Evaluating the Risk of Toxoplasma gondii Exposure to Hawaiian Monk Seals
A Conceptual Map & Research Directions

VII. Appendix of Tables

Table 1. Summary of published *T. gondii* screening in marine mammals/marine environments.

Author	Year	Location	Detection	Species	Finding
Central Pacific—Hawaii					
G. Migakit et al.	1990	Hawaii, USA	Histopath., PCR	HI Spinner Dolphin (*Stenella longirostris*)	1
Littnan et al.	2006	Hawaii, USA	Serology	HI Monk Seal (*Neomonachus schauinslandi*)	2/18
Barbieri et al.	2016	Hawaii, USA	Histopath., PCR	HI Monk Seal (*Neomonachus schauinslandi*)	7
Work et al.	2000, 2002	Hawaii, USA	Histopath.	Varied avian species	4, 5
Western Pacific—Australia/New Zealand					
Donahoe et al.	2014	Australia	Histopath., PCR	New Zealand Fur Seal (*Arctocephalus forsteri*)	1
Roe et al.	2013	New Zealand	Histopath., PCR	Hector's / Maui Dolphin (*Cephalorhynchus hectori*)	7/28
Roe et al.	2017	New Zealand	Pathology, PCR	New Zealand Sea Lioon (*Phocarctos hookeri*)	1
Michael et al.	2016	New Zealand	Serology: ELISA, LAT, Wblot	New Zealand Sea Lioon (*Phocarctos hookeri*)	5/55
Eastern Pacific—USA West Coast					
Lambourn et al.	2001	Washington, USA	Serology: MAT	Harbor Seals (*Phoca vitulina*)	29/380
Gaydos et al.	2007	Washington, Alaska, USA	Serology: IFAT	River Otters (*Lontra canadensis*)	7/40
Miller et al.	2002	California, USA	Serology	California Sea Otter (*Enhydra lutris nereis*)	115/223
Conrad et al.	2005	California, USA	uncertain	California Sea Otter (*Enhydra lutris nereis*)	159/305 dead 98/257 live
Shapiro et al.	2012	California, USA	Histopath.	California Sea Otter (*Enhydra lutris nereis*)	11–19% / 128

Author	Year	Location	Detection	Species	Finding
Southern Pacific—South America					
Calvo-Mac et al.	2020	Chile		Marine otter (*Lontra felina*)	1/19
				Domestic cats (*Felis catus*)	4/50
Western Atlantic/Canadian Arctic					
Measures et al.	2004	E. Canada	Serology: MAT	Grey seal (*Halichoerus grypus*)	11/22
				Hooded seal (*Cystophora cristata*)	1/60
				Harp seals (*Pagophilus groenlandicus*)	0/112
Bachand et al.	2019	Nunavut, CAN	PCR, Serology: MAT	Ringed seals (*Pusa hispida*)	12/61
				Walruses (*Odobenus rosmarus*)	0/27
				Caribou (*Rangifer tarandus*)	8/31
				Ptarmigan (*Lagopus lago-pus*)	0/66
				Geese (*Branta* spp., *Chen* spp.)	14/156
Northern Atlantic/Europe					
Forman et al.	2009	England	Serology: Sabin Feldman Dye Test	Varied—Cetaceans	8/101
Jensen et al.	2010	Svalbard, Norway	Serology: Direct Agglutination	Polar bears (*Ursus maritimus*)	46%
				Ringed seals (*Pusa hispida*)	19%
				Bearded seals (*Erignathus barbatus*)	67%
				Harbour seals (*Phoca vitulina*)	0
				White whales (*Delphinapterus leucas*)	0

Author	Year	Location	Detection	Species	Finding
				Narwhals (*Monodon monoceros*)	0
van de Velde et al.	2016	N. Sea and E. Atlantic Ocean	PCR, Serology: MAT, ELISA, IFA	Harbour porpoise (*Phocoena phocoena*)	2/193 PCRs
				Varied—Marine Mammal	7–41%
Mediterranean					
Bigal et al.	2018	Israel	PCR	Bottlenose Dolphin (*Tursiops truncatus*)	3
Antarctica					
Rengifo-Herrera et al.	2012	Antarctic	Serology	Southern elephant seals (*Mirounga leonina*)	10/13
				Weddell seals (*Leptonychotes weddellii*)	13/31
				Antarctic fur seals (*Arctocephalus gazella*)	4/165
				Crabeater seals (*Lobodon carcinophaga*)	1/2
Multi-basin Surveys					
Gibson et al.	2011	Widespread	PCR	Varied - Marine Mammal	94/161
Dubey et al.	2003	Widespread	Serology: MAT	Sea otters (*Enhydra lutris*)	9/115
				Pacific harbor seals (*Phoca vitulina*)	51/311
				Sea lions (*Zalophus californianus*)	19/45
				Ringed seals (*Phoca hispida*)	5/32
				Bearded seals (*Erignathus barbatus*)	4/8
				Spotted seals (*Phoca largha*)	1/9
				Atl. bottlenose dolphins (*Tursiops truncatus*)	141/138
				Walruses (*Odobenus rosmarus*)	3/53

Table 2. Summary of published research applying spatial / ecological models to assess risks associated with *T. gondii*.

Citation	Location	Disease Data	Analysis Methods	Risk Factor Variables	Findings
Miller et al. 2002	California, USA	223 California sea otters (Seroprevalence 52%)	Logistic regression	Sex	Tg > male
				Age	Tg > older
				Sample location	Tg > Morro Bay
				Proximity to freshwater runoff	Tg > more runoff
				Human population density	NS
				Proximity to sewage outflow	NS
Shapiro et al. 2012	California, USA	128 California sea otters (Histopathology; 11–19%)	Odds ratio tests via regression	Age	Tg > Adults
				Sex	NS
				Location	Some risk factors showed Bay-specific associations
				River flow	NS
				Rainfall	Tg > lower 60 day rainfall (at Monterey Bay; Note - stronger association between rain/river flow in more acute S. neurona)
Afonso et al. 2013	France	210 felids (Seroprevalence 62%) European wildcat, Domestic cat	Spatial and temporal cluster detection	Species (or hybrid based on genotype)	NS
				Sex	NS
				Age	Tg > in adults
				Farm density	Tg > high farm density
				North Atlantic Oscilation index (weather pattern)	Tg > years with cool and moist winters
Simon et al. 2013	Canadian Arctic	Oocyst load—estimated	Watershed-based hydrological model	NA	NA
				Daily snowmelt/stream flow	Tg oocyst runoff > at beginning of the snowmelt
				River discharge location	Tg oocysts at low concentration at river outlets
				Habitat/landcover type	Tg oocyst accumulation in the estuarine areas likely sufficient to contaminate prey species

Citation	Location	Disease Data	Analysis Methods	Risk Factor Variables	indings
VanWormer et al. 2014	California, USA	373 carnivores (PCR screening) Feral domestic cats (30%), Mountain lions (14%), Bobcats (41%), Foxes (17%), Coyotes(4%)	Geographical cluster detection, Odds ratio tests via regression	carnivore group (feral domestic cat, wild felid, wild canid),	Tg Type X > in wild carnivores
				Age class (juvenile, adult)	NS
				Sex	NS
				Year	NS
				Season (wet, dry)	NS
				Location	1 cluster of Tg Type II, 2 clusters of Tg Type X
				Land use / Development	Type II cluster > developent, Type X clusters < development
VanWormer et al. 2016	California, USA	Oocyst load—estimated	GIS Hydrological model	NA	NA
				Transport time (slope, roughness)	Transport times < in developed areas
				Rainfall	Greater precipitation -> greater oocyst transport
				Cat distribution—based on phone surveys, landcover types	Domestic cats > developed areas, Developed areas with > domestic cats and < Transport times correlated w Tg
				Oocyst loading—based on published shedding rates	Oocysts > domestic cats
Burgess et al. 2018	California, USA	710 California sea otters (131 tracked) (Seroprevalence 26%)	Logistic model of weighted individual exposure risk	Age class	Tg > with age
			Logistic model of weighted individual exposure risk	Sex	Tg > Male
				Diet	Tg > snail specialists
				Landcover	Tg > crop cover, Tg < forest cover
				Road density	Tg > road density
				Census data for population density, housing density,	Tg > housing and population density

Table 3. Descriptions of variables and associated datasets to be used to model spatial and ecological processes relevant to Hawaiian monk seal risk of *T. gondii* exposure

Variable	Description	Rationale	Data Source	Potential for Data Improvements
Oocyst Loading				
Companion cats	Estimates of outdoor cats / household x households	Important component of oocyst-shedding source, tied to pet treatment / management	Ward Research 2012 Survey Report summarized by Hawaii Humane Society	* More recent * Repeatable index * Spatially / environmentally explicit
Stray cats	Estimates of outdoor cats / household x households	Important component of oocyst-shedding source, tied to cat abandonment, food source management	Ward Research 2012 Survey Report summarized by Hawaii Humane Society	* More recent * Repeatable index * Spatially / environmentally explicit
Colony cats	Known colony locations, estimated average cats / colony	Important component of oocyst-shedding source, tied to cat abandonment, food source management, colony care-taking	Ward Research 2012 Survey Report summarized by Hawaii Humane Society; Lepcezk et al., 2020; PIRO unpublished data	* Specific to HI enironments * Repeatable index
Feral cats	Approximated by Landcover type and expected feral cat territory size	Important component of oocyst-shedding source, tied to predator control, natural lands management	Goltz et al., 2008; Hess et al., 2009	* More comprehensive * Repeatable index
Household density	Households per census block	Link to distribution of cats associated with human households / development	2015 US census update data	Data quality sufficient
Residential zoning	Property zone and type (area, # units)	May refine outdoor cat distribution based on residence type (yards)	Tax Map Key data	Data quality sufficient
Tg infection rates	Annual average infection rate for cats	Provides a measure of disease expected per cat population	Wallace 1971; Danner et al., 2007; Davis et al., 2018	* Specific to HI enironments / cat populations
Oocyst shedding rates	Average shedding rate x average oocysts shed per event	Provides a measure of oocyst contamination per cat population	Dabritz et al. 2007; Afonso et al. 2010; VanWormer et al. 2013	* Specific to HI enironments / cat populations

Variable	Description	Rationale	Data Source	Potential for Data Improvements
Land-Sea Transport				
Precipitation	Annual average rainfall level	Rainfall is a key factor in mobilizing oocysts deposited on land, and runoff to coastal waters	HI rain gauge data	Data quality sufficient
Streamflow	Daily gauge level from USGS	Streamflow is a key factor in transporting oocysts from land to coastal waters	https://waterdata.usgs.gov/hi/nwis/current/?type=flow	Data quality sufficient, though not even across islands
Topography	USGS DEM at 10m res.	Elevation and slope are influential in water flow dynamics and erosion	https://www.pacioos.hawaii.edu/metadata/usgs_dem_10m_oahu.html	Data quality sufficient
Landuse / Landcover	MRLC classification, 1-5 m res.	Vegetative cover and land hardening/development are influential in water flow dynamics and erosion	https://www.mrlc.gov/data/noaa-2011-high-resolution-land-cover-hawaii-0	Data quality sufficient
Hawaiian Monk Seal Exposure				
T. gondii cases	Confirmed or suspected cases	Case information and location can be used to assess relationships with risk factors (note: few cases may often lead to qualitative rather than statistically significant conclusions)	HMSRP strandings / health monitoring data	* Higher / more consistent detection rates * Serial serological sampling to determine non-lethal exposure
Sex	Sex of known seals	Female monk seals are observed to have higher incidence of Tg strandings	HMSRP sightings database	Data quality sufficient
Age	Age of known seals	Breeding aged (adult) monk seals are observed to have higher incidence of Tg strandings	HMSRP sightings database	Data quality sufficient
Utilization distribution	Area used, and intensity of use, by known seals	Use of coastal areas will provide an estimate of potential oocyst exposure	HMSRP sightings database	* Higher resolution tracking, especially for female seals
Diet items	Prey items consumed by monk seals	Consumption of potential oocyst accumulators will provide an estimate of potential oocyst exposure	Not specified in model	* Improved analysis of individual diet variation in MHI

Table 4. Summary of *T. gondii*-related mortalities in Hawaiian monk seals (2004–2020)

Seal ID	Stranding date	Island	Year	Size	Sex	Case Designation* (Prob. T. g. COD**)	Diagnostic Notes***
R011	10/2/07	Maui	2007	A	F	Suspect (0.90)	Carcass in advanced decomposition, tissues autolyzed, T. gondii detected on PCR
RK29	9/14/05	Oahu	2005	A	M	Suspect (0.75)	Cessation of cardiac function with intense myocarditis, suspected association with Toxoplasma-like cysts observed in lung tissue
RK07	1/23/04	Kauai	2004	A	M	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
KA060D03	5/22/06	Kauai	2006	J2	M	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
RH40	3/17/10	Kauai	2010	A	M	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
RTX1	1/25/10	Molokai	2010	P1	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC, presumed transmission from the dam which was not sighted again / presumed dead but never detected / evaluated
R017	4/15/14	Oahu	2014	A	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
RB24	3/17/15	Oahu	2015	A	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC, died after attempted rehabilitation
RGX2	3/11/15	Oahu	2015	P0	M	Non-case (1.0)	Death secondary to dam's (RB24) severe T. g. infection, pup aborted ~one week prior to death of dam, though not detected in pup tissues, death was considered ultimately related to T.g.
RN36	11/13/15	Oahu	2015	A	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
RK60	5/15/18	Oahu	2018	A	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
RKD2	5/16/18	Oahu	2018	P1	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC, genetic tests confirmed pup to be offspring of RT10, also died from T. g.
RT10	5/17/18	Oahu	2018	A	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
RKC1	1/26/20	Oahu	2020	J1	M	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC
RO28	4/1/20	Oahu	2020	A	F	Confirmed (1.0)	Disseminated Toxoplasmosis, confirmed with IHC, died after >2 months of rehabilitative care

* Case definitions as defined in Barbieri et al. 2016.

** COD: cause-of-death probabilities determined as in Harting et al. 2020.

*** Notes summarized from NOAA HMSRP necropsy findings.