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A population model of the impact of a rodenticide containing strychnine on Great Basin Gophersnakes (*Pituophis catenifer deserticola*)

Christine A. Bishop[1] · Kathleen E. Williams[2] · David A. Kirk[3] · Patrick Nantel[4] · Eric Reed[5] · John E. Elliott[1]

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Abstract Strychnine is a neurotoxin and an active ingredient in some rodenticides which are placed in burrows to suppress pocket gopher (*Thomomys talpoides*) populations in range and crop land in western North America. The population level impact was modelled of the use of strychnine-based rodenticides on a non-target snake species, the Great Basin Gophersnake (*Pituophis catenifer deserticola*), which is a predator of pocket gopher and a Species at Risk in Canada. Using information on population density, demographics, and movement and habitat suitability for the Gophersnake living in an agricultural valley in BC, Canada, we estimated the impact of the poisoning of adult snakes on the long-term population size. To determine the area where Gophersnakes could be exposed to strychnine, we used vendor records of a rodenticide, and quantified the landcover areas of orchards and vineyards where the compound was most commonly applied. GIS analysis determined the areas of overlap between those agricultural lands and suitable habitats used by Gophersnakes. Stage-based population matrix models revealed that in a low density (0.1/ha) population scenario, a diet of one pocket gopher per year wherein 10 % of them carried enough strychnine to kill an adult snake could cause the loss of 2 females annually from the population and this would reduce the population by 35.3 % in 25 years. Under the same dietary exposure, up to 35 females could die per year in a high density (0.4/ha) population which would result in a loss of 50 % of adults in 25 years.

Keywords Rodenticide · Strychnine · Snakes · Population impact · Gopher · Reptiles · Stage-based population matrix models

✉ Christine A. Bishop
cab.bishop@canada.ca

Kathleen E. Williams
katywilliams83@gmail.com

David A. Kirk
david@aquilaecology.com

Patrick Nantel
patrick.nantel@pc.gc.ca

Eric Reed
eric.reed@canada.ca

John E. Elliott
john.elliott@canada.ca

1 Environment and Climate Change Canada, Science and Technology Branch, 5421 Robertson Road, Delta, BC V4K3N2, Canada

2 Van Hees Environmental, 206 Glover Street, Twisp, WA 98856, USA

3 Aquila Conservation & Environment Consulting, 75 Albert Street, Suite 300, Ottawa, ON K1P 5E7, Canada

4 Parks Canada, Office of the Chief Ecosystem Scientist, 30 Victoria St., 3rd Floor, PC-03-D, Gatineau, QC J8X 0B3, Canada

5 Environment and Climate Change Canada, Canadian Wildlife Service, 5019- 52 Street, Yellowknife, NT X1A 2P7, Canada

Introduction

Environmental contaminants are considered one of the six top threats to reptile populations globally (Gibbons et al. 2000). However, there are no cases documented in which the direct impact of a pollutant has caused a reptile population to decline. We do know that (1) snakes can be exposed to pesticides via food, inhalation and dermal absorption (Weir et al. 2014); (2) long-lived reptile populations are highly sensitive to any loss of reproductively mature adults (Congdon et al. 1994); (3) that globally snake populations have declined in size and number (Reading et al. 2010) and (4) that the incremental loss of cryptic species such as snakes often goes unnoticed until the populations are critically low or extirpated (Reading et al. 2010). In this study, we estimated the population level impact of the consumption of strychnine-poisoned rodents by a free-ranging constrictor living in remnant grassland habitats in a predominantly agricultural valley.

The Okanagan valley in the southern interior of British Columbia contains Canada's only desert, a northern-protruding extension of the Great Basin which extends slightly north into Canada (Lea 2008). The south Okanagan valley thus contains one of the most endangered and biologically diverse ecosystems (Lea 2008) and the highest species richness in Canada (Habitat Atlas for Wildlife at Risk 1998; Warman et al. 2004). The valley also has a high rate of urban and agricultural development (Okanagan Valley Economic Development Society 2013). The overlapping occurrence of rare species with human development within the south Okanagan valley can result in the exposure of wildlife to many human-sourced risks to their survival (COSEWIC 2002a). For example, the Great Basin Gophersnake (*Pituophis catenifer deserticola*) (threatened Species at Risk in Canada; COSEWIC 2013) is a large oviparous constrictor that spends much of its time in rodent burrows while foraging and for shelter (Rodriguez-Robles, 2002). The geographic occurrence of this species in Canada is restricted to the now-remnant dry interior grassland,and riparian habitats and agricultural lands adjacent to natural habitat (COSEWIC 2002a, b) in southern British Columbia including the south Okanagan valley. Pocket gopher (*Thomomys talpoides*), and other rodents are preyed upon by Great Basin Gophersnakes (Rodriguez-Robles 2002; McAllister et al. 2015). Rodents, such as pocket gopher are fossorial and eat young roots, including grapevine and also chew bark which can girdle orchard trees. Therefore, strychnine-based rodenticide is placed in pocket gopher burrows to try to suppress Gopher populations in the south Okanagan valley.

In Canada, when rodents such as pocket gopher and Richardson's ground squirrel (*Urocitellus richardsonii*) become problematic to crop production, "ready-to-use-bait" containing strychnine is used in a below-ground placement or in a protected bait station (Health Canada 2016a, b). The lethal dose of strychnine (LD50) for pocket gophers is approximately 8 mg/kg (Nolte and Wagner 2001). Once pocket gophers have consumed strychnine, symptoms appear within five to 30 min with death generally occurring within 20 min of ingesting a lethal dose (Nolte and Wagner 2001). Concern for Gophersnake survival in the Okanagan valley arises because they track their prey through smell therefore even dead pocket gophers may be potential prey. In captivity, when presented with dead or moribund mice poisoned by strychnine, snakes consumed the dead rodents and 14 % of Gophersnakes died and 76 % exhibited tremors but survived (Brock 1965). Although that study was limited in its design and scope, concerns for snakes also exist in the environment where strychnine is not bioaccumulative but retains its toxicity under heat or cold conditions (PMRA 2011a) and can be cached by pocket gophers (Nolte and Wagner 2001). Resistance can develop in rodents (Lee et al. 1990) suggesting live Pocket Gophers may contain strychnine which increases the likelihood that snakes are exposed.

To estimate whether strychnine in the rodenticide in Elston Gopher Getter® I bait used in the Okanagan valley posed a risk to the Gophersnake population living there, we modelled the consumption of poisoned Pocket Gophers under two population density scenarios. Because population growth rates in snake populations are very sensitive to removal of just a few adult individuals per year (Row et al. 2007), we predicted that even in low density populations with low rates of exposures, population growth (λ) could be reduced to below 1.0 with a measurable impact on population size within 25 years.

Methods

Elston Gopher Getter® I bait containing 0.4 % strychnine has been sold in the Okanagan valley and used primarily in vineyards and orchards (Tables 1, 2). We estimated Great Basin Gophersnake exposure and population impact of strychnine consumption in habitats suitable for this species and which overlapped with agricultural use areas for Elston Gopher Getter® I in the south Okanagan valley from Penticton (49°27′N, 119°36′W) to Osoyoos (49°1′N, 119°26′W), British Columbia, a linear distance of approximately 66 km. Osoyoos is located on the USA and Canadian border (Fig. 1). For this valley, we based the potential for

Table 1 Volume of Elston Gopher Getter® I bait (kg) sold in the South Okanagan valley, BC, Canada during 2005 and 2006, from all the vendors

Vendor	2005	2006
Sunfresh, 900	291.9	ND
Sunfresh, 731	61.9	ND
South valley sales, Oliver	510.6	202.4
Growers, Penticton	527.7	437.5
Growers, Osoyoos	ND	176.1
Okanagan-similkameen co-op	68.2	187.7
Terralink	375.4	584.5

Several vendors did not sell Strychnine in 2006, and one did not sell Strychnine in 2005, hence no data reported (ND)

Table 2 Data from Terralink Horticulture Inc. (one of the 2 largest vendors in the south Okanagan valley, BC, Canada) on volume of sales (kg) of Elston gopher getter® I bait during 2005–2007 showing the customer type associated with sales

Customer type	2005	2006	2007
Vegetable grower	18	0	20.3
Ranch/forage	2.3	72	90
Packer/grower	38.3	18	27.2
Treefruit grower	207.2	378.4	153.2
Nursery	0	0	18
Fruitstand	45.2	54	0
Feed customer	0	0	18
Grape grower	27.6	25.3	0
Fruit/vegetable	2.3	0	0
Tree and grape	2.3	0	0
Golf course	0	4.6	0

exposure on habitat suitability modelled for Great Basin Gophersnakes (Warman et al. 1998) combined with known movement distances, and density estimates of Gophersnakes (Williams et al. 2012, 2014, 2015) and the extent of orchard and vineyard habitats (Ecological Data Committee 2000). We incorporated information from the literature on feeding frequency, prey composition, and potential consumption of poisoned pocket gophers by Gophersnakes into a model to estimate of the number of snakes that might be killed annually in high and low extremes of densities previously estimated for this population (Williams et al. 2014). Once the number of snakes potentially killed per year due to strychnine exposure was estimated for those scenarios, the long-term effect on the population was determined using a stage-based population projection matrix model.

Strychnine sales and use patterns

Data on sales of Elston Gopher Getter® I bait were obtained from the pesticide division of BC Ministry of Environment, Penticton, BC, from vendors local to the south Okanagan valley, BC, Canada. We used detailed records for two years from 2005 to 2007 (Tables 1, 2). Suggested applications for the Okanagan were 1–2.25 kg/ha, depending on the level of infestation (PMRA 2011a). At each application site, 5–15 g of Elston Gopher Getter® I bait could be placed in an underground tunnel (PMRA 2011a).

Terralink, one of the two largest suppliers of Gopher Getter in the south Okanagan, provided us with data for 2005–2007 (Table 1) on the amount of strychnine purchased per customer type (e.g., packer/grower, treefruit grower, golf course, fruit stand) (Table 2). By grouping these into the larger categories of range (customer types: ranch/forage and feed customer), Orchard/Vineyard (customer types: packer/grower, treefruit grower, fruitstand, grape grower, fruit/vegetable, and tree & grape), and other (customer types: vegetable, nursery, and golf course) (Table 1), we calculated the percentage of strychnine that was sold to these three types of customers. Because we found the highest percentage of purchases of Gopher Getter was for use in vineyards and orchards, we only estimated impacts to Gophersnakes on these land base types. Although orchards and vineyards were the highest volume purchasers, the amount sold to grape growers was only, on average, 6.5 % of that in orchards in 2005–2007.

Gophersnake population density and pocket gophers in their diet

From radio telemetry and mark-recapture data collected during 2006 and 2007 in the south Okanagan valley, the high density population sites had approximately 0.4 adult Gophersnakes per hectare, while lower density sites had approximately 0.1 adult Gophersnakes per hectare (Williams et al. 2014). Density is assumed to be equal for males and females in our model. The estimates apply only to adults and therefore juveniles were not considered in the population size in this model. Also, pocket gophers can range in size up to 22 cm in length (Washington Department of Fish and Wildlife 2005) and therefore adult pocket gophers may not be a realistic food item for juvenile Gophersnakes.

Gophersnakes feed upon subterranean, nocturnal and diurnal prey (Rodriguez-Robles 2002). In the Okanagan valley population, it is estimated that adult Gophersnakes can consume at least 270 g of food each year (Shewchuk 1996), the equivalent of roughly two to three adult Pocket Gophers (adult size: 78–130 g; Burt 1980). However, there is limited information on exactly how many pocket gophers are consumed per year by Gophersnakes in this population. The proportion of the diet composed of pocket gophers based on 68 road-killed Gophersnakes collected in the south Okanagan valley during 2010–2013 (McAllister et al. 2015) indicated that 2 of 68 (0.3 %) specimens contained pocket gophers at the time of collection. While that analysis confirms Gophersnakes eat pocket gophers in the Okanagan valley, the sample was from non-randomly collected road-killed snakes. They were primarily collected adjacent to non-agricultural sites so the rate at which pocket gophers are actually consumed is unknown however in our model we estimated a 0.1 % rate. We do know that the Baird's Pocket Gopher (*Geomys breviceps*) is the most common prey in a related snake species Louisiana pine snake (*Pituophis ruthveni*) (Randolph et al. 2002).

When designing our model we also considered an assessment of the ecological risks of strychnine use in the USA (Durkin 2010) considered the reported possible case

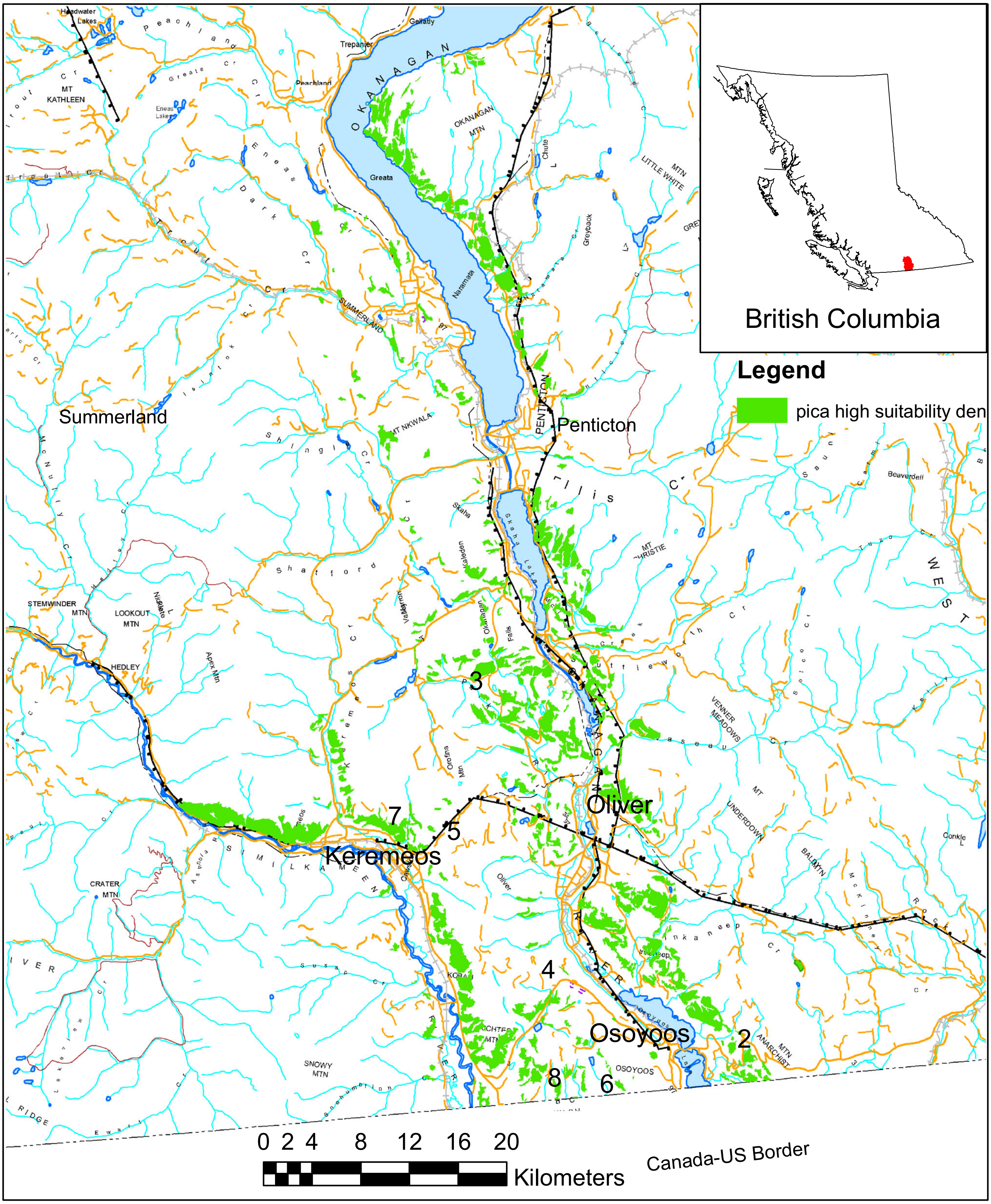

Fig. 1 Area of high suitability den habitat for Great Basin Gophersnakes (pica) (*Pituophis catenifer deserticola*) in the south Okanagan based on habitat capability and suitability modeling by Warman et al. (1998)

of exposure in the Prairie rattlesnake and calculated exposure "based on the study by Evans et al. (1990), average residues in pocket gophers after strychnine treated baiting range from about 3 to 8 mg per Gopher. Campbell (1982) notes that a rattlesnake possibly poisoned by strychnine was an average size adult. Durkin (2010) calculated that an average-sized Prairie rattlesnake (*Crotalus viridis*) weighs about one pound (0.4536 kg). From these estimates of the snake's body mass and the average strychnine residues in baited Gophers, the dose to a rattlesnake consuming a single pocket gopher is estimated to range from about 7–18 mg/kg bw [3 mg to 8 mg/0.4536 kg $\approx$ 6.614 to 17.64 mg/kg bw]. Based on information in the study by Brock (1965), it is reasonable to assume that this range of doses would be fatal to a Prairie rattlesnake."

With the limited information available, and because snakes consume the entire animal, and Great basin Gophersnakes are larger in length and weight than Prairie rattlesnakes, our model tested the impact of consumption of one pocket gopher per year by Gophersnakes in the Okanagan valley. In low and high density populations, we examined a range of possible consumption rates of poisoned pocket gophers by modelling scenarios in which 0.1–10 % of the consumed Pocket Gophers contained enough strychnine to kill a Gophersnake. We assumed a consistent consumption rate through 25 years because Pocket gopher populations are stable compared to most arvicolids (Ostfeld 1992).

Habitat mapping

Using ARCmap 10.1, we overlaid terrestrial ecosystem mapping (Ecological Data Committee 2000) with Great Basin Gophersnake habitat suitability mapping of the south Okanagan valley (Warman et al. 1998; 2004) and a den suitability model (Warman et al. 1998; 2004) to determine the areas of medium and highly suitable habitat for Gophersnakes in the south Okanagan valley (Figs. 1, 2).

GIS analysis

Based on radio telemetry data for 18 individual Gophersnakes from three sites in the Okanagan valley during 2006 and 2007 (Williams et al. 2012; 2014; 2015), we averaged the distance Gophersnakes moved from their hibernation site for all tracking times that they were away from their den site during the active season. We estimated a distance of 357 m as the average distance from suitable den habitat that a Gophersnake would move. We then used the maximum distances Gophersnakes moved from their dens in 2006 and 2007, and averaged these to get the average maximum distance that snakes (729 m) might move from their dens.

Vineyards and orchards within 357 m of high suitability den habitat or within 729 m of moderate suitability den habitat were selected as potential areas of strychnine bait exposure. There were 2315 hectares of vineyards and 2917 ha of orchard in the south Okanagan valley as represented in the Terrestrial Ecosystem Mapping and Ministry of Agriculture data (BC Ministry of Agriculture 2004; Table 3; Figs. 3, 4, 5). It was assumed that Gophersnakes could encounter a poisoned pocket gopher on all of the orchard area which overlapped with suitable habitat (high suitability = 363 ha; moderate suitability = 1634 ha) (Table 3; Figs. 3, 4, 5). Because, on average, the volume of Gopher getter purchased by grape growers was about 6.5 % of that purchased for use on fruit in 2005–2007 (Table 2), we reduced the area of vineyards considered as potential Gopher getter exposure to 6.5 % of the total moderate or high suitability areas from den habitat (Table 3) so that orchards and vineyards were included on a 1:1 basis in the same exposure calculations. That amounted to 70 ha of high suitability habitat and 114 ha of moderate suitability habitat in vineyards (Table 3).

Estimation of annual Gophersnake mortality due to strychnine exposure

We assumed that the estimated density of the population in either case (low or high) was applicable throughout the entire area in which suitable Gophersnake habitat existed in the landscape. In the case of the low density scenario (0.1/ha), the adult female population (assuming 1:1 sex ratio) the potentially poisoned number of females was estimated as: (see also Table 4)

$$\begin{aligned}&(\text{density of Gophersnakes})(\text{area of orchards} + \text{vineyards}\\&\quad\text{near suitable habitat for selected density})\\&\quad(\text{number of pocket gophers consumed per year})\\&\quad(\%\ \text{poisoned pocket gophers of those consumed}\\&\quad\text{per year})/2\end{aligned}$$

For example:

$$\begin{aligned}&= (0.1/\text{ha})(363 + 70\ \text{ha})(1)(10\,\%)/2\\&\quad = 2\ \text{female adults poisoned in a low density population}\\&\quad\text{on high suitability habitat when 1 pocket gopher consumed}\\&\quad\text{per year and 10 \% of those prey are poisoned}\end{aligned}$$

$$\begin{aligned}&= (0.4/\text{ha})(1634 + 114\ \text{ha})(1)(10\,\%)/2\\&\quad = 35\ \text{female adults poisoned in a high density}\\&\quad\text{population in high + moderate suitability habitat}\\&\quad\text{when 1 pocket gopher consumed per year and 10 \%}\\&\quad\text{of those prey are poisoned}\end{aligned}$$

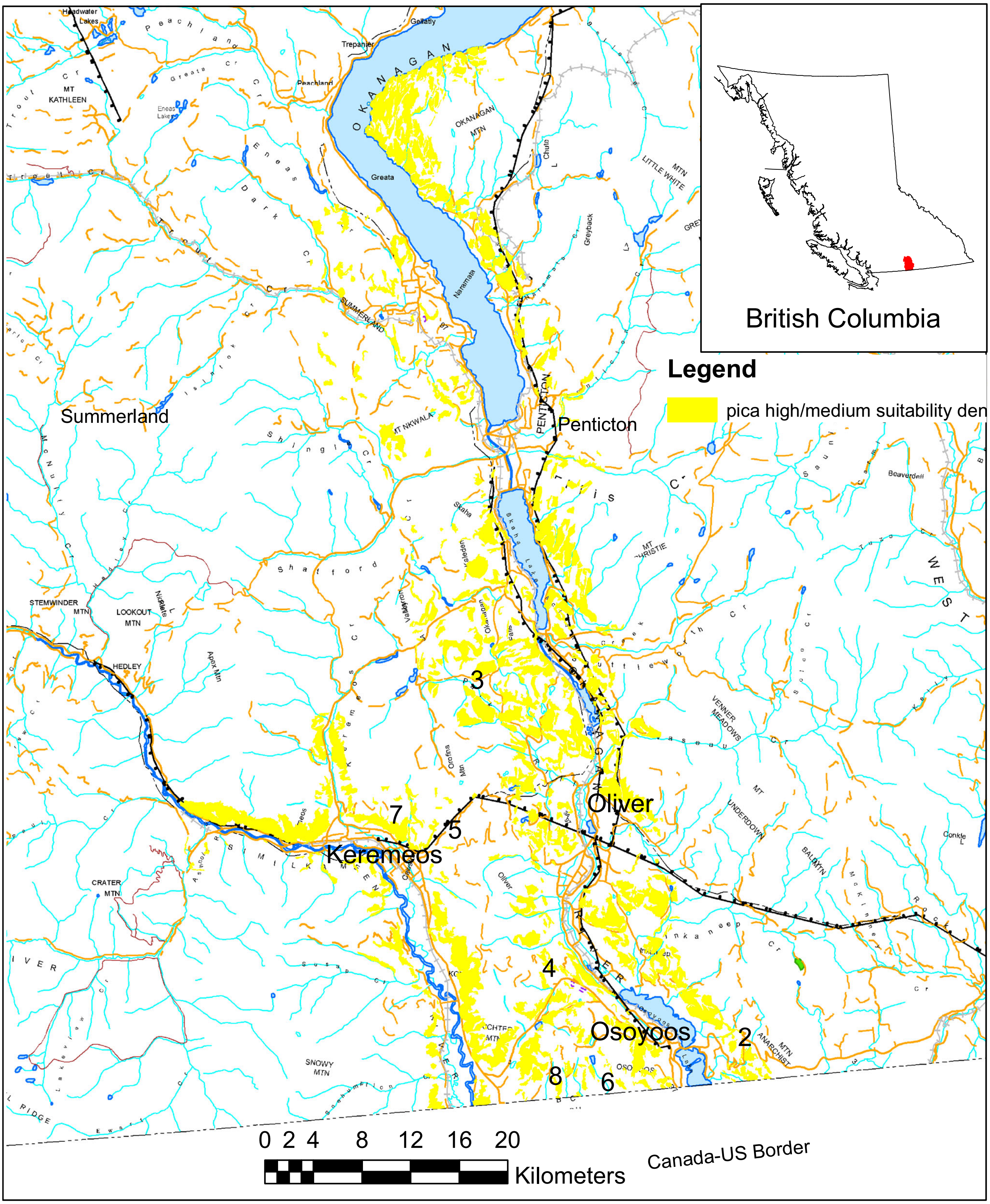

Fig. 2 Area of high and medium suitability den habitat for Gophersnakes (pica) (*Pituophis catenifer deserticola*) in the south Okanagan based on habitat capability and suitability modeling by Warman et al. (1998)

Table 3 Estimates of exposure and dispersal parameters used to estimate the number of Gophersnakes (*Pituophis catenifer deserticola*) poisoned by strychnine-based rodenticide use in the south Okanagan valley BC (Penticton to Osoyoos, BC) in a low and high exposure scenario

Value	Scenario 1 (low exposure)	Scenario 2 (high exposure)	Source
# of Gophersnakes in a hectare	(0.1/ha)	(0.4/ha)	Williams et al. (2012, 2014)
Area of vineyards in Okanagan	2315 ha		BC Ministry of Agriculture (2004)
Area of orchards in valley	2917 ha		BC Ministry of Agriculture (2004)
Distance Gophersnake will move from den habitat	357 m	729 m	Williams et al. (2012, 2014, 2015)
Area of orchards within 357 m or 729 m of suitable den habitat	363 ha (highly suitable den habitat)	1634 ha (highly and moderately suitable den habitat)	Warman et al. (1998), Terrestrial Ecosystem Mapping (Ecological Data Committee. 2000), BC Ministry of Agriculture (2004)
Area of vineyards within 357 m or 729 m of suitable den habitat	1075 ha (highly suitable den habitat) 6.5 % of 1075 ha = 70 ha	1758 ha (highly and moderately suitable den habitat) 6.5 % of 1758 ha = 114 ha	Warman et al. 1998, Terrestrial Ecosystem Mapping (Ecological Data Committee. 2000), BC Ministry of Agriculture (2004)
Initial population estimate for gophersnakes (male + female adults)	144 = 0.1/ha (363 ha + 1075 ha) on highly suitable den habitat	1357 = 0.4/ha (1634 + 1758 ha) on highly + moderately suitable den habitat	

Stage-based population projection matrix model

To examine the potential demographic impact of poisoning, we built a stage-based population projection matrix model (Tables 5, 6, 7) that allowed us to compute the stable population growth rate (λ) and population size 25 years into the future, with an incremental percentage of snakes being poisoned. The model was female-based and included four stages: hatchling, yearling, juvenile, and mature individuals (aged 4 and older). We assumed that immatures do not reproduce and adults all reproduce with fecundity f_4. Hatchlings (less than one year of age) survive to age one at the rate of σ_1, while survival of yearling and juveniles was assumed to be constant across the two stages (Table 5). Adult survival was also assumed constant from age 4 (four) to death, with a life span estimated to be 16 years. Fertility was estimated as the product of clutch size, sex ratio at hatching (females only model), and breeding propensity. Survival rates of females were based on initial estimates of total population in low and high density population scenarios of Gophersnakes exposed to Gopher getter in their habitats within the south Okanagan valley.

Stage transition (γ_i) was estimated using the stage-duration distributions approach (Caswell 2001, Eq. 6.103), assuming fixed stage durations (T_i), such that:

$$\gamma_i = \frac{\left(\frac{\sigma_i}{\lambda}\right)^{T_i} - \left(\frac{\sigma_i}{\lambda}\right)^{T_i - 1}}{\left(\frac{\sigma_i}{\lambda}\right)^{T_i} - 1}$$

where σ_i = P (survival of an individual in stage *i*) and λ is the annual population growth rate. Entries of the transition matrix **A** are then:

Proportion of individuals moving from stage *i* to *i + 1:* $G_i = \gamma_i\ \sigma_i$

Proportion of individuals in stage *i* remaining in stage *i*: $P_i = \sigma_i\ (1 - \gamma_i)$.

Initially, γ_i were estimated with λ = 1, and then λ was calculated as the dominant eigenvalue of **A**, which was fed back to the equation above, and the process repeated until it converged to a matrix whose entries were compatible with its own eigenvalues (Caswell 2001). The initial lambda selection had no effect on the model output. Among values within the range of estimates for fecundity and survival, we selected those that yielded a matrix with λ close to 1.

Model assumptions

1. There is no density-dependence. There is no evidence in the literature of density-dependence in snakes. Reductions in population size do not result in an increase in survival or fecundity.
2. Sex ratio at hatch is 1:1. Model represents female dynamics only, so 50 % of clutch is assumed to be females.
3. All eggs laid hatch successfully.
4. Current fecundity and survival estimates assume a stable population (λ ~ 1).
5. Only adults are impacted.
6. The rodenticide decreases survival rates, but not fecundity rates.

We used the same demographic parameter values presented in the 2013 Canadian status report for this species

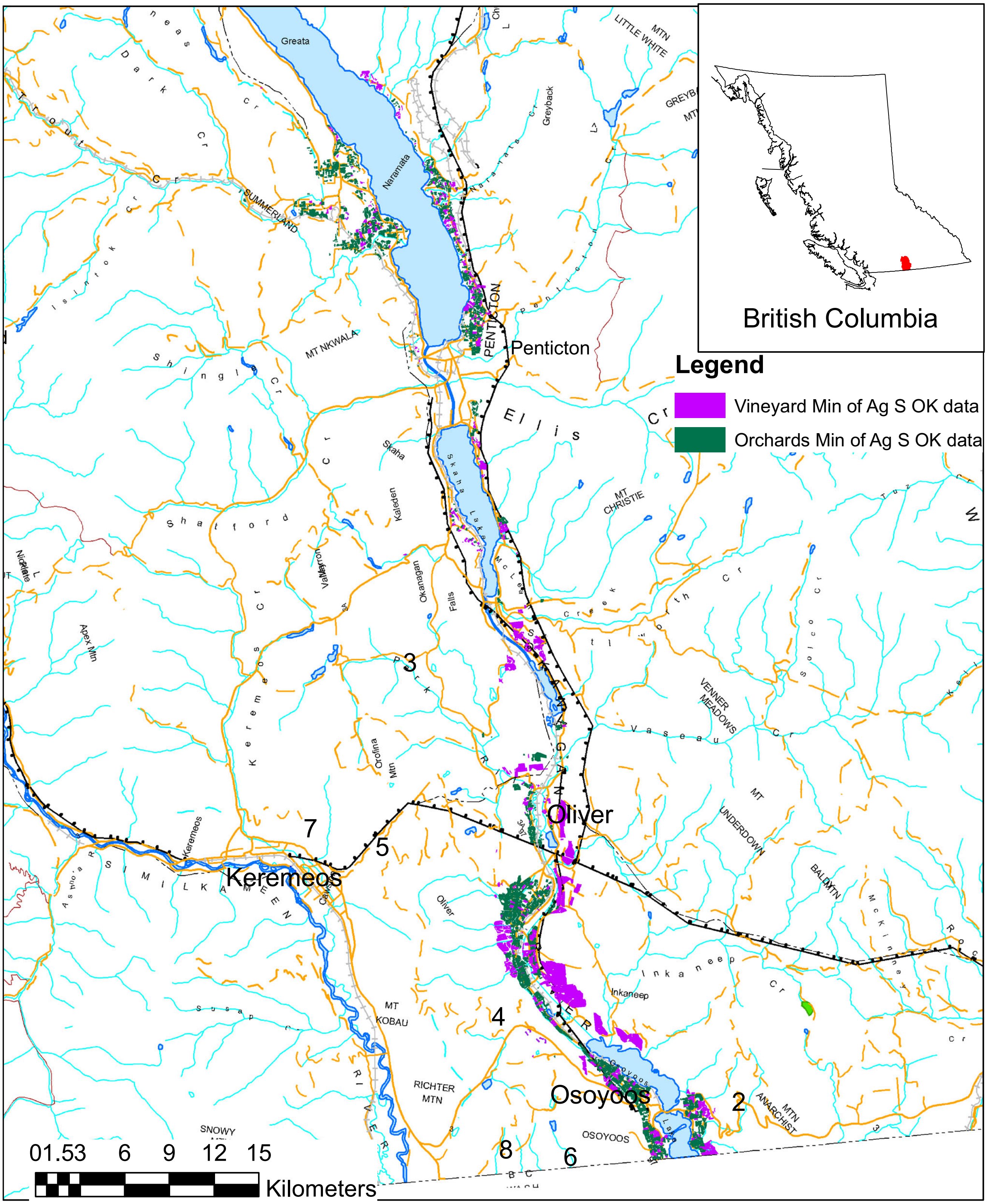

Fig. 3 Orchards and Vineyards in the south Okanagan, as identified by BC Ministry of Agriculture mapping, 2004

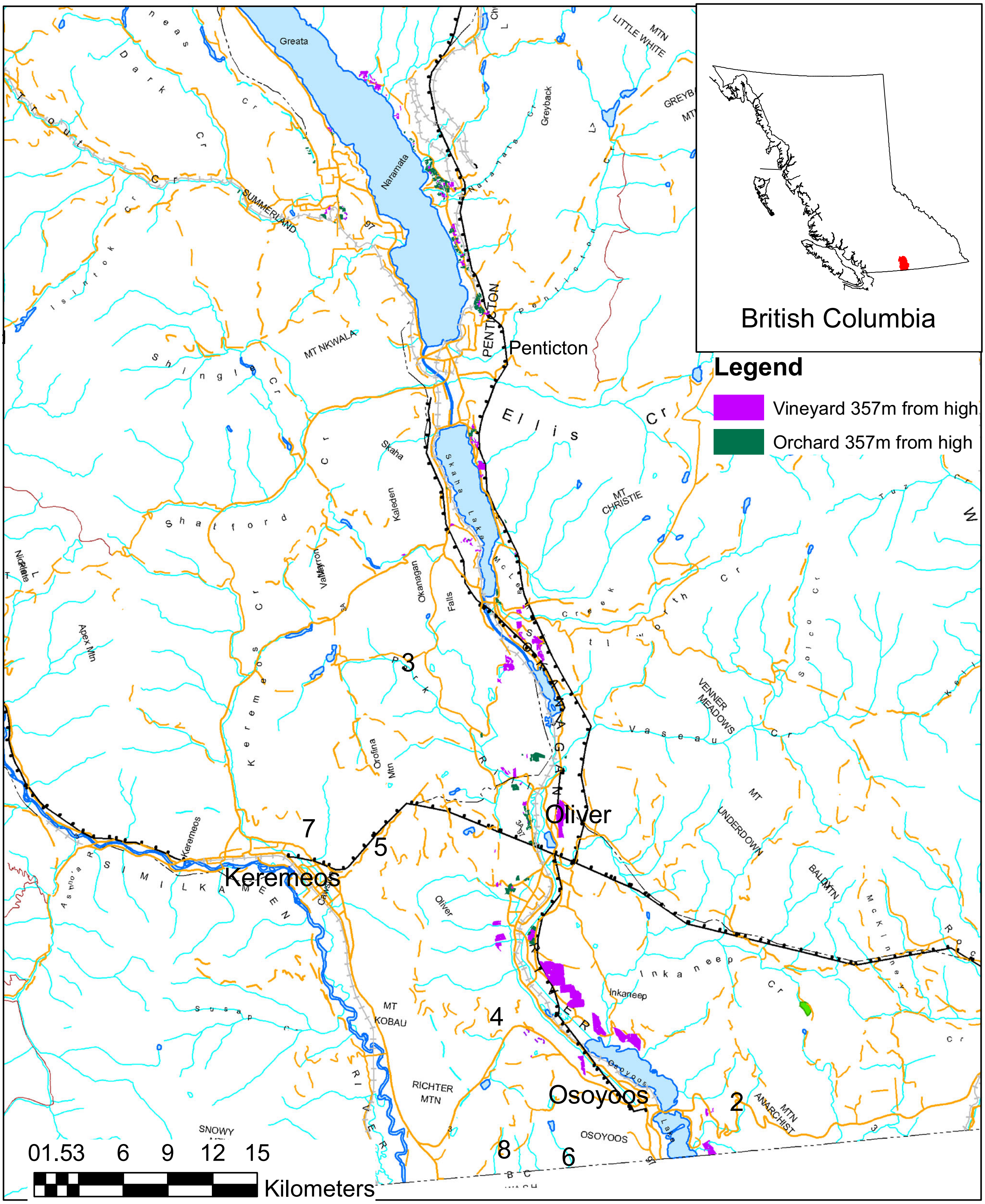

Fig. 4 Orchards and Vineyards in the south Okanagan within 357 m of high suitability den habitat for Great basin Gophersnakes (*Pituophis catenifer deserticola*)

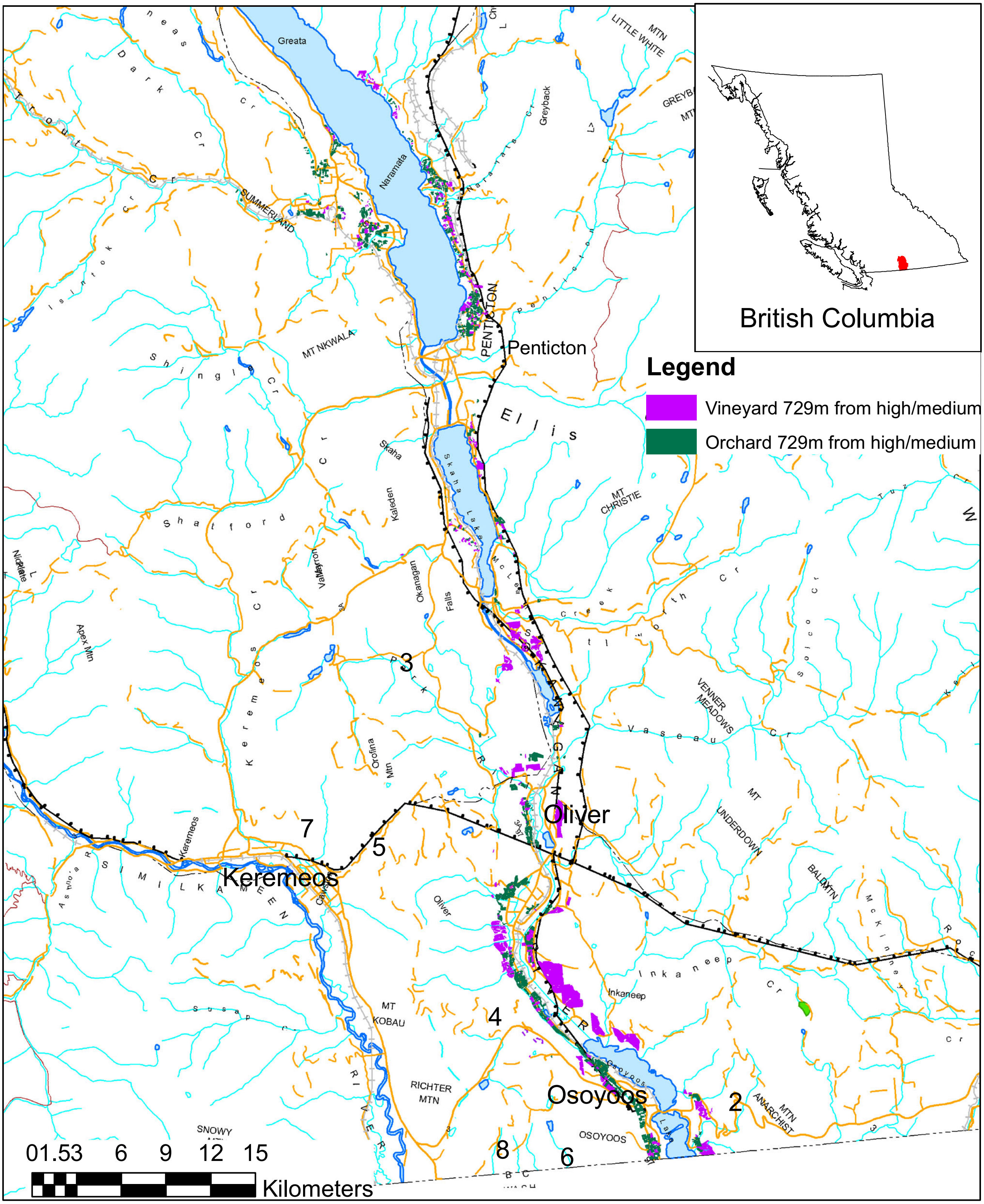

Fig. 5 Orchards and Vineyards in the south Okanagan within 729 m of high and medium suitability den habitat for Great basin Gophersnakes (*Pituophis catenifer deserticola*)

Table 4 Number of female Great basin Gophersnakes (*Pituophis catenifer deserticola*) potentially poisoned per year by three possible consumption rates and three possible occurrences of poisoned pocket gophers consumed in the Okanagan Valley, BC

% poisoned pocket gophers of those consumed per year	Number of female Great basin Gophersnakes potentially poisoned per year in a low density population (0.1/ha) in which 1.0 pocket gopher consumed per year	Number of female Great basin Gophersnakes potentially poisoned per year in a high density population (0.4/ha) in which 1.0 pocket gopher consumed per year
10 %	2	35
5 %	1	17
1.0 %	0.2	3
0.1 %	0.02	0.3

* Calculated number of female adults poisoned in a population with a 1:1 sex ratio is determined as: = (density of Gophersnakes) (area of orchards + vineyards near suitable habitat for selected density) (number of pocket gophers consumed per year) (% poisoned pocket gophers of those consumed per year)/2

Table 5 Demographic parameters used in age-based population projection matrix model for Great basin Gophersnake (*Pituophis catenifer deserticola*) population, Okanagan valley, BC, Canada

Parameter	Published values	Source
Breeding propensity*	0.5[a]	Shewchuk (1996)[a]
	0.8[b]	Williams et al. (2014)[b]
Clutch size**	2 to 8[b] (used 8 in model)	COSEWIC (2002a)[b]
Sexual maturity***	4[c,d]	Diller and Johnson (1982)[c]
		Parker and Brown (1980)[d]
Hatchling survival (0–1 year)	0.20	Parker and Brown (1980)[d]
Immature survival (1–4 years)	0.76	Parker and Brown (1980)[d]
Adult survival (4+ years)****	M:0.78, F:0.63[d]	Williams et al. (2012)[b]
	M:0.795, F:0.853[b]	Parker and Brown (1980)[d]

* Breeding propensity estimates derived from studies from the Okanagan Valley

** Lower clutch size estimate derived from Okanagan valley

*** Sexual maturity taken from studies in Idaho and Utah

**** Adult survival estimates from Utah (Parker and Brown 1980) might be underestimates because of the methods used in that study do not take emigration to other den sites into account. Estimates from Williams et al. (2012) are based on telemetry

Table 6 Demographic parameter estimates for a stage-based, post-breeding, population projection matrix for female Great basin Gophersnake (*Pituophis catenifer deserticola*) in South Okanagan

Stage	Stage duration (T_i)	Survival (s_i)	Stage transition (g_i)[1]	P_i	G_i	$\boldsymbol{F_i}$
Hatchling	1	0.2000	1	0	0.2000	0
Yearling	1	0.7600	1	0	0.7600	0
Juvenile	2	0.7600	0.4319	0.4317	0.3283	0
Adult	12	0.8500	0	0.8500	0	1.7

1-Stage transition was estimated using Eq. 6.103, p 161 in Caswell (2001)

Proportion of individuals moving from stage i to $i + 1$: $G_i = \gamma_i \sigma_i$

Proportion of individuals in stage i remaining in stage i: $P_i = \sigma_i (1-\gamma_i)$

Age-specific fertilities = Fi

(COSEWIC 2013; Parker and Brown 1980, Diller and Johnson 1982, Shewchuk 1996, Williams et al. 2012; 2014; 2015) (Table 5). Although we list two breeding propensity estimates, 0.5 and 0.8 (Table 5), we used the lower value (0.5) to develop a more conservative model. We used an age at first breeding of four years. This was based on studies of this species in more southern parts of the range in the USA (Parker and Brown 1980; Diller and Johnson 1982) and therefore may underestimate the age of mature adults living in northern parts of the range. However, simulations showed that using either four or six years for age at first breeding had little effect on the model output. For annual survival, we used values of 0.85 for adult females, 0.20 for hatchling, and 0.76 for yearlings and juveniles. The range for clutch size from the Canadian study (COSEWIC 2002a) was between two and eight. We used a value of eight for clutch size to have a population growth rate (λ) of one as a benchmark. Fecundity was

Table 7 Age-based population matrix model estimates of population size (N), growth rate (λ) and intrinsic rate of increase in a low (0.1/ha) and high (0.4/ha) density Great basin Gophersnake (*Pituophis catenifer deserticola*) population in which adult female snakes are removed from the population by poisoning due to consumption of prey containing strychnine-bait rodenticide for Pocket gopher control in the south Okanagan valley, BC, Canada

Low Density Population (0.1/ha)
Area of suitable habitat 433 ha
Initial Population estimate of adult males + females = 144
Initial Population estimate females only = 72
Sex ratio assumed 1: 1

Female Adult Gophersnakes dead/year (see Table 4 for modelled scenarios due to strychnine exposure)	Adult Si	λ	N (females) after 25 years
0	0.8500	0.9995	71
1	0.8361	0.9909	57
2	0.8222	0.9824	46
4	0.7944	0.9659	30
5	0.7805	0.9578	24
6	0.7666	0.9499	20
10	0.7109	0.9196	9
20	0.5718	0.8533	1
30	0.4328	0.7990	0

High Density Population (0.4/ha)
Area of suitable habitat 1748 ha
Initial Population estimate of adult males + females = 1357
Initial Population estimate females only = 678
Sex ratio assumed 1:1

Female Adult Gophersnakes dead/year (see Table 4 for modelled scenarios due to strychnine exposure)	Adult Si	λ	N (females) after 25 years
0	0.8500	0.9995	671
1	0.8485	0.9986	655
2	0.8471	0.9977	640
4	0.8441	0.9959	611
6	0.8412	0.9940	584
10	0.8353	0.9904	533
30	0.8058	0.9726	339
50	0.7763	0.9554	217
80	0.7321	0.9309	113

clutch size (8) times breeding propensity (0.5; 50 % of mature females reproduce each year) times ratio of females (0.5, assuming a 1:1 sex ratio), yielding a fecundity rate of 2 (Tables 5, 6).

The models were built with Microsoft Excel and were run using PopTools (Hood 2011).

Results

In this population model of female adult snakes, growth rate (λ) is less than 1 in low and high density models (Table 7) even when no snakes are lost to poisonings in any year. In the low and high density population scenarios, the initial population size can only remain stable if no deaths of female adults occur during the next 25 years (Table 7). Therefore, the model indicates that the Great Basin Gophersnake population in the Okanagan valley is highly vulnerable to any anthropogenic sources of mortality which cause any losses of female adults.

The potential poisoning scenarios in Table 4 show that even in a low density population, using only high quality habitat where it overlaps with agricultural land, a diet of 1 pocket gopher per year wherein 10 % contained enough strychnine to kill an adult snake, could cause approximately 2 females to die annually. This alone could reduce the population by 35.3 % in 25 years from about 71 to 46 female adults (Tables 4, 7). In a high density population, up to 35 females could be lost a year when one pocket gopher per year was consumed and 10 % of these were poisoned (Tables 4, 7). If 35 females died annually it results in a loss of 50 % of the adult females reducing the population from 671 to 339 females in 25 years (Tables 4, 7). However, diets with less than 1.0 % of pocket gophers poisoned in low density populations would pose little additional threat to the population size. In the high density population scenario, the diet would have to contain 0.1 % of poisoned prey to have no effect on the population (Tables 4, 7).

Discussion

In the Okanagan valley, our model indicates that strychnine poisoning alone could cause the population to decrease by 35 to 50 % within 25 years. This assumes no source of mortality, which is clearly unrealistic, in this population which is predicted to be declining in our model, but at best, stable in its size in 25 years. While our models can only estimate pocket gopher consumption and exposure in the future, it is also possible that strychnine use for the past decades in the Okanagan valley may have contributed to the current status of the population size and growth rate. Other threats such as habitat loss, and road mortality are considered to be major factors causing a declining population trend (COSEWIC 2013). Even if Gophersnakes never consume a poisoned pocket gopher, rather populations of pocket gophers are suppressed by rodenticide use, this could impact the Great basin Gophersnake population. For example, in west Gulf Coast plains longleaf pine savannah, the loss of pocket gophers as a key prey item is thought to be the primary factor in declining population size of a related *Pituophis* species, the Louisiana pine snake (*Pituophis ruthveni*) (Randolph et al. 2002). While there is potential for immigration of Gophersnakes from its southern range into the Okanagan valley, the northern tip of the range of this species, the barriers to a rescue effect are substantial due to extensive road networks, habitat loss, as well as persecution to large snakes. We believe that our study is also relevant in a broader sense in that risk resulting from gopher control using strychnine estimated in this model in a single valley may also apply much more widely to snakes in western North America.

Strychnine was first registered in Canada in 1928 (Proulx et al. 2010) for the control of Richardson's Ground Squirrels (*Spermophilus richardsonii*). It had been used in Saskatchewan as early as 1912 (Isern 1988). Access to strychnine was restricted in 1992 by Agriculture and Agri-Food Canada and Health Canada and in 2008, a re-evaluation note informed registrants, pesticide regulatory officials and the Canadian public that Health Canada's Pest Management Regulatory Agency (PMRA) was implementing interim measures for products containing strychnine (PMRA 2007). The PMRA determined that the use of strychnine to control Northern pocket gophers, ground squirrels (*Spermophilus* spp), skunks (*Mephitis* spp), pigeons (Columbiformes), wolves (*Canis lupus)*, Coyotes (*Canis latrans)* and Black Bears *(Ursus americanus)* was acceptable for continued registration with the implementation of mitigation measures (Health Canada 2016a).

Strychnine alkaloid and strychnine sulfate formulations were registered in the U.S. in 1947 (U.S. EPA/OPP 1996; Durkin 2010). In the USA, strychnine is restricted in its usage to pocket gopher control (U.S. EPA/OPP 1996) and is only to be used in areas where endangered species would not be exposed to it (U.S. EPA/OPP 1996). Similar to Canada, strychnine cannot be applied in habitats of certain rare and endangered species (Durkin 2010). However, outside of North America, all forms of strychnine are banned in the European Union, and Israel (Makarovsky et al. 2008).

In Canada, the registration was discontinued as of 28 December 2015 for Elston Gopher Getter Bait I and registration for Bait II was discontinued in 2012 (Health Canada 2016a). However the use of other strychnine-based rodenticides continues for the control of Richardson's ground squirrel throughout areas of Alberta, Saskatchewan and Manitoba and, in BC, for control of Richardson's ground squirrel and pocket gopher control (Health Canada 2016a). There are restrictions on where the compound can be used relative to habitats occupied by Species at Risk (Health Canada 2016b; PMRA 2011b). For example, the Canadian pesticide label for strychnine dry bait reads "Species at risk, including the burrowing owl (*Athene cunicularia*) and the swift fox (*Vulpes velox*), are known to frequent habitat occupied by ground squirrels. Do not apply this product if these or other species at risk that may feed on strychnine bait or ground squirrels are present in your area. For information on species at risk in your area, contact your local, provincial or federal wildlife officials" (Health Canada 2016b).In the Okanagan valley, besides Great Basin Gophersnake, other Species at Risk snakes occur, as well as other species that use burrows such as the endangered burrowing owl, and badger (*Taxidea taxus)*, blotched tiger salamander (*Ambystoma mavortium*) and threatened Great basin spadefoot (*Spea intermontana*) (British Columbia Southern Interior Reptile and Amphibian Recovery Team 2008; Jeffersonii Badger Recovery Team 2008; Southern Interior Reptile and Amphibian Recovery Team 2008; Environment Canada 2012). A risk assessment for the California red-legged frog (*Rana draytonii*) and the California tiger salamander (*Ambystoma californiense*; U.S. EPA/OPP 2009) determined that below-ground use of strychnine treated bait may adversely affect these endangered species: although exposure via dermal absorption and via consumption of invertebrates cannot be estimated, the potential exists for dermal exposure and consumption of invertebrates that have been in contact with the bait.

As a rodenticide, strychnine is used primarily in the western states and provinces of North America which overlap with the geographic range of many large snake species that are primarily rodent consumers (Behler and King 1979). Typically, the goal of strychnine application is to reduce the gopher population by at least 80 % and that may involve more than one application (Nolte and Wagner 2001). In Canada, the area of strychnine use in BC, and the prairie provinces overlaps with the geographic ranges of the Gophersnake and the bullsnake (*Pituophis catenifer sayi*) and two species of rattlesnake: the Northern pacific rattlesnake (*Crotalus oreganus*) and the prairie rattlesnake (*Crotalus viridis*). With the exception of Bullsnake, which is listed as data deficient (COSEWIC 2002a, b) all of those species are listed in Canada as threatened Species at Risk (COSEWIC 2002b). They all consume rodents as a main dietary item (Rodriguez-Robles 2002). In the western USA, the geographic range for 14 species of pit vipers as well as most of the geographic range of Gophersnakes and bullsnakes and at least four other fossorial rodent feeding snakes overlap with areas of the USA where strychnine is still used (Behler and King 1979). However, rattlesnakes tend to be less fossorial and therefore are less likely to be exposed. Also, our model does not incorporate variation in feeding, exposure and size and cycling of rodent populations in other areas. Nonetheless, the only documented case of possible snake poisoning by strychnine rodenticide was a prairie rattlesnake collected from an area of New Mexico, USA, in which strychnine grain bait was used the previous day in burrow baiting for rodent control (Campbell 1982). The snake displayed aggressive behavior and shortly after collection the snake convulsed and died, and the body of the snake became atypically rigid exhibiting symptoms of possible strychnine exposure. However, the snake was neither necropsied nor analyzed for strychnine residue (Campbell 1982).

There have been other efforts to evaluate the risk to snakes from non-target impacts of vertebrate control operations (USFWS 1993; Durkin 2010). Three (aluminum or magnesium phosphide, potassium nitrate) of 16 compounds were determined to be potentially hazardous to snakes by the US Fish and Wildlife Service (USFWS 1993). However, strychnine was not examined whereas Durkin (2010) focused on strychnine-based baits and found snakes to be potentially sensitive and at risk. Here, we did not consider the potential impact of other pesticides, or rodenticides. DDT was intensively applied in the Okanagan valley and levels in wildlife within the Okanagan valley remain quite high in some areas (>100 ppm p,p'-DDE in some bird eggs; Harris et al. 2000). In areas where organochlorine pesticides were heavily used in the past, for example, agro-ecosystems in Texas, snakes were found dead containing high residue concentrations and populations declined concurrently (George and Stickel 1949; Fleet et al. 1972; Fleet and Papp 1978). Current-use pesticides in the Okanagan valley, and in agriculture throughout North America, such as organophosphate and carbamate insecticides, are highly neurotoxic to vertebrates and are absorbed dermally as well as exposure through inhalation (Hill 1995) although there are no reports of dead or dying snakes exposed to these compounds. Snakes are also sensitive to synthetic pyrethroid insecticides (Brooks et al. 1998a, b; Alexander et al. 2002) including exposure by dermal absorption (Abe et al. 1994). Recently, links have been made between the widespread use of neonicotinoid insecticides and population declines in various taxa (see Mineau and Palmer 2013; Main et al. 2014) including snakes (Santos and Llorente 2009). Besides strychnine, traps, fumigants and other rodenticides such as zinc phosphide and anticoagulants such as chlorophacinone are used in Canada for ground squirrels and pocket gophers (Alberta Environment 2007).

The implications of these types of stressors for wildlife are substantial and, like other areas in North America, the Okanagan valley has experienced a loss of more than 80 % of native grassland and riparian habitats (Lea 2008). Wildlife live in the remaining natural habitat remnants and on the fringes of agriculture or on farms when seeking alternate foraging sites which may be rich in food resources such as rodents. This is not unique to the Okanagan valley. Snake populations globally are subject to multiple anthropogenic threats (Gibbons et al. 2000). This population of Great Basin Gophersnakes may be representative of snake populations in many agricultural, urban and grassland habitat mosaics in western North America.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with humans or with animals performed by any of the authors.

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