Michigan. The American Midland Naturalist 159, 403-412.

[b] Van Deelen, T.R., Campa III, H., Haufler, J.B., Thompson, P.D., 1997. Mortality patterns of white-tailed deer in Michigan's Upper Peninsula. The Journal of wildlife management, 903-910.

[c] Derived from hunter-harvest data collected by Missouri Department of Conservation.

Table 3. Additional parameters used in MO*Ov*POP*surveillance*. An asterix indicates values used for the simulations described here.

Parameter	**Description**	**Value**
ClusteredDistribution?	If true, CWD+ deer are distributed in the landscape in a clustered fashion. If false, CWD+ deer are randomly distributed in the landscape.	True / False
%CWDlandscape	Proportion of the model landscape where 75% of CWD+ cases occur when simulating clustered CWD distribution	0.10*
CWD_prevalence	True prevalence; percentage of adult deer that change their status to CWD+	0.1 to 1%*
SampleSizeMaleHarvest	Proportion of total adult male deer harvest tested for CWD	0.01 to 0.6*
SampleSizeFemaleHarvest	Proportion of total adult female deer harvest tested for CWD	0.01 to 0.6*