AdaptNSW

Wildlife Disease Surveillance

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Cover Image: A bush rat (*Rattus fuscipes*) is groomed to collect ticks for pathogen metatranscriptomics and discovery. Credit: Jane Hall

WILDLIFE DISEASE SURVEILLANCE

EXECUTIVE SUMMARY

The Australian Registry of Wildlife Health (the Registry) holds over 30 years of wildlife health data, placing it in a unique position to identify risk factors for disease outbreaks and extrapolate likely infectious disease hotspots. The transmission dynamics of many pathogens are linked inextricably to environmental factors, and patterns of disease emergence have been correlated with climate cycles. Climate change is likely to intensify the prevalence and severity of some infectious diseases, with implications for human, domestic animal and wildlife health, and biodiversity. This project, an initiative of the AdaptNSW program, will interrogate the existing Registry dataset to predict the consequences of a warming climate for disease distribution.

In consultation with the NSW Office of Environment and Heritage (OEH), this information will be used to inform conservation planning initiatives. Additionally, ongoing disease surveillance programs will be guided to collect better baseline wildlife heath data, critical for early detection of emerging pathogens and identifying changing patterns over time.

OBJECTIVES

- Gain a greater understanding of the relationship between wildlife disease and climate factors
- Identify climate risk factors for disease emergence and infer potential disease hotspots
- Collect baseline data on wildlife health from diagnostic submissions to the Registry
- Gather expert perspectives on wildlife health, vector-borne disease, climate change and conservation planning to workshop ideas and identify opportunities for further collaboration
- Advise conservation planning with respect to likely impacts of wildlife disease

APPROACH

- Interrogate 20 years of wildlife health data from the Registry to correlate wildlife health datasets with climate variables and identify factors associated with disease emergence.
- Investigate current mortality events and disease outbreaks that may be linked to climate events.
- Conduct a preliminary workshop with OEH and NPWS representatives to identify avenues to incorporate Registry data and research findings into conservation management actions

OUTPUTS

- Evaluate methods for predicting climate-related changes in disease distribution based on historic Registry case data
- Identify climate-related risk factors for expansion of wildlife disease emergence
- In consultation with the NSW Office of Environment and Heritage, identify strategies for mitigating the risk of wildlife disease outbreaks and incorporating disease risk analysis into conservation initiatives.

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WILDLIFE DISEASE SURVEILLANCE

PROJECT OVERVIEW

Anthropogenic climate change is an important factor driving global biodiversity loss. The effect of climate change on wildlife disease is poorly understood however, climate warming has already influenced the range, prevalence and severity of some infectious diseases of animals and people[1], and these trends are expected to continue. As climate systems warm, the widespread extinction of plants and animals proceeds at an alarming rate[2]. Current models project the extinction of up to one sixth of all species on earth by the year 2100 if global warming continues unabated[3]. The Intergovernmental Panel on Climate Change (IPCC) forecasts elevations in average global temperatures, increased climatic variability, more frequent extreme weather events, changing precipitation patterns, and rising sea levels. Pronounced biodiversity loss is projected, with increased habitat degradation, disrupted seasonal biologic cycles, and limited options for endemic wildlife to shift geographic range[2].

CLIMATE CHANGE AND WILDLIFE HEALTH

Climate change is a driving factor in wildlife disease emergence; indirectly through habitat loss and species redistribution, and directly via climate-related fluctuations in disease and vector prevalence. Synergies between pathogens and environmental factors such as temperature, rainfall, and humidity will in some cases favour disease emergence and transmission, as well as host susceptibility to disease[1,4].

The transmission dynamics of many pathogens are closely linked with environmental factors, however vector-borne diseases are particularly climate-sensitive, with incidence closely tied to climate drivers such as rainfall and temperature[5]. With climate change, temperate environments are projected to have shorter, milder winters that favour vector survival and replication by removing the effect of over-wintering on pathogen life cycles[6]. As biting insects expand their ranges, so too have the incidence and distribution of significant vector-borne diseases such as malaria, Rift Valley fever and Lyme disease.

Lyme disease is now the most common vector-borne disease in temperate climates, and the most common tick-borne disease globally[7]. The clinical syndrome is caused by bacterial spirochetes in the *Borrelia burgdorferi* (sensu lato) complex, and transmitted by Ixodid ticks. Lyme disease typically manifests as an influenza-like illness in people and, in a minority of patients, progresses to chronic, debilitating syndromes characterised by arthritis or neurologic symptoms. Human risk is directly correlated with the prevalence of infected ticks and the abundance and diversity of wildlife reservoirs. In the northeastern United States, the prevalence of Lyme disease has increasingly been influenced by mild winters, during which spirochaete-infected nymphs feed in synchrony with uninfected larval black-legged ticks, resulting in increased pathogen transmission[8,9]. Understanding the environmental factors that favour tick persistence and *Borrelia* transmission has enabled public health and wildlife management agencies to develop risk maps that forecast vector ranges under future climate projections[7]. These predictive models permit public health authorities to target resources to at-risk populations.

The incidence of tick-related disease and anaphylaxis is increasing on Australia's east coast[10,11]. No evidence exists to support the presence of *B. burgdorferi* in Australia; however, other significant pathogens do circulate in Australian ticks, including several *Rickettsia* species[12] and *Francisella tularensis*[13]. The latter is the causative agent of tularaemia, a notifiable zoonotic disease characterised by clinical syndromes ranging from lymph node enlargement, to pneumonia and death. The transmission dynamics of tularaemia are well described in North America and Europe, where epizootics often present as sudden death in wildlife. In the United States, the distribution of human tularaemia cases has changed over the last 40 years, with an advancing northern trajectory that is thought to reflect shifting climatic factors that favour vector and reservoir host abundance[14].

Tularaemia was thought to be exotic to Australia until the recent discovery of *F. tularensis* in archival ringtail possum samples that were collected by the Registry's diagnostic service more than 15 years previously. This finding led to the development of gold standard diagnostic protocols in state and national reference laboratories, and enhanced capabilities for *F. tularensis* diagnosis and management. Overseas, this pathogen has the capacity to modulate wildlife populations and cause sudden, sharp population declines; however, little is known about the host range and prevalence of *F. tularensis* in Australian wildlife, and the factors that might contribute to tularaemia epizootics. Subsequently, there is a paucity of public health advice for individuals who frequently come into contact with wildlife and these disease vectors.

Recent meta-transcriptomic studies have further identified a suite of undescribed viruses in the east Australian tick microbiome[15]. Of these, a novel virus in the genus *Coltivirus* warrants further investigation due to its close phylogenetic relationship to the human pathogen Colorado tick fever virus. The recent discovery of these two important wildlife and zoonotic pathogens in the course of routine surveillance highlights significant knowledge gaps and emphasises the need for both active and passive surveillance, particularly in the context of a warming climate and expanding insect vector ranges.

CLIMATE PROJECTIONS FOR NSW

The IPCC has concluded that, at the end of the 21st century, global mean-surface warming will exceed 1.5°C relative to the years 1850-1900. Heat waves and extreme precipitation events will occur with higher frequency, and in most areas there will be more hot days and fewer cold days. Warming will not be regionally uniform; however, climate projections for Eastern Australia likewise forecast increased average temperatures with more hot days, decreased winter and spring rainfall with increased intensity of extreme rainfall events, rising sea levels and more severe fire weather[16].

The implications for biodiversity are profound. In vulnerable populations, disease outbreaks may be a driving force behind local or global species extinction[17,18]. As climate change increasingly alters complex host-pathogen-environment relationships, the resilience or adaptability of wild populations is likely to be complicated by concurrent habitat loss, and the role of disease in species decline is likely to be intensified.

PROJECT OBJECTIVES

The overarching objective of this project is to explore the impact of climate change on wildlife disease emergence in NSW. Identifying environmental factors relevant to pathogen prevalence and distribution is critical to early detection and response to disease outbreaks. Through retrospective analysis and active field monitoring, this project aims to:

- Gain a greater understanding of the relationship between wildlife disease and climate factors
- Identify climate risk factors for disease emergence and infer potential disease hotspots
- Collect baseline data on wildlife health from diagnostic submissions to the Registry
- Gather expert perspectives on wildlife health, vector-borne disease, climate change and conservation planning to workshop ideas and identify opportunities for further collaboration
- Advise conservation planning with respect to likely impacts of wildlife disease

APPROACH

Extracting unambiguous evidence of climate-related disease outbreaks from complicated host-pathogen-environmental interactions is exceedingly difficult. Baseline data on the health of wild populations are critical to predict the impact of climate change on biodiversity[6]; however, diseases of wildlife are largely neglected and global monitoring programs are predominantly concerned with detecting diseases of livestock and humans[19]. Surveillance and monitoring programs are crucial for early detection of emerging diseases and for understanding population-level impacts of climate-sensitive endemic diseases.

In Australia, passive monitoring of wildlife disease is conducted by government departments, university teaching hospitals, zoological institutions and rarely, commercial diagnostic laboratories. Government laboratories have historically pursued wildlife disease investigations in order to safeguard the health and biosecurity of domestic species and human health, and to protect Australian livestock industries. Capabilities to specifically investigate and record wildlife disease events are critical for conservation programs, particularly where disease outbreaks threaten to further destabilise already vulnerable populations of endangered species.

In the Australian diagnostic pathology community, the Australian Registry of Wildlife Health is unique in that the core mission of the Registry is to improve Australia's ability to detect and diagnose endemic, emerging and exotic wildlife diseases that could have negative impacts on biodiversity, human health or the Australian economy. Located at Taronga Zoo, the Registry is a wildlife diagnostic service and resource centre that has evolved over 30 years to become a significant research hub, endeavouring to better understand the health of Australian ecosystems. Data generated from each diagnostic case is archived in a secure, web-based platform, spatially located and linked to a wide variety of digital assets, facilitating outbreak investigation, disease surveillance and research. Crucially, the Registry archive provides a platform for evaluating temporal patterns in wildlife disease events.

The objectives of this project will be pursued using the following approaches:

- **Patterns in wildlife disease emergence:** Interrogate 20 years of wildlife health data from the Registry to correlate wildlife health datasets with climate variables and identify factors associated with disease emergence.
- **Wildlife disease surveillance:** Investigate current mortality events and disease outbreaks that may be linked to climate events.
- **Wildlife Health in Conservation Planning:** A preliminary workshop, held in September 2017, identified avenues to incorporate Registry data and research findings into conservation management actions undertaken by NSW OEH (Appendix 1).

PATTERNS IN WILDLIFE DISEASE EMERGENCE

Over three decades, the Registry has amassed a wealth of carefully curated wildlife health data, providing a unique insight into temporal trends and emerging climate-related patterns. Archival Registry data has previously been correlated with climate factors to show that outbreaks of systemic coccidiosis in green turtles are more likely during El Niño-like events[20].

A pilot study examining the landscape suitability of *Angiostrongylus cantonensis* will explore the utility of Registry case material to model and predict changes in disease distribution. As the vast majority of submissions to the Registry are for post mortem examination, case material will be linked to wildlife mortality events. The wide variety of non-fatal impacts climate change is likely to have on wild populations (immunosuppression, reduced fitness and reproductive success, altering geographic range and dispersal) are beyond the scope of this analysis.

This analysis will take into account:

- Host factors including species, age, body condition and necropsy findings
- Time of year
- The influence of climate and environmental variables including temperature, water-soil balance, vegetation cover and water-flow accumulation on disease distribution

Climate projections can then be utilised to predict changes in vector ranges in order to extrapolate future disease hotspots.

WILDLIFE DISEASE SURVEILLANCE

The extent to which infectious disease contributes to faunal declines is not well understood and is likely under recognised[21]. Occasionally, explosive disease outbreaks result in mass morbidity and mortality, and directly threaten species with extinction, as with the 2015 outbreak of pasteurellosis in critically endangered Saiga antelope[22], and in the same year, a mass mortality of Bellinger River Snapping Turtles that collapsed the wild population[23]. However, mass mortalities more than likely represent a small proportion of the disease outbreaks causing wildlife population declines. Important baseline data are critical to recognising emergent disease trends. Countries with established wildlife disease surveillance programs have a profoundly better understanding of regional disease dynamics and are thus far better prepared to respond to outbreaks and protect wildlife, domestic animal and human populations[24]. These programs may be broadly divided into passive monitoring and active surveillance measures.

Passive monitoring programs tend to aggregate individual case reports generated from spontaneous outbreaks and mortality events. These often present short-lived opportunities for disease investigation, necessitating adaptable, responsive and highly trained personnel to ensure appropriate data relating to wildlife biology, behaviour, clinical findings and environmental factors are collected to complement pathology results. Individual case reports generated from passive monitoring programs collectively form a valuable record, enabling identification of temporal patterns and emerging trends, such as shifts in disease range or climate-dependent epizootics. Opportunistic investigations of wildlife mortality events may also identify diseases with serious public health implications that necessitate immediate action, as with the identification of West Nile virus in the USA[25].

For those diseases that hold particular significance for wildlife or human health, active surveillance programs may be necessary to address specific questions relating to disease prevalence, distribution and host range. Whereas passive monitoring programs tend to opportunistically record individual accessions over time, active or targeted surveillance programs systematically collect and interpret information in order to meet specific objectives pertaining to disease management and wildlife conservation[26].

The bulk of the Registry's diagnostic caseload constitutes passive monitoring; however, the recent discovery of *Francisella tularensis* in ringtail possums clearly demonstrates the importance of active surveillance programs, directed at both detections of known pathogens, and the discovery of novel pathogen using non-biased, sequencing-based approaches.

The Registry's wildlife disease surveillance activities provide a basis for early detection and mitigation of emerging diseases, and a reference dataset that provides insight into temporal changes in disease prevalence. The latter is critical for recognising climate-related changes in disease prevalence and severity, and for making evidence-based decisions around conservation interventions.

PATTERNS IN WILDLIFE DISEASE EMERGENCE

PILOT STUDY: PREDICTING THE EFFECT OF CLIMATE CHANGE ON THE DISTRIBUTION OF ANGIOSTRONGYLIASIS IN NSW

Infectious diseases that cycle through intermediate hosts or insect vectors are particularly climate sensitive due to the effects of rainfall and temperature on vector and host survival and replication[5]. Environmental changes that facilitate host range expansion will have implications for the incidence and distribution of associated pathogens. For this pilot study, Registry cases of the rat lungworm (*Angiostrongylus cantonensis*) were evaluated to determine the significance of various climatic and environmental factors on the current and likely future distribution of the parasite.

Angiostrongylus cantonensis is the most common cause of eosinophilic meningitis in people worldwide, including Australia. It is widely distributed throughout the Asia-Pacific region, with an expanding geographic range that now includes parts of New South Wales[27,28].

The widespread distribution of *A. cantonensis* is attributed in part to the ubiquity of definitive and intermediate hosts. *Rattus* sp. rats are the definitive hosts of *A. cantonensis*; however, host specificity is highly plastic, and 17 rodent species, including non-*Rattus* rats, have been implicated in the lifecycle of *A. cantonensis*[27]. Rats are infected upon ingestion of intermediate or incidental hosts infected with third-stage (L3) larvae. These undergo several moults in the rat central nervous system before being redistributed to the pulmonary vasculature. Adult nematodes reside within pulmonary arteries and produce eggs that hatch L1 larvae. These are eventually excreted in faeces and the life cycle proceeds through intermediate terrestrial and aquatic mollusc hosts, ultimately resulting in maturation of infectious L3 larvae.

In Australia, two introduced snail species are implicated in diseases transmission; the common garden snail (*Cornu aspersum*) and Asian trampsnail (*Bradybaenia similaris*)[28]. Snails infected with L3 larvae are a source of infection for accidental, dead-end hosts, including people, companion animals and wildlife. In people, transmission typically occurs via the ingestion of raw or undercooked intermediate or incidental hosts, or unwashed fresh produce contaminated by snail mucus. The hallmark of angiostrongyliasis in people is eosinophilic meningitis. Clinical disease is associated with considerable morbidity and occasionally mortality.

Factors affecting the distribution and prevalence of *A. cantonensis* include the range and behaviour of definitive and intermediate hosts, and environmental variables such as temperature and humidity. Mollusc infection occurs with greater efficiency in warm, humid environments. Tropical climates with high rainfall favour transmission; however, range expansion into temperate climates has recently been reported in North and South America, and parts of Asia[29–32]. Sporadic cases of angiostrongyliasis in people have been reported in eastern Australia since 1971 and a recent series of severe cases in the Sydney area has prompted concern that the range and prevalence of *A. cantonensis* may be increasing[27,28].

In Australia, angiostrongyliasis has been reported in a wide range of companion animals and wild species, including dogs, horses, tawny frogmouths, brushtail possums, Bennett's wallabies, rufous bettongs, gang-gang and yellow-tailed black cockatoos, and black and grey-headed flying foxes[27]. Recent epidemics of angiostrongyliasis in tawny frogmouths coincided with a spate of human cases in NSW, leading to the proposition that certain wild species may be sentinels for disease in people[33] (Figure 1).

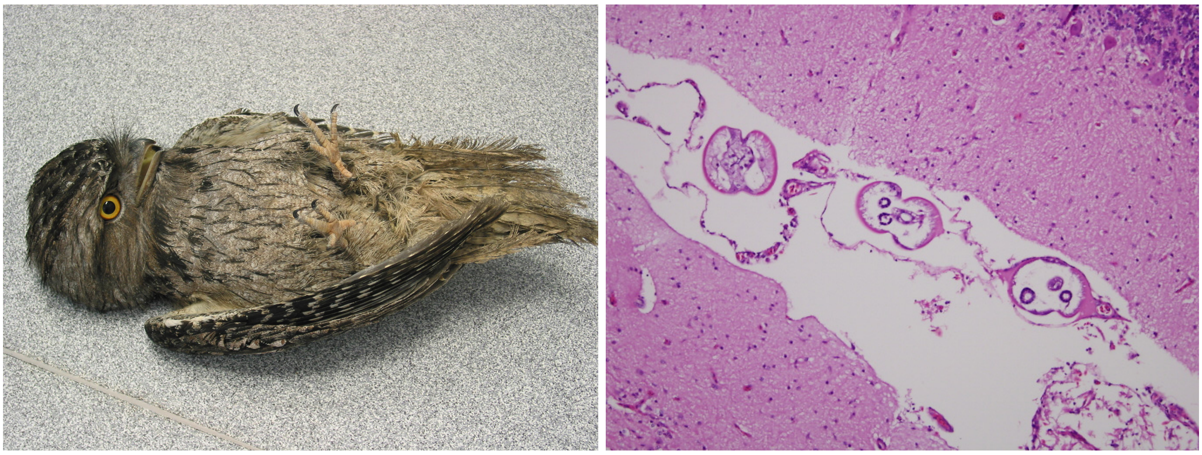

Figure 1. Angiostrongyliasis in a tawny frogmouth (*Podargus strigoides*). Birds present with neurological symptoms including inability to fly or stand and variably reduced mentation (left). Histopathology (right) demonstrates the presence of parasites within the brain of affected animals.

Diagnosis may be delayed in areas where angiostrongyliasis has not previously been reported, complicating medical management. Modelling climate conditions that favour parasite persistence and transmission facilitates targeted surveillance of wildlife sentinels and may improve detection in human patients.

Given the impact of temperature and rainfall on host and parasite survival, climate change is likely to alter the range and prevalence of *A. cantonensis*. Studies have predicted a net decline in globally suitable host habitat by 2050-2070, under climate change scenarios described by the IPCC[34]. Nevertheless, *A. cantonensis* is projected to expand its current range in the near future, with a southeastern sweep away from the equator in the southern hemisphere.

The prevalence of angiostrongyliasis in tawny frogmouths that present to veterinary hospitals with neurological disease is high in NSW[33], and there is a strong seasonal pattern associated with clinical disease. Nematode larvae halt development at temperatures <15°C and cases tend to peak in late summer and autumn[27]. We used historic Registry data to model the landscape suitability for *A. cantonensis* in NSW under environmental projections for 2050.

METHODS

The Registry database was interrogated for all diagnostic submissions with a final diagnosis of angiostrongyliasis. Cases in the dataset include free-ranging wildlife, zoo collection animals, and free-ranging wildlife found on zoo grounds (Appendix 2). Case data included species, sex, age group, date of death, history, death circumstance, presenting syndrome, history, gross and histopathology findings, parasitology and diagnoses. Cases were tagged with a latitude and longitude and duplicates were removed so that individual sites (eg. Taronga Zoo) contributed only one point to the data set.

The landscape suitability of *A. cantonensis* was modelled as its ecological niche using the Maxent machine learning algorithm. This biogeographical approach allowed for the evaluation of angiostrongyliasis with respect to environmental features including temperature, water-soil balance, vegetation cover and water-flow accumulation, and then the subsequent projection of risk from environmental to geographic space. Mean annual temperature projected for the year 2050 was constructed by the Coupled Model Intercomparison Project Phase 5 (CMIP5), which is a collaborative project incorporating twenty modelling groups to predict future climate under the representative concentration pathways (RCPs) adopted in the fifth report of the Intergovernmental Panel on Climate Change[35,36]. The future global estimate used here was the mean of the 19 CMIP5 climate models evaluated at 4.5 W m-2 radiative forcing due to CO2[37]. Background points used in the model were weighted by the human footprint[38] to correct for the spatial sampling bias associated with reporting effort[39] .

RESULTS

The database search yielded 109 cases of angiostrongyliasis, which were submitted to the Registry between 1999 and 2017. Free-ranging cases predominated (n=90; 83%) and were largely concentrated in the greater Sydney region, with rare exceptions (n=4; Dubbo NSW, Coomera QLD, Ningi QLD and Christmas Island). Cases were submitted throughout the year; however, cases peaked in late summer and autumn. Tawny frogmouths (*Podargus strigoides*) were significantly over-represented (n=82; 75%) and no sex predisposition was found. These findings are consistent with previous findings[33].

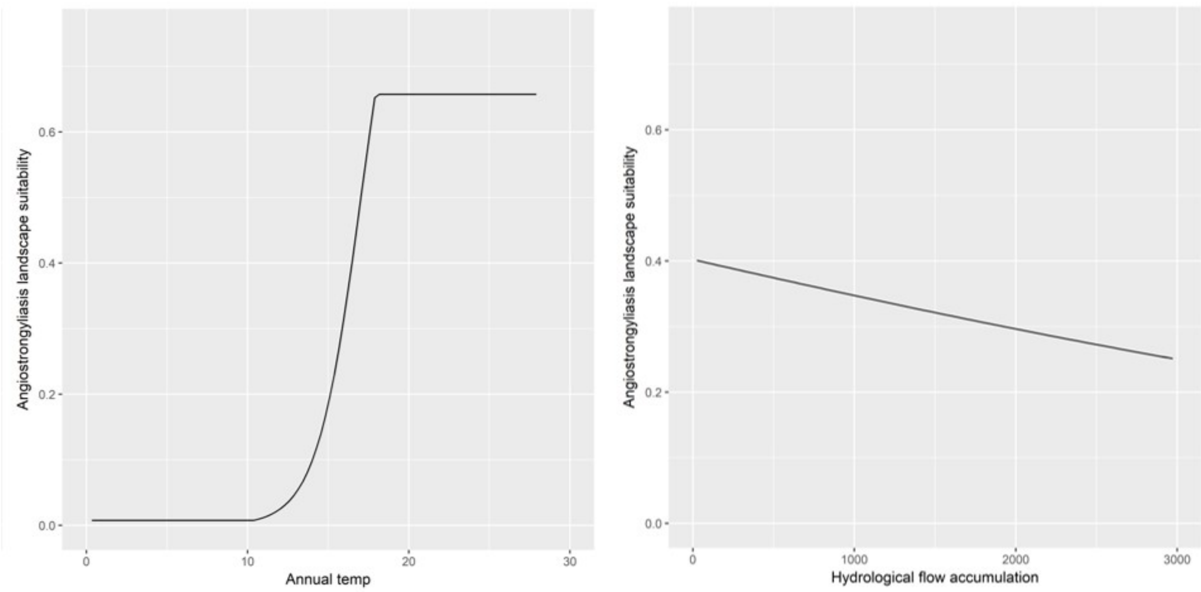

Figure 2. Response curves demonstrating the impact of two significant environmental predictors for *A. cantonensis* landscape suitability; annual temperature and hydrological flow accumulation.

Biogeographic modelling results indicate that *A. cantonensis* landscape suitability was most significantly influenced by annual temperature and water flow accumulation (Figure 2). Mean annual temperature was the dominant factor influencing landscape suitability, with a permutation importance of 82%, followed by water flow accumulation (15.3%) and water-soil balance (2.4%; not pictured).

Based on Registry submissions, the current range of *A. cantonensis* is likely to be focused in the Sydney Metropolitan area, with some extension into parts of the NSW north coast (Figure 3). Under increased warming predictions, the geographic range of *A. cantonensis* in NSW is expected to expand considerably by 2050, incorporating the New England northwest and Hunter regions, as well as the Illawarra and south east coast.

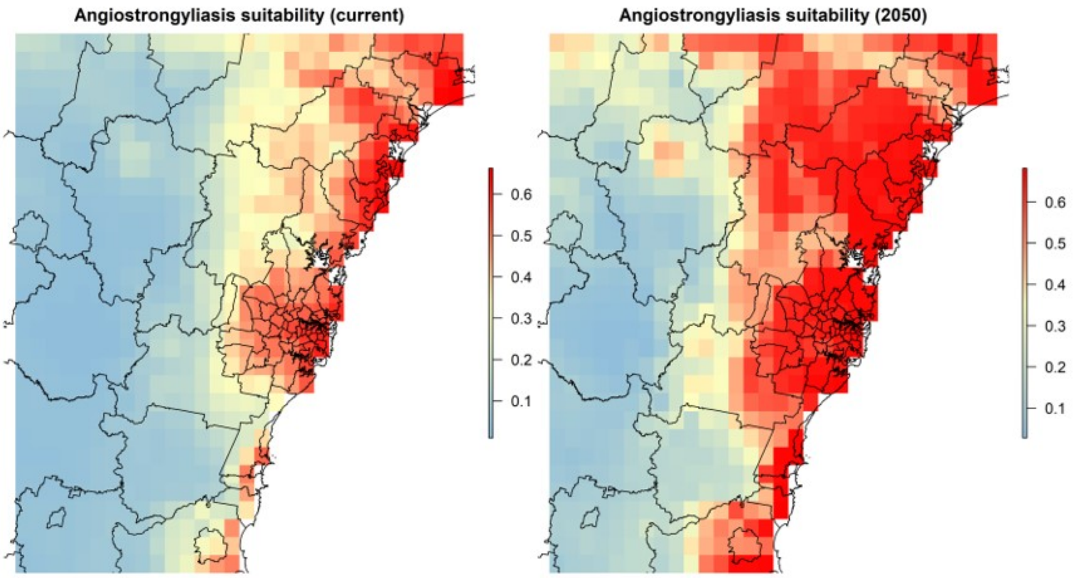

Figure 3. Current *A. cantonensis* landscape suitability was determined by modelling the distribution of Registry cases as a function of relevant environmental features. Based on climate predictions for 2050, the distribution of *A. cantonensis* in NSW is expected to expand.

DISCUSSION

This pilot study was undertaken to evaluate the utility of the Registry database for predicting wildlife disease outbreaks in NSW under IPCC climate change projections. Existing case data were used to predict the landscape suitability and likely future distribution of *Angiostrongylus cantonensis*. Pathogen selection was based on the likelihood that factors influencing disease prevalence are climate-sensitive[5]. Existing pathogen distribution was determined by spatiotemporal data linked to Registry accessions and the current range was correlated with environmental variables to define the parasite's landscape suitability and tolerance to temperature, water-soil balance, vegetation cover and water-flow. New range boundaries were then modelled using IPCC climate projections for 2050.

This study successfully utilised Registry case data to demonstrate pathogen range shifts related to climate factors; however, there are various limitations associated with this approach. Accurately predicting the impact of climate change on disease prevalence and range is challenging, and there is some debate regarding the most appropriate approach[1].

The approach used in this study is relatively uncomplicated and most appropriate for making landscape suitability predictions from coarse disease data sets. Where Registry case data substantiates the existence of a climate envelope delineating the spatial distribution of a pathogen, future geographic boundaries can be extrapolated. This approach does not capture complex host, pathogen and environmental interactions, which may play a significant role, even within climatically determined geographic margins. For example, Lyme disease prevalence is influenced by climate factors that impact the diversity and abundance of vectors and wildlife reservoirs[9]. However, intricate mechanistic processes in disease transmission are further influenced by the interplay of dynamic factors varying from land use, to micro-environmental fluctuations in temperature and humidity, and host immunocompetence.

The specific biological and ecological variables that influence the distribution of individual pathogens cannot be captured within a single model. More complex predictive models that factor in mechanistic processes may identify ecological niches at higher resolution[1,40]; however, the approach used here forecasts changes in disease landscape in sufficient detail for forward conservation planning.

Limitations surrounding reporting bias and variable case characteristics must be taken into account in the analysis of Registry case submissions. The majority of cases in the Registry database are spatially aggregated within cities and populated regional areas, reflecting the distribution of submitting veterinary practitioners and wildlife carers, as well as the logistical practicalities surrounding shipment of fresh carcasses for post mortem examination (Figure 4). Information regarding wildlife disease outbreaks outside of these geographic areas is limited, and the true distribution of some diseases may be much more extensive than the Registry dataset would suggest.

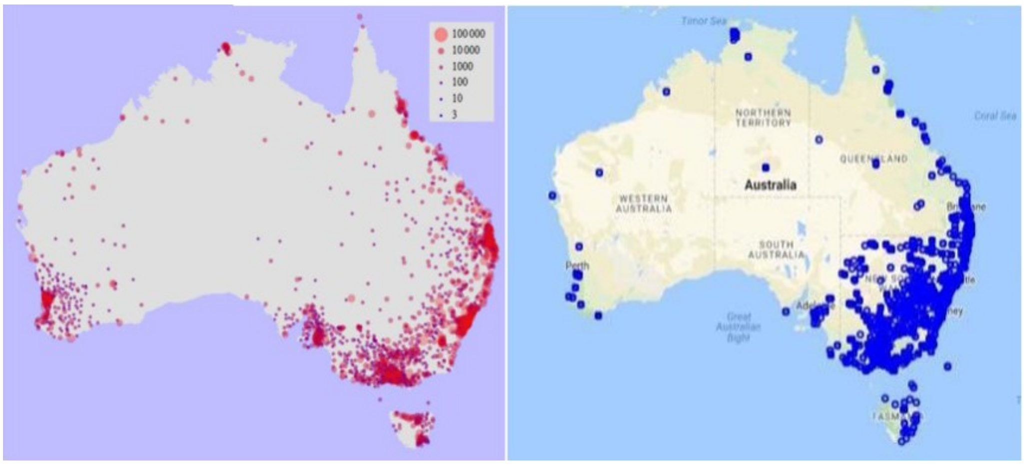

Figure 4. Australian population by postcode in 2011 (left) compared with wildlife health submissions to the Australian Registry of Wildlife Health (right).

Case submissions may also be biased by patterns of submitter behaviour. Diagnostic submissions to the Registry tend to rise over spring and summer months when increased outdoor activity correlates with more frequent encounters with morbid or deceased wildlife. Diagnoses may be pursued more vigorously in certain species, or when particular diseases are suspected. Early outbreaks of neurological disease in tawny frogmouths initially motivated carers to submit large numbers of morbid birds in pursuit of a diagnosis. Once angiostrongyliasis was established as the cause of disease, tawny frogmouth submissions diminished and eventually subsided. Current submissions are sporadic and likely reflect the low prevalence of disease; however, the effect of submitter behaviour cannot be accounted for in this analysis of Registry case data.

The introduction of management interventions (eg. vaccination, pest control) or changes in surveillance strategies (passive to active) may likewise have altered reporting incidence for some diseases. These factors cannot be accounted for in this type of analysis.

Nevertheless, the principal strength of this approach is the large wildlife disease dataset, which is broadly representative of NSW species, endemic diseases and their distribution. This study demonstrates the utility of simple models to predict range shifts using relatively coarse data sets and highlights the value in detecting zoonotic pathogens in sentinel species. Exploring the relationship between climate-sensitive wildlife pathogens and key weather patterns has the potential to improve disease forecasting, conservation planning and in some cases, public health outcomes.

WILDLIFE HEALTH IN CONSERVATION PLANNING

A preliminary workshop in 2017 identified avenues for integration of Registry research and diagnostic activities into existing OEH programs (Appendix 2). Detecting and understanding infectious disease in wildlife is critical to conservation planning and risk mitigation. Existing management protocols do not incorporate consideration of wildlife disease into planning for conservation interventions such as translocations and reintroductions. Workshop participants determined that Registry expertise is directly relevant to the new NSW National Parks Climate Change Adaptation Strategy in particular.

NATIONAL PARKS CLIMATE CHANGE ADAPTATION STRATGEY

In mid-2018 The Office of Environment and Heritage endorsed the NSW National Parks Climate Change Adaptation Strategy. The document was developed to address the escalating impacts climate change is expected to have on various national parks assets, and highlights the need for flexible conservation management interventions in the face of a rapidly changing environment. The strategy utilises a planning tool to index planning, management and communication around intensifying levels of climate risk and impact.

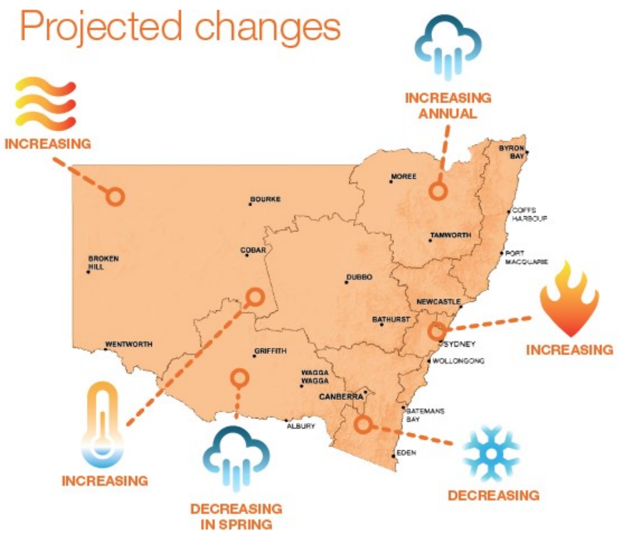

FIGURE 5. A snapshot of climate change-related changes forecast for NSW based on NARCliM modelling. From: https://climatechange.environment.nsw.gov.au/

The strategy was founded on a series of workshops in which NPWS sectors discussed climate change associated risks and mitigating management actions. The workshops pivoted on impact reports compiled using NSW and ACT Regional Climate Modelling (NARCliM) data for 14 regions in NSW[41]. NARCliM provides climate projections for south-east Australia at a 10km resolution and generates data for more than 100 meteorological variables, including temperature, precipitation, humidity, wind speed, soil moisture and sea surface temperature. A NARCliM snapshot of NSW predicts an increase in hot days with an associated increase in spring and summer severe fire weather in the near (2020-2039) and far future (2060-2079). Projected changes in seasonal rainfall vary across inland and coastal regions with implications for drought and floods (Figure 5). These changes are expected to profoundly impact NSW national parks, with outcomes ranging from prolonged fire seasons to habitat fragmentation and loss of Aboriginal heritage sites.

During preparatory workshops, personnel from each NPWS sector identified relevant climate change impacts and ranked them in minimal to high-risk categories. The key risks managed by each branch were identified and a frequency scale was devised to identify the level of risk for various climate change impacts. For the Nature Conservation branch, events such as storms and east coast lows were respectively classified as events that are 'almost certain' and 'likely' to happen, whereas wildlife disease outbreaks resulting in extinction were identified as 'rare' events.

Impact	**Catastrophic** Extinction/ Permanent loss of biodiversity /nature conservation value, population or ecological function	**Major** Significant reduction in value, population or ecological function	**Moderate** Localised loss of value, population or ecological function	**Minor** Local decline in value, population or ecological function	Insignificant No detectable decline in value, population or ecological function
Almost certain Occurs multiple times per year e.g Storms	Extreme	Extreme	High	Medium	Medium
Likely Occurs annually i.e. less than once per year e.g. East Coast Low or whale stranding	Extreme	High	Medium	Medium	Low
Possible Occurs infrequently (3- years) e.g. flying fox heat stress.	High	High	Medium	Low	Low
Unlikely Occurs very infrequently (10 yrs) e.g. fire impacting a local population	High	Medium	Medium	Low	Negligible
Rare Occurs rarely e.g. wildlife disease outbreak that results in extinction	Medium	Medium	Low	Negligible	Negligible

Figure 6. Risk matrix for nature conservation, which combines the likelihood (frequency) and consequence (impact) of climate related events on assets. From: National Parks Climate Change Adaptation Strategy, NSW and Office of Environment and Heritage (2018)

Risk matrices were developed by plotting the frequency of climate change related events against their impact. For example, east coast lows (expected to occur annually) may have major or catastrophic impacts on assets managed by the Nature Conservation branch justifying a high level of risk (Figure 6). Extinction-level wildlife disease outbreaks have a major impact; however, the projected rare occurrence of such events warrants a medium level of risk based on this risk matrix. Management actions are then linked to risk levels, whereby low risk impacts are matched with conservative strategies (eg. monitoring, pest management) and high risk impacts trigger increasingly interventional actions, such as fauna translocations or off-site breeding programs (Figure 7). The document does not elaborate on the implementation of these management strategies.

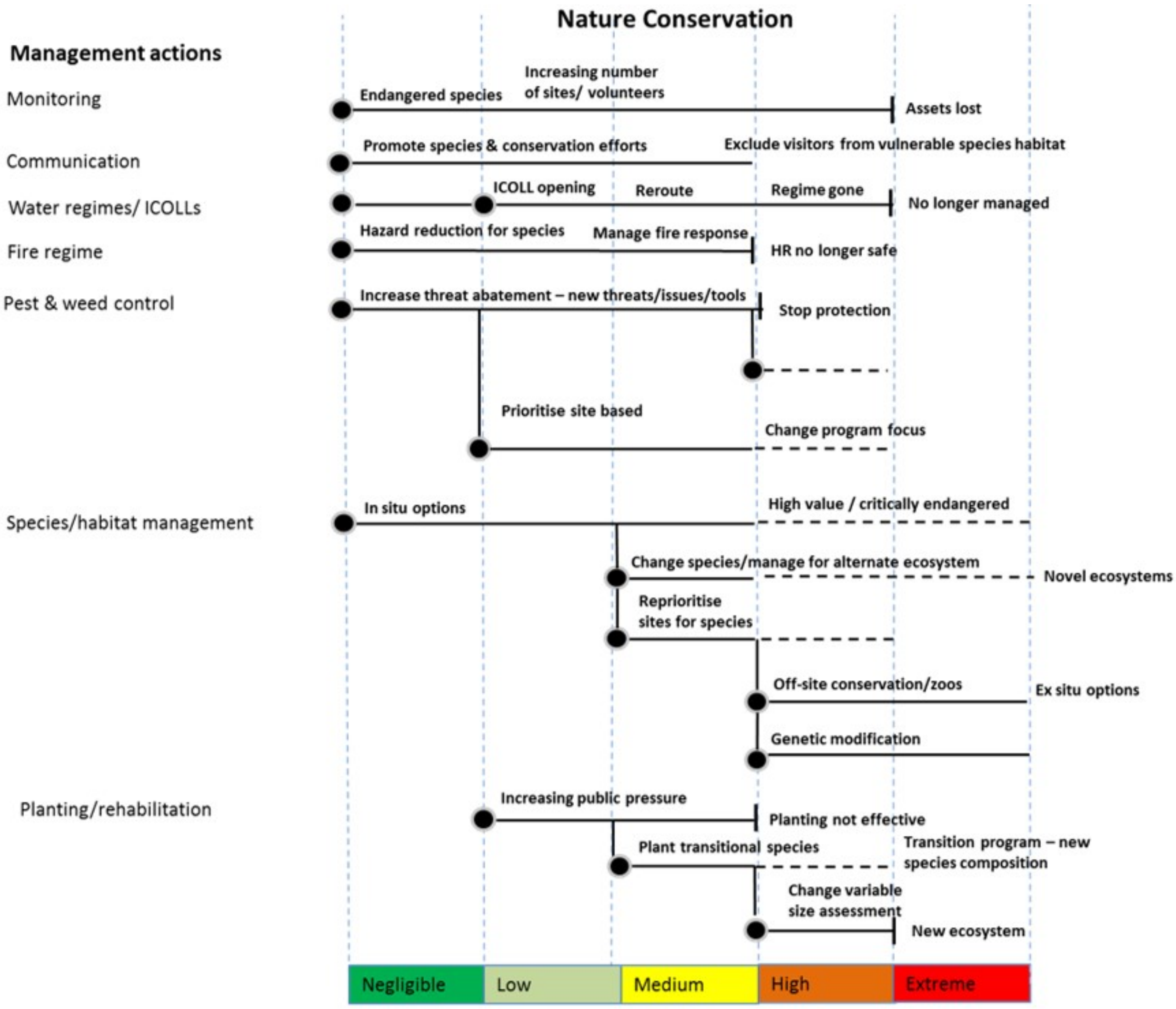

Figure 7. Nature conservation adaptation pathway. From: National Parks Climate Change Adaptation Strategy, NSW and Office of Environment and Heritage (2018)

NSW policies and procedures surrounding species translocation are detailed in the 2001 OEH document 'Policy for the Translocation of Threatened Fauna in NSW.' The policy provides guidelines for the preparation of a translocation proposal, following the 1998 IUCN Guidelines for re-introductions. The threat of disease to translocated fauna and host environments is briefly acknowledged; however, the policy and guidelines do not require new translocation proposals to complete a comprehensive disease risk assessment (DRA) or investigate the health status of source and recipient populations.

Since the preparation of the NSW policy, the ICUN have issued updated Guidelines for Reintroductions and Other Conservation Translocations[42], as well as Guidelines for Wildlife Disease Risk Analysis[43], co-published with the Office International des Épizooties (OIE). The latter document provides a framework for identifying hazards, assessing and managing risk, and communicating management outcomes. This process clarifies and prioritises current threats and potential impediments in a variety of scenarios, including fauna re-introductions or translocations, investigations into population declines, and land-use planning. Where zoonotic diseases are of concern, DRA may inform occupational health and safety practices. The IUCN/OIE document guides users through a stepwise process of problem description, hazard identification, risk assessment, risk management, implementation and review. This process was recently utilised by OEH to excellent effect in responding to an isolated mortality event that now threatens the Bellinger river snapping turtle with extinction[23,44].

IUCN Guidelines for Reintroductions and Other Conservation Translocations note that conservation translocations and other intensive wildlife management actions are likely to become increasingly important as climate change results in accelerating ecological degradation and habitat loss. Wildlife disease outbreaks pose an additional threat to biodiversity, and are increasingly likely to trigger conservation interventions under a changing climate.

The recently adopted NSW National Parks Climate Change Adaptation Strategy identifies wildlife disease outbreaks resulting in extinction as a rare event. In fact, climate change is predicted to result in a confluence of synergistic processes that drive species towards extinction through habitat loss, resource depletion and emerging disease[45]. Extinction due to disease is likely to become more common as multiple cascading threats compound the impact of each individual driver.

Infectious disease has already played a measurable role in global species decline. Widespread amphibian population crashes have been attributed to a combination of climate factors and the emergence of chytrid fungus[46,47]. Locally, the extinction of endemic Christmas Island rats (*Rattus macleari*) has been attributed to the arrival of black rats (*Rattus rattus*) and concurrent introduction of *Trypanosoma lewisi*[48]. More recently, the emergence of devil facial tumour disease (DFTD) in the Tasmanian devil (*Sarcophilus harrisii*) demonstrated that even single-host pathogens can have a devastating effect on previously robust populations[49].

Outbreaks of DFTD and Bellinger River Virus underscored the importance of rapid responses to wildlife disease outbreaks, even when very little is known about the causative pathogen or mode of transmission. Almost a decade passed between the first DFTD sighting and characterisation of tumour pathogenesis. The Bellinger river snapping turtle suffered catastrophic population crashes within a matter of days, well before a novel virus was isolated and characterised. In both cases, identification of an infectious process and rapid, biosecurity-focused interventions secured disease free populations and captive breeding commenced while investigators collaborated to identify causative agents.

Wildlife disease surveillance is critical to early detection of emerging wildlife diseases[50]. The Australian Registry of Wildlife Health plays an essential role in the diagnosis and detection of wildlife disease in NSW. Government and commercial laboratories are principally concerned with the exclusion of wildlife diseases that are likely to impact human health and livestock biosecurity. The Registry's core mission is to improve Australia's ability to detect and diagnose endemic, emerging and exotic disease in free-ranging wildlife. With over 30 years of case material archived in a secure, web-based database, the Registry provides a platform for identifying temporal trends and climate links in wildlife disease events. The Registry is additionally partnered with investigators in the fields of bioinformatics and pathogen discovery, facilitating the rapid identification of novel wildlife pathogens. The Registry's routine diagnostic activities have been critical to urgent conservation interventions[44], strategic planning and identification of novel zoonotic pathogens such as *Francisella tularensis*[13].

Climate change is a major driving force in accelerating biodiversity loss and a critical threat to wildlife health globally. Prevailing climate models forecast dramatic changes that are likely to fragment wildlife habitats, alter the distribution of disease vectors, and compound the threats already faced by vulnerable species. The role of disease in species decline is likely to be intensified and conservation managers will increasingly resort to urgent and intensive conservation strategies such as fauna translocations. Improved wildlife disease surveillance will be critical to pre-empt and control disease outbreaks, identify novel and emerging pathogens, and assist in the strategic use of resources for conservation planning and management.

CONCLUSIONS AND RECOMMENDATIONS

The Australian Registry of Wildlife Health is dedicated to the diagnosis of diseases that could negatively impact the health of Australia's free-ranging wildlife. The Registry's wildlife disease surveillance program provides a no-cost to low cost diagnostic service to various state and federal government departments, community groups and conservation organisations. Since 1998, the Registry has worked closely with OEH on a variety of wildlife health management activities. Registry personnel currently conduct mass mortality investigations, provide a necropsy service for aquatic animals and managed wildlife populations, perform health assessments for captive management and translocation programs, and routinely consult with wildlife managers on a variety of conservation and research programs. This work is partly supported by NSW OEH and has been documented in a series of memoranda of understanding since 2003; however, current diagnostic and research activities significantly exceed the modest contribution from OEH and are funded through unpredictable research grants. Demand for Registry services continues to grow and necropsy submissions are expected to increase as climate change continues to impact animal health.

Recommendations arising from this project include:

- Continue to support and strengthen the Registry's wildlife disease surveillance program.
- Consider developing a system to facilitate transportation of diagnostic specimens to the Registry from outside the Sydney basin to expand wildlife disease surveillance across NSW.
- Support active surveillance programs of climate-sensitive diseases with wildlife reservoirs (eg. Ross River virus, *Francisella tularensis*, coltivirus) to better understand disease dynamics in NSW environments and predict climate-change impacts.
- Maintain and cultivate ongoing multi-disciplinary collaborations between NSW OEH, NPWS, the Registry, field ecologists and veterinary and human public health specialists.
- Expand collaborations among Registry personnel and OEH climate scientists to include ongoing analysis of climate variables with respect to wildlife disease emergence and transmission.
- Review and update the 2001 OEH Policy for the Translocation of Threatened Fauna in NSW to reference the most recent IUCN Guidelines for Reintroductions and Other Conservation Translocations and the IUCN Guidelines for Wildlife Disease Risk Analysis
- Elevate the risk of a wildlife disease outbreak resulting in extinction from 'medium' to 'high' risk in the NSW National Parks Climate Change Adaptation Strategy risk matrix
- Develop and document procedures, protocols and multi-agency agreements for responding to wildlife disease outbreaks

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REFERENCES

1. Altizer, S., Ostfeld, R. S., Johnson, P. T. J., Kutz, S. & Harvell, C. D. Climate Change and Infectious Diseases: From Evidence to a Predictive Framework. *Science* **341**, 514–519 (2013).
2. Thomas, C. D. *et al.* Extinction risk from climate change. *Nature* **427**, 145–148 (2004).
3. Urban, M. C. Accelerating extinction risk from climate change. *Science* **348**, 571–573 (2015).
4. Raffel, T. R. *et al.* Disease and thermal acclimation in a more variable and unpredictable climate. *Nat. Clim. Change* **3**, 146–151 (2012).
5. McIntyre, K. M. *et al.* Systematic Assessment of the Climate Sensitivity of Important Human and Domestic Animals Pathogens in Europe. *Sci. Rep.* **7**, 7134 (2017).
6. Harvell, C. D. *et al.* Climate warming and disease risks for terrestrial and marine biota. *Science* **296**, 2158–2162 (2002).
7. Ogden, N. H. *et al.* Risk maps for range expansion of the Lyme disease vector, Ixodes scapularis, in Canada now and with climate change. *Int. J. Health Geogr.* **7**, 24 (2008).
8. Kurtenbach, K. *et al.* Fundamental processes in the evolutionary ecology of Lyme borreliosis. *Nat. Rev. Microbiol.* **4**, 660–669 (2006).
9. Werden, L. *et al.* Geography, deer, and host biodiversity shape the pattern of Lyme disease emergence in the Thousand Islands Archipelago of Ontario, Canada. *PloS One* **9**, e85640 (2014).
10. van Nunen, S. A. Tick-induced allergies: mammalian meat allergy and tick anaphylaxis. *Med. J. Aust.* **208**, 316–321 (2018).
11. Mullins, R. J., Wainstein, B. K., Barnes, E. H., Liew, W. K. & Campbell, D. E. Increases in anaphylaxis fatalities in Australia from 1997 to 2013. *Clin. Exp. Allergy J. Br. Soc. Allergy Clin. Immunol.* **46**, 1099–1110 (2016).
12. Graves, S. R. & Stenos, J. Tick-borne infectious diseases in Australia. *Med. J. Aust.* **206**, (2017).
13. Eden, J.-S. *et al.* Francisella tularensis ssp. holarctica in Ringtail Possums, Australia. *Emerg. Infect. Dis.* **23**, 1198–1201 (2017).
14. Kwit, N. & Mead, P. Northern Trajectory of Human Tularemia — United States, 1965–2013. in (2017).
15. Harvey, E. *et al.* Extensive Diversity of RNA Viruses in Australian Ticks. *J. Virol.* (2018). doi:10.1128/JVI.01358-18

16. CSIRO and Bureau of Meteorology. *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia*. (2015).
17. Aguirre, A. A. & Tabor, G. M. Global Factors Driving Emerging Infectious Diseases. *Ann. N. Y. Acad. Sci.* **1149**, 1–3 (2008).
18. Daszak, P., Cunningham, A. A. & Hyatt, A. D. Emerging infectious diseases of wildlife--threats to biodiversity and human health. *Science* **287**, 443–449 (2000).
19. Grogan, L. F. *et al.* Surveillance for Emerging Biodiversity Diseases of Wildlife. *PLOS Pathog.* **10**, e1004015 (2014).
20. Ban de Gouvea Pedroso, S. *et al.* Coccidiosis in green turtles (Chelonia mydas) in Australia: Pathogenesis, distribution, temporal and climate-related determinants of disease outbreaks. *Prep.*
21. Preece, N. D. *et al.* A guide for ecologists: Detecting the role of disease in faunal declines and managing population recovery. *Biol. Conserv.* **214**, 136–146 (2017).
22. Milner-Gulland, E. J. Catastrophe and hope for the saiga. *Oryx Camb.* **49**, 577–577 (2015).
23. Zhang, J. *et al.* Identification of a novel nidovirus as a potential cause of large scale mortalities in the endangered Bellinger River snapping turtle (Myuchelys georgesi). *PloS One* **13**, e0205209 (2018).
24. Mörner, T., Obendorf, D. L., Artois, M. & Woodford, M. H. Surveillance and monitoring of wildlife diseases. *Rev. Sci. Tech. Int. Off. Epizoot.* **21**, 67–76 (2002).
25. Lanciotti, R. S. *et al.* Origin of the West Nile virus responsible for an outbreak of encephalitis in the northeastern United States. *Science* **286**, 2333–2337 (1999).
26. Artois, M. *et al.* Wildlife Disease Surveillance and Monitoring. in *Management of Disease in Wild Mammals* 187–213 (Springer, Tokyo, 2009). doi:10.1007/978-4-431-77134-0_10
27. Barratt, J. *et al.* Angiostrongylus cantonensis: a review of its distribution, molecular biology and clinical significance as a human pathogen. *Parasitology* **143**, 1087–1118 (2016).
28. Chan, D. *et al.* The Prevalence of Angiostrongylus cantonensis/mackerrasae Complex in Molluscs from the Sydney Region. *PloS One* **10**, e0128128 (2015).
29. Moreira, V. L. C. *et al.* Endemic angiostrongyliasis in the Brazilian Amazon: natural parasitism of Angiostrongylus cantonensis in Rattus rattus and R. norvegicus, and sympatric giant African land snails, Achatina fulica. *Acta Trop.* **125**, 90–97 (2013).
30. Liu, E. W. *et al.* Rat Lungworm Infection Associated with Central Nervous System Disease - Eight U.S. States, January 2011-January 2017. *MMWR Morb. Mortal. Wkly. Rep.* **67**, 825–828 (2018).
31. Teem, J. L. *et al.* The occurrence of the rat lungworm, Angiostrongylus cantonensis, in nonindigenous snails in the Gulf of Mexico region of the United States. *Hawaii J. Med. Public Health J. Asia Pac. Med. Public Health* **72**, 11–14 (2013).
32. Iwanowicz, D. D. *et al.* Spread of the Rat Lungworm (Angiostrongylus cantonensis) in Giant African Land Snails (Lissachatina fulica) in Florida, USA. *J. Wildl. Dis.* **51**, 749–753 (2015).
33. Ma, G., Dennis, M., Rose, K., Spratt, D. & Spielman, D. Tawny frogmouths and brushtail possums as sentinels for Angiostrongylus cantonensis, the rat lungworm. *Vet. Parasitol.* **192**, 158–165 (2013).
34. York, E. M., Butler, C. J. & Lord, W. D. Global decline in suitable habitat for Angiostrongylus (= Parastrongylus) cantonensis: the role of climate change. *PloS One* **9**, e103831 (2014).

35. The WCRP Coupled Model Intercomparison Project - Phase 5 (CMIP5), CLIVAR Exchanges. *CLIVAR Exch.* **16**, 32 (2011).
36. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An Overview of CMIP5 and the Experiment Design. *Bull. Am. Meteorol. Soc.* **93**, 485–498 (2011).
37. Moss, R. H. *et al.* The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756 (2010).
38. Sanderson, E. W. *et al.* The Human Footprint and the Last of the WildThe human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not. *BioScience* **52**, 891–904 (2002).
39. Phillips, S. J. *et al.* Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. *Ecol. Appl. Publ. Ecol. Soc. Am.* **19**, 181–197 (2009).
40. Soucy, J.-P. R. *et al.* High-Resolution Ecological Niche Modeling of Ixodes scapularis Ticks Based on Passive Surveillance Data at the Northern Frontier of Lyme Disease Emergence in North America. *Vector Borne Zoonotic Dis. Larchmt. N* **18**, 235–242 (2018).
41. Evans, J. P. *et al.* Design of a regional climate modelling projection ensemble experiment – NARCliM. *Geosci. Model Dev.* **7**, 621–629 (2014).
42. IUCN/SSC. Guidelines for Reintroductions and Other Conservation Translocations. (2013).
43. *Guidelines for wildlife disease risk analysis*. (OIE, 2014).
44. Bellinger River Snapping Turtle Status Review, Disease Risk Analysis and Conservation Plan | Conservation Planning Specialist Group. Available at: http://www.cpsg.org/content/bellinger-river-snapping-turtle. (Accessed: 11th December 2018)
45. Brook, B. W., Sodhi, N. S. & Bradshaw, C. J. A. Synergies among extinction drivers under global change. *Trends Ecol. Evol.* **23**, 453–460 (2008).
46. Pounds, J. A. & Crump, M. L. Amphibian Declines and Climate Disturbance: The Case of the Golden Toad and the Harlequin Frog. *Conserv. Biol.* **8**, 72–85 (1994).
47. Lips, K. R. Overview of chytrid emergence and impacts on amphibians. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **371**, (2016).
48. Wyatt, K. B. *et al.* Historical mammal extinction on Christmas Island (Indian Ocean) correlates with introduced infectious disease. *PloS One* **3**, e3602 (2008).
49. McCallum, H. Tasmanian devil facial tumour disease: lessons for conservation biology. *Trends Ecol. Evol.* **23**, 631–637 (2008).
50. Tompkins, D. M., Carver, S., Jones, M. E., Krkošek, M. & Skerratt, L. F. Emerging infectious diseases of wildlife: a critical perspective. *Trends Parasitol.* **31**, 149–159 (2015).

APPENDIX 1: Preliminary Workshop Report

OUTCOMES OF A PRELIMINARY WORKSHOP
21st SEPTMEBER 2017

CHIEF INVESTIGATORS	Australian Registry of Wildlife Health Hannah Bender BVSc, PhD, DACVP Karrie Rose DVM, DVSc
PROJECT PARTNERS	NSW Office of Environment and Heritage Macquarie University Bureau of Meteorology University of Sydney NSW Health

WILDLIFE DISEASE SURVEILLANCE

EXECUTIVE SUMMARY

Anthropogenic climate change is a driving factor in wildlife disease emergence, indirectly through habitat loss and species redistribution, and directly via climate-related fluctuations in disease and vector prevalence. Complex interactions between pathogens and environmental factors such as temperature, rainfall, and humidity will in some cases favour disease emergence and transmission, as well as host susceptibility to disease. Vector-borne diseases are particularly climate-sensitive, with incidence closely tied to climate drivers such as rainfall and temperature. Climate projections for temperate environments in NSW forecast altered host-pathogen-environment dynamics that are tipped in favour of vector survival by the onset of shorter, milder winters that remove the effect of over-wintering on pathogen life cycles.

In a research initiative of the AdaptNSW program, the Australian Registry of Wildlife Health will interrogate existing wildlife disease datasets with respect to climate factors to predict the consequences of a warming climate for biodiversity in NSW. In consultation with the NSW Office of Environment and Heritage, this information will be used to inform conservation planning initiatives such as translocation, reintroduction and emergency response programs. Additionally, ongoing disease surveillance programs will collect baseline wildlife heath data, critical for early detection of emerging pathogens and identifying changing patterns over time.

PRELIMINARY WORKSHOP

INTRODUCTION

This report documents outcomes of a preliminary workshop to explore strategies for incorporating wildlife disease surveillance data and research findings into conservation management actions undertaken by the NSW Office of Environment and Heritage (OEH). The workshop gathered multi-disciplinary expertise in wildlife health and management, climate science and vector-borne disease to discuss the projected impact of climate change on wildlife disease outbreaks, and how the activities of the Australian Registry of Wildlife Health (the Registry), could be formally incorporated into OEH protocols and procedures. Workshop participants are listed in Appendix 1. Prior to the workshop, a discussion paper was circulated to introduce participants to the objectives of the Registry's research under the AdaptNSW biodiversity node, and to provide context for group discussions; this is provided in Appendix 2.

FRAMING THE DISCUSSION

The workshop was opened by Ms Polly Mitchell, senior team leader at NSW OEH, who welcomed participants and provided a background to the AdaptNSW program, a collaborative initiative between OEH and research partners to provide an evidence basis for agency decision making around climate change adaptation. The Registry collaborates with the Biodiversity Node, which investigates the capacity for species and ecosystems adaptation, and explores how land-use can mitigate biodiversity loss.

In order to frame the discussion, brief presentations from Registry personnel and collaborators were delivered:

Dr Hannah Bender – Veterinary pathologist, Australian Registry of Wildlife Health

- An introduction to wildlife disease outbreaks in the context of climate change, and a summary of Adapt project rationale, aims, methods and anticipated outputs

Dr Michael Terkildsen – Statistician and senior research scientist, Bureau of Meteorology

- An approach to predictive data modelling in quantitatively linking climate with wildlife disease and mortality using green turtle coccidiosis as an illustrative example

Dr Cameron Webb – Medical entomologist, NSW Health and University of Sydney

- The complex biology and ecology of arthropod vectors of wildlife pathogens, including environmental drivers, landscape influence and vector competency

Dr Claire Harrison – Veterinary officer, NSW Department of Primary Industries

- Demonstration of an Excel-based decision support tool to assist coordinated responses to wildlife health incidents that are timely and appropriate to risk-level

OUTPUTS IDENTIFIED

Participants broke into small, multi-disciplinary groups to workshop tangible outputs for Registry research. Findings under the AdaptNSW project were determined to be directly relevant to the following priorities of NSW OEH:

1. CONSERVATION INTERVENTIONS

Understanding infectious disease risk is critical to planning management programs such as wildlife translocations and reintroductions. Consideration of disease risks is not currently incorporated into intervention planning by established protocols. An opportunity to formalise this process was recognised by Polly Mitchell, who is driving development of a stepwise adaptation pathway. The pathway implements escalating management interventions when triggered by environmental indicators. Impact mapping for national park assets, including biodiversity, was undertaken to identify appropriate management actions for trigger points related to the frequency and consequence of environmental events forecast under climate projections for NSW (eg. increased incidence of east coast lows, severe fire weather). Polly identified scope to include climate variables that either forecast increased risk of wildlife disease outbreaks, or trigger urgent conservation actions such as translocations, for which disease risk should be a consideration.

2. BIOSECURITY

Peter Stathis, Senior Leader in Biodiversity and Wildlife, identified biosecurity as a priority, relating to both conservation programs (eg. movement of animals) and occupational health and safety. Information related to ticks and tick-borne disease is of particular interest in some jurisdictions, and the utility of proxies for tick and tick-borne disease prevalence were discussed, including cases of tick paralysis in companion animals, and tick-borne disease and red meat allergy in people. No specific programs were flagged for Registry participation; however, it was recognised that ongoing passive surveillance and pathology reporting is critical for aggregation of baseline data necessary for understanding biosecurity risks to both people and wildlife.

3. OTHER

It was noted that outcomes of Registry research could inform urban greening projects by incorporating initiatives to improve biodiversity, and in doing so decrease risk of wildlife disease.

Greg Summerell, Director of Ecosystem Management Science at OEH, commented that the Biodiversity Knowledge Strategy continuously reviews processes for measuring biodiversity with scope to expand criteria and incorporate wildlife indicators, including disease.

FUTURE DIRECTIONS

1. ADAPTATION PATHWAY

A small group desk-top exercise was proposed for early 2018, to identify where elevated risk of wildlife disease could trigger management actions in the adaptation pathway. Drs Hannah Bender and Karrie Rose will coordinate this exercise with Polly Mitchell and relevant personnel in NSW OEH. It is anticipated that this exercise will generate a list of climate-related risk factors related to increased risk of wildlife disease, and will ensure disease risk is assessed in planning and implementing management interventions.

2. PILOT PROJECT – TAMMAR ORBIVIRUS

This project will proceed as described in the discussion paper, evaluating climate variables related to recurrent outbreaks of a vector-borne diseases in Tammar wallabies. This project will identify climate links and potentially generate additional risk factors to inform adaptation planning. Predictive modelling will be explored to map disease hot spots under NSW climate projections.

3. ONGOING WILDLIFE DISEASE SURVEILLANCE

It was acknowledged that ongoing disease surveillance is critical to establish baseline data on wildlife health and disease prevalence. This is a core activity of the Registry, also addressed in the discussion paper, which is integral to early identification of emerging wildlife diseases.

AGENDA

WILDLIFE DISEASE SURVEILLANCE WORKSHOP

September 21, 2017
9:00am – 12:00pm
Vibe Hotel Sydney, 111 Goulburn St, Sydney NSW 2000 (Galaxy Room)

Attendees:

Hannah Bender – Australian Registry of Wildlife Health (Meeting Chair)
Karrie Rose – Australian Registry of Wildlife Health
Jane Hall – Australian Registry of Wildlife Health
Michael Terkildsen – Climate scientist
Cameron Webb - The University of Sydney, NSW Health
John-Sebastien Eden - The University of Sydney
Claire Harrison - NSW Department of Primary Industries
Victoria Graham – Macquarie University
Tiggy Grillo – Wildlife Health Australia
Peter Stathis – NSW Office of Environment and Heritage
Gregory Summerell – NSW Office of Environment and Heritage
Polly Mitchell – NSW Office of Environment and Heritage
Kathleen Beyer – NSW Office of Environment and Heritage
Mike Fleming – NSW Office of Environment and Heritage
Matt Riley – NSW Office of Environment and Heritage
Amy Wardrop – NSW Office of Environment and Heritage
Benjamin Russell – NSW Office of Environment and Heritage

Please read: Adapt NSW discussion paper (sent via email)

9:00am	**Introduction & Round Table**	
9:10am	**Wildlife disease surveillance project**	Dr Hannah Bender
9:25am	**Linking climate to wildlife mortality and disease**	Dr Michael Terkildsen
9:40am	**Understanding the biology and ecology of arthropod vectors of wildlife pathogens**	Dr Cameron Webb
9:55am	**Group Discussion**	
10:30am	**Morning Tea**	
10:45am	**Wildlife Incident Classification Tool demonstration**	Dr Claire Harrison
10:50am	**Breakaway groups**	
10:30am	**Group discussion, conclusions & meeting close**	

AdaptNSW

TARONGA CONSERVATION SOCIETY AUSTRALIA
Australian Registry of Wildlife Health

APPENDIX 2: Cases of Angiostrongyliasis in the Australian Registry of Wildlife Health

REGISTRY ID	SPECIES	SEX	AGE	DATE	DEATH	DIAGNOSIS	LOCATION	LATITUDE	LONGITUDE
TARZ-548.1	Rattus norvegicus	Female	Adult	31/03/1999	Euthanased	Euthanasia	Mosman	-33.829077	151.24409
TARZ-630.1	Trichosurus vulpecula	Male	Adult	8/05/1999	Euthanased	Myelomalacia	Mosman	-33.829077	151.24409
TARZ-548.37	Rattus norvegicus	Female	Adult	22/06/1999	Euthanased	Interstitial pneumonia	Mosman	-33.829077	151.24409
TARZ-548.66	Rattus rattus	Male	Adult	18/02/2000	Euthanased	Euthanasia	Mosman	-33.829077	151.24409
TARZ-1722.1	Ammotragus lervia	Female	Adult	26/07/2000	Euthanased	Meningitis	Mosman	-33.829077	151.24409
TARZ-2027.1	Podargus strigoides	Female	Subadult	27/12/2000	Euthanased	Nematodiasis	Mosman	-33.829077	151.24409
TARZ-2225.1	Petrogale purpercollis	Male	Adult	29/03/2001	Euthanased	Euthanasia	North Ryde	-33.798595	151.133903
TARZ-2367.1	Saimiri sciureus	Male	Adult	13/06/2001	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-2434.1	Macropus parma	Female	Adult	9/08/2001	Euthanased	Meningitis	Mosman	-33.829077	151.24409
TARZ-2827.1	Podargus strigoides	Male	Adult	9/05/2002	Euthanased	Nematodiasis	Neutral Bay	-33.83112	151.221232
TARZ-2964.1	Saguinus oedipus oedipus	Female	Adult	10/07/2002	Found Dead	Parasitism	Mosman	-33.829077	151.24409
TARZ-3330.1	Macropus eugenii	Female	Adult	10/02/2003	Euthanased	Parasitism	North Ryde	-33.798595	151.133903
TARZ-3715.1	Macropus fuliginosus	Female	Adult	17/09/2003	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-3778.1	Lasiorhinus latifrons	Female	Adult	28/10/2003	Euthanased	Malacia	Mosman	-33.829077	151.24409
TARZ-4025.1	Podargus strigoides	Unknown	Adult	3/03/2004	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4068.1	Podargus strigoides	Male	Adult	21/03/2004	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4071.1	Podargus strigoides	Female	Subadult	24/03/2004	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4073.1	Podargus strigoides	Female	Adult	29/03/2004	Euthanased	Parasitism	CREMORNE	-33.833333	151.225
TARZ-4114.1	Podargus strigoides	Female	Adult	27/04/2004	Died	Parasitism	Lane Cove	-33.814599	151.168722
TARZ-4702.1	Podargus strigoides	Female	Juvenile	3/05/2004	Died	Toxoplasmosis	Canley Heights	-33.9	150.933333
TARZ-4127.1	Podargus strigoides	Unknown	Adult	5/05/2004	Euthanased	Parasitism	Cremorne	-33.828131	151.230233
TARZ-4128.1	Podargus strigoides	Unknown	Adult	7/05/2004	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4129.1	Podargus strigoides	Unknown	Adult	7/05/2004	Euthanased	Parasitism	Lane Cove	-33.814599	151.168722
TARZ-4130.1	Podargus strigoides	Unknown	Adult	7/05/2004	Euthanased	Parasitism	Wahroonga	-33.720999	151.097331
TARZ-4137.1	Podargus strigoides	Male	Juvenile	14/05/2004	Died	Meningomyelitis	Terrey Hills	-33.683333	151.233333
TARZ-4146.1	Podargus strigoides	Male	Adult	25/05/2004	Euthanased	Nematodiasis	Clareville	-33.633333	151.316667
TARZ-4168.1	Podargus strigoides	Male	Adult	3/06/2004	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4195.1	Podargus strigoides	Male	Adult	11/06/2004	Euthanased	Nematodiasis - Cerebrospinal	Richmond	-33.618877	150.707372
TARZ-4191.1	Podargus strigoides	Female	Subadult	17/06/2004	Euthanased	Nematodiasis	St Leonards	-33.833333	151.216667
TARZ-4213.1	Podargus strigoides	Female	Adult	5/07/2004	Died	Larval migrans	West Ryde	-33.799441	151.07959
TARZ-4235.1	Podargus strigoides	Unknown	Adult	15/07/2004	Euthanased	Larval migrans	Lane Cove	-33.814599	151.168722
TARZ-4380.1	Podargus strigoides	Male	Adult	5/08/2004		Larval migrans	Terrey Hills	-33.683333	151.233333
TARZ-4516.1	Podargus strigoides	Female	Adult	17/01/2005	Euthanased	Parasitism	Rydalmere	-33.811244	151.034464
TARZ-4537.1	Podargus strigoides	Male	Adult	2/02/2005	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4585.1	Podargus strigoides	Unknown	Adult	8/03/2005	Euthanased	Parasitism	West Pymble	-33.74414	151.141103

TARZ-4586.1	Podargus strigoides	Unknown	Adult	8/03/2005	Euthanased	Encephalitis	Clifton Gardens	-33.829077	151.24409
TARZ-4594.1	Podargus strigoides	Unknown	Adult	21/03/2005	Euthanased	Euthanasia	Manly	-33.797144	151.28804
TARZ-4619.1	Podargus strigoides	Unknown	Adult	31/03/2005	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4641.1	Podargus strigoides	Unknown	Adult	18/04/2005	Died	Parasitism	Castlecrag	-33.802403	151.212643
TARZ-4647.1	Podargus strigoides	Female	Adult	23/04/2005	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4655.1	Podargus strigoides	Female	Adult	1/05/2005	Found Dead	Parasitism	Mosman	-33.829077	151.24409
TARZ-4656.1	Podargus strigoides	Female	Adult	1/05/2005	Euthanased	Fracture	Neutral Bay	-33.83112	151.221232
TARZ-4671.1	Podargus strigoides	Female	Adult	13/05/2005	Euthanased	Arthritis	Killara	-33.753498	151.170003
TARZ-4676.1	Podargus strigoides	Male	Adult	16/05/2005	Euthanased	Euthanasia	Mosman	-33.829077	151.24409
TARZ-4685.1	Podargus strigoides	Unknown	Adult	31/05/2005	Euthanased	Parasitism	Cammeray	-33.821953	151.21043
TARZ-4686.1	Macrotis lagotis	Male	Adult	3/06/2005	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-4730.1	Podargus strigoides	Female	Adult	14/06/2005	Euthanased	Encephalomalacia	Cremorne	-33.828131	151.230233
TARZ-4755.1	Podargus strigoides	Male	Adult	2/07/2005	Found Dead	Predation	Neutral Bay	-33.83112	151.221232
TARZ-4758.1	Podargus strigoides	Female	Adult	7/07/2005	Euthanased	Parasitism	Castlecrag	-33.802403	151.212643
TARZ-5087.1	Podargus strigoides	Female	Adult	13/02/2006	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-5092.1	Podargus strigoides	Female	Adult	15/02/2006	Found Dead	Euthanasia	Thornleigh	-33.738681	151.071433
TARZ-5097.1	Podargus strigoides	Male	Adult	16/02/2006	Euthanased	Parasitism	Ryde	-33.761498	151.137807
TARZ-5098.1	Podargus strigoides	Male	Adult	16/02/2006	Euthanased	Parasitism	Killara	-33.753498	151.170003
TARZ-5135.2	Scythrops novaehollandiae		Subadult	14/03/2006	Euthanased	Euthanasia	Killarney Heights	-33.762011	151.21406
TARZ-5161.1	Podargus strigoides	Unknown	Adult	24/03/2006	Euthanased	Parasitism	Lane Cove	-33.814599	151.168722
TARZ-5208.1	Podargus strigoides	Male	Adult	5/05/2006	Euthanased	Parasitism	North Sydney	-33.802837	151.104935
TARZ-5218.1	Podargus strigoides	Male	Adult	18/05/2006	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-5291.1	Podargus strigoides	Male	Adult	26/06/2006	Euthanased	Nematodiasis - Cerebrospinal	Mosman	-33.829077	151.24409
TARZ-5337.1	Podargus strigoides	Female	Adult	21/07/2006	Euthanased	Meningitis	Greenwich	-33.82609	151.199192
TARZ-5384.1	Podargus strigoides	Unknown	Adult	4/09/2006	Died	Pericarditis	Cremorne Point	-33.828131	151.230233
TARZ-5595.1	Podargus strigoides	Female	Adult	17/01/2007	Euthanased	Myelopathy	Mosman	-33.829077	151.24409
TARZ-5619.1	Podargus strigoides	Male	Adult	31/01/2007	Euthanased	Ganglioneuritis	Mosman	-33.829077	151.24409
TARZ-5661.1	Podargus strigoides	Female	Adult	23/02/2007	Euthanased	Meningoencephalitis - Protozoan-like	Manly Vale	-33.794121	151.26268
TARZ-5691.1	Podargus strigoides	Unknown	Adult	18/03/2007	Euthanased	Meningomyelitis	Centennial Park	-33.893632	151.219357
TARZ-5715.1	Pteropus poliocephalus	Female	Adult	10/04/2007	Euthanased	Parasitism	Waverton	-33.840633	151.19497
TARZ-5720.1	Podargus strigoides	Female	Subadult	13/04/2007	Died	Parasitism	Mosman	-33.829077	151.24409
TARZ-5722.1	Podargus strigoides	Male	Adult	13/04/2007	Euthanased	Parasitism	Mcmahons Point	-33.840633	151.19497
TARZ-5727.1	Podargus strigoides	Male	Adult	16/04/2007	Euthanased	Parakeratosis	Mosman	-33.829077	151.24409
TARZ-5744.1	Podargus strigoides	Male	Subadult	19/04/2007	Found	Septicaemia	Neutral Bay	-33.83112	151.221232

					Dead				
TARZ-5745.1	Podargus strigoides	Male	Adult	23/04/2007	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-5811.1	Trichosurus vulpecula	Female	Subadult	4/06/2007	Died	Cachexia	Castlecrag	-33.802403	151.212643
TARZ-5847.1	Trichosurus vulpecula	Male	Subadult	9/07/2007	Died	Haemorrhage	Terrey Hills	-33.683333	151.233333
TARZ-5944.1	Podargus strigoides	Male	Adult	15/09/2007	Euthanased	Meningitis	Mosman	-33.829077	151.24409
TARZ-5948.1	Podargus strigoides	Unknown	Adult	18/09/2007	Euthanased	Meningitis	Mosman	-33.829077	151.24409
TARZ-6097.1	Podargus strigoides	Female	Subadult	22/12/2007	Euthanased	Parasitism	Clifton Gardens	-33.829077	151.24409
TARZ-6128.1	Podargus strigoides	Unknown	Adult	9/01/2008	Euthanased	Parasitism	Neutral Bay	-33.83112	151.221232
TARZ-6202.1	Podargus strigoides	Male	Adult	18/02/2008	Euthanased	Parasitism	Cremorne Point	-33.828131	151.230233
TARZ-6203.1	Podargus strigoides	Female	Juvenile	18/02/2008	Died	Parasitism	Mosman	-33.829077	151.24409
TARZ-6206.1	Podargus strigoides	Male	Adult	22/02/2008	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-6207.1	Podargus strigoides	Male	Adult	23/02/2008	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-6223.1	Podargus strigoides	Male	Adult	3/03/2008	Euthanased	Parasitism	Gordon	-33.757349	151.155678
TARZ-6208.1	Podargus strigoides	Female	Adult	10/03/2008	Euthanased	Trauma	Kearsley	-32.8442	151.376514
TARZ-6244.1	Podargus strigoides	Female	Adult	19/03/2008	Euthanased	Trauma	Neutral Bay	-33.83112	151.221232
TARZ-6249.1	Podargus strigoides	Male	Adult	25/03/2008	Euthanased	Trauma	Mosman	-33.829077	151.24409
TARZ-6265.1	Podargus strigoides	Unknown	Adult	27/03/2008	Euthanased	Trauma	Gladesville	-33.820941	151.140067
TARZ-6316.1	Podargus strigoides	Female	Adult	30/04/2008	Euthanased	Parasitism	West Pymble	-33.74414	151.141103
TARZ-6329.1	Podargus strigoides	Unknown	Adult	7/05/2008	Euthanased	Unknown - Unidentified	Mosman	-33.829077	151.24409
TARZ-6426.1	Podargus strigoides	Female	Adult	20/07/2008	Euthanased	Parasitism	Kirribilli	-33.846275	151.212705
TARZ-6472.1	Podargus strigoides	Male	Adult	25/08/2008	Euthanased	Parasitism	Cremorne	-33.828131	151.230233
TARZ-6473.1	Podargus strigoides	Female	Adult	25/08/2008	Euthanased	Parasitism	Clontarf	-33.794121	151.26268
TARZ-6817.1	Podargus strigoides	Unknown	Adult	16/02/2009	Euthanased	Meningoencephalitis	Waverton	-33.840633	151.19497
TARZ-6824.1	Podargus strigoides	Male	Adult	22/02/2009	Euthanased	Parasitism	Clontarf	-33.794121	151.26268
TARZ-6829.1	Podargus strigoides	Male	Subadult	24/02/2009	Euthanased	Myelopathy	North Sydney	-33.802837	151.104935
TARZ-6835.1	Podargus strigoides	Female	Adult	25/02/2009	Euthanased	Parasitism	Mosman	-33.829077	151.24409
TARZ-6858.1	Macropus parma	Male - Neuter	Adult	16/03/2009	Euthanased	Nematodiasis	Mosman	-33.829077	151.24409
TARZ-6866.1	Podargus strigoides	Female	Adult	19/03/2009	Euthanased	Parasitism	Balgowlah	-33.794121	151.26268
TARZ-6912.1	Wallabia bicolor	Male	Subadult	15/04/2009	Euthanased	Parasitism	Heathcote	-34.065716	151.012663
TARZ-8032.1	Podargus strigoides	Male	Adult	7/03/2011	Euthanased	Meningitis	Lindfield	-33.766415	151.186095
TARZ-8033.1	Podargus strigoides	Male	Adult	7/03/2011	Euthanased	Ganglioneuritis	St Ives	-33.730601	151.158551
TARZ-8036.1	Podargus strigoides	Male	Adult	8/03/2011	Euthanased	Myelopathy	St Ives	-33.730601	151.158551
TARZ-9253.1	Pteropus poliocephalus	Male	Subadult	14/04/2013	Found Dead	Parasitism	Wahroonga	-33.716667	151.116667
TARZ-9848.1	Pteropus poliocephalus	Female	Adult	9/04/2014	Euthanased	Encephalitis	Sydney	-33.8625203	151.2161448
TARZ-10089.1	Trichosurus vulpecula	Male	Adult	24/08/2014	Euthanased	Pneumonia	Mosman	-33.827778	151.233333
TARZ-	Trichosurus vulpecula	Female	Adult	31/03/2016	Died	Torsion	Mosman	-33.827778	151.233333

11120.1									
TARZ-11380.1	Rattus rattus	Unknown	Adult	12/08/2016	Euthanased	Parasitism	Christmas Island	-10.4993107	105.548036
TARZ-11889.1	Trichosurus vulpecula	Female	Adult	20/06/2017	Found Dead	Encephalitis	Dubbo	-32.25	148.616667
TARZ-4597.1	Podargus strigoides	Male	Adult	22/03/3005	Euthanased	Parasitism	Mosman	-33.829077	151.24409