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MORBIDITY AND MORTALITY IN ONTARIO RODENTS AND LAGOMORPHS: A 30-YEAR RETROSPECTIVE REVIEW

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ABSTRACT: Passive surveillance is an important component of wildlife health surveillance that allows for the identification of emerging pathogens as well as population-level threats. We investigated the most common causes of morbidity and mortality in rodents and lagomorphs submitted to the Canadian Wildlife Health Cooperative (CWHC) in Ontario and the Ontario Veterinary College (OVC) over a 30-yr period. A total of 836 cases representing 13 species of rodents and three species of lagomorph were submitted to the CWHC and the OVC wildlife pathology service. Infectious or inflammatory diagnoses were most common in our data set, followed by trauma and unknown diagnoses. The most frequently identified primary diagnosis was encephalitis with histological lesions consistent with neural larva migrans including the presence of inflammation and malacia of brain tissue and, in some cases, characteristic nematode larvae. Other infectious diagnoses were squirrel fibroma virus and *Toxoplasma gondii* infections. Knowledge of common pathogens observed in various species of rodents and lagomorphs can aid in triage and treatment decisions at veterinary clinics and wildlife rehabilitation centers, and guide sample collection and test requisition at post-mortem examination.

Key words: Infectious disease, morbidity, mortality, neural larva migrans, Ontario, rabbit, retrospective, rodent.

INTRODUCTION

Passive surveillance is an important part of assessing and maintaining wildlife health (Stallknecht 2007; Hoinville et al. 2013). Using databases containing information on submissions of animals for post-mortem evaluation allows retrospective analysis of disease emergence as well as monitoring for species-specific and ecosystem-health trends (Smith et al. 2018). Some species, such as birds of prey, are frequently assessed through such approaches (Morishita et al. 1998; Wendell et al. 2002; Smith et al. 2018); however, published data on causes of morbidity and mortality in wild rodents and lagomorphs are limited. Instead, these species are often examined from the perspective of determining prevalence estimates for specific pathogens of public health significance (e.g., *Francisella tularensis*, *Yersina pestis*, *Anaplasma phagocytophilum*; Bunnell et al. 1998; Wobeser et al. 2009).

Although focusing surveillance on zoonotic pathogens is common and important for protecting public health (Belant and Deese 2010; Grogan et al. 2014), understanding the variety of infectious disease agents and events affecting wildlife is important for assessing potential impacts of disease on wildlife populations. In addition to identifying new and emerging diseases of medical and veterinary concern, some diseases can have significant population-level effects, particularly for isolated or endangered species (Morner et al. 2002; Ryser-Degiorgis 2013). One such pathogen is *Baylisascaris procyonis*; the larval stage of this parasite has been implicated in the extirpation of the Allegheny woodrat (*Neotoma magister*) from portions of its range in the US (Logiudice 2003; Page 2013). The larval stage of *B. procyonis* has also been reported to cause neurological disease in more than 150 species of birds and mammals, including humans (Kazacos 2016). This para-

site, which is highly pathogenic in many small vertebrates (Tiner 1953a; Sapp et al. 2016), undergoes extensive somatic migration after ingestion by paratenic hosts, often migrating to the central nervous system and causing significant damage, a condition referred to as neural larva migrans (NLM; Kazacos 2016). Rodents, particularly *Peromyscus* spp. mice, are often considered to play an important role in the lifecycle of *B. procyonis*, acting as paratenic hosts (Page et al. 2001; Kazacos 2016). Investigating infectious causes of morbidity and mortality in rodents would allow us to better quantify the role this parasite plays in the mortality of Ontario rodents and lagomorphs.

We used 30 yr of post-mortem surveillance data to identify causes of morbidity and mortality in rodents and lagomorphs in Ontario. Through this retrospective analysis, we aimed to determine the most common primary diagnoses of rodents and lagomorphs, and to identify specific infectious causes of morbidity and mortality. We also investigated the frequency and causes of neurological disease to determine the role NLM plays in rodent and lagomorph mortality in Ontario. This information could help inform wildlife rehabilitators, veterinarians, and pathologists in making triage and diagnostic decisions, as well as potentially developing standard protocols for specific species or clinical signs.

MATERIALS AND METHODS

We reviewed post-mortem diagnostic reports for all rodents and lagomorphs submitted to the Ontario-Nunavut node of the Canadian Wildlife Health Cooperative (CWHC) from 1991 to 2018, and to the Ontario Veterinary College Wildlife Pathology Service in 1989 and 1990. Carcasses were received from throughout Ontario, Canada (Fig. 1) and were submitted from a variety of sources, including government agencies, wildlife rehabilitation centers, private citizens, and veterinary clinics. In addition to necropsy reports and ancillary testing as indicated (e.g., histopathology, virus isolation, bacterial culture), reports also contained demographic information including age (i.e., adult or juvenile), sex, location found, date of death or discovery, and case history when available. All slide preparation and ancillary tests

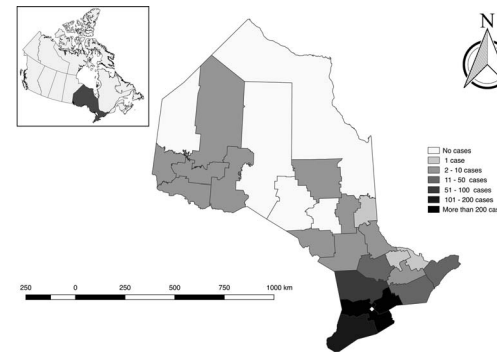

FIGURE 1. Number of rodent and lagomorph case submissions received by the Canadian Wildlife Health Cooperative and the Ontario Veterinary College between 1989 and 2018 classified by Ontario Ministry of Natural Resources district. Guelph, the location of the Canadian Wildlife Health Cooperative Ontario-Nunavut node, is indicated by the white diamond.

were performed at the Animal Health Laboratory, University of Guelph, except for some toxicological panels performed at the Michigan State University Diagnostic Center for Population and Animal Health. We excluded cases if the species was not reported or a complete necropsy was not performed. We specifically noted cases that did not have tissues examined histologically, as they could not be included in some detailed analyses. Within each report, a pathologist provided a primary and, in some cases, additional causes of morbidity or mortality on the basis of gross pathology, history, and ancillary testing as appropriate. In cases where a post-mortem diagnosis could not be determined, the diagnosis was classified as "unknown."

When available, the following background information was recorded for each case: age, sex, date of death, and date of submission. For most necropsy reports, the municipality or township of collection was provided; animals were classified by region and district as used by the Ontario Ministry of Natural Resources (OMNR; Ministry of Natural Resources and Forestry 2014). We generated a submitter ID and recorded the general submitter type (wildlife rehabilitation, public or government) to allow us to investigate and control for the influence of different submission sources. We also recorded whether the animal received treatment prior to submission, and whether it was euthanized. Species were classified as small (<150 g), medium (150 g to 1 kg), or large (>1 kg) based on the average body mass for the species (Reid 2006), to determine any associations between body size and diagnoses.

Initially we categorized the primary diagnosis, i.e., the cause of death or major morbidity, for

TABLE 1. Demographic information for rodents and lagomorphs submitted to the Ontario-Nunavut node of the Canadian Wildlife Health Cooperative and the Ontario Veterinary College for post-mortem evaluation between January 1989 and December 2018 (n=836). (Percentage contribution to species is provided in parentheses.)

	Age			Sex		
Species[a]	Adult	Juvenile	Unknown	Female	Male	Unknown
American beaver[b]	23 (56)	6 (15)	12 (29)	17 (41)	16 (39)	8 (20)
American red squirrel[c]	18 (39)	19 (41)	9 (20)	16 (35)	26 (57)	4 (9)
Peromyscus sp. mouse[d]	2 (22)	2 (22)	5 (56)	2 (22)	5 (56)	2 (22)
Eastern chipmunk[d]	21 (53)	11 (28)	8 (20)	13 (33)	18 (45)	9 (23)
Eastern cottontail[b]	44 (34)	76 (59)	8 (6)	35 (27)	41 (32)	52 (41)
Eastern gray squirrel[c]	170 (46)	165 (44)	38 (10)	115 (31)	187 (50)	71 (19)
European hare[b]	1 (100)	0	0	0	0	1 (100)
Groundhog[b]	26 (31)	44 (52)	15 (18)	29 (34)	31 (36)	25 (29)
Mus sp. mouse[d]	1 (25)	2 (50)	1 (25)	0	2 (50)	2 (50)
Meadow vole[d]	3 (43)	0	4 (57)	2 (29)	3 (43)	2 (29)
Muskrat[b]	16 (42)	4 (11)	18 (47)	11 (29)	10 (26)	17 (45)
Northern flying squirrel[d]	2 (66)	1 (33)	0	2 (66)	1 (33)	0
Norway rat[c]	4 (50)	2 (25)	2 (25)	0	4 (50)	4 (50)
North American porcupine[b]	16 (46)	19 (54)	0	23 (66)	11 (31)	1 (3)
Snowshoe hare[b]	5 (71)	0	2 (29)	3 (43)	2 (29)	2 (29)
Southern flying squirrel[c]	9 (82)	2 (18)	0	5 (45)	3 (27)	3 (27)
Total	361 (43)	353 (42)	122 (15)	273 (33)	360 (43)	203 (24)

[a] Scientific names: American beaver (*Castor canadensis*), American red squirrel (*Tamiasciurus hudsonicus*), eastern chipmunk (*Tamias striatus*), eastern cottontail (*Sylvilagus floridanus*), eastern gray squirrel (*Sciurus carolinensis*), European hare (*Lepus europaeus*), groundhog (*Marmota monax*), meadow vole (*Microtus pennsylvanicus*), muskrat (*Ondatra zibethicus*), northern flying squirrel (*Glaucomys sabrinus*), Norway rat (*Rattus norvegicus*), North American porcupine (*Erethizon dorsatum*), snowshoe hare (*Lepus americanus*), southern flying squirrel (*Glaucomys volans*). Body size was categorized as follows: [b] large (>1 kg), [c] medium (150 g to 1 kg), [d] small (<150 g).

each animal as infectious, non-infectious, or unknown. We then classified the diagnosis as one of seven categories: infectious or inflammatory, trauma, emaciation, toxin, other, unknown, or normal (i.e., hunted or trapped animals submitted with no abnormal findings). The specific diagnosis was recorded using consistent terminology. Additionally, we recorded the presence or absence of other diagnoses, subdividing infectious and inflammatory lesions into bacterial, fungal, viral, parasitic, and "suspected infection" (infectious etiology not confirmed by additional testing). As the diagnostics performed on each case varied based on clinical history and presentation, the denominator for each pathogen group excluded animals where associated testing was not performed. Given our specific interest in neurological disease associated with NLM, for all animals with histological reports we indicated the presence of a lesion consistent with NLM, whether ascarid larvae were visualized in brain tissue, and if the primary diagnosis was consistent with NLM (i.e., if NLM was the apparent cause of death based on final diagnosis and pathologist interpretation; in some cases, these lesions were identified incidentally during histological examination of tissues). Consistent lesions include areas of malacia within the neuropil, which are often associated with inflammation (typically macrophages and eosinophils) and gliosis. Characteristic nematode larvae are seen in occasional cases (Kazacos 2016).

We determined the percentage of cases that were assigned each primary diagnosis for the total number of animals submitted and by each species individually. Multivariable logistic regression models were fitted through backwards elimination using STATA15 (StatCorp, College Station, Texas, USA) to evaluate the association between individual demographic and submission factors and the infectious etiology diagnosis and NLM. A variable was retained in the model if it was statistically significant or acted as an explanatory antecedent (i.e., a confounding variable). A variable was defined as an explanatory antecedent if it was a non-intervening variable and its removal

TABLE 1. Extended.

Submission source				Treatment before submission			Euthanasia			
Wildlife rehabilitation center	Government organization	Public	Unknown	Yes	No	Unknown	Yes	No	Unknown	Total
15 (37)	17 (41)	5 (13)	4 (10)	6 (15)	34 (83)	1 (2)	10 (24)	29 (71)	2 (5)	41
8 (17)	14 (30)	20 (43)	4 (9)	8 (17)	36 (78)	2 (4)	7 (15)	34 (74)	5 (11)	46
0	4 (44)	5 (56)	0	0	9 (100)	0	0	9 (100)	0	9
5 (13)	23 (58)	12 (30)	0	0	39 (98)	1 (3)	10 (25)	29 (73)	1 (3)	40
58 (45)	7 (5)	62 (48)	1 (4)	12 (9)	114 (89)	2 (2)	31 (24)	93 (73)	4 (3)	128
109 (29)	100 (27)	133 (36)	31 (8)	29 (8)	316 (85)	28 (8)	83 (22)	251 (67)	39 (10)	373
0	0	1 (100)	0	0	1 (100)	0	0	1 (100)	0	1
30 (35)	11 (13)	37 (44)	7 (8)	10 (12)	70 (82)	5 (6)	45 (53)	25 (29)	15 (18)	85
0	1 (25)	3 (75)	0	0	4 (100)	0	0	4 (100)	0	4
2 (29)	2 (29)	2 (29)	1 (14)	1 (14)	5 (71)	1 (14)	2 (29)	4 (57)	1 (14)	7
3 (8)	22 (58)	11 (29)	2 (5)	2 (5)	31 (82)	5 (13)	2 (5)	35 (92)	1 (3)	38
0	1 (33)	2 (67)	0	0	3 (100)	0	1 (33)	2 (66)	0	3
1 (13)	1 (13)	6 (75)	0	0	8 (100)	0	3 (38)	4 (50)	1 (13)	8
22 (63)	0	11 (31)	2 (6)	9 (26)	26 (74)	0	14 (40)	19 (54)	2 (6)	35
0	6 (86)	1 (14)	0	0	7 (100)	0	1 (14)	6 (86)	0	7
0	1 (9)	6 (55)	4 (36)	1 (9)	10 (91)	0	2 (18)	9 (82)	0	11
253 (30)	210 (25)	317 (40)	56 (7)	78 (9)	713 (85)	45 (5)	211 (25)	554 (66)	71 (8)	836

resulted in a 30% or greater change of a statistically significant coefficient. We assessed overall model fit using Pearson chi-squared goodness of fit and identified potential outliers using Pearson residuals and influential observations with the following diagnostics: delta-beta, delta-χ^2, and delta-deviance. We used a significance level of 5% (α=0.05) for all statistical analyses. Models were initially fit with a random intercept for submitter; however, the random intercept was removed from the model since the variance component was not significant and was negligible (i.e., less than 1×10^{-10}).

RESULTS

Descriptive statistics

Our final data set included 836 animals submitted between 1989 and 2018, comprising 700 rodents and 136 lagomorphs. Rodents and lagomorphs represented less than 2% of all animals submitted to the CWHC between 1991 and 2018. Thirteen species of rodent and three species of lagomorph were included in the database (Table 1). The most frequently submitted species were eastern gray squirrels (*Sciurus carolinensis*; 45%, 373/836), eastern cottontails (*Sylvilagus floridanus*; 15%, 128/836), and groundhogs (*Marmota monax*; 10%, 85/836). Submissions were received from throughout Ontario; however, they were not evenly distributed and did not include all OMNR districts (Fig. 1). The age distribution of the cases was roughly equal between adults and juveniles (adult 43%, juvenile 42%, unknown 15%), with more male animals submitted than females (male 43%, female 33%, unknown 24%). The body size distribution was uneven, with animals categorized as large (40%) and medium (51%; 87% of medium-sized animals were eastern gray squirrels) being submitted more frequently than those categorized as small (9%).

The average number of submissions in a year was 28 (range 11–81), with the largest number of animals being submitted in 2003, and the fewest submitted in 1998. Submissions were most frequent in the summer (34%, 284/836) and lowest in the winter (14%, 121/836); spring and fall saw similar numbers

TABLE 2. Primary diagnosis assigned to all rodents and lagomorphs submitted to the Ontario-Nunavut node of the Canadian Wildlife Health Cooperative and the Ontario Veterinary College for post-mortem evaluation between January 1989 and December 2018 (n=837). (Percentage contribution to species is provided in parentheses.)

	Infectious	Non-infectious				Unknown	
Species[a]	Infectious/ Inflammatory	Trauma	Emaciation	Toxin	Other	Unknown	Normal
American beaver	22 (54)	3 (7)	9 (22)	0	3 (7)	3 (7)	1 (2)
American red squirrel	6 (13)	10 (22)	10 (22)	1 (2)	8 (17)	11 (24)	0
Peromyscus sp. Mouse	2 (22)	0	0	3 (33)	0	4 (44)	0
Eastern chipmunk	10 (24)	16 (40)	0	5 (13)	1 (3)	8 (20)	0
Eastern cottontail	67 (52)	43 (34)	7 (5)	0	5 (4)	6 (5)	0
Eastern gray squirrel	98 (26)	75 (20)	13 (3)	47 (13)	37 (10)	101 (27)	2 (1)
European hare	0	1 (100)	0	0	0	0	0
Groundhog	66 (78)	11 (13)	0	0	5 (6)	3 (4)	0
Mus sp. Mouse	1 (25)	2 (50)	0	0	0	1 (25)	0
Meadow vole	1 (14)	2 (29)	1 (14)	0	1 (14)	2 (29)	0
Muskrat	10 (26)	11 (29)	5 (13)	3 (8)	0	4 (11)	5 (13)
Northern flying squirrel	1 (33)	1 (33)	1 (33)	0	0	0	0
Norway rat	1 (13)	3 (38)	0	4 (50)	0	0	0
North American porcupine	24 (69)	3 (9)	4 (11)	1 (3)	2 (6)	1 (3)	0
Snowshoe hare	3 (43)	2 (29)	1 (14)	0	1 (14)	0	0
Southern flying squirrel	1 (9)	6 (55)	2 (18)	0	0	2 (18)	0
Total	313 (37)	189 (23)	53 (6)	64 (8)	63 (8)	146 (17)	8 (1)

[a] Scientific names: American beaver (*Castor canadensis*), American red squirrel (*Tamiasciurus hudsonicus*), eastern chipmunk (*Tamias striatus*), eastern cottontail (*Sylvilagus floridanus*), eastern gray squirrel (*Sciurus carolinensis*), European hare (*Lepus europaeus*), groundhog (*Marmota monax*), meadow vole (*Microtus pennsylvanicus*), muskrat (*Ondatra zibethicus*), northern flying squirrel (*Glaucomys sabrinus*), Norway rat (*Rattus norvegicus*), North American porcupine (*Erethizon dorsatum*), snowshoe hare (*Lepus americanus*), southern flying squirrel (*Glaucomys volans*).

of submissions (28%, 232/836 and 22%, 183/836, respectively). Rehabilitation centers submitted 33% of cases (252/775), and 9% of all submissions had received some form of medical treatment prior to submission (78/836). Euthanasia was reported in 25% of reviewed cases (211/836); for this reason, we classified animals by their primary diagnosis (i.e., the condition that led to euthanasia) instead of by proximal cause of death.

Infectious and inflammatory conditions were the most frequent type of primary diagnosis observed across species (37%, 313/836), with trauma being the second most frequent diagnosis (23%, 189/836). A total of 44% of cases were classified as non-infectious (369/836; includes trauma cases). In 17% of cases (146/836), no diagnosis could be identified, and these cases were classified as unknown (Table 2).

The most frequently identified lesions were parasitic in nature (28%, 195/693), followed by lesions associated with bacterial infection (15%, 101/691). Viral-associated lesions were documented in 38 cases, and fungal lesions were noted in three. An additional 52 cases had lesions consistent with an infectious process but lacked verification through ancillary testing. Multiple infectious lesions caused by different types of pathogens were recorded in 7% of cases (23/313), with the greatest number of concurrent distinct infectious lesions being three.

Encephalitis was the most common infectious diagnosis identified, representing 44% (139/313) of infectious diagnoses and 17% (139/836) of all cases included in this study. In 90% of encephalitis cases, lesions were consistent with NLM (125/139), however larvae were identified in only 27% of these

TABLE 3. Multivariable logistic regression model examining the association between demographic and submission factors and being given a primary diagnosis that was infectious in nature in rodents and lagomorphs submitted to the Ontario-Nunavut node of the Canadian Wildlife Health Cooperative and the Ontario Veterinary College between January 1989 and December 2018. (The percent of individuals with an infectious diagnosis is included in parentheses.) Statistically significant values are indicated in boldface type.

Variable	Category (% positive)	Odds ratio	*P* value	95% Confidence interval	Wald χ^2 test[b]
Species[a]	Groundhog (80)		Referent category		**<0.001**
	American beaver (59)	0.22	**0.005**	0.08–0.64	
	American red squirrel (17)	0.04	**<0.001**	0.01–0.14	
	Eastern chipmunk (31)	0.07	**<0.001**	0.02–0.25	
	Eastern cottontail (55)	0.2	**<0.001**	0.09–0.48	
	Eastern gray squirrel (36)	0.12	**<0.001**	0.06–0.27	
	Muskrat (34)	0.05	**<0.001**	0.01–0.24	
	North American porcupine (71)	0.41	0.101	0.14–1.19	
	Other species (24)	0.11	**<0.001**	0.03–0.34	
Sex	Female (39)		Referent category		
	Male (45)	1.54	**0.044**	1.01–2.34	
Submission type	Wildlife rehabilitation (69)		Referent category		**<0.001**
	Government (41)	0.44	**0.003**	0.26–0.77	
	Public (30)	0.23	**<0.001**	0.14–0.37	

[a] Scientific names: American beaver (*Castor canadensis*), American red squirrel (*Tamiasciurus hudsonicus*), eastern chipmunk (*Tamias striatus*), eastern cottontail (*Sylvilagus floridanus*), eastern gray squirrel (*Sciurus carolinensis*), groundhog (*Marmota monax*), muskrat (*Ondatra zibethicus*), North American porcupine (*Erethizon dorsatum*).

[b] Used as a global test of significance of variables with >2 categories.

cases (37/139); the majority of these diagnoses were presumptive based on compatible histologic lesions and in some cases the provided history. Other diagnosed causes of encephalitis included toxoplasmosis (*n*=2) and bacterial infection (*n*=3). Where a history was available, neurological signs were reported in 92% of the animals diagnosed with encephalitis (109/118). Additionally, lesions consistent with NLM were identified in 64% of animals with a parasitic lesion of any kind (presumptive or confirmed; 125/195).

Other frequently identified infectious pathogens or conditions included *Pasteurella multocida*, primarily in eastern cottontails (43/313), squirrel fibroma virus in eastern gray squirrels (18/313), and toxoplasmosis, primarily in eastern gray squirrels (11/313). Additional notable diagnoses identified were alveolar echinococcosis associated with *Echinococcus multilocularis* (*n*=1), *F. tularensis* (*n*=3), *Clostridium piliforme* (*n*=3), and West Nile virus infection (*n*=8).

Multivariable models

For both a primary diagnosis of infectious etiology, and for lesions consistent with NLM, the odds of being diagnosed were lower for all species relative to groundhogs; this was statistically significant for eastern gray squirrels, eastern cottontails, eastern chipmunks (*Tamias striatus*), red squirrels (*Tamiasciurus hudsonicus*), and the other species group in both models (Tables 3, 4; see Supplementary Material Tables 1, 2 for univariable models). For beavers (*Castor canadensis*), the relationship was significant only when looking at the odds of an infectious diagnosis (Table 3). In both models, male animals had higher odds of a diagnosis of an infectious disease or NLM compared to female animals (Tables 3, 4). We also observed that animals were significantly more likely to be diagnosed with an infectious primary diagnosis or NLM if they were submitted by a wildlife rehabilitator than if they were submitted by either other submission group (Tables 3, 4). The Pearson chi-squared goodness-of-fit tests for the infectious

TABLE 4. Multivariable logistic regression model examining the association between demographic and submission factors and the identification of histological lesions consistent with neural larva migrans (NLM) in rodents and lagomorphs submitted to Ontario-Nunavut node of the Canadian Wildlife Health Cooperative and the Ontario Veterinary College between January 1989 and December 2018. (The percent of individuals with lesions consistent with NLM is included in parentheses.) Statistically significant values are indicated in boldface type.

Variable	Category (% positive)	Odds ratio	*P* value	95% Confidence interval	Wald χ^2 test[b]
Species[a]	Groundhog (70)		Referent category		**<0.001**
	American beaver (52)	0.31	0.052	0.10–1.01	
	American red squirrel (6)	0.01	**<0.001**	0.001–0.09	
	Eastern chipmunk (8)	0.02	**0.001**	0.003–0.20	
	Eastern cottontail (12)	0.06	**<0.001**	0.02–0.16	
	Eastern gray squirrel (11)	0.04	**<0.001**	0.02–0.08	
	North American porcupine (67)	0.44	0.134	0.15–1.28	
	Other species (13)	0.06	**<0.001**	0.01–0.25	
Sex	Female (23)		Referent category		
	Male (23)	1.95	0.032	1.06–3.59	
Submission type	Wildlife rehabilitation (39)		Referent category		**<0.001**
	Government (11)	0.28	0.002	0.13–0.62	
	Public (19)	0.37	0.002	0.20–0.70	

[a] Scientific names: American beaver (*Castor canadensis*), American red squirrel (*Tamiasciurus hudsonicus*), eastern chipmunk (*Tamias striatus*), eastern cottontail (*Sylvilagus floridanus*), eastern gray squirrel (*Sciurus carolinensis*), groundhog (*Marmota monax*), muskrat (*Ondatra zibethicus*), North American porcupine (*Erethizon dorsatum*). Muskrat was omitted from species analysis because no animals submitted had lesions consistent with NLM.

[b] Used as a global test of significance of variables with >2 categories.

disease (P=0.356) and NLM (P=0.731) models were not statistically significant (i.e., there was no evidence that the models did not fit the data). We also did not identify outliers in either model based on Pearson residuals. We identified one and two covariate patterns with very high influence on the infectious disease and NLM models, respectively, using various diagnostics. However, these observations were retained in the model since there was no valid reason to remove them (e.g., recording errors), and controlling for their effect did not change the interpretation of these models.

DISCUSSION

The most frequently recorded primary diagnoses in rodents and lagomorphs submitted to the CWHC and the Ontario Veterinary College wildlife pathology service between 1989 and 2018 were infectious or inflammatory in nature. Neural larva migrans and the accompanying encephalitis, the most frequent specific diagnosis in these species, are typically associated with *B. procyonis* and other *Baylisascaris* spp. (Sheppard and Kazacos 1997; Kazacos 2016). Although there are few similar studies, NLM, and more specifically *B. procyonis*, is acknowledged as a frequent cause of neurological disease in animals throughout the range of the raccoon (*Procyon lotor*) definitive host (Kazacos et al. 1981; Tseng 1997). For example, based on examining admission reports for eastern cottontail submission to a wildlife rehabilitation center in Minnesota, Santos (2018) suggested that *B. procyonis* may be a primary cause of neurological disease in submitted rabbits.

The majority of species we identified with NLM lesions have previously been identified as potential paratenic hosts for *B. procyonis*, either from naturally occurring (groundhog, beaver, porcupine [*Erethizon dorsatum*], eastern cottontail, American red squirrel, eastern gray squirrel, eastern chipmunk) or from experimental infections (groundhog, laboratory rat [*Rattus norvegicus*], eastern cottontail, eastern gray squirrel, eastern chipmunk; Tiner

1954; Kazacos 2016). Additionally, we identified lesions in three species for which NLM has not been previously reported: the northern flying squirrel (*Glaucomys sabrinus*), southern flying squirrel (*Glaucomys volans*), and snowshoe hare (*Lepus americanus*).

Reports of NLM in groundhogs appear most frequently in the literature describing this condition in rodents and lagomorphs (e.g., Richter and Kradel 1964; Roth et al. 1982), and this was the animal species in our database with the highest number of cases and proportional morbidity due to NLM. It is possible that groundhogs are more susceptible to *Baylisascaris* spp. larval migration, but their size and behavior may contribute to the large number of reports: groundhogs are most active during the day and are often found in proximity to humans, which may make any abnormal behavior more likely to be observed (Flemming and Caslick 1978).

Additionally, controlling for species, we found that male animals had greater odds of being diagnosed both with an infectious disease and with NLM specifically. Given the known sex-based differences in immune function and infection prevalence in mammals, this finding may have a biological explanation (Klein and Flanagan 2016). Alternatively, there may be a behavioral component associated with sex that affects the types of mortality events that are most frequently found by people.

Neural larva migrans cases in North America are typically attributed to *B. procyonis*, but histologically the larvae of *Baylisascaris* spp. cannot be differentiated (Flemming and Caslick 1978; McKown et al. 1995; Bugmyrin and Spiridonov 2019). Diagnosis of the specific species is often based on supporting epidemiological evidence, such as the presence of, or history of the area being used by, raccoons (Fitzgerald et al. 1991; Kazacos 2001; Thompson et al. 2008). Although *B. procyonis* is considered the most pathogenic species in rodents (Tiner 1953b; Sprent 1968; Kazacos 2016), it is important to recognize that skunks (*Mephitis mephitis*), American badgers (*Taxidea taxus*), and American black bears (*Ursus americanus*) are found in Ontario, and their associated *Baylisascaris* spp. (*B. columnaris*, *B. melis*, and *B. transfuga*, respectively) could contribute to a subset of these cases. Furthermore, without visualization of individual larvae, diagnosis is presumptive, based on characteristic histological lesions, so such findings may represent infections with other nematode larvae.

Abnormal behavior, as well as carcasses, is generally more conspicuous with larger mammals, and thus more likely to be noticed by concerned citizens (Kazacos et al. 1981), whereas smaller mammals may not be seen in the environment (Stallknecht 2007) or may rapidly decompose (Wobeser and Wobeser 1992). Our data support this, with 40% of submissions comprising animals over 1 kg whereas only 9% of submissions were less than 150 g.

In addition to bias associated with species submissions, the geographic distribution of our submissions was not evenly distributed across Ontario, a bias that becomes more dramatic for species with fewer submissions. Of the total submissions, 95% were from the OMNR's southern region, and 62% of all submissions came from only two districts: Aurora, which includes the Greater Toronto Area, and Guelph, where the Ontario-Nunavut node of the CWHC is located. The types of cases submitted are dependent on human observation (Stallknecht 2007), thus it is possible that in unrepresented areas the causes of morbidity and mortality may be different from those reported here. Due to a lack of specific location data (i.e., GPS points or addresses of collection) a finer scale control for geographic distribution could not be performed.

A large proportion of our submissions (32%) were received from wildlife rehabilitation centers, which likely influenced the distribution of primary diagnoses we identified. Based on our regression model, animals were significantly more likely to be given a diagnosis that was infectious in origin if they were submitted by a wildlife rehabilitation center. These facilities would probably not submit cases in which the cause of morbidity or mortality is clear (e.g., trauma) and would focus on infectious cases that may have consequences

for their captive populations and unusual cases with an unclear pathogenesis. After controlling for submitter type, we still identified differences in disease diagnoses by species, indicating the importance of controlling for submitter type or source in these types of studies. It is also important to note that receiving a large number of submissions from a single source or event may inflate the perceived importance of a specific pathogen and influence descriptive statistics. For example, in our data set a large number of eastern cottontails were submitted during an outbreak of *P. multocida* at one facility, making it the second most frequently diagnosed infectious cause of disease in our database.

Despite these challenges, passive surveillance is an excellent tool for identifying new and emerging pathogens (Morner et al. 2002). For example, CWHC surveillance data identified *E. multilocularis* infection in a new intermediate host species and for the first time in Ontario (French et al. 2018). Passive surveillance is also potentially excellent for identifying rare events (Morner et al. 2002). As such, we identified cases of tularemia (*F. tularensis*) in beavers, Tyzzer's disease (*C. piliforme* infection) in muskrats, and toxoplasmosis (*T. gondii* infection) and West Nile virus in eastern gray squirrels, which, although identified rarely, are caused by pathogens of public health and veterinary significance. Such discoveries can also provide evidence to guide development of future investigations and hazard-specific surveillance.

Knowledge of common pathogens in different animal species can aid in treatment decisions, as well as in sample collection and test requisition during post-mortem examination. Since abnormally behaving rodents and rabbits may be submitted as rabies suspects, by reporting other pathologies associated with abnormal behavior these cases may undergo full post-mortem examination more frequently, leading to a diagnosis (Flemming and Caslick 1978; Kazacos et al. 1981; Roth et al. 1982).

Last, assessment of surveillance data provides information about the natural history of various pathogens and their potential importance in the population dynamics of specific species. This, in turn, can inform detailed research into disease ecology. Continued identification of the conditions observed in wildlife populations is important for developing and prioritizing actions to protect human, domestic animal, and wildlife health (Stephen 2015).

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SUPPLEMENTARY MATERIAL

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