Causes of Morbidity and Mortality in Wild Raptors of Northern California Presented to the University of California, Davis Veterinary Medicine Teaching Hospital from 1995-2022

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Abstract

Morbidity and mortality studies using data from wildlife rehabilitation facilities can be useful for understanding threats to free-ranging raptor populations. This study utilized medical and necropsy records of free-ranging sick and/or injured raptors presenting to the UC Davis Veterinary Medicine Teaching Hospital from 1995-2022 (n=3,840). A similar published study evaluating raptors at the same institution from 1983-1994 provides a unique opportunity to assess patterns in morbidity and mortality among raptors presenting to this hospital over a forty-year period. A supervised machine-learning approach was utilized to classify each case according to a diagnostic category from free text data entered into the fields of ‘presenting complaint,’ ‘physical exam findings,’ and ‘clinical diagnosis,’ in the raptors’ medical records. Diagnostic categories were entered manually from necropsy records. A time series analysis evaluated trends over time in numbers of raptor admissions and logistic regression models evaluated factors associated with increased odds of survival. Red-tailed hawks (*Buteo jamaicensis*), barn owls (*Tyto alba*), and great-horned owls (*Bubo virginianus*) were the most common species admitted to the hospital for clinical care. This dataset, compared to the previously published study, had comparatively fewer western screech owls (*Megascops kennicottii*) and American kestrels (*Falco sparverius*) while red-shouldered hawks (*Buteo lineatus*) and Cooper’s hawks (*Accipiter cooperii*) numbers were increased. The most common infectious diseases identified were *Aspergillus* spp., *Chlamydia* spp., West Nile virus (WNV), and *Trichomonas* spp. Overall, traumatic injury and infectious disease were the most common causes of morbidity and mortality in this study. No significant trends were detected in the numbers of cases presenting across our study period nor in the numbers of traumatic, infectious, and orphaned cases. Disease category, life stage, and season were significantly associated with survival. Birds with an infectious diagnosis had lower odds of survival while orphaned birds had higher odds of survival. Species, life stage, and season were significantly associated with infectious disease status. Summer, fall, and winter were associated with a higher odds of aspergillosis. Diurnal species also had higher odds of being diagnosed with aspergillus. Winter and spring seasons, diurnal species and sub-adult birds were all significantly associated with a chlamydia diagnosis. Summer, diurnal and adult life stage were significantly associated with WNV diagnosis. Nocturnal species was significantly associated with trichomoniasis diagnosis. The data compiled over this extensive forty-year period provides a valuable resource for understanding the causes and dynamics of morbidity and mortality in California raptor populations, which can be useful in informing wildlife conservation strategies and rehabilitation efforts.

Introduction

Due to their ecological position as top predators and their sensitivity to environmental change, raptors can serve as sentinel species or valuable indicators of the health of the environment and potential threats to other species. Furthermore, raptors provide valuable ecosystem services as scavengers and predators, contributing to the removal of carrion that can serve as a source of pathogens; preventing expansion of invasive, facultative scavenger species; and preying on pest species (Buechley and Şekercioğlu 2016; Jareño et al. 2023). Understanding causes of mortality and anthropogenic impacts on birds of prey can therefore be important for ecosystem conservation efforts. Analysis of morbidity and mortality data has been used to gauge threats to free-ranging raptor populations globally (Fix and Barrows 1990; Deem et al. 1998;

Morishita et al. 1998; Wendell et al. 2002; Ress and Guyer 2004; Komnenou et al. 2005; Rodriguez et al. 2010; Molina-López et al. 2011; Thompson et al. 2013; Montesdeoca et al. 2016; Smith et al. 2018; Hernandez et al. 2018; Panter et al. 2022; Cococcetta et al. 2022; Kadlecova et al. 2022). These studies have revealed that in addition to infectious diseases, raptors commonly die from anthropogenic causes such as collisions with man-made structures, exposure to environmental toxins, and electrocution. For example, DDT historically contributed to the population decline of many avian species, including bald eagles (*Haliaeetus leucocephalus*) and peregrine falcons (*Falco peregrinus*) (Cox 1991). A ban on DDT use in the U.S. coupled with reintroduction efforts have allowed bald eagle and peregrine falcon populations to rebound (Grier 1982; Sorenson et al. 2017). In addition, deaths due to the ingestion of carrion contaminated with lead from ammunition in one of the most critically endangered birds, the California Condor (*Gymnogyps californianus*), affected a total legislative ban on the use of lead ammunition for hunting in California in 2019, partially achieving policy objectives for reducing cases of lead poisonings in this endangered species (Schulz et al. 2023).

Morbidity and mortality records from wildlife rehabilitation organizations can serve to illustrate how threats to free-ranging raptors change over time. For instance, several infectious diseases of importance to raptors have emerged in recent history, significantly altering reasons for presentation to wildlife rehabilitation organizations (Alba et al. 2017; Hall et al. 2024). Rehabilitation records can be useful for learning about these diseases that would otherwise be difficult to study in free-ranging raptor populations (Alba et al. 2017; Hall et al. 2024). The causes of morbidity and mortality among free-ranging raptors has also been found to vary seasonally, highlighting the importance of understanding temporal patterns for informing raptor conservation efforts. For instance, some infectious diseases of raptors, including West Nile Virus

(WNV) and chlamydiosis, demonstrate distinct seasonal patterns (Ellis et al. 2007; Seibert 2017; Alba et al. 2017; Seibert et al. 2021). Published reports also indicate seasonality in the incidence of traumatic injury in raptors (Molina-López et al. 2011). Both long-term trends and seasonal variations in the various species admitted to rehabilitation organizations have also been observed (Panter et al. 2022; Cococcetta et al. 2022). Temporal patterns in the number and species admitted to rehabilitation organizations are also informative, as they may indicate high-risk time periods during which there is increased vulnerability of and/or threats to certain species. Admission patterns over time and season could also indicate a changing abundance or distribution of a species, as there is evidence for distribution shifts in several raptor species likely in response to climate change (Paprocki et al. 2014).

Variables pertaining to individual raptors, such as species and life stage, can also influence the infectious diseases that threaten raptor populations. For example, infectious disease risk in raptors can vary according to differences in age-class, foraging behavior, prey sources, habitat utilization, and evolutionary histories. There have been trends in life stage observed with WNV, although the results are not entirely straightforward: one study revealed a higher odds of WNV in immature red-tailed hawks as compared to adults (Smith et al. 2018); on the other hand, investigators in Ontario found that birds over one year of age were more likely to experience mortality due to WNV (Gancz et al. 2004). Species differences have also been observed, with barn owls exhibiting less severe clinical signs and lesions with WNV infection compared to other species, such as red-tailed hawks (Nemeth et al. 2006). Furthermore, a serology study of owl species in northern California only found 1/71 samples testing positive for WNV, perhaps suggesting they are less likely to be exposed (Captanian et al. 2017). In addition, trichomoniasis, another common infectious disease of raptors, is more prevalent in young birds, as has been documented in nestling Cooper's hawks: this increased prevalence is believed to be linked to differences in oral pH in nestlings and other age classes (Urban and Mannan 2014). Similarly, species differences in vulnerability have been reported : in Spain, a relationship between trichomoniasis lesion severity and avian order was demonstrated, with Falconiformes and Strigiformes exhibiting more severe lesions compared to Accipitriformes (Martínez-Herrero et al. 2020).

Several factors influence the likelihood of survival and release of wild animals following rehabilitation, including issues related to their initial presentation as well as conditions that may develop during their care. This includes euthanasia of animals due to severe illness or injury that precludes successful recovery for release back to the wild. While researchers have investigated factors that contribute to successful wildlife rehabilitation outcomes, few studies have specifically focused on raptors. Studies investigating a range of wildlife species have identified severity of injury, clinical diagnosis, season, and body condition as factors that influence the likelihood of survival and release back to the wild (Kelly and Bland 2006; Molony et al. 2007; Parsons et al. 2018). A study of raptor rehabilitation conducted in Italy determined that season of admission, body condition score (BCS), and reason for admission all significantly influenced the odds of raptor survival (Cococcetta et al. 2022). Raptors presenting to organizations in South Africa as a result of being orphaned or grounded (unable to fly) had a significantly higher odds of survival until release than those that were involved in a vehicle collision (Maphalala et al. 2021). Similarly, a study in Great Britain found orphaned raptors to have higher odds of survival than birds with infectious diseases (Panter et al. 2022). These studies are informative for determining prognosis for rehabilitation patients and prioritizing cases that have a higher probability of successful release.

The goal of this study was to investigate causes of morbidity and mortality in free-ranging raptors presenting to the UC Davis Veterinary Medicine Teaching Hospital (VMTH) from 1995 through 2022. The VMTH is associated with the California Raptor Center, a rehabilitation and educational center that works exclusively with raptors. We aimed to determine factors that influenced the odds of survival until release in this patient cohort. We also aimed to assess the most common infectious diseases affecting this population of raptors, and explore factors that may place birds at a higher risk of death due to these diseases. A prior study examined the causes of morbidity and mortality in raptors admitted to this same hospital from 1983-1994 (Morishita et al. 1998), provided a unique opportunity to compare causes of raptor mortality observed at the same institution over a 40-year period.

Methods

Medical Records

All medical records of raptor species native to California and admitted to the VMTH from 01/01/1995 through 12/31/2022 were extracted from the hospital's patient records database (the Veterinary Medical and Administrative Computer System). Only data from the first visit for each individual bird were retained for this study. The data fields extracted for analyses were: date, species, sex, life stage (adult versus sub-adult), presenting complaint/reason for admission, physical examination findings, clinical diagnosis, and disposition (alive, dead, or euthanized). Adult versus sub-adult classification was based on which of these designations was entered into the medical record by the clinician. Because the UC Davis VMTH also provides care for non-releasable educational ambassador birds from nearby zoos and raptor centers, birds with medical records ranging over more than one year were excluded from the study.

Classification of Raptor Cases According to Diagnostic Categories

To classify all the raptor cases into distinct diagnostic categories for the purposes of analysis, a supervised machine-learning approach was employed, utilizing a Bidirectional Encoder Representations from Transformers (BERT)-based model fine-tuned for multi-class, multi-label classification of cases. The model used free text data entered into the fields of 'presenting complaint,' 'physical exam findings,' and 'clinical diagnosis,' in the raptors' medical records to derive diagnostic categories for each case.

A total of 1,006 raptor cases were randomly selected to form the training dataset for the machine learning model. Each case was annotated with one or more of the diagnostic categories by a subject matter expert (traumatic, infectious, inflammatory, orphaned, congenital, toxicosis, and undetermined). From this dataset, 20% (approximately 200 cases) were randomly chosen to create an independent test dataset for model validation, while the remaining 80% was used for training and cross-validation of the model.

The text data were preprocessed using the "bert-base-uncased" tokenizer from the Hugging Face Transformers library (Wolf et al. 2020). The tokenizer converts the input text into tokenized sequences by applying subword tokenization, segmenting words into meaningful pieces. Unlike a "bag of words" approach (Zhang et al. 2010), this method preserves the context and order of words, which is crucial for understanding the nuances of clinical language. The classification model was built using the AutoModelForSequenceClassification function, which leverages a pre-trained BERT model as the backbone. The model architecture included an input layer which took in tokenized text sequences, each padded to a fixed length (up to 256 tokens) to accommodate the BERT model's requirements. This was followed by a layer with classification head which includes a dense layer that maps the final hidden state of the [CLS] token (a special token representing the entire sequence) to a vector of logits, with a dimension equal to the number of diagnostic categories (number of labels = 6). In this case, a sigmoid activation was used to handle the multi-label classification, where each label is predicted independently with the final vector of probabilities corresponding to each diagnostic category as an output. The entire modeling process, including tokenization, training, and evaluation, was implemented in Python using the Hugging Face Transformers and Datasets libraries (Wolf et al. 2020).

Pathology Records

An additional and separate search was performed to retrieve all pathology records of raptor species native to California from another VMTH database maintained by the VMTH Anatomic Pathology Service from the same time period. The data fields extracted for analysis were: date of request, species, sex, life stage, clinical abstract, necropsy findings and diagnoses, and final comments. Birds determined to have been in captivity for at least one year as per the clinical abstract in the pathology record were also excluded from analysis. Additionally, only pathology records with full necropsies performed were retained for analysis.

The primary cause of mortality from the pathology records was determined for each record by evaluating all sections of the pathology report. Cause of mortality was categorized using the following diagnostic categories: vascular, metabolic, neoplastic, degenerative, congenital, inflammatory, toxicologic, nutritional, infectious, traumatic and undetermined. Traumatic and infectious causes of death were further subcategorized, as these were the two most common categories observed in the dataset. Individuals with more than one cause of mortality were also noted and contributing mortality causes were classified according to the same scheme. Information from the pathology report was also used to generate data for the life stage and sex data fields whenever possible.

Time Series Analysis

Time series analyses were performed to evaluate trends in admissions for the overall number of cases as well as for all cases of infectious disease, traumatic injury, and orphaned animals in the clinical dataset. These diagnostic categories were selected for time series analyses because they had sufficient sample size to evaluate trends. To assess the presence of trends within each time series, a Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test for trend was performed.

Factors Associated with Survival

A logistic regression model was developed to investigate factors associated with survival until release in raptors using data entered into the birds' medical records. The outcome of interest was bird status (alive or dead/euthanized). Predictors evaluated in the model included: species, life stage, season of admission, presence of feather lice, BCS, diagnostic category (traumatic injury, infectious, inflammatory, orphaned, and toxicosis), and presence of comorbidity. Because the accuracy of model predictions for congenital and toxicologic cases was low, these diagnostic categories were not included in the model. Life stage was categorized as adult or sub-adult, as indicated in the medical record. Season of admission was organized as: fall (September 1st – November 30th, winter (December 1st – February 28th), spring (March 1st – May 31st), and summer (June 1st – August 31st). Each bird was categorized as to whether it was a diurnal or nocturnal species. BCS (1-9) was collapsed into two categories (thin: scores 1-3 and not thin: scores 4-9). A bird was indicated to have a comorbidity if they had more than one diagnostic category as predicted by the machine learning model. Feather lice was explored as an indicator of level of debilitation (Hudelson and Hudelson 1995).

Predictors with significance ($p<0.05$) in the univariate modeling were incorporated into both full main effects and interaction effects multivariable logistic regression models. Prior to building the model, directed acyclic graphs were generated to assess for confounding. Predictors with significance in the full main effects or interaction effects model were then entered into a backward stepwise selection process to select the best fitting model based on Akaike information criterion (AIC) score (Bozdogan 1987). Variance inflation factor was evaluated to assess for multicollinearity of interdependent variables. The final model fit was evaluated by The Hosmer Lemeshow Goodness of Fit test and graphical residual diagnostics. Adjusted odds ratios with 95% confidence intervals were estimated to assess the strength of association between each factor and survival.

Factors Associated with Infectious Diseases as Cause of Mortality

Additional logistic regression models were performed for the most common infectious diseases in the pathology dataset: aspergillosis, WNV, chlamydiosis, and trichomoniasis. The outcome of interest was whether a bird had a diagnosis of each disease at time of necropsy. Predictors of interest included in each model were: season of admission, sex, life stage (adult versus sub-adult), and species according to activity pattern (nocturnal versus diurnal).

Predictors with significance ($p<0.05$) in the univariate modeling were incorporated into full main effects and interaction effects multivariable logistic regression models. Predictors with significance in the full main effects or interaction effects model were then entered into a backward stepwise selection process to select the best fitting model based on Akaike information criterion (AIC) score. Variance inflation factor was evaluated to assess for multicollinearity of interdependent variables. The final model fit for each model was evaluated by the Hosmer Lemeshow Goodness of Fit test ($p>0.05$) and residual diagnostics. Adjusted odds ratios with

95% confidence intervals were estimated to assess the strength of association between each factor and disease status.

All statistical analyses were performed in R (R Core Team 2023), using the MASS and tseries packages (Venables and Ripley 2002; Trapletti and Hornik 2023).

Results

Descriptive Results from Medical Records

Medical records for wild raptors admitted to the UC Davis VMTH from 1995-2022 (n = 9,385) were extracted from the VMTH database. Any captive birds were excluded and only the first visit for each patient was retained (n=3,840) (Table 1). These records encompassed 26 species representing three orders of birds (15 species within Acciptiriformes, three species within Falconiformes, and eight species within Strigiformes) (Table 2). The most common species represented within the dataset were barn owls (*Tyto alba*) (n =909, 23.7%) followed by red-tailed hawks (*Buteo jamaicensis*) (n=852, 22.2%) and great horned owls (*Bubo virginianus*) (n=312, 8.3%). Among birds with data on BCS in the medical record (2,550/3,840), the majority were thin (n=1,465, 57.5%). For birds with information on life stage in the medical record (2,224/3,840), more were adults (n=1,410, 63.4%) than (n=814, 36.6%). Sex was recorded for only 250/3,840 (6.5%) raptors; 47.8% of these were female and 52.2% were male. The season with the greatest percentage of admissions was summer (n=1,347, 35.1%), followed by winter (n=868, 22.6%), spring (n=835, 21.7%), and fall (n=790, 20.6%). The most common diagnostic category was traumatic injury (n=2,466, 64.2%) followed by infectious disease (n=470, 12.2%), orphaned (n=185, 4.8%), toxicologic (n=26, 0.7%), inflammatory (n=22, 0.6%), and congenital disease (n=4, 0.1%). These categories were generated using the machine learning model, which was highly accurate for classifying raptors according to common reasons for admission (traumatic injury (93.0%), inflammatory disease (67.0%), orphaned (89.0%), and infectious disease (90.0%)), and moderately accurate for classifying cases with less common diagnostic categories such as toxicosis (47.0%) and congenital disease (57.0%) (Figure 1). Evidence of feather lice was noted in 12.6% of the individuals (n=485).

Table 1: Characteristics of free-ranging raptors presenting to the UC Davis VMTH from 1995-2022, that survived or died/were euthanized during the rehabilitation process.

Description of Medical Record Dataset

Characteristic	Survived (n=1,360)	Died/Euthanized (n=2,480)	p value[1]
Evidence of Feather Lice	164 (12.1%)	321 (12.9%)	0.4
Body Condition Score			<0.001
Not Thin (BCS 4-9)	510 (37.5%)	575 (23.2%)	
Thin (BCS 1-3)	428 (31.5%)	1,037 (41.8%)	
Uncertain	422 (31.0%)	868 (35.0%)	
Life Stage			<0.001
Adult	435 (32.0%)	975 (39.3%)	
Sub-Adult	415 (30.5%)	399 (16.1%)	
Uncertain	510 (37.5%)	1,106 (45.0%)	
Season Admitted			<0.001
Autumn	235 (17.3%)	555 (22.4%)	
Spring	378 (27.8%)	457 (18.4%)	
Summer	516 (37.9%)	831 (33.5%)	
Winter	231 (17.0%)	637 (25.7%)	
Species			0.001
Diurnal	756 (55.6%)	1,513 (61.0%)	
Nocturnal	604 (44.4%)	967 (39.0%)	
Infectious Diagnosis	145 (10.7%)	325 (13.1%)	0.027
Traumatic Diagnosis	690 (50.7%)	1,776 (71.6%)	<0.001
Orphaned Diagnosis	149 (11.0%)	36 (1.5%)	<0.001
Toxicosis Diagnosis	12 (0.9%)	14 (0.6%)	0.3
Inflammatory Diagnosis	7 (0.5%)	15 (0.6%)	0.7
Other/Undetermined Diagnosis	401 (29.5%)	408 (16.5%)	<0.001

[1] Pearson's Chi-squared test

Table 2: Distribution of raptor species presenting to the UC Davis VMTH, represented in the medical records (“Clinical”), and necropsied by the Anatomic Pathology Service, represented in the pathology dataset (“Pathology”), from 1995-2022.

Species Distribution in Medical and Pathology Datasets (% of Cases)

Species	Clinical	Pathology
American Kestrel (*Falco sparverius*	2.1	1.6
Bald Eagle (*Haliaeetus leucocephalus*)	0.8	1.9
Barn Owl (*Tyto alba*)	23.7	17.4
Burrowing Owl (*Athene cunicularia*)	1.5	1.3
Cooper's Hawk (*Accipiter cooperii*)	4.8	6.3
Ferruginous Hawk (*Buteo regalis*)	0.1	0.2
Flammulated Owl (*Psiloscops flammeolus*)	0.05	0.09
Golden Eagle (*Aquila chrysaetos*)	1.8	3.6
Goshawk (*Accipiter gentilis*)	0.1	NA
Great Grey Owl (*Strix nebulosa*)	0.05	0.09
Great Horned Owl (*Bubo virginianus*)	8.1	8.4
Long Eared Owl (*Asio otus*)	0.2	0.3
Northern Harrier (*Circus cyaneus*)	1.1	1.3
Osprey (*Pandion haliaetus*)	0.3	0.7
Peregrine Falcon (*Falco peregrinus*)	1.0	1.1
Prairie Falcon (*Falco mexicanus*)	0.2	0.4
Red-Shouldered Hawk (*Buteo lineatus*)	5.7	5.7
Red-Tailed Hawk (*Buteo jamaicensis*)	22.2	31.2
Rough-Legged Hawk (*Buteo lagopus*)	0.1	0.4
Sharp Shinned Hawk (*Accipiter striatus*)	0.8	1.0
Spotted Owl (*Strix occidentalis*)	0.1	NA
Swainson's Hawk (*Buteo swainsoni*)	2.4	2.4
Turkey Vulture (*Cathartes aura*)	1.9	1.9
Unidentified Eagle	0.1	NA
Unidentified Falcon	0.6	0.2
Unidentified Hawk	10.2	5.4
Unidentified Owl	5.9	1.6
Western Screech Owl (*Megascops kennicottii*)	1.3	2.0
White-Tailed Kite (*Elanus leucurus*)	2.7	2.8
Northern Pygmy Owl (*Glaucidium californicum*)	NA	0.09
Spotted Owl (*Strix occidentalis*)	NA	0.4

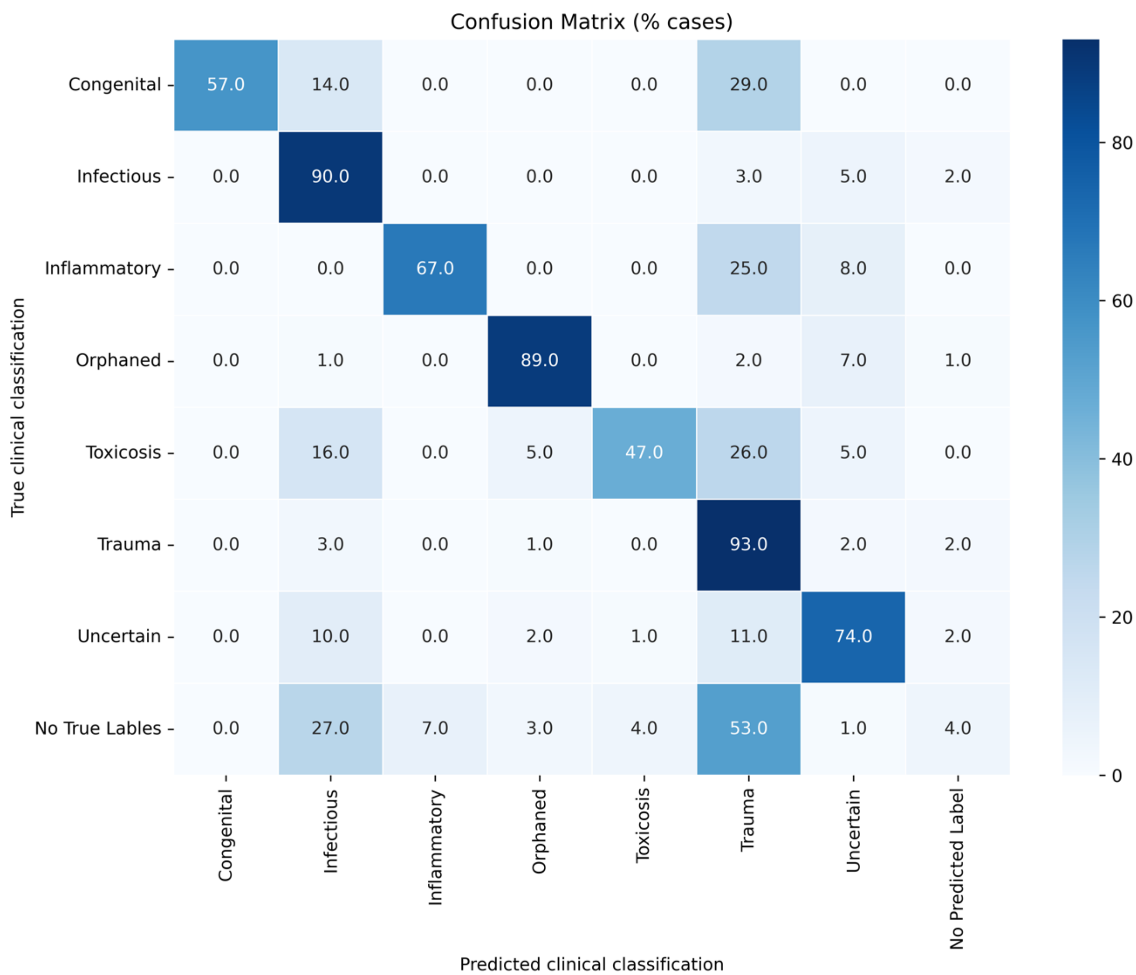

Figure 1: The confusion matrix compares the machine learning model's predicted classifications to classifications manually designated by an expert. The proportion of raptor cases in the medical records (clinical dataset) correctly categorized by the machine learning model is displayed.

Descriptive Results from Pathology Records

Complete post-mortem examinations were performed by the VMTH Anatomic Pathology Service on a portion (n=1,125) of raptor patients that died or were euthanized. Species representation in this pathology dataset was similar to the larger clinical record dataset, with the exception that the most common species in the pathology dataset was the red-tailed hawk while the most common species in the medical record dataset was the barn owl. Among the birds in the necropsy dataset, 44.4% were adults and 55.6% were sub-adults. Sex was identified in the majority of pathology cases (n=969/1,125) with an almost even distribution between males (46.7%) and females (53.3%). The most common cause of death in these birds was traumatic injury (n=458) followed by infectious disease (n=413). Among birds that died or were euthanized as a result of traumatic injury, the specific causes of the injury were most often unknown (n=335) with vehicle collision (n=38), gunshot (n=23), window collision (n=14) and electrocution (n=12) reported for those cases with known causes. Among birds with infectious disease as the cause of death, the most common infectious diseases were aspergillosis (n=105), West Nile virus (n=81), chlamydiosis (n=51), and trichomoniasis (n=42). Some birds (15.7%) had more than one contributing cause of mortality; 25.0% of birds who died or were euthanized due to traumatic injury also had evidence of infectious disease.

Time Series Analysis

Annual raptor admissions to the UC Davis VMTH ranged from 55 (in 2022) to 180 (in 2004), with a mean of 129 raptor patients admitted each year (Figure 2). Survival was variable across years, with the highest survival in 2005 (48.9%) compared to the lowest in 2019 (10.4%). Overall survival across all years was 34.8%.

No trend was detected in the number of infectious cases by month over the study period (p=0.1). However, there was a significant downward trend in the overall number of cases by month over time (p=0.01) as well as the number of orphaned (p=0.02) and traumatic injury cases (p=0.01). Visual inspection of the decomposed plots revealed a substantial decrease in the overall number of admissions in the last four years of the study period (2019-2022). The aforementioned significant trends were no longer significant when a subset of the data excluding

2019-2022 was explored to better understand the stationarity of the time series (overall: p=0.08, orpahend: p=0.06, traumatic: p=0.1).

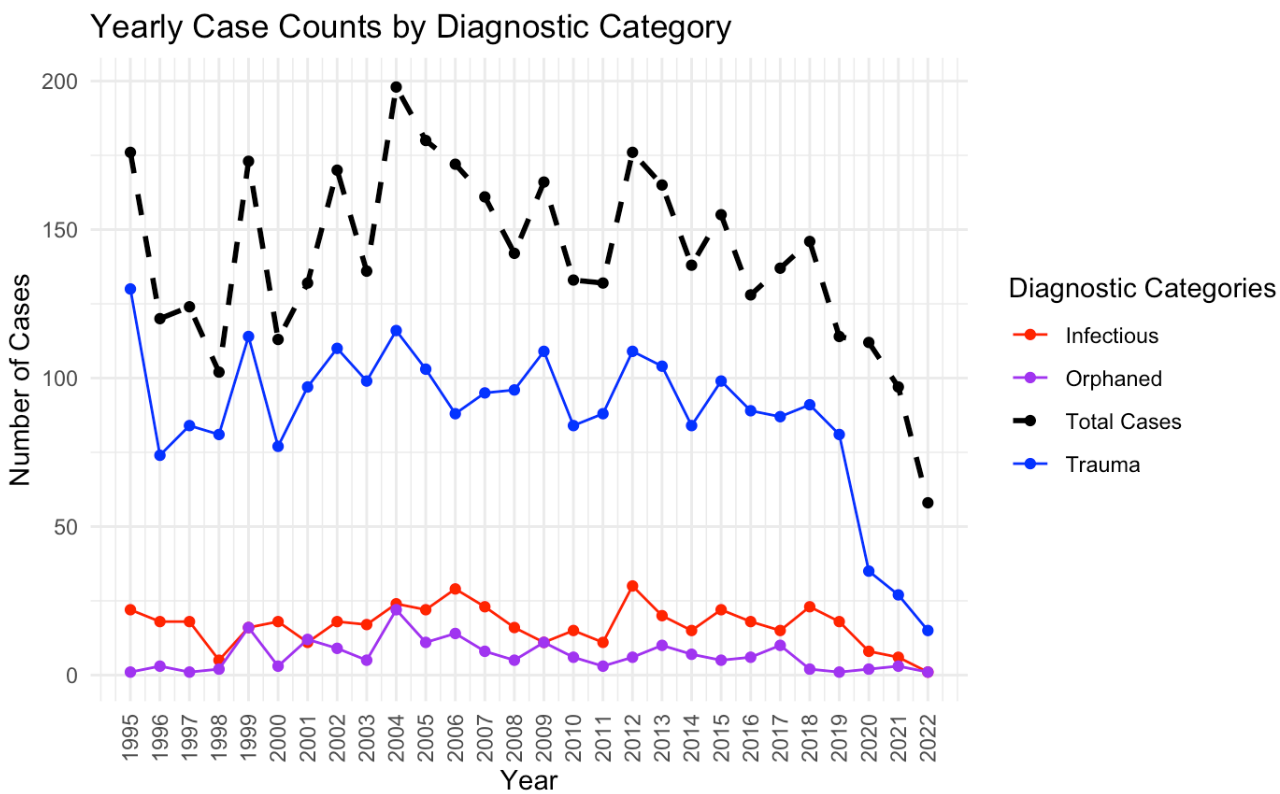

Figure 2: Number of infectious, traumatic, orphaned, and total cases of raptors presenting to the UC Davis VMTH over time from 1995-2022.

Factors Associated with Survival in Raptors Undergoing Rehabilitation

Several factors were explored for association with survival (as opposed to death or euthanasia during rehabilitation). These included diagnostic category (traumatic, infectious, inflammatory, and orphaned), diurnal versus nocturnal species, season of admission, life stage, evidence of ectoparasites, presence of comorbidity, and body condition. Because sex was known for so few cases, it was not included in the analyses. The final best-fitting model included the following predictors: the main effects of season, body condition, life stage, traumatic injury, orphaned, and infectious disease, as well as the interaction effects of traumatic injury and season, body condition, and life stage (Table 3, Figure 3). An orphaned diagnosis was associated with an increased odds of survival (OR=3.1, 95% CI 2.1-4.7, p<0.0001), with orphaned birds having 3.1 times higher odds of survival compared to those without an orphaned diagnosis. Alternatively, the results demonstrated that infectious disease was significantly associated with a decreased odds of survival (OR=0.7, 95% CI 0.5-0.9, p<0.001, with animals diagnosed with infectious disease having a 33% lower odds of survival compared to those without an infectious diagnosis.

Birds presenting with traumatic injuries had lower odds of survival (OR = 0.6, 95% CI 0.4-0.9, p=0.01) with 43% lower odds of survival in injured birds compared to those without a traumatic injury diagnosis. Similarly, birds in poor body condition had lower odds of survival (OR = 0.3, 95% CI 0.2-0.4, p<0.0001) with animals in poor body condition (thin) having 71% lower odds of survival compared to birds that were categorized as “not thin”. The interaction between traumatic injury and being in the thin BCS category was significant in the model (OR=1.9, 95% CI 1.3-2.7, p<0.001). The odds ratio suggests that the combined presence of both factors (i.e., traumatic injury and thin BCS) has a positive effect on survival, with a 1.9 times higher odds of survival in birds with both factors compared to birds with neither condition.

Patients presenting in spring and summer had increased odds of survival (OR = 2.4, 95% CI 1.6-3.6, p<0.0001; OR = 1.8, 95% CI 1.3-2.6, p<0.001, respectively), compared with winter: birds presenting in spring had 2.4 times higher odds of survival than birds presenting in the winter, while birds presenting in the summer had 1.8 times higher odds of survival than birds in winter. However, the interaction between traumatic injury diagnosis and season (spring and summer) was significant and negative (spring: OR=0.6, 95% CI 0.3-0.9, p=0.01; summer: OR=0.6, 95% CI 0.4-0.9, p=0.02). This indicates that the combined effect of a traumatic injury diagnosis and presenting in spring or summer reduced the odds of survival compared to animals with neither condition. In addition, sub-adults had 2.4 times higher odds of survival (OR=2.4, 95% CI 1.7-3.3, $p<0.0001$) compared to adults. The interaction between traumatic diagnosis and life stage (sub-adult) was significant and negative (OR=0.5, 95% CI 0.3-0.8, $p<0.001$). Therefore, subadult raptors with a traumatic diagnosis had lower odds of survival compared to the baseline group (adult raptors without traumatic injury).

Table 3: Results from the best fitting logistic regression model for predicting survival in wild raptor cases presenting to the UC Davis VMTH from 1995-2022. Odds ratios, 95% confidence intervals, and p values are reported.

Variable	Odds Ratio	95% Confidence Interval	p value
Body Condition Score			
Thin (BCS 1-3)	0.3	0.2-0.4	<0.0001
Uncertain	0.4	0.3-0.6	<0.0001
Not Thin (BCS 4-9) (Reference Category)			
Life Stage			
Sub-Adult	2.4	1.7-3.3	<0.0001
Uncertain	1.1	0.8-1.4	0.7
Adult (Reference Category)			
Season Admitted			
Spring	2.4	1.6-3.6	<0.0001
Summer	1.8	1.3-2.6	<0.001
Autumn	1.1	0.7-1.6	0.8
Winter (Reference Category			
Diagnostic Category			
Infectious	0.7	0.5-0.9	<0.001
Traumatic	0.6	0.4-0.9	0.01
Orphaned	3.1	2.1-4.7	<0.0001
Traumatic Diagnosis + Sub-Adult	0.5	0.3-0.8	<0.001
Traumatic Diagnosis + Uncertain Life Stage	0.8	0.5-1.1	0.1
Traumatic Diagnosis + Thin (BCS 1-3)	1.9	1.3-2.7	<0.001
Traumatic Diagnosis + Uncertain BCS	1.4	0.9-2.1	0.1
Traumatic Diagnosis + Spring Admission	0.6	0.3-0.9	0.01
Traumatic Diagnosis + Summer Admission	0.6	0.4-0.9	0.02
Traumatic Diagnosis + Autumn Admission	1.1	0.7-1.8	0.8

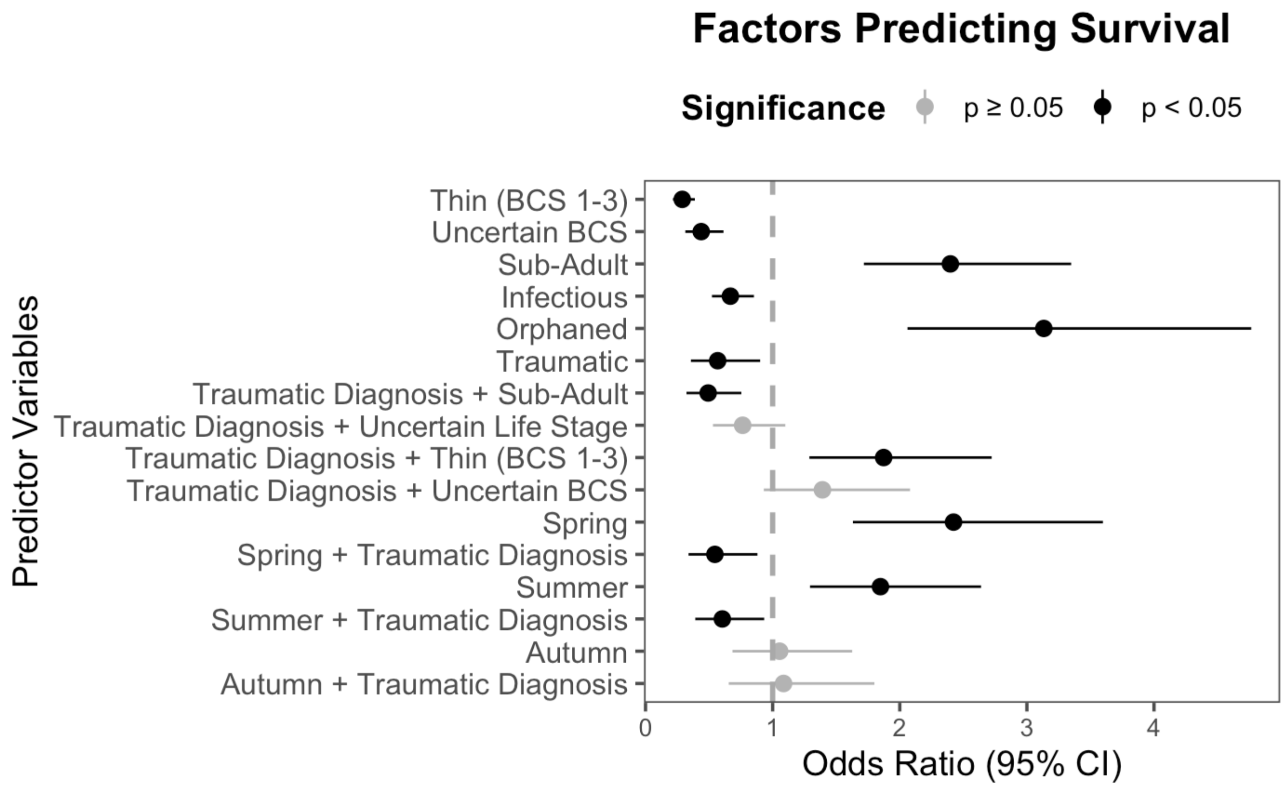

Figure 3: Results from the best fitting logistic regression model for predicting survival in wild raptor cases presenting to the UC Davis VMTH from 1995-2022. Odds ratios are displayed with their 95% confidence intervals.

Factors Associated with Death due to Infectious Disease Cause

Logistic regression models were used to evaluate factors associated with death due to each of the most common infectious disease agents compared to other causes of death. Predictors evaluated in each model were: diurnal versus nocturnal species, season, life stage, and sex. The best fitting model for West Nile virus included season, species (diurnal versus nocturnal), and life stage (Table 4, Figure 4). Birds had a significantly higher odds of dying due to West Nile virus (OR=2.8, 95% CI 1.4-5.5, p=0.004) in the summer months as compared to the fall, while birds dying in the spring (OR=0.1, 95% CI 0.01-0.8, p=0.03) or winter (OR=0.2, 95% CI .04-0.5, p=0.004) had significantly lower odds of dying due to West Nile virus relative to fall. This indicates that birds who died or were euthanized in the summer had 2.8 times the odds of being diagnosed with West Nile virus compared to the fall. Furthermore, diurnal species had a significantly higher odds of dying due to West Nile virus than nocturnal species (OR=34.9, 95% CI 4.8-255.2, $p<0.001$). This indicates that diurnal species had 35 times the odds of being diagnosed with West Nile virus on necropsy compared to nocturnal species. Similarly, adults had a higher odds of dying due to West Nile virus as compared to sub-adult raptors (OR=1.9, 95% CI 1.0-3.4, $p=0.04$). This indicates that adult birds had 1.9 times the odds of being diagnosed with West Nile virus at necropsy compared to sub-adult birds.

Table 4: Results from the best fitting logistic regression model for factors associated with mortality due to WNV versus another cause in free-ranging raptors necropsied by the UC Davis Anatomic Pathology Service from 1995-2022.

Variable	Odds Ratio	95% Confidence Interval	p value
Species			
Diurnal	34.9	4.8-255.2	<0.001
Nocturnal (Reference Category)			
Season Admitted			
Winter	0.2	0.04-0.5	0.004
Spring	0.1	0.01-0.8	0.03
Summer	2.8	1.4-5.5	0.004
Autumn (Reference Category			
Life Stage			
Adult	1.9	1.0-3.4	0.04
Sub-Adult (Reference Category			

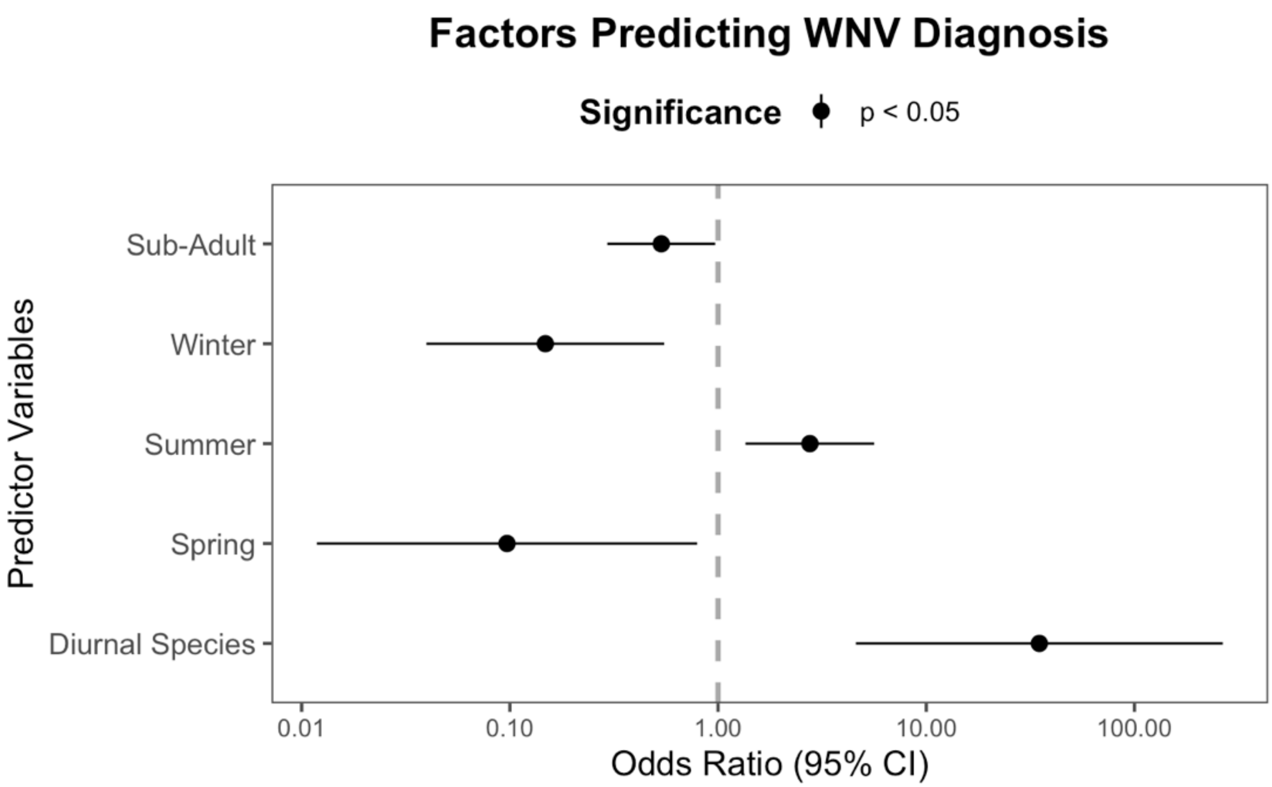

Figure 4: Results from the best fitting logistic regression model for factors associated with mortality due to WNV versus another cause in free-ranging raptors necropsied by the UC Davis Anatomic Pathology Department from 1995-2022.

The best fitting logistic regression model for avian chlamydiosis included season, species, and life stage (Table 5, Figure 5). Birds dying in the winter (OR=6.8, 95% CI 2.0-23.0, p=0.002) and spring (OR=4.5, 95% CI 1.1-17.5, p=0.03) had significantly higher odds of mortality associated with chlamydia, compared to the fall. This indicates that birds who died or were euthanized in the winter had 6.8 times the odds of being diagnosed with chlamydia on necropsy compared to the fall. Furthermore, diurnal species and sub-adults had significantly higher odds of dying due to chlamydia than nocturnal species (OR=16.4, 95% CI 2.2-123.6, p=0.008) or adults (OR=2.5, 95% CI 1.3-5.0, p=0.008), respectively. This indicates that diurnal species had 16 times the odds of being diagnosed with chlamydia on necropsy compared to nocturnal species and adult birds had 2.5 times the odds of being diagnosed with chlamydia on necropsy compared to sub-adult birds.

Table 5: Results from the best fitting logistic regression model for factors associated with mortality due to avian chlamydiosis versus another cause in free-ranging raptors necropsied by the UC Davis Anatomic Pathology Department from 1995-2022.

Variable	Odds Ratio	95% Confidence Interval	p value
Species			
Diurnal	16.4	2.2-123.6	0.007
Nocturnal (Reference Category)			
Season Admitted			
Winter	6.8	2.0-23.0	0.002
Spring	4.5	1.1-17.5	0.03
Summer	0.2	0.02-1.6	0.1
Autumn (Reference Category			
Life Stage			
Sub-Adult	2.5	1.3-5.0	0.008
Adult (Reference Category			

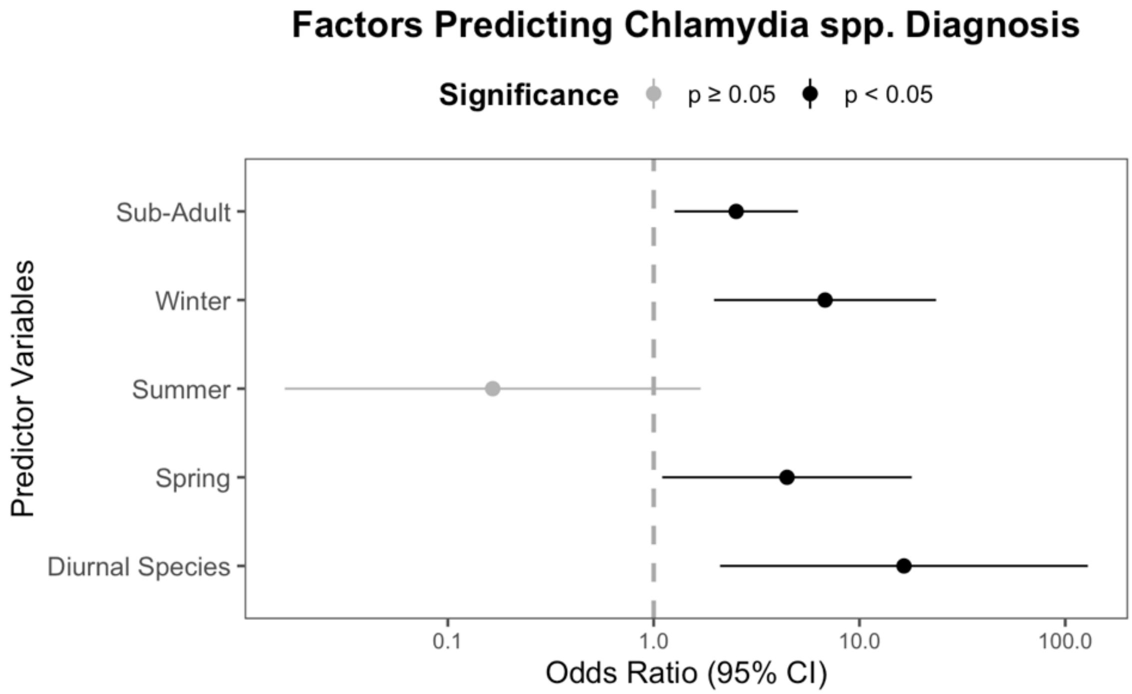

Figure 5: Results from the best fitting logistic regression model for factors associated with mortality due to avian chlamydiosis versus another cause in free-ranging raptors necropsied by the UC Davis Anatomic Pathology Department from 1995-2022.

The best fitting logistic regression model for aspergillosis included season and species (Table 6, Figure 6). Birds necropsied in the summer (OR=2.6, 95% CI 1.2-5.7, p=0.02), fall (OR=2.9, 95% CI 1.3-6.5, p=0.01), and winter (OR= 3.3, 95% CI 1.5-7.2, p=0.003) had a significantly higher odds of dying due to aspergillosis than those necropsied in the spring. This suggests that bird necropsied in the summer had 2.6 times the odds of being diagnosed with aspergillus compared to those necropsied in the spring, birds necropsied in fall had 2.9 times the odds of being diagnosed with aspergillus compared to those necropsied in the spring, and birds necropsied in the winter had 3.3 times the odds of being diagnosed with aspergillus compared to those necropsied in the spring. Furthermore, diurnal species had significantly higher odds of dying due to aspergillosis than nocturnal species (OR=2.2, 95% CI 1.3-3.6, p=0.002). This suggests that diurnal species had 2.2 times the odds of aspergillus diagnosis on necropsy compared to nocturnal species. Sex and life stage were not found to be significant predictors of mortality due to aspergillosis.

Table 6: Results from the best fitting logistic regression model for factors associated with mortality due to aspergillosis versus another cause in free-ranging raptors necropsied by the UC Davis Anatomic Pathology Department from 1995-2022.

Variable	Odds Ratio	95% Confidence Interval	p value
Species			
Diurnal	2.2	1.3-3.6	0.002
Nocturnal (Reference Category)			
Season Admitted			
Winter	3.3	1.5-7.2	0.003
Autumn	2.9	1.3-6.5	0.01
Summer	2.6	1.2-5.7	0.02
Spring (Reference Category)			

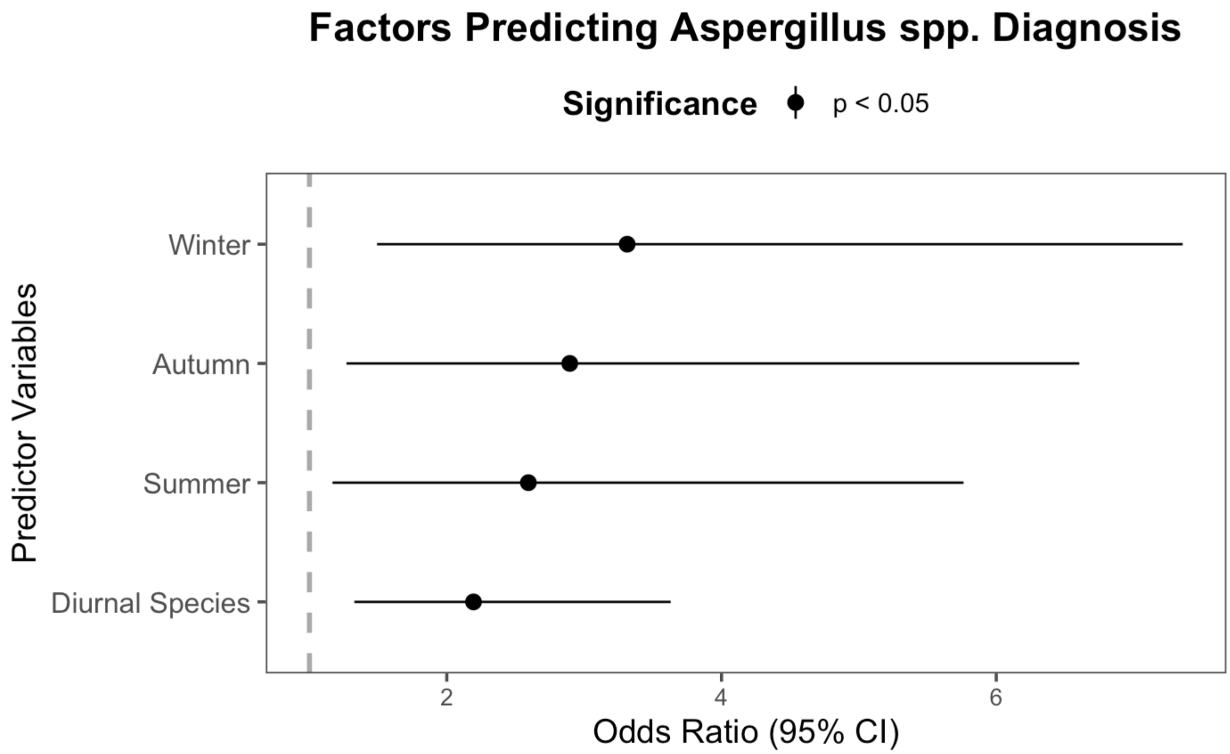

Figure 6: Results from the best fitting logistic regression model for factors associated with mortality due to aspergillosis versus another cause in free-ranging raptors necropsied by the UC Davis Anatomic Pathology Department from 1995-2022.

The best fitting logistics regression model for trichomoniasis only included diurnal versus nocturnal species: diurnal species had significantly lower odds of dying due to trichomoniasis (OR=0.5, 95% CI 0.3-0.8, p=0.008) than did nocturnal birds (Table 7, Figure 7). Season, sex, and life stage were not found to be significantly associated with mortality due to trichomoniasis in this study.

Table 7: Results from the best fitting logistic regression model for predicting mortality due to trichomoniasis versus another cause in wild raptors necropsied by the UC Davis Anatomic Pathology Department from 1995-2022.

Variable	Odds Ratio	95% Confidence Interval	p value
Species			
Diurnal	0.5	0.3-0.8	0.008
Diurnal (Reference Category)			

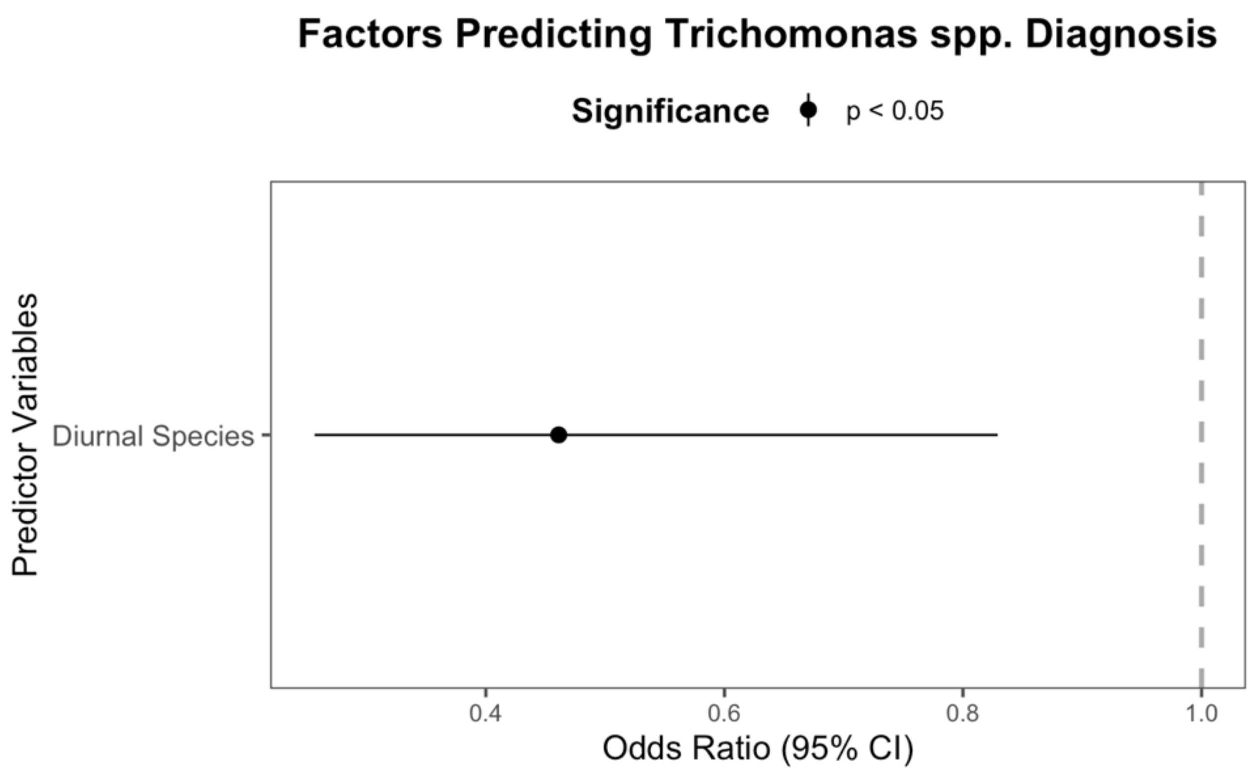

Figure 7: Results from the best fitting logistic regression model for predicting mortality due to trichomoniasis versus another cause in wild raptors necropsied by the UC Davis Anatomic Pathology Department from 1995-2022.

Discussion:

This study provides an overview of morbidity and mortality in free-ranging raptors presenting to the UC Davis VMTH over a 27-year period. The most frequently represented species among clinical and necropsy cases were red-tailed hawks, barn owls and great horned owls. A comparable species distribution was previously reported at the same hospital in the previous 11-year period (1983-1994), although Western screech-owls (*Megascops kennicottii*) and American kestrels (*Falco sparverius*) comprised a slightly larger proportion of necropsy cases at that time, whereas Cooper's hawks (*Accipiter cooperii*), red-shouldered hawks (*Buteo lineatus*), and Swainson's hawks (*Buteo swainsoni*) were seen less frequently (Morishita et al. 1998). This could reflect changing mortality dynamics or changing local population sizes of these species between study periods, or could also be a result of chance fluctuations in overall species composition seen at the hospital throughout time. With the expansion of barred owl (*Strix varia*) populations throughout the Pacific Northwest, there has been concern about the impact of predation on smaller owl species such as the Northern spotted owl and Western-screech owl (Rugg et al. 2023): while Northern California is at the southern edge of barred owl range expansion, it would be interesting to explore if the decrease in screech owl cases is a true reflection of changing population size.

The most common cause of mortality was traumatic injury, which is consistent with the earlier Morishita et al. study and other investigations around the world (Fix and Barrows 1990; Deem et al. 1998; Morishita et al. 1998; Komnenou et al. 2005; Rodriguez et al. 2010; Molina-López et al. 2011; Montesdeoca et al. 2016; Cococcetta et al. 2022; Kadlecova et al. 2022). While the cause of traumatic injury was unknown for most cases, anthropogenic causes (vehicle collision, window collision, and gunshot) were the most frequently identified causes among cases with data, consistent with findings from the previous study from the same hospital (Morishita et al. 1998).

There was a dramatic shift in the most common infectious disease agents reported in 1999-2022 compared to the prior study. While aspergillosis was common during both time periods, WNV, avian chlamydiosis, and trichomoniasis were not reported in the Morishita et al. study (Morishita et al. 1998). In the present study, the first case of WNV (as determined by necropsy) was documented in September 2004. West Nile virus was first identified in California in July 2003 and it has since constituted a major threat to avian populations throughout the state (Reisen et al. 2004; Snyder et al. 2020). *Chlamydia* spp. (originally identified as *C. psittaci*) was first isolated in raptors in North America in 1983 in four red-tailed hawks that died in northern California, and 41% of captive raptors subsequently tested were seropositive, suggesting avian chlamydiosis was endemic in the population at the time (Fowler et al. 1990). This pathogen has subsequently been identified as a new Chlamydial species, proposed as *C. buteonis*, with a PCR prevalence of 1.37% in healthy, free-ranging *Buteo* hawks (Luján-Vega et al. 2018; Laroucau et al. 2019). A more recent study of five rehabilitation centers in California found a 4.18% PCR prevalence of *Chlamydia* spp. among birds presented for rehabilitation, similar to the prevalence of 4.3% observed in the dataset reported here (Seibert et al. 2021). Avian poxvirus was frequently detected (17.7% of cases) among raptors in the previous study; however, it was only implicated in 1.6% of cases in the current study. This was likely due to an outbreak of avian poxvirus that occurred in raptors in Northern California between 1990 and 1994, which resulted in the higher number of avian poxvirus cases presenting to the VMTH during that period (Morishita et al. 1997).

There were no significant trends over the current study period in the number of overall clinical cases, or in the numbers of traumatic, infectious, or orphaned cases. Initial trend analysis indicated significant patterns for overall cases, as well as for traumatic and orphaned cases during the study period. However, visual inspection of the time series graphs suggested that the observed significance was likely driven by a decrease in case numbers during the last four years of the study period (2019-2022). This is likely a result of the changing hospital protocols in these years due to both COVID-19 and highly pathogenic avian influenza (HPAI) biosecurity protocols, which limited the number of birds admitted to the VMTH. We therefore decided to re-evaluate the trends excluding this four-year period, upon which the trends became non-significant. This indicates that the number of overall clinical cases as well as infectious, traumatic, and orphaned cases over time during our study period was relatively stable, neither increasing nor decreasing significantly. It would be interesting to explore trends over time for sub-categories of disease such as specific infectious diseases or inciting causes of traumatic injury; however, a larger dataset would be needed to parse out these dynamics.

Season, body condition, life stage, and diagnostic category (traumatic, infectious, and orphaned) were all included in the best fitting model for investigating factors associated with survival. Raptors with an infectious disease diagnosis had significantly lower odds of surviving compared to other diagnostic categories, which is consistent with a similar study conducted in the United Kingdom (Panter et al. 2022). Because these clinical diagnoses were made upon admission to the hospital, these birds were most likely exhibiting clinical signs severe enough to warrant strong suspicion of an infectious illness. More mild infectious processes or underlying subclinical infectious diseases would likely not be diagnosed at this stage. Therefore, the infectious disease classification in the medical record dataset likely represents only the more severe infectious disease cases. This could be a contributing reason for why infectious disease diagnosis is associated with decreased odds of survival. Orphaned raptors had significantly higher odds of surviving than birds with other diagnostic categories, which is also consistent with other studies of rehabilitated birds (Maphalala et al. 2021; Panter et al. 2022). This is logical, as orphaned birds are often relatively healthy on presentation as compared to other cases admitted sick or injured to wildlife rehabilitation organizations.

Traumatic injury was significantly associated with a decreased odds of survival. Another raptor rehabilitation center found birds with collision injuries to be associated with a decreased likelihood for release, suggesting that these injuries pose a major threat to raptors (Maphalala et al. 2021). It is also probable that euthanasia was opted for many of these cases when full recovery was determined to be unlikely; 64% of traumatic cases were euthanized at some point during rehabilitation while only 8% died naturally at some point during rehabilitaiton. The interaction effects of traumatic injury with season, body condition, and life stage in the model are more unexpected. The model demonstrates that raptors with a traumatic injury presenting in spring and summer have an even worse prognosis than if they had presented in the winter. However, the independent effect of presenting during the spring or summer is positive, prognostically. Prior studies have found seasonal patterns in types of traumatic injuries experienced by raptors, but this is primarily due to gunshot injuries being more commonly observed during the hunting season (Molina-López et al. 2011; Cococcetta et al. 2022). While gunshot injuries were one of the most commonly identified specific traumatic injuries in our dataset, the large number of traumatic injuries with an unidentified specific inciting cause precluded finer analyses. It is also possible that, because spring and summer are the busy seasons at the rehabilitation center, that cases with better prognoses (such as orphaned chicks) may have been prioritized over traumatic cases thereby decreasing the prognosis for traumatic cases in these seasons. The model also illustrates that sub-adult birds presenting with traumatic injuries had even lower odds of survival than adult birds with traumatic injuries. Falling from the nest was another common subcategory of traumatic injury which would be unique to sub-adult birds. This therefore may carry a worse prognosis than other types of traumatic injuries more likely to be experienced by adult raptors. The fracture repair options also tend to differ between adult birds and chicks, which could influence rehabilitation outcome.

There was also a significant positive interaction effect between traumatic diagnosis and a body condition score (BCS) of thin. This interaction indicates that while traumatic diagnosis and thin BCS each reduce the likelihood of survival when considered individually, animals with both conditions had a higher chance of survival than would be expected from the main effects alone. This was a somewhat surprising finding: it has been previously reported in raptors that having a higher body condition score is greatly associated with increased likelihood of rehabilitation success (Molina-López et al. 2015; Cococcetta et al. 2022). These birds were likely less debilitated, as their higher body condition score indicated less impairment of their hunting abilities. Independent of a traumatic diagnosis, raptors in our study population with thin body condition scores had significantly decreased odds of survival, which is consistent with this line of reasoning. It is possible that due to the advanced stage of debilitation, injured and thin birds may have been provided with more intensive care, increasing their odds of survival. However, it is also possible that these results are spurious due to some bias or misclassification in the dataset.

Season, species and life stage were all significantly associated with mortality due to WNV in this study. Relative to the fall season, the odds of mortality due to WNV was higher in the summer and lower in the spring and winter months. This is consistent with WNV surveillance in California, in that the most WNV positive mosquito pools are identified between July and October and the highest number of dead birds occur in August (Snyder et al. 2020). Taxonomy was also a significant predictor of mortality in this model, with diurnal species 41 times more likely to die from WNV compared to nocturnal species. Of the nocturnal species, there was only a single barn owl diagnosed with WNV at necropsy in this dataset. A study of natural and experimental infection of WNV in raptors found that levels of viremia, amount of viral shedding and severity of pathological lesions were reduced in barn owls compared to other species, suggesting they are less susceptible to the disease (Nemeth et al. 2006). It has been proposed that this may be due to their evolutionary history, as they were likely exposed to the virus as Old World birds (Nemeth et al. 2006). Conversely, great horned owls are affected by WNV in other regions of North America, as demonstrated by a survey of wildlife rehabilitators in the midwestern states and a mortality event in captive owls in Ontario in 2002 (Gancz et al. 2004; Saito et al. 2007). Thus, it is interesting there are no cases in great horned owls in this dataset. A previous study from this institution found only 1/71 samples were positive for WNV antibodies, although the reason remains unclear. It was suggested that owls in Northern California may be less exposed to mosquitoes, as most species are predominantly active at night, or perhaps owls may die due to WNV in locations where they are less likely to be found and reported by the public (Captanian et al. 2017). Life stage also had a significant influence in the model with sub-adults having lower odds of dying due to WNV compared to adults.

Similar to West Nile virus, season, species, and life stage were also significantly associated with mortality due to avian chlamydiosis. Spring and winter were found to be associated with an increased odds of mortality due to chlamydia, compared to fall. Another study evaluating chlamydia infections in hawks at rehabilitation centers in California also found infections to be most prevalent in the winter (Seibert et al. 2021). Winter is often a stressful season, especially for young raptors that commonly present with emaciation during this time of year due to difficulty learning to hunt and prey scarcity (Graham and Heatley 2007). This stress could contribute to immunosuppression which would leave these young birds more vulnerable to infectious agents during this period. Life stage was also found to be significant with sub-adults having higher odds of death due to avian chlamydiosis compared with adults. Diurnal species had higher odds of dying from avian chlamydiosis than nocturnal species. A study of raptor rehabilitation centers in California found a 6.4% prevalence of avian chlamydiosis (as determined by PCR) in the family Accipitridae and only 2% in the family Strigidae, with the most PCR-positive birds being red-tailed hawks (Seibert et al. 2021). More research is needed to characterize the host preference of this chlamydial species.

Raptors necropsied in the summer, fall, and winter had higher odds of aspergillus diagnosis than those necropsied in the spring. Prevalence of aspergillosis was highest in winter (36%) followed by summer (33%), fall (24%) and spring (7%). In North American waterfowl, most aspergillosis outbreaks occur in fall or early winter, which may be attributed to a seasonal change in birds' susceptibility to, or in the amount of, fungal spores in the environment (Arné et al. 2021). Seasonal trends of atmospheric concentrations of aspergillosis have been reported but are geographically variable: one study across the United States found fungal concentrations to be highest in the fall and summer but no seasonal variation was found in a study in California, perhaps due to general lack of seasonality in the state's climate (Shelton et al. 2002; Martony et al. 2019). Furthermore, *A. fumigatus* is an opportunistic pathogen that more commonly causes disease in captive birds that are often immunosuppressed (Beernaert et al. 2010). As discussed previously, winter is a stressful season for raptors which may lead to immunosuppression and therefore perhaps contribute to the seasonal trends of aspergillosis observed here. One review of aspergillosis noted that young raptors, specifically immature red-tailed hawks, seem to be more susceptible to aspergillosis than adults (Arné et al. 2021), although this was not observed in our model. Diurnal species were twice as likely to die from aspergillosis than nocturnal species. This is interesting, as avian isolates of aspergillus have not demonstrated host or geographic specificity (Lofgren et al. 2022). It is possible that nocturnal species may have had higher odds of death due to a different cause, which may be contributing to the trend observed.

Only taxonomical classification was included in the best-fitting model for predicting death due to trichomoniasis, with diurnal species having significantly lower odds of dying of trichomoniasis than nocturnal species and most of these patients being barn owls. A study of lesions associated with trichomoniasis across avian taxa found that the anatomic location of lesions differed with Strigiformes more commonly having lesions involving the upper region of the oropharyngeal cavity, eye, and skull base, instead of extending down the esophagus which was observed for other taxa (Martinez et al. 1993). A study in Germany sampling wild birds found the highest prevalence of trichomoniasis in Strigiformes (58%) compared to Accipitriformes (36%) and Falconiformes (28%) (Quillfeldt et al. 2018). It is speculated that species differences observed could be due to differential consumption of urban Columbiformes (Quillfeldt et al. 2018). However, we expect there to be overlap in the diet of the most common species of this dataset (red-tailed hawks, barn owls, and great-horned owls) with evidence that all of these species consume other birds and therefore could be exposed to trichomonas carried by Columbiformes (Marti et al. 1993; Bogiatto et al. 2003; Kross et al. 2016). It is therefore unclear at this point what is driving this trend in our model and if there are underlying differences in exposure or disease severity among species. Although life stage was not found to be significant in this model, a previous study of Cooper's hawks found younger birds to be more susceptible to trichomoniasis because their oral pH is less acidic (Urban and Mannan 2014). Avian oral pH development and how it relates to trichomoniasis infection has not been evaluated in other raptor species and would be interesting to explore across other taxa.

Machine learning is a powerful tool that can be used for health monitoring and surveillance, including for the identification and analysis of morbidity and mortality trends across wildlife rehabilitation centers. The ability to quickly categorize cases according to clinical presentations or syndromes using pre-diagnostic data can allow for early detection of mortality events, which in turn can facilitate action and preparedness (Kelly et al. 2021). The application of machine learning here facilitated categorization of diagnoses using data from the large medical record dataset for the purposes of data analyses. The machine learning model performance was adequate to then utilize the outputs in further analysis, with some limitations. Some less common diagnostic categories with limited sample sizes, such as toxicosis and congenital disease, demonstrated less accuracy in the machine learning outputs, precluding their use in further modelling. In addition, some of the diagnostic categories were misclassified as traumatic injury, which likely introduced some degree of error into the models run with the medical record dataset. The overall agreement for traumatic disease was quite high (93%), so we anticipate this error to be minimal. Overall, this framework could be applied to many avenues of clinical research, allowing for more efficient organization of data from hospital patient databases.

While medical and necropsy records of raptor patients presenting to rehabilitation centers and veterinary hospitals can inform our understanding of the threats to these free-ranging populations, there are limitations and biases. There is likely an over-representation of anthropogenic causes of morbidity and mortality, as birds are brought in by members of the public who may be less likely to witness and report natural causes of mortality. Furthermore, not all raptor cases resulting in death were fully necropsied, and there is bias in the type of cases that were sent to the pathology department, with fewer trauma cases having a full necropsy performed. Another limitation with this dataset is that there were many birds for which sex and life stage were listed as unknown in the medical and necropsy records, which limited our ability to assess the impact of these variables. It would be interesting in future analyses to investigate life stage and species in finer detail, parsing out dynamics in individual species and stages of development.

We also anticipate that two major threats to raptor populations during this time period are under-represented in this dataset: we were limited in our ability to categorize toxicosis cases and any suspected highly pathogenic avian influenza cases because these carcasses were immediately submitted to the California Department of Fish and Wildlife for sampling and therefore would not be captured in the pathology database. Lead and rodenticide toxicity are two significant threats to raptors, so it was surprising that so few cases were definitively diagnosed. This may be in part due to fewer cases being sent for testing due to expenses, but it is also possible that this was in part due to how data was collected from the online record system. Toxicity results are added to records later as a separate pdf attachment; if results were not manually written into the record, the data was not collected into the data sheet for subsequent analysis. A study of rehabilitation centers in California detected anticoagulant rodenticide residues in 95% of turkey vultures tested and 67% of golden eagles (Kelly et al. 2013). In addition to the adverse effects posed by anticoagulant rodenticides on individual raptors, there are conservation concerns about the impacts on populations of vulnerable species, and alternate methods of pest control should be encouraged (Gomez et al. 2021). Highly pathogenic avian influenza (HPAI) is a significant threat to raptor populations since the detection of the current clade in 2021, as raptors are ecologically positioned to have regular exposure through infected prey and carcasses (Nemeth et al. 2023). Especially severe impacts have been observed in the critically endangered California condor populations, with 21 of the estimated 350 remaining free-roaming birds dying from HPAI in 2023 (Kozlov 2023; Puryear and Runstadler 2024).

In conclusion, causes of morbidity and mortality in raptors have broadly remained similar throughout time with traumatic injuries and infectious diseases remaining highly prevalent. Although, there have been shifts in the most common infectious diseases afflicting wild raptor populations. These diseases also show trends across season, species, and life stage, most of which are not yet fully understood. Different disease types also carry different prognoses, as does presenting body condition score, season, and life stage. Understanding these patterns and their underlying causes is important for improving efforts to support raptors in the wild as well as at rehabilitation centers.

References

Alba A, Perez AM, Ponder J, Puig P, Wünschmann A, Vander Waal K, Alvarez J, Willette M. 2017. Syndromic surveillance for West Nile virus using raptors in rehabilitation. *BMC Vet Res* 13:368.

Arné P, Risco-Castillo V, Jouvion G, Le Barzic C, Guillot J. 2021. Aspergillosis in Wild Birds. *JoF* 7:241.

Beernaert LA, Pasmans F, Van Waeyenberghe L, Haesebrouck F, Martel A. 2010. *Aspergillus infections* in birds: a review. *Avian Pathology* 39:325–331.

Bogiatto RJ, Sardella BA, Essex JJ. 2003. Food habits of great horned owls in Northeastern California with notes on seasonal diet shifts. *Western North American Naturalist* 63:258–263.

Bozdogan H. 1987. Model selection and Akaike's Information Criterion (AIC): The general theory and its analytical extensions. *Psychometrika* 52:345–370.

Captanian N, Hawkins MG, Fiorello C, Thurber M, Reisen WK. 2017. Low prevalence of West Nile virus antiboeis in select Northern California owl species (2007-2014). *Journal of Zoo and Wildlife Medicine* 48:1239–1241.

Cococcetta C, Coutant T, Collarile T, Vetere A, Di Ianni F, Huynh M. 2022. Causes of Raptor Admission to the Wildlife Rehabilitation Centre in Abruzzo (Central Italy) from 2005–2016. *Animals* 12:1916.

Cox C. 1991. Pesticides and Birds: From DDT to Today's Poisons. *Journal of Pesticide Reform* 11.

Deem S, Terrell SP, Forrester DJ. 1998. A Retrospective Study of Morbidity and Mortality of Raptors in Florida: 1988-1994 on JSTOR. *Journal of Zoo and Wildlife Medicine* 29. https://www.jstor.org/stable/20095739?casa_token=9GpdMZLVO5UAAAAA%3A5hkxfUI10ti6F8zM7hsJMQcO4nh_sTJB2XVw-Oil4AcwIbSE7rKTWEVkX49zkr5uqM_R150rJsWM80K9h0ZiOa_qBHERVSHzflhS7MBfm6sXeTuEIw. Accessed.

Ellis AE, Mead DG, Allison AB, Stallknecht DE, Howerth EW. 2007. Pathology and epidemiology of natural West Nile viral infection of raptors in Georgia. *Journal of Wildlife Diseases* 43:214–223.

Fix AS, Barrows SZ. 1990. Raptors rehabilitated in Iowa during 1986 and 1987: a retrospective study. *Journal of Wildlife Diseases* 26:18–21.

Fowler ME, Schulz T, Ardans A, Reynolds B, Behymer D. 1990. Chlamydiosis in Captive Raptors. *Avian Diseases* 34:657.

Gancz AY, Barker IK, Lindsay R, Dibernardo A, McKeever K, Hunter B. 2004. West Nile Virus Outbreak in North American Owls, Ontario, 2002. *Emerg Infect Dis* 10:2135–2142.

Gomez EA, Hindmarch S, Smith JA. 2021. Conservation Letter: Raptors and Anticoagulant Rodenticides. *Journal of Raptor Research*. https://meridian.allenpress.com/rapt/article/doi/10.3356/JRR-20-122/473421/Conservation-Letter-Raptors-and-Anticoagulant. Accessed August 2024.

Graham JE, Heatley JJ. 2007. Emergency Care of Raptors. *Veterinary Clinics of North America: Exotic Animal Practice* 10:395–418.

Grier JW. 1982. Ban of DDT and Subsequent Recovery of Reproduction in Bald Eagles. *Science* 218:1232–1235.

Hall V, Cardona C, Mendoza K, Torchetti M, Lantz K, Bueno I, Franzen-Klein D. 2024. Surveillance for highly pathogenic avian influenza A (H5N1) in a raptor rehabilitation center—2022. *PLoS ONE* 19:e0299330.

Hernandez CL, Oster SC, Newbrey JL. 2018. Retrospective Study of Raptors Treated at the Southeastern Raptor Center in Auburn, Alabama. *Journal of Raptor Research* 52:379–388.

Hudelson S, Hudelson P. 1995. Dermatology of raptors: A review. *Seminars in Avian and Exotic Pet Medicine* 4:184–194.

Kadlecova G, Voslarova E, Vecerek V. 2022. Diurnal raptors at rescue centres in the Czech Republic: Reasons for admission, outcomes, and length of stay. *PLoS ONE* 17:e0279501.

Kelly TR, Pandit PS, Carion N, Dombrowski DF, Rogers KH, McMillin SC, Clifford DL, Riberi A, Ziccardi MH, Donnelly-Greenan EL, et al. 2021. Early detection of wildlife morbidity and mortality through an event-based surveillance system. *Proc R Soc B* 288:20210974.

Kelly TR, Poppenga RH, Woods LA, Hernandez YZ, Boyce WM, Samaniego FJ, Torres SG, Johnson CK. 2013. Causes of mortality and unintentional poisoning in predatory and scavenging birds in California. *Veterinary Record Open* 1:e000028.

Komnenou AT, Georgopoulou I, Savvas I, Dessiris A. 2005. A retrospective study of presentation, treatment, and outcome of free-ranging raptors in Greece (1997-2000). *Journal of Zoo and Wildlife Medicine* 36:222–228.

Kozlov M. 2023. US will vaccinate birds against avian flu for first time — what researchers think. *Nature* 618:220–221.

Kross SM, Bourbour RP, Martinico BL. 2016. Agricultural land use, barn owl diet, and vertebrate pest control implications. *Agriculture, Ecosystems & Environment* 223:167–174.

Laroucau K, Vorimore F, Aaziz R, Solmonson L, Hsia RC, Bavoil PM, Fach P, Hölzer M, Wuenschmann A, Sachse K. 2019. Chlamydia buteonis, a new Chlamydia species isolated from a red-shouldered hawk. *Systematic and Applied Microbiology* 42:125997.

Lofgren LA, Lorch JM, Cramer RA, Blehert DS, Berlowski-Zier BM, Winzeler ME, Gutierrez-Perez C, Kordana NE, Stajich JE. 2022. Avian-associated *Aspergillus fumigatus* displays broad phylogenetic distribution, no evidence for host specificity, and multiple genotypes within epizootic events. *G3* 12:jkac075.

Luján-Vega C, Hawkins MG, Johnson CK, Briggs C, Vennum C, Bloom PH, Hull JM, Cray C, Pesti D, Johnson L, et al. 2018. Atypical chlamydiaceae in wild populations of hawks (*Buteo* spp.) in California. *Journal of Zoo and Wildlife Medicine* 49:108–115.

Maphalala MI, Monadjem A, Bildstein KL, Hoffman B, Downs C. 2021. Causes of admission to a raptor rehabilitation centre and factors that can be used to predict the likelihood of release. *African Journal of Ecology* 59:510–517.

Marti CD, Steenhof K, Kochert MN, Jeffrey SM. 1993. Community trophic structure: the roles of diet, body size, and activity time in vertebrate predators. *Oikos* 67.

Martinez V, Jimenez M, Gonalons E, Vergara P. 1993. Mechanism of action of CCK in avian gastroduodenal motility: Evidence for nitric oxide involvement. *American Journal of Physiology - Gastrointestinal and Liver Physiology* 265:G842–G850.

Martínez-Herrero MC, Sansano-Maestre J, Ortega J, González F, López-Márquez I, Gómez-Muñoz MT, Garijo-Toledo MM. 2020. Oral trichomonosis: Description and severity of lesions in birds in Spain. *Veterinary Parasitology* 283:109196.

Martony M, Nollens H, Tucker M, Henry L, Schmitt T, Hernandez J. 2019. Prevalence of and environmental factors associated with aerosolised *Aspergillus* spores at a zoological park. *Veterinary Record Open* 6:e000281.

Molina-López RA, Casal J, Darwich L. 2011. Causes of Morbidity in Wild Raptor Populations Admitted at a Wildlife Rehabilitation Centre in Spain from 1995-2007: A Long Term Retrospective Study | PLOS ONE. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0024603. Accessed June 2023.

Molina-López RA, Rafael A, Casal J, Darwich L. 2015. Prognostic indicators associated with early mortality of wild raptors admitted to a wildlife rehabilitation centre in Spain. *Veterinary Quarterly* 35:9–15.

Montesdeoca N, Calabuig P, Corbera JA, Orós J. 2016. Causes of Admission for Raptors to the Tafira Wildlife Rehabilitation Center, Gran Canaria Island, Spain: 2003–13. *Journal of Wildlife Diseases* 52:647.

Morishita TY, Fullterton AT, Lowenstine LJ, Gardner IA, Brooks DL. 1998. Morbidity and mortality in free-living raptorial birds of Northern California: a retrospective study, 1983-1994. *Journal of Avian Medicine and Surgery* 12:78–81.

Morishita TY, Pyone PA, Brooks DL. 1997. A survey of diseases of raptorial birds. *Journal of Avian Medicine and Surgery*:77–92.

Nemeth N, Gould D, Bowen R, Komar N. 2006. Natural and experimental West Nile virus infection in five raptor species. *Journal of Wildlife Diseases* 42:1–13.

Nemeth NM, Ruder MG, Poulson RL, Sargent R, Breeding S, Evans MN, Zimmerman J, Hardman R, Cunningham M, Gibbs S, et al. 2023. Bald eagle mortality and nest failure due to clade 2.3.4.4 highly pathogenic H5N1 influenza a virus. *Sci Rep* 13:191.

Panter CT, Allen S, Backhouse N, Mullineaux E, Rose C, Amar A. 2022. Causes, temporal trends, and the effects of urbanization on admissions of wild raptors to rehabilitation centers in England and Wales. *Ecology and Evolution* 12:e8856.

Puryear WB, Runstadler JA. 2024. High-pathogenicity avian influenza in wildlife: a changing disease dynamic that is expanding in wild birds and having an increasing impact on a growing number of mammals. *javma*:1–9.

Quillfeldt P, Schumm YR, Marek C, Mader V, Fischer D, Marx M. 2018. Prevalence and genotyping of Trichomonas infections in wild birds in central Germany. *PLoS ONE* 13:e0200798.

R Core Team. 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/. Accessed.

Reisen W, Lothrop H, Chiles R, Madon M, Cossen C, Woods L, Husted S, Kramer V, Edman J. 2004. West Nile Virus in California. *Emerg Infect Dis* 10:1369–1378.

Ress S, Guyer C. 2004. A Retrospective Study of Mortality and Rehabilitation of Raptors A Retrospective Study of Mortality and Rehabilitation of Raptors in the Southeastern United States. *J Raptor Res* 38:77–81.

Rodriguez B, Rodriguez A, Siverio F, Siverio M. 2010. Causes of Raptor Admissions to a Wildlife Rehabilitation Center in Tenerife (Canary Islands). https://bioone.org/journals/journal-of-raptor-research/volume-44/issue-1/JRR-09-40.1/Causes-of-Raptor-Admissions-to-a-Wildlife-Rehabilitation-Center-in/10.3356/JRR-09-40.1.full. Accessed June 2023.

Rugg NM, Jenkins JMA, Lesmeister DB. 2023. Western screech-owl occupancy in the face of an invasive predator. *Global Ecology and Conservation* 48:e02753.

Saito EK, Sileo L, Green DE, Meteyer CU, McLaughlin GS, Converse KA, Docherty DE. 2007. Raptor mortality due to West Nile virus in the United States, 2002. *Journal of Wildlife Diseases* 43:206–213.

Seibert B. 2017. Chlamydial Infections in birds of prey presented to rehabilitation facilities. University of California, Davis.

Seibert BA, Keel MK, Kelly TR, Nilsen RA, Ciembor P, Pesti D, Gregory CR, Ritchie BW, Hawkins MG. 2021. Chlamydia buteonis in birds of prey presented to California wildlife rehabilitation facilities. *PLoS ONE* 16:e0258500.

Shelton BG, Kirkland KH, Flanders WD, Morris GK. 2002. Profiles of Airborne Fungi in Buildings and Outdoor Environments in the United States. *Appl Environ Microbiol* 68:1743–1753.

Smith KA, Campbell GD, Pearl DL, Jardine CM, Salgado-Bierman F, Nemeth NM. 2018. A retrospective summary of raptor mortality in Ontario, Canada (1991-2014), including the effects of West Nile virus. *Journal of Wildlife Diseases* 54:261.

Snyder RE, Feiszli T, Foss L, Messenger S, Fang Y, Barker CM, Reisen WK, Vugia DJ, Padgett KA, Kramer VL. 2020. West Nile virus in California, 2003–2018: A persistent threat. *PLoS Negl Trop Dis* 14:e0008841.

Sorenson KJ, Burnett LJ, Stake MM. 2017. Restoring a Bald Eagle Breeding Population in Central California and Monitoring 25 Years of Regional Population Growth. *Journal of Raptor Research* 51:145–152.

Thompson LJ, Hoffman B, Brown M. 2013. Causes of admissions to a raptor rehabilitation centre in KwaZulu-Natal, South Africa | African Zoology. *African Zoology*:359–366.

Trapletti A, Hornik K. 2023. tseries: Time Series Analysis and Computational Finance. https://CRAN.R-project.org/package=tseries. Accessed.

Urban EH, Mannan RW. 2014. The potential role of oral pH in the persistence of Trichomonas gallinae in Cooper's hawks (Accipiter cooperii). *Journal of Wildlife Diseases* 50:50–55.

Venables WN, Ripley BD. 2002. Modern Applied Statistics with S. New York.

Wendell MD, Sleeman JM, Kratz G. 2002. Retrospective study of morbidity and mortality of raptors admitted to Colorado State University veterinary teaching hospital during 1995 to 1998. *Journal of Wildlife Diseases* 38:101–106.

Wolf T, Debut L, Sanh V, Chaumond J, Delangue C, Moi A, Cistac P, Ma C, Jernite Y, Plu J, et al. 2020. Transformers: State-of-the-Art Natural Language Processing.

Zhang Y, Jin R, Zhou Z-H. 2010. Understanding bag-of-words model: a statistical framework. *Int J Mach Learn & Cyber* 1:43–52.