Improving the estimation of population risk to Hector's and Māui dolphins (*Cephalorhynchus hectori*) using carcass data, focussing on toxoplasmosis

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1. Abstract

Toxoplasmosis, a disease caused by the parasite *Toxoplasma gondii* for which the domestic cat (*Felis catus*) is the only definitive host in New Zealand, has been identified as major cause of mortality in Hector's and Māui dolphins (*Cephalorhynchus hectori*). A spatial multi-threat risk assessment for Hector's and Māui dolphins, informing the 2020 Threat Management Plan for the species, used information from the small available sample of necropsied beachcast dolphins to estimate the population risk from toxoplasmosis. The approach used assumed that the causes of death in the beachcast sample were representative of the wider population.

The purpose of this document was to review the potential sources of bias that might affect the estimation of population risk to Hector's and Māui dolphins from toxoplasmosis and other non-fishery threats, when using beachcast carcasses to make inferences about wider populations.

The main identified potential sources of bias included:

- Small sample size, increasing the likelihood of the beachcast sample not being representative due to stochasticity;
- spatio-temporal factors that might skew the proportional causes of death in the recovered beachcast sample, including human, dolphin behavioural, and climatic factors that affect the degree of seasonal and spatial overlap between carcass detection probability and deaths in the wider population;
- longer-term temporal variability in proportional causes of death that are not represented by existing necropsy data;
- factors that might skew the age distribution of the beachcast sample to over/under-represent individuals of reproductive age; and
- risk modelling not accounting for a potential female skew in toxoplasmosis deaths.

Several recommendations are made with respect to mitigating or accounting for the major sources of bias, including the need for increased carcass detection rate more generally, and also targeting the winter and spring periods of low beach activity, when all toxoplasmosis cases to date were reported. Dedicated effort in locations of high dolphin density, but poor public access may be required to plug probable spatial gaps in carcass reporting.

A tentative female bias in toxoplasmosis mortalities would pose an increased population risk and could be accounted for by future risk assessment modelling. Future assessments of bias could use fully quantitative methods to estimate the magnitude and direction of the key biases identified by this review, which could potentially be included in future risk assessment models fitted to necropsy data.

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Keywords: New Zealand, marine mammal, bias, carcass, risk assessment, cetacean

2. Contents

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3. Introduction

3.1. Background

Hector's dolphin (*Cephalorhynchus hectori*) and the Māui dolphin sub-species (*Cephalorhynchus hectori maui*) are endemic to the coastal waters of the New Zealand mainland. At the time of this review they were respectively listed as 'Threatened – Nationally Vulnerable' and 'Threatened – Nationally Critical' by the New Zealand Threat Classification System (Baker et al. 2019). Historically, the conservation of both South Island Hector's dolphin and Māui dolphin, which occur along the West Coast of the North Island, has focussed on using area management to mitigate the threat of entanglement and mortality in commercial and recreational fishing nets (e.g., see https://www.mpi.govt.nz/fishing-aquaculture/sustainable-fisheries/managing-the-impact-of-fishing-on-protected-species/protecting-hectors-and-Māui-dolphins/#fish-related-threats).

More recently, Roe et al. (2013) highlighted the threat to both sub-species posed by toxoplasmosis, a disease caused the unicellular parasite *Toxoplasma gondii*, based on the findings of formal necropsies of bycaught and beachcast carcasses. In New Zealand, the domestic cat (*Felis catus*) is the only known definitive host for *T. gondii*, which shed millions of oocysts in the weeks after infection, and which are then capable of infecting all bird and mammal species (reviewed for New Zealand species by Roberts et al. 2020). The precise pathways by which these dolphins then become infected with *T. gondii* is not known, although infection rates (~60% of individuals) (Roe et al. 2019) are high, even compared with many terrestrial species, including humans (Roberts et al. 2020).

A spatial multi-threat risk assessment for Hector's and Māui dolphins (Roberts et al. 2019), informing the 2020 TMP for the species (DOC/MPI 2021), used information from the small available sample of necropsied beachcast dolphins to estimate the population risk from mortalities caused by toxoplasmosis. This approach assumed that the causes of death in the beachcast sample were representative of the wider population. Roberts & Hendriks (2020) identified some factors that could bias this analysis, including a seasonal and spatial concentration in carcass detection rate in months and regions where toxoplasmosis mortalities rates are atypical.

Informed by this analysis, the TMP highlighted the need to increase the carcass detection rate to better inform the estimation of population risk from toxoplasmosis. But, given the large potential for biasing factors, how could this increased effort be optimised to mitigate or account for biases and improve the assessment of toxoplasmosis risk from carcass data?

The draft Toxoplasmosis Science Plan 2022 (DOC, in prep.) proposes priority research for filling knowledge gaps to inform management. The first Research Theme "Importance of the risk of toxoplasmosis in Hector's and Māui dolphins" and Priority Research "Improve understanding of the parasite in the dolphins through recovery of dead bodies for necropsy" are directly addressed by this review.

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3.2. This review

This research builds upon previous work on carcass detection by Roberts & Hendriks (2020), which characterised Hector's and Māui dolphin incident data, focusing on temporal (interannual and monthly) patterns. The purpose of this document is to conduct a more thorough review of the potential causes of bias that might affect the estimation of population risk to Hector's and Māui dolphins from toxoplasmosis and other non-fishery threats, when using beachcast carcass necropsy data to make inferences about wider populations.

The specific research objectives of this review were as follows:

1. Conduct a review of factors that might bias the estimation of population risk from toxoplasmosis and other causes of death using data from necropsies of beachcast dolphins.
2. Specifically with respect to Hector's and Māui dolphins, indicate the probable direction and magnitude of biases for estimating population risk from necropsies of beachcast dolphins, based on the outputs of 1.
3. Guided by the outputs of 1 and 2, provide recommendations as to how efforts to increase carcass detection rates might best be designed to:
    a. increase the precision of population risk estimates from toxoplasmosis; and
    b. minimise or account for potential biasing factors for estimating population risk.

The sources of information used by this review include scientific literature, previous analyses on Hector's and Māui dolphins, and other relevant information.

4. Summary of beachcast carcass data

In this section, the reported Hector's and Māui dolphin mortalities were characterised to provide the information requirements for reviewing the potential sources of bias when estimating population risk using the beachcast dolphin sample (see Section 5). This characterisation uses only records collated and maintained in the DOC Hector's and Māui dolphin incident database ("Hectors-Māuis-incidents-2022-04-28.xls"), downloaded from the DOC website on 1 June 2022 (DOC 2022).

4.1. Temporal patterns

The annual magnitude of Hector's and Māui dolphins reported as beachcast has fluctuated through time, including in the period since 2002, when the source (e.g., bycatch, beachcast, etc) of all dolphins in DOC (2022) was identified (Figure 1). Peaks in the number of beachcast individuals reported occurred in 2007–2009, 2012, and 2017–2018. It is not known if this pattern was driven by fluctuations in reporting rate (e.g., these years approximately coincide with the previous TMPs, when the public status of this species will have been relatively high) or by changes in the annual mortality rate of the wider population. Note the relatively low number of beachcast individuals reported annually since 2014 (e.g., relative to the period from 2000–2013). Also, the reduced rate of fishery entanglement-related mortalities in either of the bycatch or beachcast samples after 2008, when wide-scale fishing area restrictions were implemented around the North and South Island (Figure 1 and Figure 2).

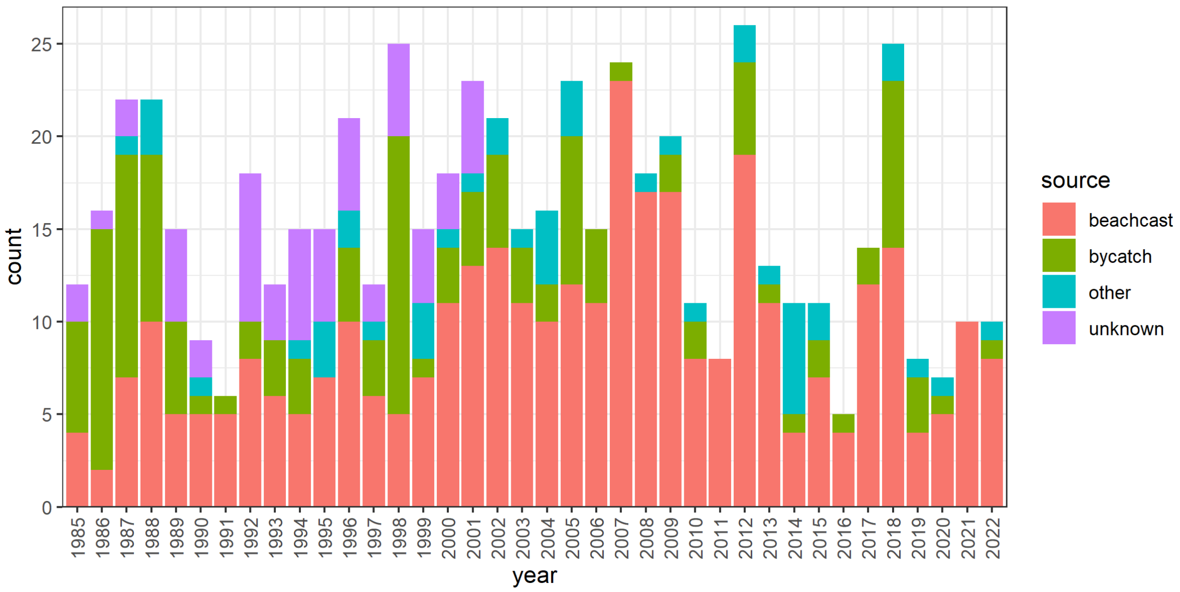

Figure 1. Number of Hector's and Māui dolphins recovered since 1985 by source. summarised from the "Observation type" field in DOC (2022). Note that "beachcast" dolphins includes several dolphins that were subsequently determined from necropsies to have died as a result of bycatch (see Figure 2).

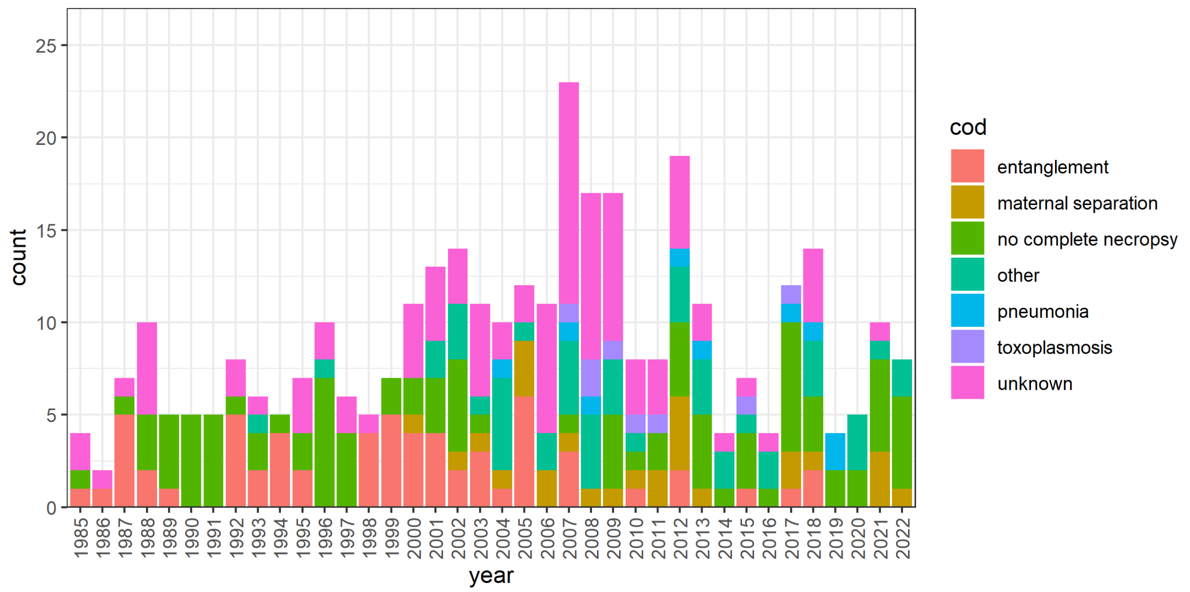

Figure 2. Annual number of Hector's and Māui dolphins in the beachcast sample since 1985 by primary cause of death determined from necropsy. Summarised from the "Necropsy results" and "necropsy results details" fields in DOC (2022). Here, "entanglement" included individuals that were identified from necropsy as "known", "probable" or "possible bycatch". Note that temporal patterns in these data will largely have resulted from changes in necropsy methods through time, particularly for non-fishery related causes of death, including toxoplasmosis.

The same data were presented by month in order to visualise seasonal patterns in the magnitude of the reported beachcast sample since 1985 (Figure A-1). This reveals a relatively higher rate of reported individuals in the period from October to March, with fewest samples in winter months. For some causes of death (e.g., entanglement in fishing gear as well as maternal separation) this can largely be explained by known or probable seasonality in deaths (e.g., commercial set net effort peaks in summer in many regions of New Zealand). However, for all causes of death, this will also appears be explained by a seasonal pattern in reporting rate, based on surveys of the number of people visiting beaches throughout the year (the 'beachgoer index' was derived from surf life save survey data collected from a selection of North Island beaches) (see Roberts & Hendriks 2020).

Note that, relative to the beachgoer index, the magnitude of reported beachcast dolphins was greatest in the period from June to December (Figure A-1). This may be indicative of seasonality in mortality rate above those identified from fishery entanglement and neonate mortality, noting that the seasonal 'beachgoer' patterns may differ around the South Island where most of the beachcast sample was located. The same plot is shown only disaggregated by sex (Figure 3). Note the much greater number of beachcast females reported in late winter and early spring, with a peak in October, which is not present for males. Also, the relatively high number of female beachcast dolphins reported in September, despite low beach activity in this month. Previously, the proportion of females in the sexed beachcast sample from August to October (0.84) was determined by Roberts & Hendriks (2020) to be significantly different from 0.5 (exact binomial test, $p < 0.001$, 2-sided). This was not evident in years prior to 2000, although the sexed sample was smaller in these years.

To date, all eight beachcast carcasses determined to have died from toxoplasmosis were recovered in the period from September to November (Figure A-2) (in addition to a Māui dolphin found floating at-sea in November). Based on increased use of beaches in summer and early spring, it seems likely that rates of toxoplasmosis mortality are much lower in these months. Conversely, the much lower use of beaches in winter months means that potential toxoplasmosis mortalities in this period are less likely to be detected.

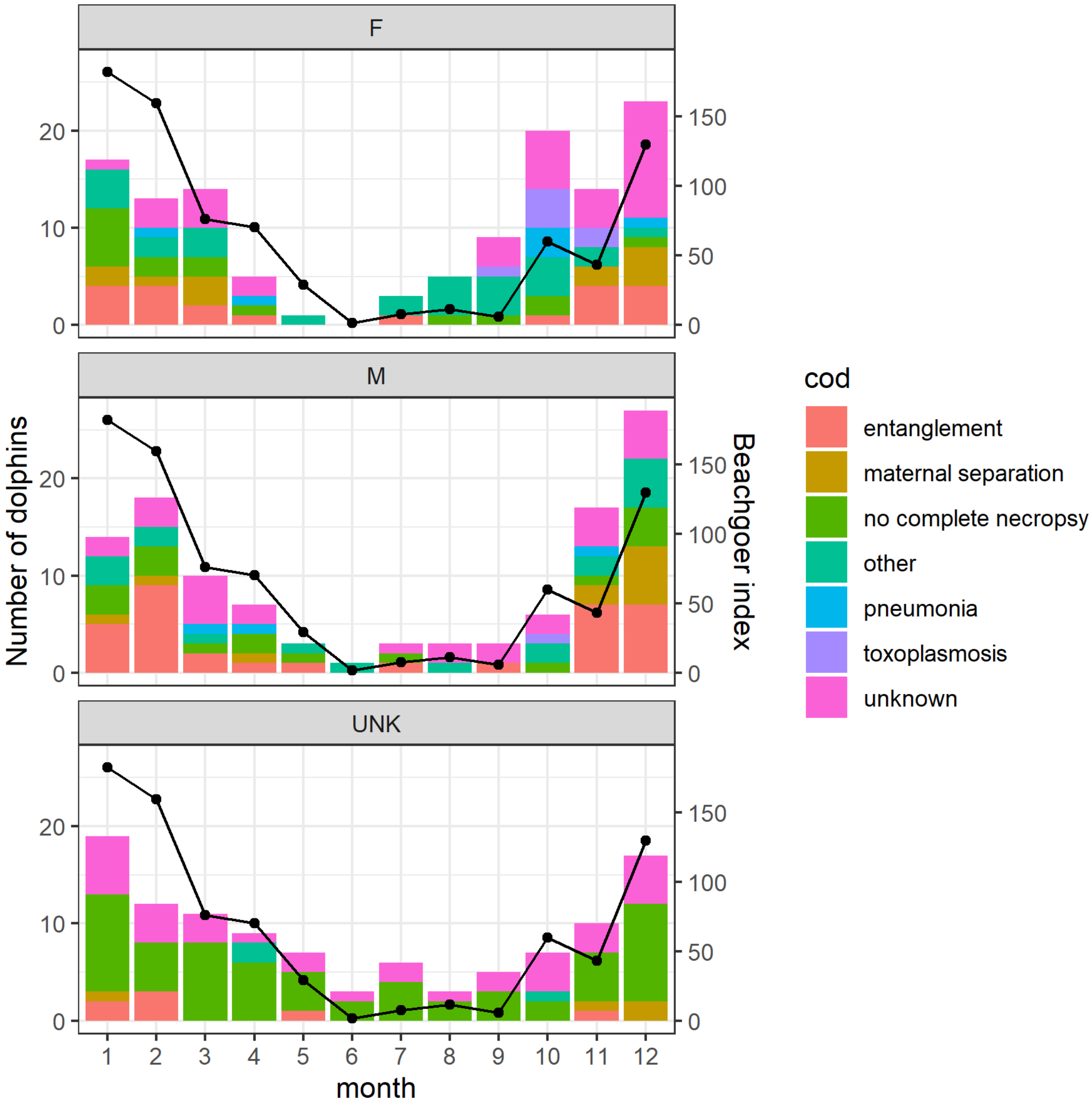

Figure 3. Monthly number of Hector's and Māui dolphins in the beachcast sample since 1985 by sex and primary cause of death determined from necropsy (Jan = '1', Feb = '2', etc). Summarised from the "Necropsy results" and "necropsy results details" fields in DOC (2022). Here, "entanglement" included individuals that were identified from necropsy as "known", "probable" or "possible bycatch". Note that comparability of the magnitude of different causes of death, including from toxoplasmosis, will be confounded with changes in necropsy methods through time. A 'beachgoer index' is superimposed (black line and points) on the bar plot and gives a rough indication of the relative number of people on beaches throughout the year (from Roberts & Hendriks 2020).

4.2. Spatial patterns

Based on an approximate estimate of the annual number of dolphins dying in each region of New Zealand, the proportion of all deaths that are then reported as beachcast carcasses (from 2007–2021, when necropsy methods have been most consistent) ranges from ~0.5% (East Coast South Island, where the most carcasses were reported) up to ~11% (West Coast North island, which will primarily be comprised of Māui dolphins) (Table 1). Given the relatively small total sample of beachcast individuals across all regions in this period (*N* = 163), the regional distribution of these samples is good, in that, while most are reported along the West and East Coasts of the South Island (where the species is most abundant), there is a higher inferred recovery rate of carcasses in smaller populations (such the West Coast North Island, where Māui dolphin occur), which are often prioritised for conservation management.

Table 1. Summary of Hector's and Māui dolphin data by region, including numbers of dolphins that were beachcast, numbers that were necropsied, and for which toxoplasmosis was identified as the primary cause of death. Also shown are the assumed population sizes for each region and the approximate number of annual deaths that would occur in the average year. For quantities relating to the beachcast sample, these are also expressed as percentages of the total annual number of deaths for each region (across 15 years from 2007–2021).

QUANTITY	WCNI	NCSI	ECSI	SCSI	WCSI	REFERENCES
Population size*	65**	214	9728	332	5482	See Table 2 of Roberts et al. (2019)
Approximate annual deaths***	6.5	21.4	972.8	33.2	548.2	
Number of beachcast carcasses from 2007–2021:						DOC (2022)
all reported	11 (11.28%)	6 (1.87%)	76 (0.52%)	11 (2.21%)	59 (0.72%)	
subjected to formal necropsy	9 (9.23%)	5 (1.56%)	55 (0.38%)	10 (2.01%)	44 (0.54%)	
of which a primary cause of death could be identified	6 (6.15%)	3 (0.93%)	37 (0.25%)	5 (1.00%)	22 (0.27%)	
of which toxoplasmosis was identified as the primary cause of death	1 (1.03%)	0 (0.00%)	5 (0.03%)	0 (0.00%)	2 (0.02%)	

*Values used for population size rescaling strata used by Roberts et al. (2019).

**2015–2016 population estimate of Māui dolphin used (63 individuals), which was near the middle of the time series of beachcast dolphins used in this table. This includes two South Island Hector's dolphin migrants identified from genetic analysis of biopsy samples (Constantine et al. 2021).

***Calculated as the total population size multiplied by 0.1 (approximating the annual proportion of dolphins dying each year)

The spatial distribution of beachcast carcasses by primary cause of death is plotted in Figure A-3 and Figure A-4. Overall, the spatial distribution of reported beachcast dolphins is consistent with the estimated at-sea spatial distribution around the South Island, and off the West Coast of the North Island. There were no obvious spatial patterns in one cause of death versus another, consistent with the causes of death being similar comparing regional populations. As also summarised in Table 1, toxoplasmosis cases were found beachcast along the East and West Coasts of the South Island, as well as one Māui dolphin off the WCNI. Notably, three of the toxoplasmosis carcasses were recovered in a region of low estimated at-sea density along the Otago Coast, although the sample size is small for making any strong inferences.

In Figure A-5 to Figure A-9, the fine-scale summer/winter distribution of reported beachcast carcasses is shown relative to: the estimated summer/winter at-sea distribution of Hector's and Māui dolphins, the locations of roads and human population density. The purpose of these plots is to identify potential locations for low carcass reporting rate, and to explore some of the human causes of this. For example, the relative lack of carcasses reported south of Raglan (Figure A-5) may relate to a relatively low at-sea density of dolphins, but also could be caused by more limited access points to the

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coast. Public access is also a strong candidate for the relatively small number of carcasses from the southern portion of the West Coast South Island (Figure A-9).

Furthermore, these plots illustrate how a reduced carcass recovery rate in winter may partially be driven by the more offshore distribution of these dolphins in winter relative to summer (e.g., see Figure A-7), which could plausibly reduce the likelihood of carcasses washing up in the coastline in this season.

In Figure A-5 to Figure A-9, the locations of New Zealand rivers are also shown relative to recovered carcasses.

4.3. Demographic composition

As noted by Roberts et al. (2019), seven of the nine recorded deaths of Hector's and Māui dolphins were females, of which six were reproductive. Although the sample size is small, this may indicate a relatively higher propensity for females to die from toxoplasmosis once infected, compared with males. Four of the cases of disseminated toxoplasmosis were aged from tooth sections, including: three females (estimated to be ages 9, 14 and 15) and one male (estimated age 4) (Roberts et al. 2019).

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5. Factors biasing the estimation of population risk

This section reviews the identified factors that might bias the estimation of population risk from toxoplasmosis and other causes of death using data from necropsies of beachcast dolphins. The selected factors are based on the characterisation in Section 4, as well as the findings of previous relevant research.

5.1. Small sample size

The relatively small sample size of beachcast Hector's and Māui dolphins, and even smaller sample of dolphins for which a primary cause of death was stated (Table 1) increases the likelihood due to stochasticity that the causes of death in the beachcast sample were not representative of wider patterns. The spatial risk model of Roberts et al. (2019) used a Bayesian implementation of a Dirichlet-multinomial model to generate prior distributions of the proportional non-fishery causes of death, including from toxoplasmosis. This approach would naturally result in increasing uncertainty around the magnitude of toxoplasmosis deaths with decreasing overall sample size, although the mean values for the proportion of deaths caused by toxoplasmosis would still be sensitive to changes in the necropsy proportions, which are more likely at small sample sizes.

The inferred carcass detection rates of Hector's and Māui dolphins vary by region (Table 1), with approximately an order of magnitude greater recovery rate along the West Coast of the North Island relative to the South Island regions. This suggests that there is considerable potential to increase carcass detection rates, particularly of South Island Hector's dolphins. However, even the carcass detection rate along the West Coast of the North Island (~11%) (Table 1) is low relative to that of some other coastal delphinids, e.g., California coastal population of bottlenose dolphins (*Tursiops truncatus*) (25%; 95% confidence interval = 0.20–0.33) (Carreta et al. 2016) and the Sarasota Bay, Florida population of the same species (33% of all known deaths and disappearances; standard deviation =

17%) (Wells et al. 2015), although, admittedly, these regions are more densely populated than most coastal regions of New Zealand.

5.2. Spatial-seasonal factors

The data characterisation in Section 4 highlighted some processes that have probably contributed to the strong seasonal pattern in beachcast carcass recoveries, including highly seasonal beach use and seasonal onshore/offshore movements of Hectors and Māui dolphins. To this list could be added seasonal patterns in weather, sea conditions and currents affecting the deposition and retention of dolphins on beaches, as well as shifting sands affecting burial/re-exposure, and potentially seasonality in scavenging rate by known marine predators. Of these, only the carcass recovery rate can be directly controlled by interventions. This would ideally should increase carcass detection rate in the winter period, which is largely under-represented in the current sample. This is currently likely to be a biasing factor for the estimation of risk, because of the seasonality in toxoplasmosis deaths and other non-fisheries causes of death.

The purpose of plots in Figure A-5 to Figure A-9 is to explore a potential bias that might arise from better public access near to river mouths, where Hector's and Māui dolphins may be more likely to be infected with *T. gondii* oocysts. This does reveal a tendency for carcasses to be recovered near to river mouths in some regions (e.g., Figure A-7 and Figure A-8), but not all (e.g., Figure A-5 and Figure A-6). However, since *T. gondii* infection rates are high in the species (~60%, although potentially increasing with age) (Roe et al. 2013; Roe et al. 2015), also since carcasses were found to be infected with *T. gondii* in nearly all months of the year when they were sampled (Roe et al. 2013), and deaths from toxoplasmosis would occur a length of time after infection, it would seem unlikely that toxoplasmosis would be any more likely to killed dolphins near to river mouths.

5.3. Long-term changes in causes of death

Necropsy methods used for Hector's and Māui dolphins have been consistent since 2007, although this only provides around 15 years of relatively complete information at the time of this review. It is not implausible that the underlying mixture of causes of death in the wider population has changed though time, although we lack a sufficiently long time series of data to assess this. Specifically with respect to toxoplasmosis, tissues collected during necropsies from 2002 to 2006 were retrospectively assessed for the prevalence of *T. gondii* infection, noting that older tissues are less likely to test positive on PCR. Disseminated toxoplasmosis was not detected in any of these carcasses, and should have been detectible for carcasses that were comparatively fresh and on which full histology was done (W. Roe pers. comm.). The significant female skew in beachcast dolphins during August to October (around the time that all toxoplasmosis mortality cases were found beachcast) highlighted by Roberts & Hendriks (2020) was evident for the 2000s and 2010s, but not in the preceding decades, although the sample of beachcast dolphins was much smaller then (Figure 2).

Taken together, there is some tentative evidence for changes in *T. gondii* infection and disseminated toxoplasmosis through time, e.g., that could cause a positive bias in the estimation of population risk, if the period of deaths was only temporary, although currently the data are from too short a time period to assess this formally.

5.4. Demographic composition

Seven of the nine recorded deaths of Hector's and Māui dolphins were females, of which six were reproductive. An earlier study by Roe et al. (2013) highlighted the presence of *T. gondii* in the uterine tissues of multiple necropsied Hector's and Māui dolphins and a case of fatal toxoplasmosis in a pregnant female that had *T. gondii* in foetal, uterine and placental tissues, and deduced that

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toxoplasmosis may be an important cause of neonatal loss. However, Roe et al. (2015) found that males were more likely to be infected with *T. gondii*. Although the sample size is small, this may indicate a propensity for females to die from toxoplasmosis once infected. The female bias in beachcast carcasses in late winter and spring (when all recorded deaths from toxoplasmosis occurred) may indicate that other toxoplasmosis cases in the sample could not be identified.

The potential skew towards toxoplasmosis fatalities in reproductive females and the increased likelihood of *T. gondii* infection with age (which is also observed in terrestrial mammals) means that it this threat be under-represented in the beachcast sample if for any reason it was skewed towards younger individuals. For this reason, the use of bycaught dolphins to make inferences about the prevalence of *T. gondii* infection in Hector's and Māui dolphins would be biased if the much higher vulnerability to capture of subadults (Davies et al. 2008) was not accounted for. For beachcast individuals, the mean estimated age of the sample analysed by Roberts et al. (2019) was age 8.2. This is slightly above the estimated age at first maturity for this species estimated by Edwards et al. (2018) (6.91; 95% credible interval = 5.82–8.24), indicating that this sample comprises a representative cross section of the age distribution of the wider population. This would not be consistent with the beachcast sample being too young or too old to give a representative proportion of deaths from toxoplasmosis, or infections with *T. gondii*.

5.5. Risk modelling approach

The risk assessment of Roberts et al. (2019) was a combined sex model, which did not use tentative existing information of a female skew in annual toxoplasmosis deaths. If this skew was representative, not doing so would have negatively biased the estimation of population risk, on the basis that female Hector's and Māui dolphins are polyandrous breeders, and reproductive output should scale to the number of females of breeding age. Other spatial risk assessments of this nature on other marine mammals have used female-only models (e.g., Large et al. 2019), which may be applicable for this species also, though would further thin out the sample used for model fitting resulting in less precise model estimates. This situation would be improved with increased carcass detection rates.

The spatial risk model assessment of Roberts et al. (2019) produced very different estimates of the relative risk posed by commercial fisheries, disease and other threats, relative to the previous TMP risk assessment, which was based on expert opinion (Currey et al. 2021). Other model-based risk assessments of cetaceans fitting to necropsy data are rare and have produced conflicting information that might imply inherent biases in beachcast dolphin data, or in the comparative data sources (e.g., Moore & Read 2008). However, this is no inherent reason that the risk assessment approach of Roberts et al. (2019) should itself have biased the mean estimates of annual toxoplasmosis mortalities, which was instead dictated by the proportional causes of death from necropsy data.

6. Discussion

Limitations of this review

The determination of representative mortality rates of all causes is problematic in cetaceans, given that most deaths occur at sea, and the detection of a non-fishery deaths is usually dependent on a carcass washing up on shore, being reported and subsequently observed, and being in a suitable state of preservation for reliable analysis. However, necropsy data can be used to identify the presence of certain threats and can provide information on the relative importance of detectible threats, particularly if biases are identified and accounted for.

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This review identified several potential biases, although others may not have been identified. Furthermore, the evaluation of biases was predominantly based on a qualitative and semi-quantitative review of the information. Future research could include fully quantitative/spatio-temporal quantification of the direction and magnitude of the main sources of bias identified here, which could ultimately be included in future statistical risk models that are fitted to necropsy data.

The potential effects of necropsy approaches were not considered by this review, though are likely to be influential of the resulting attributed primary causes of death.

Probable sources of biases for estimating risk

Based on the consideration of candidate sources of bias in Section 5, the probable sources of bias affecting the estimation of toxoplasmosis risk when using beachcast necropsy proportions are summarised in Table 2. Note that some of these sources were listed despite the potential direction of bias (based on existing necropsy data) associated with that source (e.g., small population size, and potential long-term changes in the prevalence of toxoplasmosis) being unknown. For all sources, this summary was based on a qualitative or semi-quantitative exploration of the data and supporting information, whereas fully quantitative approaches would be needed to formally estimate the magnitude and direction of bias.

Table 2. Summary of probable sources of bias for the estimation of population risk of toxoplasmosis to Hector's and Māui dolphin. In this table, a positive bias would indicate that the population risk from toxoplasmosis would be over-estimated.

PROBABLE SOURCE OF BIAS	PROBABLE DIRECTION OF BIAS	PROBABLE MAGNITUDE OF BIAS
Small population size	Neutral, though may depend on risk assessment approach.	Increasing probability of bias with decreasing sample size
Seasonality in carcasses being beachcast and reported	Negative, since all toxoplasmosis deaths to date were in spring months when beach activity is low to moderate.	Moderate
Spatial distribution of carcass detection rate	Positive, based on beachcast carcasses being predominantly found near to river mouths in some, but not all regions.	Moderate in some regions
Sex skew in toxoplasmosis deaths	Negative, since most confirmed cases to date were reproductive females, although depending on risk assessment approach used.	Strong, if the current sex skew is representative
Long-term changes in the proportion of mortality from toxoplasmosis	Unknown, given lack of longer-term monitoring required to assess this.	Unknown, though potentially large.

Conclusions and recommendations

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Small sample size issues would be addressed by implementing measures to increase beachcast carcass recovery rates. Encouragingly, while carcass recovery rates are low for this species, particularly around the South Island, a brief spatial exploration of these data found that the regional distribution of carcass recoveries, which to date have primarily been based on public reporting, was good (Table 1). At a finer scale, probable spatial gaps in carcass detection rate appear primarily driven by poor public access, indicating that more carcasses may be detected by dedicated (non-public) effort in locations with poor access and high dolphin density. The current approach also appears to result in a representative age distribution in the beachcast sample, whereas, e.g., the skew towards subadults in fishery bycatch carcasses (Davies et al. 2008) would be problematic for monitoring *T. gondii* infection rates.

The strong seasonal pattern in reported beachcast dolphins was reported previously by Roberts & Hendriks (2020) and appears to be caused by a mixture of seasonal beach activity, seasonal movements of the dolphins, and probably also seasonal sea conditions. This seasonality is a potentially major source of bias when using the beachcast sample to make inferences about the wider population, particularly given the discrete seasonality in deaths primarily attributed to toxoplasmosis, all in the period from September to November, i.e., on the shoulder of the winter period of very low beach activity. Measures to increase carcass detection probability in the winter and spring periods are recommended.

A tentative skew towards reproductive females being more vulnerable to toxoplasmosis has the potential to bias risk assessments that do not account for it. This highlights a need to focus on increasing carcass recovery rate of females specifically, which, in addition to increasing carcass detection rates more generally, could be achieved by exploiting an apparent strong female bias in beachcast carcasses detected in late winter and early spring, and that was attributed to multiple non-fishery causes of death in addition to toxoplasmosis.

Finally, future research on source of bias for toxoplasmosis and other threats could include fully quantitative/spatio-temporal estimation of the direction and magnitude of the main sources of bias identified here, which could ultimately be included in future risk assessment models fitting to necropsy data.

7. Acknowledgements

The author would like to thank numerous researchers for sharing the details of previous and ongoing research that have contributed to this review. Specifically, I would like to thank Hannah Hendriks who maintains the DOC Hector’s and Māui dolphin incident database, as well as X who reviewed an earlier version of this draft report. This research was funded by the New Zealand Department of Conservation.

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9. Appendix – supplementary data plots

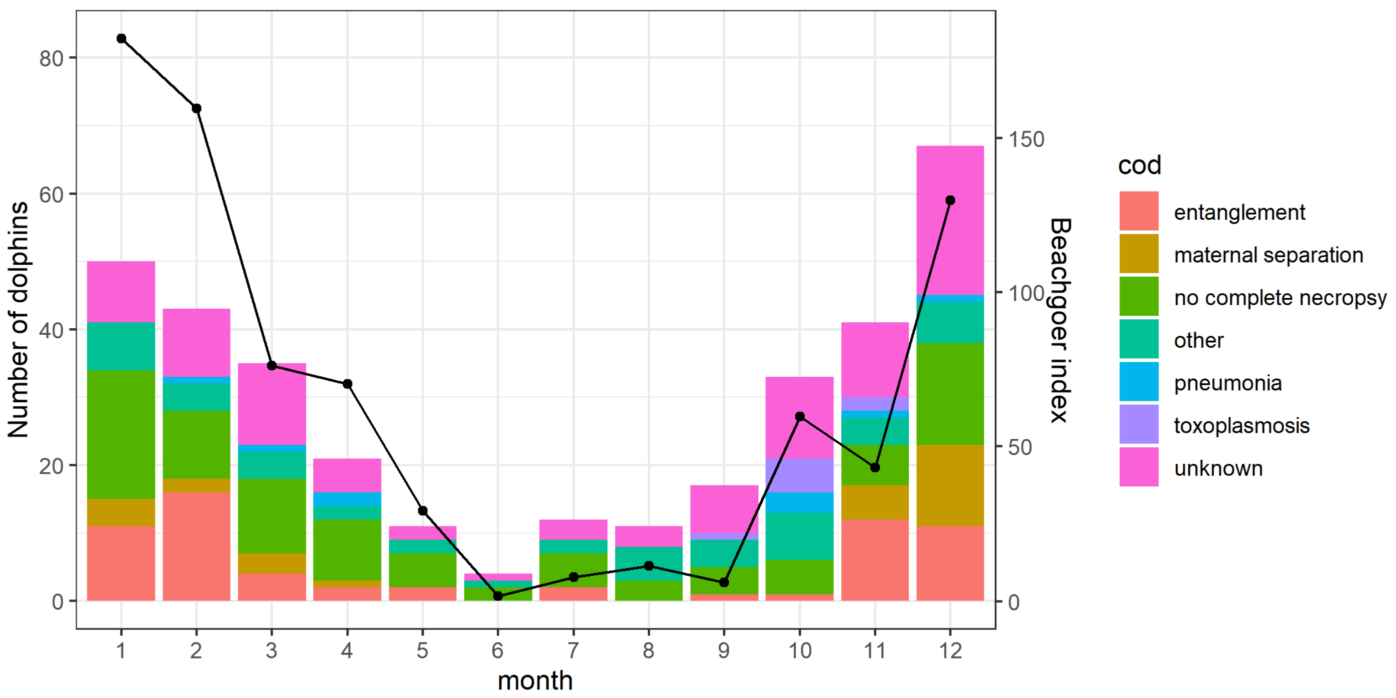

Figure A-1. Monthly number of Hector's and Māui dolphins in the beachcast sample since 1985 by primary cause of death determined from necropsy (Jan = '1', Feb = '2', etc). Summarised from the "Necropsy results" and "necropsy results details" fields in DOC (2022). Here, "entanglement" included individuals that were identified from necropsy as "known", "probable" or "possible bycatch". Note that comparability of the magnitude of different causes of death will be confounded with changes in necropsy methods through time. A 'beachgoer index' is superimposed (black line and points) on the bar plot and gives a rough indication of the relative number of people on beaches throughout the year (from Roberts & Hendriks 2020).

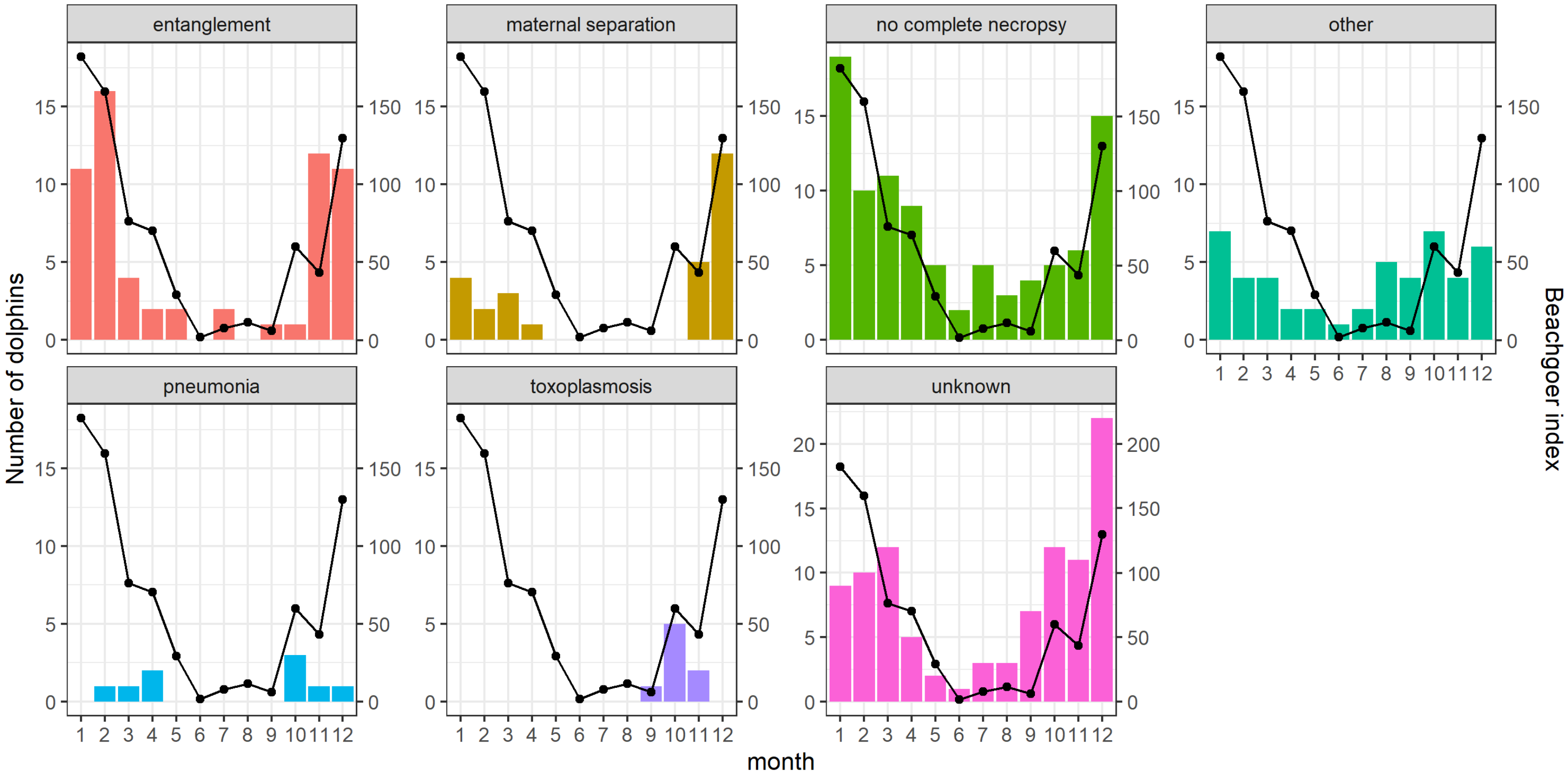

Figure A-2. Monthly number of Hector's and Māui dolphins in the beachcast sample since 1985 by primary cause of death determined from necropsy (Jan = '1', Feb = '2', etc). Summarised from the "Necropsy results" and "necropsy results details" fields in DOC (2022). Here, "entanglement" included individuals that were identified from necropsy as "known", "probable" or "possible bycatch". Note that comparability of the magnitude of different causes of death will be confounded with changes in necropsy methods through time. A 'beachgoer index' is superimposed (black line and points) on the bar plot and gives a rough indication of the relative number of people on beaches throughout the year (from Roberts & Hendriks 2020).

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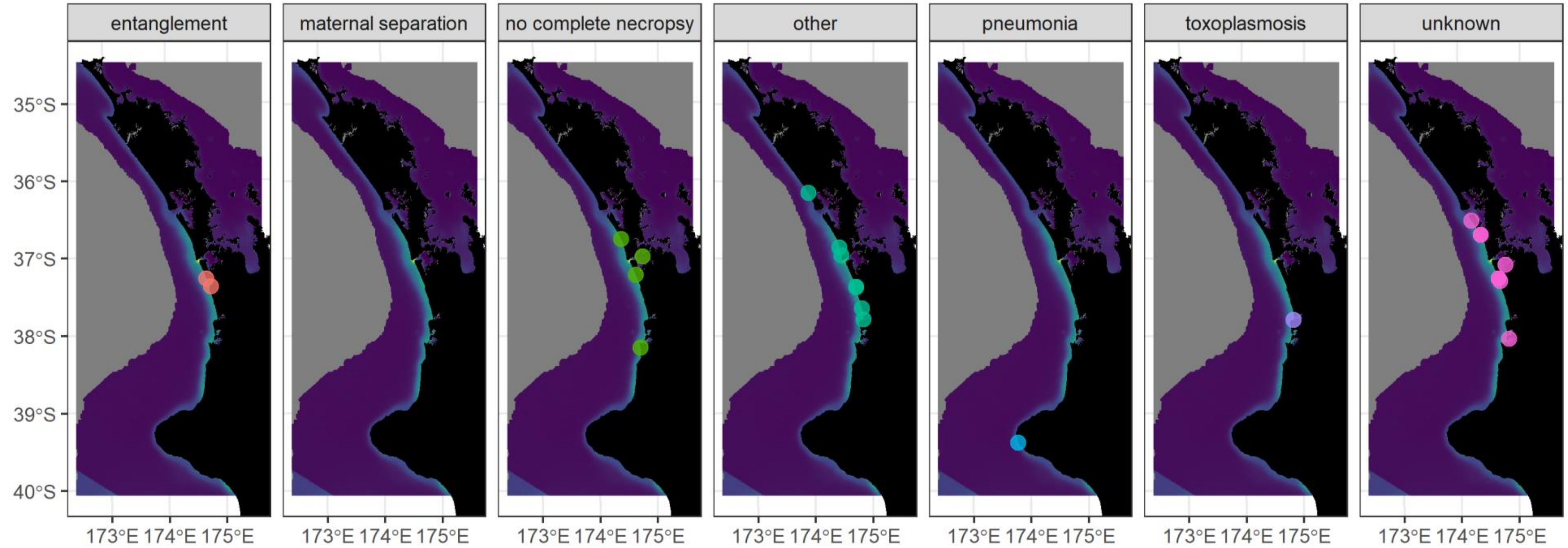

Figure A-3. Spatial distribution of reported Hector's and Māui dolphin beachcast events since 1985 along the West Coast of the North Island, by primary cause of death determined from necropsy. The estimated relative at-sea density of dolphins (yellow/blue are high/low density) is shown. Note that a second toxoplasmosis death was identified of an individual found floating 500m offshore of Raglan that does not appear in the beachcast sample shown here (located approximately 2 km from the beachcast toxoplasmosis death in the plot above).

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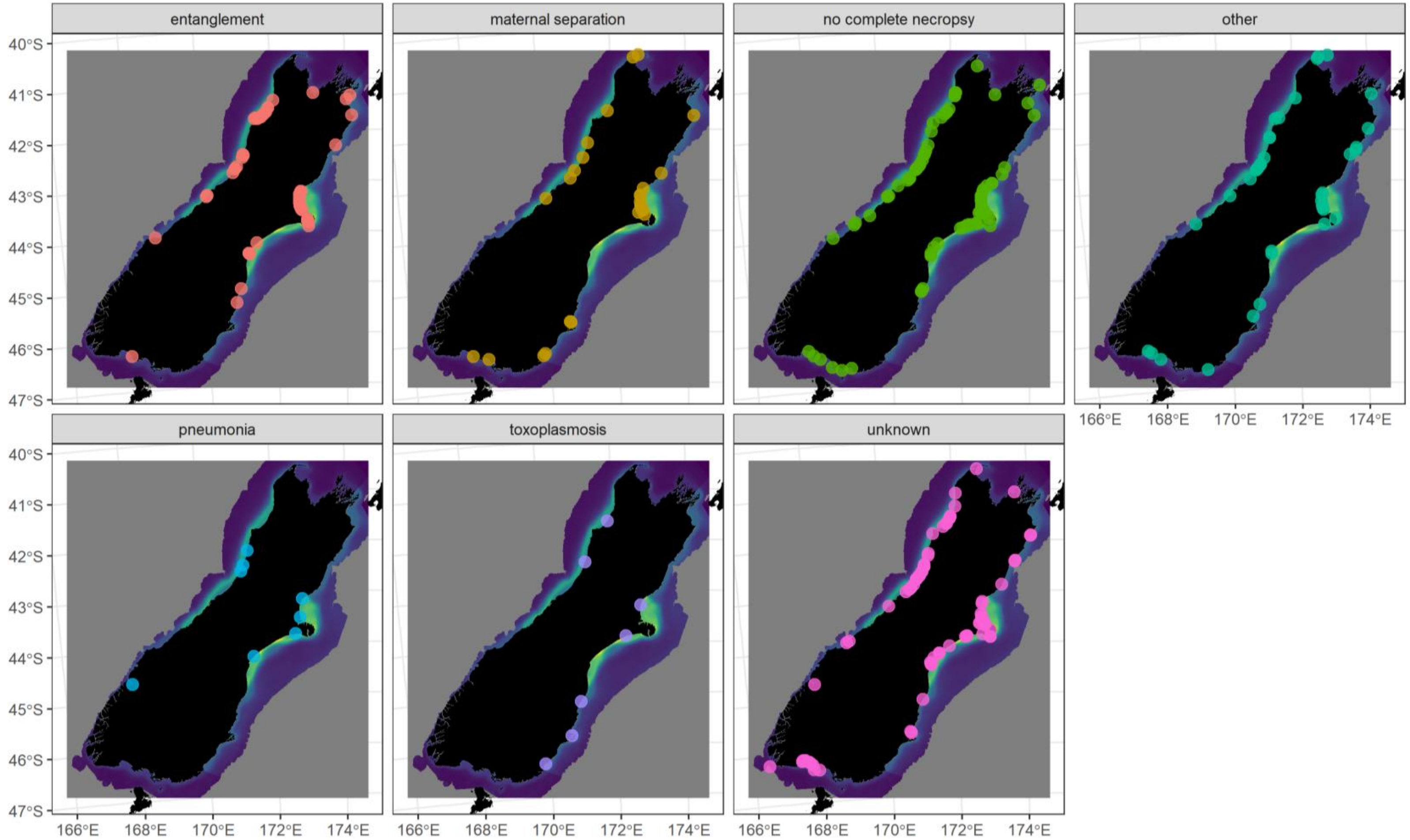

Figure A-4. Spatial distribution of reported Hector's and Māui dolphin beachcast events since 1985 around the South Island, by primary cause of death determined from necropsy. The estimated relative at-sea density of dolphins (yellow/blue are high/low density) is shown.

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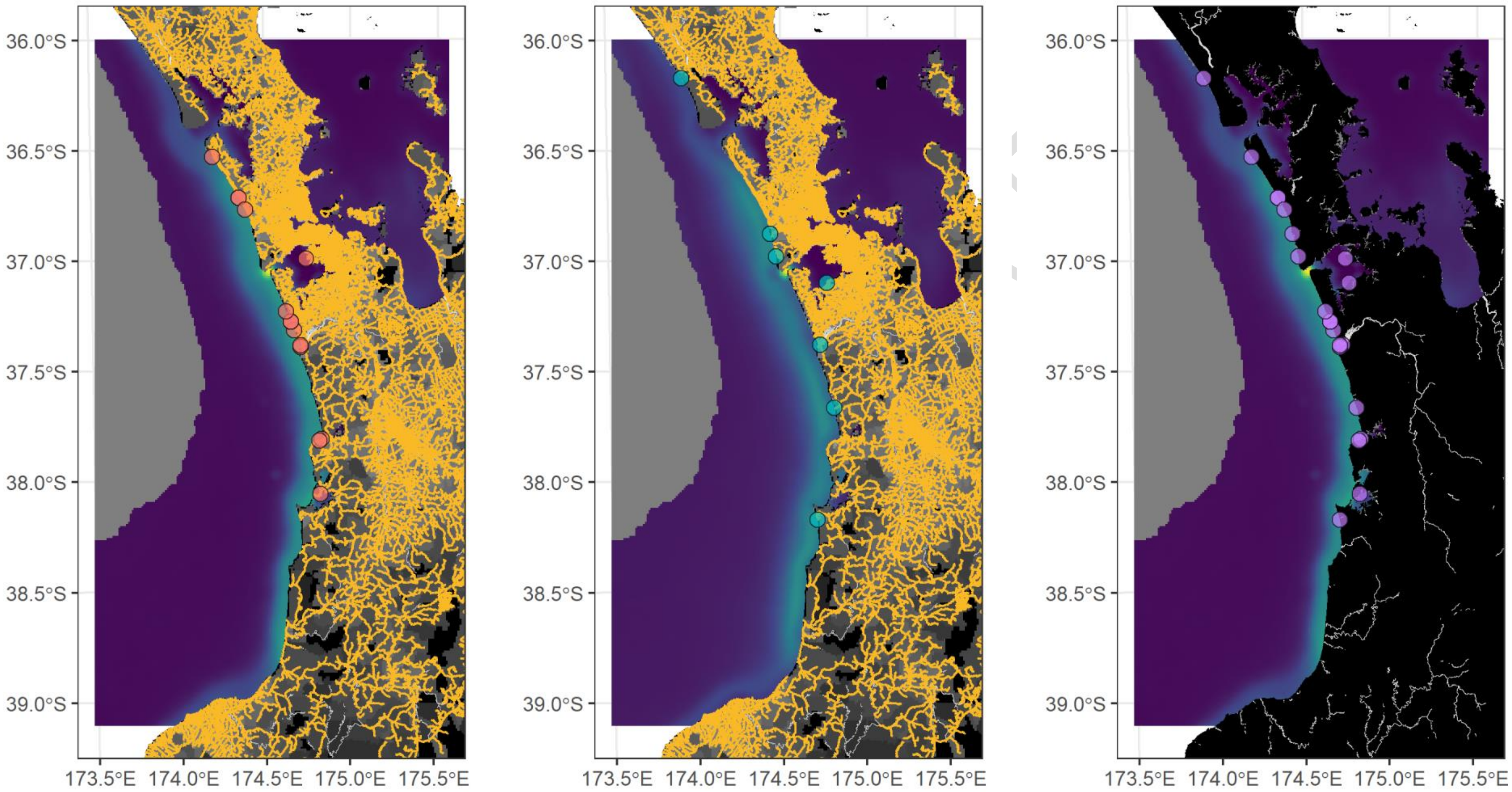


Figure A-5. Spatial distribution of reported Hector's and Māui dolphin beachcast events since 1985 along the West Coast of the North Island in summer (left), winter (centre), and in all seasons (right). The estimated relative at-sea density of dolphins (yellow/blue are high/low density) is shown for each respective season, with the summer density shown for the all-seasons plot. Public roads are represented by orange lines. Areas of very low human population density appear as black in the two left-hand plots. Roads are omitted from the right-hand plot to show the distribution of beachcast dolphins relative to river mouths.

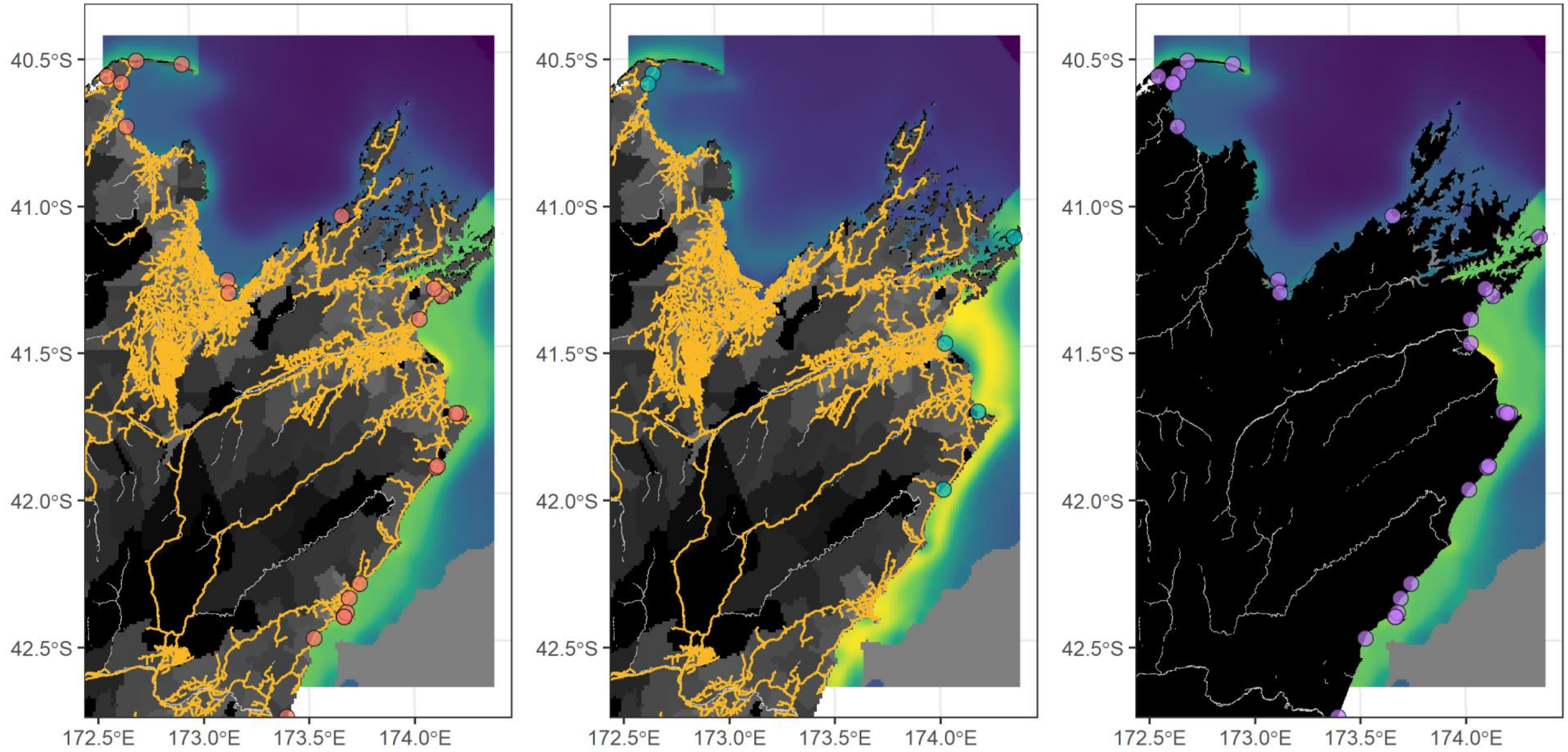
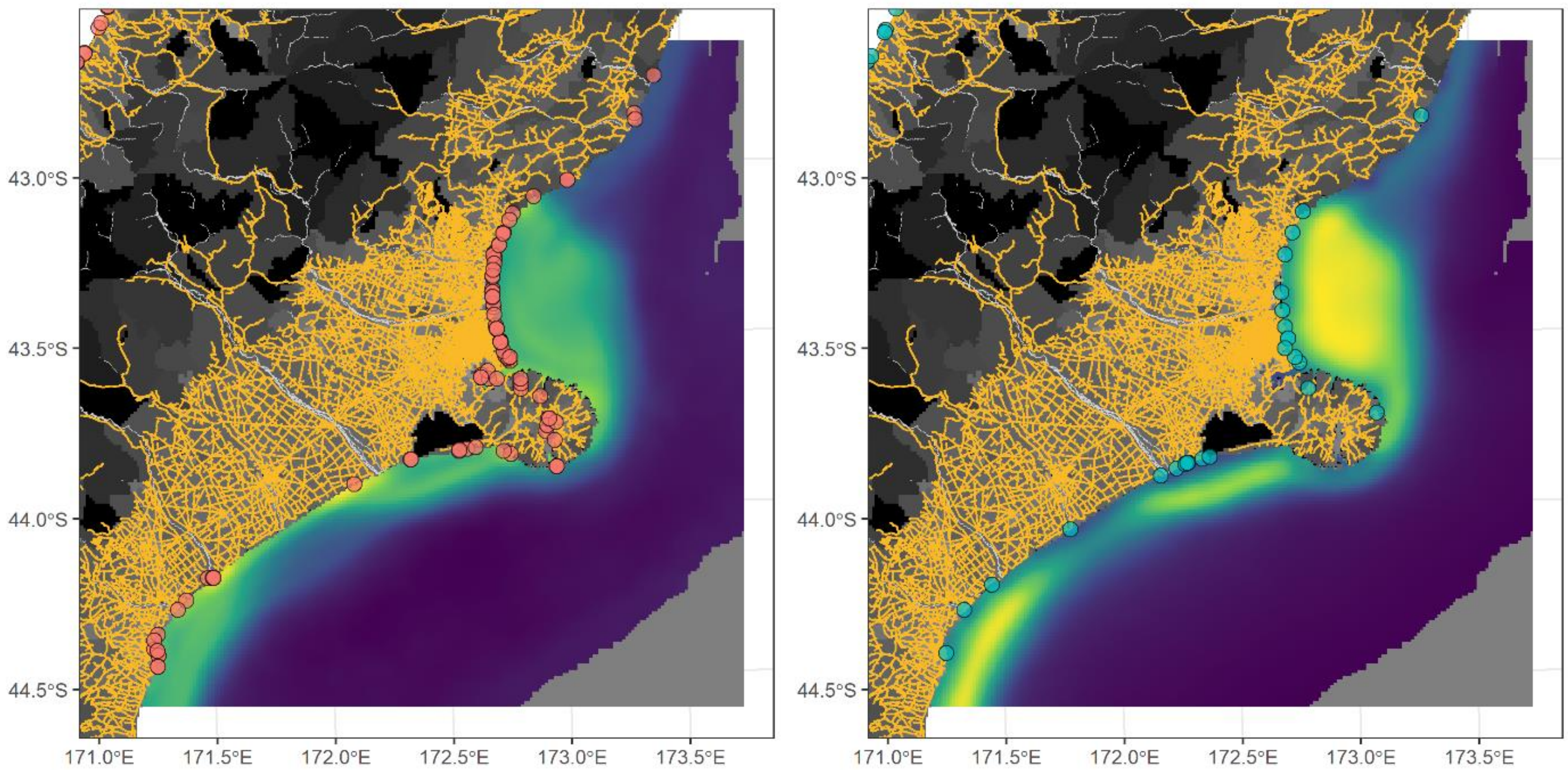


Figure A-6. Spatial distribution of reported Hector's and Māui dolphin beachcast events since 1985 along the North Coast of the South Island and Kaikoura Coast in summer (left), winter (centre), and in all seasons (right). The estimated relative at-sea density of dolphins (yellow/blue are high/low density) is shown for each respective season, with the summer density shown for the all-seasons plot. Public roads are represented by orange lines. Areas of very low human population density appear as black in the two left-hand plots. Roads are omitted from the right-hand plot to show the distribution of beachcast dolphins relative to river mouths.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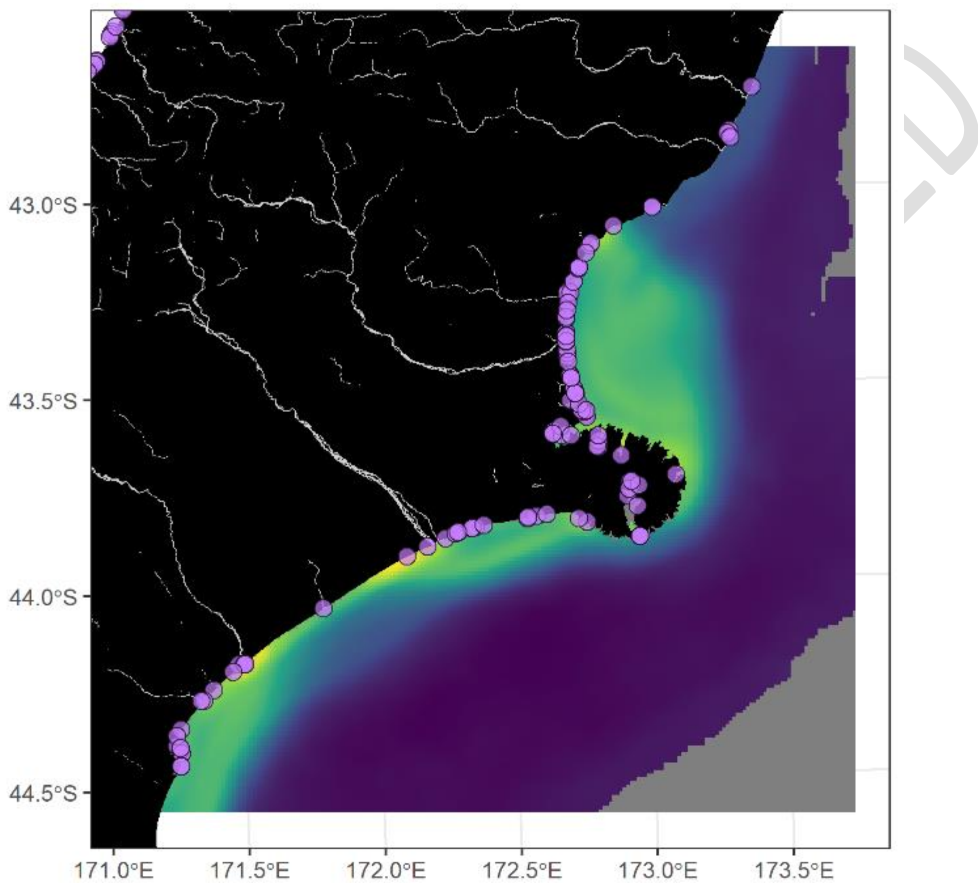
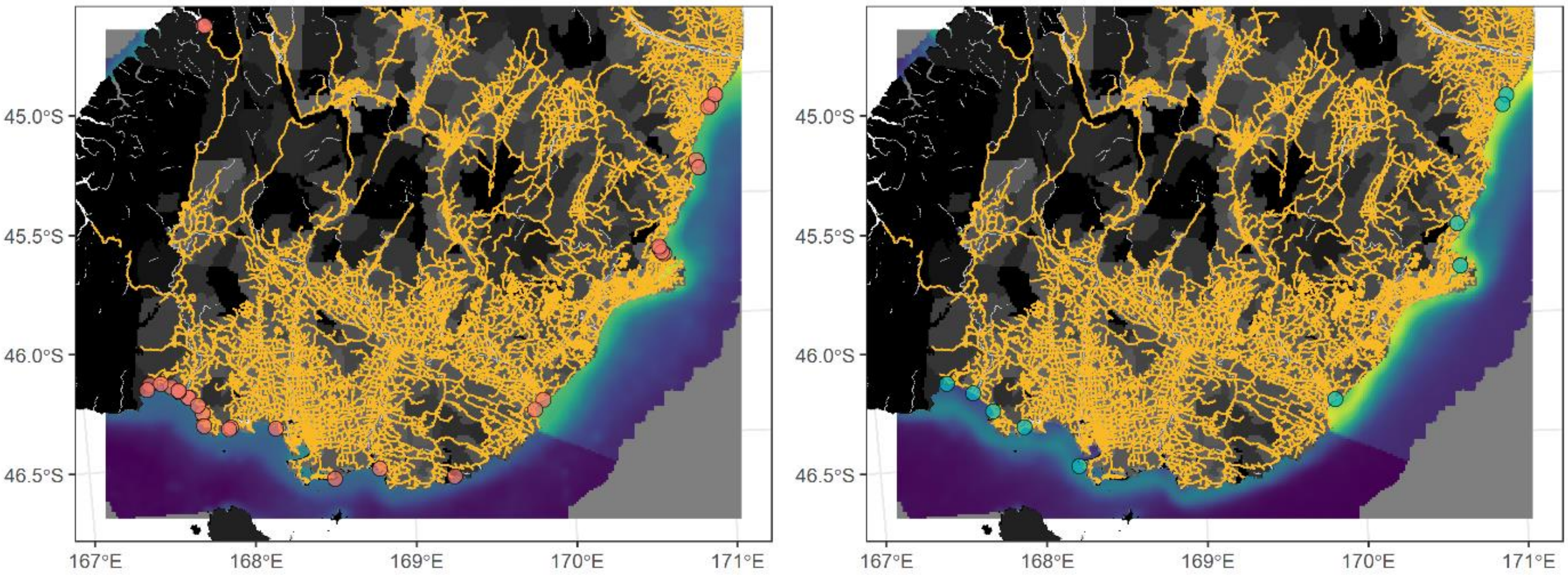


Figure A-7. Spatial distribution of reported Hector's and Māui dolphin beachcast events since 1985 along the Canterbury Coast in summer (left, previous page), winter (right, previous page), and in all seasons (above). The estimated relative at-sea density of dolphins (yellow/blue are high/low density) is shown for each respective season, with the summer density shown for the all-seasons plot. Public roads are represented by orange lines. Areas of very low human population density appear as black (in top two plots only). Roads are omitted from the plot above to show the distribution of beachcast dolphins relative to river mouths.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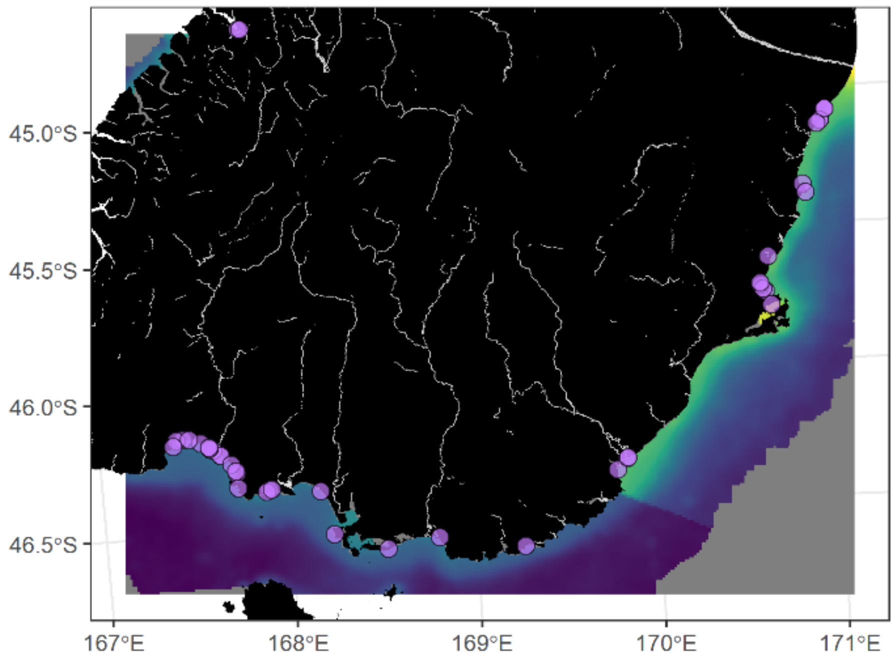

Figure A-8. Spatial distribution of reported Hector's and Māui dolphin beachcast events since 1985 along the Otago Coast and the South Coast of the South Island in summer (left, previous page), winter (right, previous page), and in all seasons (above). The estimated relative at-sea density of dolphins (yellow/blue are high/low density) is shown for each respective season, with the summer density shown for the all-seasons plot. Public roads are represented by orange lines. Areas of very low human population density appear as black (in top two plots only). Roads are omitted from the plot above to show the distribution of beachcast dolphins relative to river mouths.

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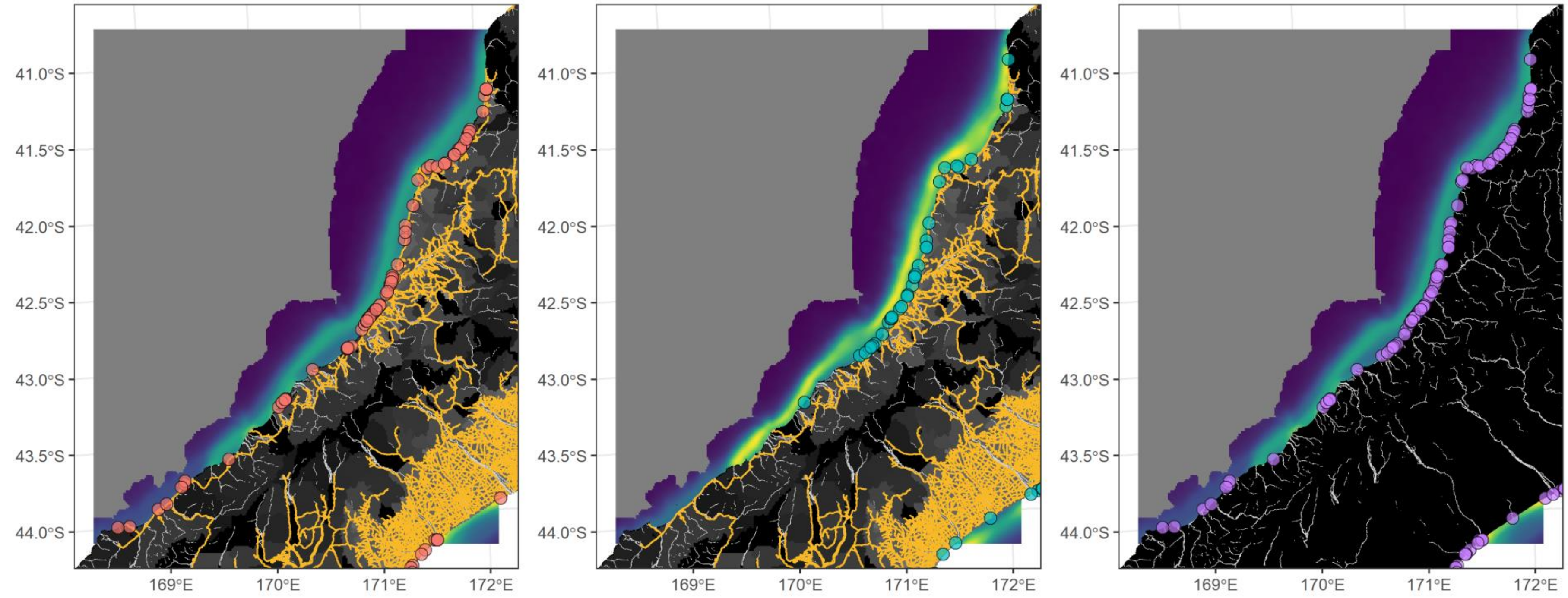

Figure A-9. Spatial distribution of reported Hector's and Māui dolphin beachcast events since 1985 along the West Coast of the South Island in summer (left), winter (centre), and in all seasons (right). The estimated relative at-sea density of dolphins (yellow/blue are high/low density) is shown for each respective season, with the summer density shown for the all-seasons plot. Public roads are represented by orange lines. Areas of very low human population density appear as black in the two left-hand plots. Roads are omitted from the right-hand plot to show the distribution of beachcast dolphins relative to river mouths.

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