Toxoplasmosis and Hector's and Māui dolphins

Background information to inform action planning

Department of Conservation
Te Papa Atawhai

New Zealand Government

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Department of Conservation,
PO Box 10 420, Wellington 6143.
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Introduction

Context

A draft action plan is being developed to address the threat of toxoplasmosis to Hector's and Māui dolphins, following public consultation on proposals for an updated Hector's and Māui dolphins Threat Management Plan in 2019. This background document aims to provide further detail on the issue and mitigation options to support the plan. The action plan draws heavily on a literature review carried out for the Department of Conservation (DOC) (J.O. Roberts, W.D. Roe and H.F.E. Jones 2020: The effects of *Toxoplasma gondii* on New Zealand wildlife: implications for conservation and management – submitted to the *Journal of Pacific Conservation Biology* – Manuscript ID PC2005) and references therein. An executive summary of that review is available here www.doc.govt.nz/toxoplasmosis-action-plan.

Toxoplasmosis is a confirmed cause of death in these dolphins [1] and recent research commissioned for the review of the threat management plan suggests that it is a significant threat[2], particularly for Māui dolphins, which are ranked as Critically Endangered under the New Zealand Threat Classification System (NZTCS).

The consultation document for the threat management plan included a proposal for the development of a toxoplasmosis action plan that would include targeted research to inform action, improve knowledge on toxoplasmosis (including the effects on dolphins and other wildlife) and, ultimately, reduce the number of dolphin deaths attributable to toxoplasmosis to near zero. Many submissions received during the consultation process agreed that toxoplasmosis is a significant threat to the dolphins and supported the development of an action plan to address this threat. Note that toxoplasmosis also impacts other species (including livestock and humans), and so although this plan is focused on addressing the threat to the dolphins, it is expected that there are likely to be wider benefits associated with the research and action proposed here.

Proposals for management measures for threats to the dolphins other than toxoplasmosis (such as interaction with fisheries, seismic surveying, seabed mining and tourism) were also included in the public consultation document, and final decisions will be described in the updated threat management plan.

Toxoplasmosis

Toxoplasma gondii is a protozoan parasite that causes the potentially fatal disease toxoplasmosis in a number of animal species. *Toxoplasma gondii* oocysts ('eggs') are released into the environment in the faeces of domestic cats and other felids (the only known animals in which the toxoplasma parasite can sexually reproduce). These oocysts remain infective in soil and freshwater for at least 1 year, and in seawater for at least 6 months[3]. Birds and mammals can become infected with *T. gondii* by ingesting contaminated soil, water, plant material or infected prey species[4]. The environmentally robust nature of toxoplasma oocysts, the potential for infection across a wide range of species (including humans, domestic and wild animals), and widespread distribution of definitive hosts

[1] Roe et al. 2013
[2] Roberts et al. 2019
[3] Dumetre & Darde 2003, Lindsay et al. 2003
[4] e.g. Dubey 2002, and see review by Shapiro et al. 2019

(owned (pet) and unowned (stray and feral) cats), means that toxoplasmosis is an exceptionally widespread disease, with multiple pathways for infection[5].

Toxoplasmosis can be fatal in many species (including humans), although this is often associated with immunosuppressed individuals. If acquired during pregnancy it can also cause foetal abnormalities or abortion[6]. Infection rates in humans range from 8 to 22% in the USA, and from 30 to 90% in Europe, Central and South America, with significant consequences for morbidity and mortality; for example, it is a leading cause of death for foodborne illness in the USA, and is associated with a range of disorders including schizophrenia and depression[7]. In New Zealand, testing of blood donors from the Waikato region indicates that infection rates in humans are around 35 to 50% [8]. In animals, infection is also known to cause sublethal effects and behavioural changes, which may affect their predation risk and reproductive success[9]. Toxoplasmosis is also known to be a cause of abortion and lamb loss in sheep, which is usually managed on farms by vaccination of livestock against the disease[10].

Although the disease is widespread and has significant consequences, toxoplasmosis is considered a 'neglected parasitic infection' in the USA[11]. Given the impacts of toxoplasmosis on human health, domestic animals, livestock and wildlife, a 'One Health' approach to toxoplasmosis management has recently been proposed in the USA, which advocates for transdisciplinary collaborations and integrative research[12]. In New Zealand, the effects of toxoplasmosis on livestock have long been well understood and are typically managed by vaccination. Information on the human health implications of the disease, at least with regards to pregnant or immunosuppressed individuals, is widely available, but it has only recently been identified as a threat to New Zealand native wildlife; in particular, Hector's and Māui dolphins[13].

Effects on Hector's and Māui dolphins

Hector's and Māui dolphins (*Cephalorhynchus hectori hectori*) are small coastal dolphins that are only found in New Zealand. Māui dolphins are found only on the west coast of the North Island and were recognised as a separate subspecies (*C. h. maui*) in 2002[14]. The Hector's dolphin (mainly found in the South Island) is ranked as Nationally Vulnerable in the NZTCS[15] and there are around 15,000 dolphins[16]. The Māui dolphin is estimated to have a population of around 63 individuals above 1 year old and is ranked as Nationally Critical in the NZTCS[15].

Carcasses of dead Hector's and Māui dolphins are examined for cause of death when in suitable condition. Of the deaths that were not fishing related, toxoplasmosis was identified as the cause in 29% of the non-calf dolphins examined between 2007 and 2018 (9 of 31 dolphins; 7 of these were mature females[13]. Two toxoplasmosis-related deaths were from the west coast of the North Island (Māui dolphin habitat), five from the east coast of the South Island and two from the west coast of

[5] Shapiro et al. 2019
[6] e.g. Tenter et al. 2000
[7] see review by Aguirre et al. 2019
[8] Zarkovic et al. 2007
[9] e.g. Webster 2001, Kreuder et al. 2003
[10] Dubey 2009
[11] CDC 2018
[12] Aguirre et al. 2019
[13] Roe et al. 2013, Roberts et al. 2019
[14] Baker et al. 2002
[15] Baker et al. 2019
[16] MacKenzie & Clement 2014, 2016

the South Island, which suggests the parasite may be widespread in the marine environment. Most of the deaths occurred in October and November, indicating there may be a seasonal bias, either in mortality or in recovery of carcasses. These fatal cases of toxoplasmosis were associated with necrotising and haemorrhagic lesions in the lung, lymph nodes, liver and adrenal glands[17].

Furthermore, 61% of the carcasses assessed by Roe et al. (2013) were positive for the presence of *T. gondii* DNA, indicating that latent infection rates are high even if disease symptoms are not obvious in all of these animals. Latent *T. gondii* infections are known to have indirect effects on mammal populations by affecting behaviour and reproductive success[18]. Combined with the high number of deaths of mature females (seven out of nine cases; see above), this suggests that this disease could be important for the sustainability of these dolphin populations, particularly for the Nationally Critical Māui dolphin.

Contamination of freshwater by cat faeces is the source of toxoplasma oocysts in the marine environment – rainwater and runoff transport the oocysts to the sea through streams, rivers and stormwater drains[19]. Spatial distribution models and sightings data for Hector's and Māui dolphins indicate that dolphin densities are highest close to shore where water is turbid from river-borne sediment[20]. This preference for near-shore habitat and turbid river plumes exposes the dolphins to toxoplasma infection either through contaminated water or prey.

A spatial risk assessment has been used to estimate the number of dolphins dying from various threats, including anthropogenic threats such as fishing and toxoplasmosis, and other causes of death, such as predation[20]. The risk assessment estimates the spatial overlap between the dolphins and the threats. The probability of death is estimated from data collected by fisheries observers (for fishery-related threats) and necropsies from recovered dolphin carcasses (for non-fishery-related deaths). It is important to note that the estimates for the probability of death from commercial fisheries mortalities (set net and inshore trawl) are based on fisheries observer data and have been estimated with high certainty, whereas toxoplasmosis deaths have been estimated from necropsy results, which relies on the relative detectability of dolphin carcasses that have died from various causes, resulting in greater uncertainty around the estimates.

The risk assessment indicates that toxoplasmosis is a significant anthropogenic threat to Māui and Hector's dolphins. The pathway of infection appears to relate to the proximity of the marine mammal population to developed coastal areas, which tend to have high densities of cats, and areas of high freshwater runoff which can transport the parasite from land to sea[21]. The presence of *Toxoplasma gondii* in New Zealand mussels[22], New Zealand sea lions[23] and Hector's and Māui dolphins[24] indicate that the parasite could be widespread in the New Zealand environment and is potentially an ecologically significant contaminant that crosses the land–sea boundary[25]. In the risk assessment the spatial density of *Toxoplasma gondii* oocysts in the marine environment was estimated following the approach of VanWormer et al. (2016), by using a spatially resolved hydrological model (TopNet) and spatial information on unowned cat density to predict oocyst loading to rivers and then to coastal waters[20]. This indicated that large rivers such as the Waikato

[17] Roe et al. 2013
[18] Webster 2001, Kreuder et al. 2003
[19] e.g. Conrad et al. 2005, VanWormer et al. 2016
[20] Roberts et al. 2019
[21] Burgess et al. 2018, Conrad et al. 2005, VanWormer et al. 2016
[22] Coupe et al. 2018
[23] Michael et al. 2016
[24] Roe et al. 2013
[25] Hunt & Jones 2020

River, which flow through urban or pastoral landscapes (where cat densities are predicted to be high) are hotpots of *Toxoplasma* contamination to the marine environment. Species distribution modelling indicates that unowned cat densities are likely to be highest in the North Island, particularly around large urban centres, such as Auckland and Hamilton, and in the lower Waikato River catchment[26].

Māui dolphins are the population most exposed to toxoplasmosis risk; it is estimated that toxoplasmosis is responsible for roughly two (probably ranging between 0.5 and 3.3) Māui dolphin deaths per year[20]. The estimates of mortality associated with toxoplasmosis rely on assumptions around the relative detectability of carcasses dying from different causes of death and reporting of dead dolphins by the public for subsequent necropsy. As a result, there is substantial uncertainty around the estimated number of toxoplasmosis-related deaths, and these estimates may be biased either high or low.

However, even though the estimates are highly uncertain, the risk to the dolphins is significant (even at the lower bound of the estimates) and the risk assessment indicates that toxoplasmosis may kill more dolphins than any other human threat. A Māui dolphin population demographic model produced independently from the risk assessment[27] also estimated that toxoplasmosis risk is sufficient to drive ongoing population decline even in the absence of any other human-related threat.

Hector’s dolphins are also exposed to toxoplasmosis risk. At the scale of the whole South Island, the risk assessment estimates roughly 300 (probably ranging between 50 and 700) Hector’s dolphin deaths per year from toxoplasmosis, but the risk is not uniform across the four populations[28] and is subject to the same uncertainty described above.

Wider effects

In addition to the effects of toxoplasmosis on Hector’s and Māui dolphin, other native species also develop the disease, which has the potential to impact on New Zealand biodiversity in general. Toxoplasma oocysts can potentially infect most mammal and bird species, but the factors that lead to fatal toxoplasmosis in some species or populations, or sub-lethal effects that affect behaviour or reproductive success, are not clear.

Overseas, toxoplasmosis is known to cause mortality in other marine mammals, such as the southern sea otter (*Enhydra lutris)* in California[29] and the Hawaiian monk seal (*Monachus schauinslandi*)[30].

Toxoplasmosis causes fatal encephalitis in sea otters and was found to be a major cause of death in Californian sea otters examined between 1998 and 2001[29]. Proximity to freshwater runoff and human population density has been shown to be associated with increased prevalence of *T. gondii* infection in this species[31]. Furthermore, spatial modelling of oocyst loading and freshwater flow has shown that areas with high levels of coastal development and domestic cat populations increase oocyst delivery to the sea and are associated with high levels of infection in sea otters[32]. A similar

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[26] Aguilar et al. 2015
[27] Cooke et al. 2019
[28] Roberts et al. 2019
[29] Kreuder et al. 2003
[30] Honnold et al. 2005
[31] Miller et al. 2002, Burgess et al. 2018
[32] VanWormer et al. 2016

approach was used to estimate oocyst loading in the New Zealand marine environment to assess the spatial overlap between toxoplasma oocyst density and Hectors's and Māui dolphin distribution[28].

Disseminated toxoplasmosis, with lesions observed in multiple tissues (including lymph nodes, spleen, adrenal glands and brain), was first reported in a Hawaiian monk seal in 2005[30]. Although antibodies to *Toxoplasma gondii* were rarely found in infectious disease monitoring of these seals between 1997 and 2001[33], recent studies have confirmed further toxoplasmosis-related mortalities (eight cases between 2001 and 2015), implying the disease could suppress any recovery of this endangered seal species[34]. Spinner dolphins (*Stenalla longirostris*) in Hawai'i have also been reported to have died from toxoplasmosis[35], and it is known to have lethal and sublethal effects on several Hawaiian native bird species[36]. In island ecosystems with no native cats, native wildlife may be more susceptible to toxoplasma infection and related morbidity and mortality[37]; the situation in Hawai'i and New Zealand, with regards to the effects of this parasite on native species, may therefore be quite similar.

In New Zealand, there is evidence to suggest that toxoplasma infection is causing morbidity and mortality in endemic and endangered species, in addition to Hector's and Māui dolphins. Recent research has shown toxoplasmosis to be a cause of death in three endemic bird species – kererū (*Hemiphaga novaeseelandiae*), North Island brown kiwi (*Apteryx mantelli*) and North Island kākā (*Nestor meridionalis*)[38]. Toxoplasma infection has also recently been identified as a casual factor in the death of a New Zealand sea lion (*Phocarctos hookeri*) in Otago[39]. It is unknown how many native species might be susceptible to toxoplasmosis, or the overall effect of this disease on biodiversity.

In addition to effects on threatened species and biodiversity, there are significant societal and economic costs associated with the impact of toxoplasmosis on agriculture and human health[40]. For example, toxoplasmosis has long been recognised as cause of abortions in sheep, goats and pigs, and the farming community in New Zealand currently incurs significant cost vaccinating ewes against the disease in order to prevent lamb loss[41]. The societal and economic cost of this disease in humans is also likely to be significant, although assessing actual costs is difficult for several reasons. For example, as treatment for toxoplasmosis will usually only occur for acute infections, records of hospital admissions are likely to be underestimates of the true rates of morbidity. However, studies overseas have estimated the annual health care costs associated with toxoplasmosis at millions of dollars per year[42]. A recent study looking at the risks to health posed by toxoplasma tissue cysts in red meat products concluded there is a need to assess the burden of toxoplasmosis on New Zealand from a human health perspective[43].

Given the threatened species status of Hector's and Māui dolphins, and the cause of toxoplasma infection in the dolphins being the result of transmission from an introduced species, there are also potential public image and economic impacts (e.g. on the eco-tourism industry) of any toxoplasmosis-related decline in dolphin populations.

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[33] Aguirre et al. 2007
[34] Barbieri et al. 2016
[35] e.g. Migaki et al. 1990
[36] Work et al. 2002, 2016
[37] Hollings et al. 2013
[38] Howe et al. 2014
[39] Roe et al. 2017
[40] e.g. Suijerkerbuijk et al. 2018, Stelzer et al. 2019
[41] e.g. Tompkins 2014.
[42] e.g. Prusa et al 2017, Suijerkerbuijk et al. 2018
[43] MPI 2015

Roles and responsibilities

The Department of Conservation is the leading central government agency responsible for the conservation of New Zealand's natural and historic heritage (under the Conservation Act 1987). The Department may advocate for the protection of Hector's and Māui dolphins through statutory processes; for example, under the Resource Management Act 1991 (RMA) and the Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act 2012 (EEZ Act), or by encouraging protection through non-regulatory means.

In addition, the following policies from the Conservation General Policy apply to this Hector's and Māui dolphin Toxoplasmosis Action Plan:

- Marine protected species should be managed for their long-term viability and recovery throughout their natural range.
- The Department [DOC] should work with other agencies and interests to protect marine species.

Section 4 of the Conservation Act 1987 requires DOC to give effect to the principles of the Treaty of Waitangi. The Treaty principle of active protection includes the promise to protect taonga. Hector's and Māui dolphins are a taonga species, and active protection will only be possible if the threat from toxoplasmosis, and actions to address it, are properly researched and understood. The Treaty principles of partnership and informed decision-making will also be highly relevant, in terms of the involvement of Māori in toxoplasmosis research and management actions through consultation, and research or working groups.

Other central and local government agencies have mandates and responsibilities in relation to the management of the marine and freshwater environment, cats, and diseases such as toxoplasmosis. These include Biosecurity New Zealand (MPI), the Ministry for the Environment (MfE), the Ministry of Health (MoH), and local government. DOC will need to work with these agencies to manage the threat of toxoplasmosis to Hector's and Māui dolphins.

Approaches to mitigation

There are two approaches to reduce the parasite *Toxoplasma gondii* entering the marine environment:

1. **Reduce the transfer of toxoplasma oocysts from cats to the environment**
    - Unowned (feral and stray) cat populations
    - Owned (pet) cat populations
    - Pest management of cat prey species (controlling reservoir populations and future infections of cats)

2. **limiting the transfer into the sea of toxoplasma oocysts already in the environment – interventions focussed on hydrological networks**
    - Restoring wetlands
    - Riparian planting
    - Storm/waste water treatment

Management strategies that aim to mitigate or remediate an environment already contaminated with toxoplasma oocysts are likely to be very challenging, require significant investment in terms of design and implementation, and may be highly uncertain in terms of likely efficacy; however, these strategies are socially very acceptable. In contrast, management strategies aimed at reducing toxoplasma loading at the source by reducing cat numbers, or containing cats indoors, are more likely to be effective in terms of reducing environmental contamination with toxoplasma, but present greater challenges in terms of social license to operate, resourcing and lack of consistent legislation.

1. Reduce loading of toxoplasma oocysts to the environment – Interventions focussed on cats

Domestic cats primarily acquire toxoplasma via the predation of infected prey, and the level of the parasite in the population is generally higher in unowned (feral and stray) cats than in owned (pet) cats due to an elevated dietary intake and access to infected wild prey [44]Consistent with this, owned cats with outdoor access to wild prey tend to have higher toxoplasma seroprevalence than cats confined indoors.[44]

- Feral cats:

  In New Zealand, feral cats mostly prey on rabbits, rats, mice, small birds and (where abundant) lizards and insects.[45]

  Feral cat control is significantly hampered where there is high re-incursion of strays from owned cat populations; because of this, cat eradication has only worked successfully on smaller offshore islands or within predator-proof-fenced areas. In mainland areas the goal has been to supress cat populations around localised key biodiversity sites at key times e.g. breeding and nesting periods for birds.

  Current management:
  Feral cat control may be carried out on public conservation land by DOC to reduce impacts of predation on native birds, bats, lizards, mice, wētā and other insects. Control is generally localised around discrete biodiversity outcomes and is resource dependent. Feral cats on private land can also be managed by regional councils and unitary authorities under the Biosecurity Act but implementation is inconsistent throughout the country, is typically focused at high-value biodiversity sites, and is dependent on resourcing available.

  Feral cats are generally managed through trapping that is highly resource intensive. With the likelihood of re-incursion of cats into areas where their populations have been supressed, and the social licence issues associated with cat controls, there is presently little appetite for broad-scale cat control in mainland areas.

  Unowned cats have shorter life spans (a few years cf. 15+ years for owned cats), breed more rapidly and have a greater population turnover. When coupled with oocyst shedding typically occurring early in cats' lives, this results in greater oocyst loading to the environment from unowned cats.

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[44] Roberts et al. 2020 paper submitted to journal – an executive summary is available from DOC
[45] Fitzgerald & Karl 1979, Murphy et al. 2004

There are also different strains of toxoplasmosis, one of which is virulent to Hector's and Māui dolphins. Feral cat populations that carry the virulent strain of toxoplasmosis should be identified and targeted as a priority.

- Stray and owned cats:

  Methods for controlling owned cat populations are generally targeted around containment of cats and limiting their ability to roam, in turn restricting their ability to catch wild prey, and to reduce defecation outdoors.

  New Zealand has one of the highest levels of pet cat ownership in the world, with an estimated 44% of households owning at least one cat. This puts the estimated number of owned cats in New Zealand to over a million.

  In contrast with feral cats, there is currently no legislation that gives government departments the authority to control stray cats, and there is considerable debate about the requirement for, and ethics relating to, stray cat management[46]. A draft National Cat Management Strategy was developed in 2017 that called for a consistent, national approach for cat management, and this is likely to be critically important to enable effective management of the risks to wildlife posed by toxoplasma.

  The New Zealand National Cat Management Strategy discussion paper[47] is a joint effort by groups including the NZ Veterinary Association, the Society for the Prevention of Cruelty to Animals (SPCA), DOC and the Morgan Foundation. The strategy has a focus on responsible cat ownership, the treatment of stray cats and the regulatory frameworks that may be required to enable local bodies to develop their own strategies to protect both vulnerable wildlife and owned cats. Clearly separating loved owned cats from feral and stray cats better allows for appropriate management action to be taken. Local government (such as district or city councils) may enact bylaws focused on cat management under the Local Government Act 2002 relating to the keeping of animals. However, not many local government agencies have enacted bylaws relating to cat management. Local government agencies may also conduct educational campaigns relating to responsible cat ownership.

  All mammal pest control tools and techniques must be humane, and this extends to cats. Finding appropriate controls that allow for ownership of cats in New Zealand is essential.

  Voluntary measures for keeping cats indoors can be advocated. This simple action can be taken by any cat owner and will make a significant difference in reducing dolphins' exposure to toxoplasma. Keeping owned cats inside means they are far less likely to contract the toxoplasma parasite, and by disposing of their kitty litter in the rubbish, rather than flushing it down the toilet, they will not be shedding the parasite into the environment through their faeces.

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[46] Farnworth et al. 2011

[47] NZCMS (2017). New Zealand National Cat Management Strategy Discussion Paper. Available at: http://www.nzcac.org.nz/images/downloads/nz-national-cat-management-strategy-discussion-paper.pdf

An alternative to the containment of owned cats could be their widespread vaccination against toxoplasmosis. Several experimental cat-specific vaccines have been developed, but their implementation has been limited by high costs, short vaccine shelf-life and limited interest or incentives for cat owners to use them, since toxoplasmosis is rarely fatal to the cat. Consequently, there is currently no internationally available commercial vaccine. However, if feasible, the development and commercialisation of a vaccine to prevent the infection of domestic cats with toxoplasma, along with controls on the management of owned cats, could provide a long-term solution to the loading of toxoplasma oocysts into the environment.

- Pest management (controlling reservoir populations and future infections of cats):

  Carnivores, omnivores, and apex predators are particularly susceptible to toxoplasma infection via the consumption of prey containing tissue cysts. Other ground-dwelling species are also prone to infection via the incidental ingestion of oocysts while foraging for food. In this way rodents, mustelids and lagomorphs (rabbits and hares) may harbour infections of the parasite. Oocysts do not form in these host species, but because they are the prey of cats, they act as a reservoir of the parasite in the environment. Hunting small prey constitutes a risk factor for cats acquiring toxoplasma infection; however, the risk is related to the general prey availability and the composition of prey species[48].

  If toxoplasma is present in these prey species, cats that prey on them can become infected. It has been discovered that vertical transmission of the parasite (where it is passed on to offspring) occurs in mice, which allows for toxoplasma to persist in a cat-free environment for some time.

  The Department of Conservation is the coordinating agency for Predator Free 2050 (PF2050), which involves Predator Free 2050 Ltd, the Predator Free NZ Trust, the Biological Heritage National Science Challenge, local government, MPI, NGOs and other groups and organisations. The goal of PF2050 is to rid New Zealand of the most damaging introduced predators by 2050. While the PF2050 programme is focused on stoats, rats and possums, related projects such as the Maukahuka Pest Free Auckland Island Project do include feral cat control. Regional councils and unitary authorities manage pests on private land via Regional Pest Management Plans (RPMP) under the Biosecurity Act 1993 and the Biosecurity Law Reform Act 2012.

  Elimination of pest species from key habitats will be fundamental to supporting the elimination of these toxoplasma reservoirs.

2. **Limiting the transport of toxoplasma oocysts that are already in the environment – interventions focussed on hydrological networks**

   Hydrological networks provide the essential means by which toxoplasma oocysts are transported to the marine environment.

[48] Afonso et al. 2007

A complication when assessing or designing toxoplasma management interventions for hydrological networks is the poorly developed methodology for measuring toxoplasma oocyst concentration in water samples. This makes it difficult to assess the relative contribution of wastewater treatment plants, stormwater systems or particular catchments to the loading of toxoplasma oocysts to aquatic environments, and then to monitor or assess the efficacy of any mitigation measures that are implemented.

Methods looking at the accumulation of toxoplasma oocysts in green lipped mussels have been trialled and show some promise for use as bio-sentinels of toxoplasma contamination of the New Zealand marine environment.

The Essential Freshwater work programme, led by MfE and MPI (but with a taskforce including representation from other government agencies), aims to stop the degradation of freshwater, promote restoration of waterways and address water allocation issues. Linked to this is the Three Waters Review, led by the Department of Internal Affairs, and initiatives by MfE to improve management of urban water. Such programmes may provide opportunities to incorporate needs for mitigating the transport of toxoplasma oocysts.

- Restoring wetlands:

  Wetlands can reduce the transmission of toxoplasma oocysts into estuarine and coastal environments by retarding water flow, enhancing the likelihood of oocysts settling out of the water and by trapping oocysts in wetland vegetation and associated biofilms. However, the efficacy of wetlands at processing any type of contaminant is dependent on multiple factors, including hydrology, wetland size, location, type of vegetation and contaminant loading.

  Wetland restoration plans are developed through regional councils and local authorities.

- Riparian planting:

  Studies from the USA have suggested that the difference between vegetated and non-vegetated margins of waterways can have as much as a 6-fold magnitude difference in reducing toxoplasma oocyst load into the associated waterway (Shapiro et al. 2010). The applicability of this to New Zealand systems is unknown. Revegetating riparian margins within key catchments could be a useful first step in reducing the loading to the marine environment.

  Currently there are various catchment management programmes operating (often collaboratively) throughout the country at different levels and with different responsible agencies including DOC, MfE, MPI, councils, iwi groups, NGOs, Industry groups (including Fonterra), farmers and community groups.

  Some examples within catchments that flow to core Māui dolphin habitat include programmes through the Waikato River Authority, Whaingaroa catchment work and other work being done by the Waikato Regional Council (e.g. the Healthy Farms, Healthy Rivers project).

  A new study has demonstrated that the Waikato River plume is relatively stable and overlaps greatly with the core Māui dolphin habitat. Concentrations of oocysts are predicted to be highest in areas known as Estuarine Turbidity Maxima. Essentially, in the case of the Waikato river, the river's plume drives this offshore from the estuarine environment into the marine environment that is most preferred by the dolphins. It is assumed also that these areas are high productivity areas, and therefore associated with concentrations of prey species. This is an area that needs further examination.

Hydrological models of some of these west coast North Island systems are quite advanced (e.g. Water Care Auckland Manukau harbour model), so it is possible that they could help predictive targeting of sites for riparian planting to reduce toxoplasma loading in key catchments.

- Waste and storm water treatment:

  Urban stormwater is potentially a significant pathway for oocysts to waterways, as rainfall runoff in urban environments (involving predominantly impervious surfaces) is likely to transport cat faeces into stormwater drains which, in New Zealand as in many other countries, tend to discharge directly into streams, rivers or the marine environment.

  Disposing of cat faeces (particularly through flushing faeces from kitty litter trays down the toilet and into wastewater systems) presents a pathway for oocysts to travel into the marine environment.

  Oocysts are not affected by currently used methods of wastewater treatment (including disinfectants and ultraviolet light), so new technologies will need to be found and trialled.

  Design of green infrastructure, such as vegetated areas or constructed wetlands in stormwater and wastewater treatment plants, may enable oocyst transmission into waterways to be reduced. However, the efficacy of these interventions are presently unknown, and any new approaches or technologies would likely need to be retrofitted into existing infrastructure.

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Appendix 1: Potential research projects

Identifying 'hotspots' of toxoplasma contamination in marine and freshwater environments

To inform spatial prioritisation of management actions, there is a need to determine whether there are spatial 'hotspots' of toxoplasma contamination and where these might be, and whether there are particular cat host population(s) which carry the atypical *Toxoplasma gondii* genotype that has been shown to be lethal to the dolphins[49]. A spatially resolved cat sampling programme would determine whether the lethal toxoplasma genotype originates in certain cat populations, with populations defined spatially and by type (i.e. owned (pet) or unowned (stray or feral)).

Direct testing for toxoplasma oocyst loading in water samples is not straightforward. There is a need to investigate the viable options for sampling toxoplasma in water (for example, by using filter-feeding organisms such as mussels) to validate estimates of oocyst loading to marine environments and help identify sources of contamination within freshwater catchments.

Improved hydrological models and/or spatial analysis, incorporating data from the above, may help to identify 'hotspots' and better understand the spread of toxoplasma oocysts from land to sea. This needs to be at a spatial resolution that is useful for prioritisation of management actions (i.e. catchment or sub-catchment scales) and to consider transport pathways for oocysts between the terrestrial and the marine environment and how these might be mediated by different habitat and land use types (e.g. urban vs. rural, vegetated vs. non-vegetated). This research may also need to consider potential seasonal or temporal patterns in toxoplasma contamination related to, for example, seasonally variable freshwater flows, or toxoplasma oocyst shedding by cats, and whether this could influence infection or mortality rates in dolphins.

Vaccination of cats against toxoplasmosis

Widespread vaccination of domestic cats against toxoplasmosis could reduce *Toxoplasma* loading to the environment. Sheep can be vaccinated against toxoplasmosis using a vaccine (Toxovax®) that is widely used in several countries including New Zealand and the UK to reduce abortions and lamb loss due to infection with this disease[50]. Several experimental cat-specific vaccines have been developed[51], but no vaccine is currently commercially available in New Zealand or overseas. The potential for commercialisation of a vaccine that could be used in domestic cats needs to be investigated; this could provide a long-term solution to the impacts of toxoplasmosis on dolphins and other affected species (including people).

Note that development of a vaccine would likely be extremely expensive (i.e. requiring millions of dollars) and would need to be driven commercially. It is unlikely to be funded only in the context of conservation of Hector's and Māui dolphins; but is mentioned here for completeness and to highlight the potential need in the wider context of toxoplasmosis management for wildlife, agriculture and human health.

Identify and address the barriers to cat owner behaviour change

Changing people's behaviour is challenging and some behaviours that are likely to be effective for conservation, such as keeping cats indoors, have been shown to be unlikely to be adopted by cat

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[49] Roe et al. 2013
[50] e.g. Innes et al. 2009, Garcia et al. 2014
[51] e.g. Frenkel et al. 1991, Ramakrishnan et al. 2019

owners[52]. There is a need to confirm the cat owner behaviours that would reduce toxoplasma transmission, determine what barriers prevent or reduce people complying with these and what potential interventions could increase compliance with desired behaviours.

Review and/or develop stormwater and wastewater toxoplasma treatment options

Toxoplasma oocysts are resistant to standard wastewater disinfection processes, including UV treatment, and so are unlikely to be removed in wastewater treatment. If cat faeces are introduced into the sewage system, then wastewater treatment plant discharges would be a source of toxoplasma to freshwater and marine environments. Urban stormwater is potentially a significant source of toxoplasma to waterways, as rainfall runoff in urban environments (with predominantly impervious surfaces) is likely to transport cat faeces into stormwater drains. There is a need to review the potential for design (or retrofitting) of stormwater treatment devices to reduce toxoplasma transmission to freshwater or marine environments. For example, there may be potential to trap oocysts in catch pit inserts, especially where oocysts may flocculate, or attach to sediment or other particulates.

Develop guidelines for wetland restoration

Wetlands can reduce transmission of toxoplasma into freshwater and marine environments by trapping oocysts in wetland vegetation. Wetland restoration and riparian planting is already undertaken in many catchments to improve biodiversity and water quality; mitigating the threat of toxoplasmosis to the marine environment would provide further justification for this work. However, wetlands would need to have adequate capacity to process peak (flood) flows (i.e. be large enough) and contain dense vegetation to be effective at trapping oocysts. Furthermore, wetlands cannot be implemented everywhere (e.g. where urban development is located on the edge of waterways, and/or where urban stormwater infrastructure cannot be re-routed). It is also important that pest control is incorporated in wetland or riparian restoration projects, otherwise these areas can provide habitat for stray or feral cat populations, which could counteract other toxoplasma mitigation measures. Guidelines for wetland design (including size, location, type of vegetation and pest control measures) need to be developed to ensure any wetland restoration is effective at reducing toxoplasma oocyst input to marine environments.

Review stranding rates by cause of death

Currently, estimates of mortality associated with toxoplasmosis rely on the assumption that the outcomes of examinations of beachcast dolphins are representative of all possible causes of death. There is a need to review existing information with respect to stranding rates by cause of death to explore this assumption. The review should assess the likely discovery rate for dead dolphins and whether this varies by subpopulation, geographic location, time of year etc., as well as cause of death.

Increase necropsy data available

Increased necropsy data gained from an increased recovery rate of dolphin carcasses would also reduce uncertainty in the estimation of dolphin mortality rates due to toxoplasmosis and other causes. The review of stranding rates and cause of death might also to be able to provide recommendations around how carcass recovery rates could be increased. For example, by surveying beaches at certain times of year, following onshore winds, or locations known to be debris collection points. Likely stranding locations might be informed by modelling the drift of carcasses in ocean

[52] e.g. Linklater et al. 2019

currents[53], in a similar way to that used for predicting oil dispersal, or the trajectories of other floating objects, based on hydrodynamic models.

A social science study could be used to understand what (if anything) prevents the public from reporting dead dolphins, and how best to target an education campaign that would improve awareness around the importance of reporting beachcast dolphins to the DOC Hotline.

If more beachcast carcasses were able to be recovered, then the necropsy programme would likely need greater funding to handle the increased volume of necropsies and associated tests required.

Increase sampling for toxoplasma infection in other species

Hector's and Māui dolphins are not the only species impacted by toxoplasmosis, although the full extent of this disease on New Zealand's conservation values, economic values and human health is presently unknown. Increased sampling for toxoplasma infection, and associated morbidity and mortality, in native species (particularly other marine mammals) identified through the literature review, or through other research, will help to ascertain the wider implications of this parasite on biodiversity in general. Combined with existing knowledge on the impacts of toxoplasmosis on agriculture and human health, an understanding of its effects on wider biodiversity values may help to guide and prioritise future research, actions and investment.

Identifying the pathway of infection to the dolphins

Sampling for toxoplasma in paratenic hosts in marine food chains, such as fish and invertebrates, would improve understanding of the pathway of infection between cats and dolphins and may provide opportunity for potential management actions.

Increasing understanding of other factors that might increase the dolphins' susceptibility to toxoplasma infection and associated morbidity and mortality

Although fatal toxoplasmosis in many species is often associated with immunosuppressed individuals, the Hector's and Maui dolphins that are confirmed to have died from toxoplasmosis did not appear to be immunocompromised (in that there was no evidence of underlying morbillivirus infection[54] . However, there is a need to increase understanding of other factors (e.g. contamination with other pollutants, other infections, genetics, pregnancy, prey availability) that might increase susceptibility in the dolphins to toxoplasma infection and associated morbidity or mortality.

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[53] e.g. Peltier et al. 2012
[54] Roe et al. 2013

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