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PRIORITISING SURVEILLANCE SITES FOR EXOTIC *CAULERPA* IN NORTHLAND

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1. BACKGROUND

In 2021–2022, extensive populations (> 100 hectares) of two non-indigenous species of the green alga *Caulerpa* (*C. brachypus* and *C. parvifolia*, hereafter referred to as 'exotic *Caulerpa*'), were discovered at Great Barrier Island / Aotea (GBI), and Great Mercury Island / Ahuahu (GMI). The algae appear to proliferate rapidly in infested locations, creating monospecific meadows that pose significant risks to ecological and cultural values. Following trials of various treatment and control techniques and given the extent and depth range of the established populations, the New Zealand Government decided to discontinue attempts at eradication and instead focus on limiting the spread and impacts of the species.

Exotic *Caulerpa* is thought to spread readily through fragmentation and via the entrainment of fragments in vessels' anchoring gear. Given the high levels of vessel activity between GBI / GMI and the northeast coast of mainland Aotearoa New Zealand, Northland Regional Council (NRC) are concerned about vessel-mediated translocation of exotic *Caulerpa* to its coastlines. Since exotic *Caulerpa*'s discovery, vessel visits and anchoring have been highly regulated in infested areas via controlled area notices (CAN). Surveys of the extent of the populations at GBI and GMI suggest the species may have been present for some time. As such, entrainment and transport of exotic *Caulerpa* in vessels' anchoring gear may have occurred prior to its first discovery.

Northland Regional Council engaged the Cawthron Institute (Cawthron) and their collaborator, the Australian Institute of Marine Science (AIMS), to assist with the prioritisation of sites for exotic *Caulerpa* surveillance along the Northland coast using existing survey and Automatic Identification System (AIS) datasets on nationwide recreational and commercial vessel movements. Contracting was undertaken via MBIE's Envirolink funding scheme (Grant No. 2343-NLRC238).

2. SCOPE

The specific objectives of this project were to use Cawthron and AIMS' existing datasets and pathway modelling framework (collated via the Marine Biosecurity Toolbox research programme[1]) to:

i. identify and map the 'reachability' network, or all locations around Northland that have received vessel traffic from known sites of exotic *Caulerpa* infestation (GBI and GMI), and the relative strength of these connections; and

[1] https://www.biosecurity-toolbox.org.nz/manage-respond/

ii. quantify and map potential anchoring events along the Northland coast of vessels that had previously (within 10 days, the assumed survival period of exotic *Caulerpa* fragments) resided at known sites of infestation.

These outputs were delivered via a half-day hybrid (online and in-person) workshop with NRC[2] and are summarised in this report.

At the time of contracting, known sites of infestation included those around GBI and GMI. Shortly after the start of the project, exotic *Caulerpa* was detected at Omakiwi Cove, Bay of Islands. Given the extent of the local population, covering an area of approximately 16 hectares, exotic *Caulerpa* may have been locally established for some time. For this reason, the population at Omakiwi Cove was included in the objectives described above.

3. METHODS

Our analyses were based on two complementary datasets: the first captured all vessel movements from GBI as AIS signal tracks, and the second contained voyage records derived via a survey of recreational vessel owners. To be comparable, both datasets were aligned and standardised, and presented across consistent geographies (described below). The sections below broadly describe the datasets and the analyses performed.[3]

3.1. Vessel movement data

We used two different datasets to develop the models and results described in this report. Both datasets had been collated for research in the Marine Biosecurity Toolbox research programme, and prior to the first discovery of exotic *Caulerpa*.

3.1.1. AIS signal data

This dataset consisted of georeferenced AIS signals for all AIS-equipped vessels that came within 2 km of GBI over a 1-year period (June 2019–June 2020) prior to the initial discovery of exotic *Caulerpa*. The AIS tracks were obtained from Xerra Earth Observation Institute and included 454 unique vessels. Although the majority (89%) were recreational vessels (sailing yachts and motor launches), cargo, passenger,

[2] Due to the national interest in the spread of exotic *Caulerpa*, this workshop was also attended by representatives from Auckland Council, Waikato Regional Council, Bay of Plenty Regional Council, the Department of Conservation and the Ministry for Primary Industries.

[3] Given the timeframes and resourcing of this Envirolink project, it is not feasible to provide a detailed description of every step of our data formatting and analysis pipelines. Instead, these steps were discussed in detail during a project workshop with NRC where results were presented. More information is also available from the authors.

tourism, fishing, military, and search and rescue vessels also had visited GBI during the 1-year period. It should be noted that recreational vessels are not required to be equipped with AIS and, as a result, our data only capture a proportion – perhaps a minority – of the recreational vessels that visited GBI (and presumably anchored) during this period (Serra-Sogas et al. 2021). The AIS tracks included the vessels' locations over the entire 1-year period only. The time-stamped AIS signals were standardised to hourly average locations and speeds of all vessels contained in the data.

3.1.2. Recreational boater survey data

This second dataset consisted of recreational vessel (sailing yachts and motor launches) movements collected via an online survey of domestic boat owners. The survey was developed by Cawthron, Deakin University and Scion Research, and was distributed to recreational vessel owners nationwide with assistance from the Aotearoa New Zealand boating and marina industry. The survey used the online, map-based citizen engagement platform Maptionnaire. Vessel owners were asked to indicate their homeports and the destinations they visited (in chronological sequence, beginning and ending at their homeports) in their vessel during their five 'most significant voyages' between January 2019 and October 2021. Survey respondents logged their visits by placing virtual anchors onto an interactive map using their computer, tablet or smartphone. Such 'anchor drops' created georeferenced visit events and were logged in a cloud-based database. For each destination visited, vessel owners also provided information on the duration of their stay. The owners of a total of approximately 1,800 unique vessels returned the survey and logged a total of approx. 12,000 visit events. This sample size represented approximately 8% of the total domestic recreational vessel population. The vessels' homeports, the chronological sequence of their visits to their various destinations, and the time spent at each destination enabled the creation of detailed itineraries for each voyage logged by each vessel owner.

3.2. Potential anchoring locations (nodes)

The combination of AIS signal position data and the georeferenced survey-based visitation data resulted in dozens to hundreds of vessel visits to distinct coastal locations, such as bays, beaches, estuaries, marinas or other environments. For mapping and analysis consistency, a clustering approach – using a distance of 10 km – was used to coalesce neighbouring vessel visits into single meaningful anchoring sites ('nodes' in a vessel network). Spatial clustering resulted in approximately 600 distinct coastal nodes, which were used as the departure and / or destination locations for vessel movements. This enabled accurate mapping and analysis to determine the cumulative number of vessel visits to each node around the Aotearoa New Zealand coastline.

3.3. Network development and analysis

We created vessel movement network models to examine patterns and volumes of potential traffic between GBI / GMI and coastal locations around the Northland Region. These network models were analysed to identify priority locations for surveillance of exotic *Caulerpa*. Separate networks were created for the 'AIS' and the 'Survey' datasets because of the differences in data format, assumptions and timeframes. For each dataset, two networks were created that each focused on different spatial and temporal scales (see sections 3.3.1 and 3.3.2 below). The AIS data networks were based on the movements undertaken by the 454 vessels between June 2019 to June 2020. A different approach had to be taken for the survey data network. In this case, vessel movement frequencies provided by the survey respondents (a sub-set of the total boater population) were 'scaled up' to represent the estimated movement frequencies undertaken by the entire domestic recreational vessel population.[4] In the sections below, the term 'nodes' is used to describe the *locations vessels visited*, and 'edges' describe the *vessel movement between nodes* and their strength based on movement frequencies. Network development and analysis were completed using the R software (R Core Team 2023) package 'igraph' (Csárdi et al. 2023), and ArcGIS Pro was used for visualisation.

3.3.1. Networks to determine 'maximum domestic reachability' of GBI and GMI

The AIS dataset was already (by design) restricted to vessels that had visited GBI (within 2 km of the island) at some point during the 12-month period. In contrast, the Survey dataset included all nationwide recreational vessel itineraries, including those vessels that had never visited GBI or GMI. The Survey dataset was thus constrained to only those vessels that had visited locations around GBI or GMI at some point during the 18-month period.

For each of the two datasets, an independent network was developed whose nodes captured all the destinations that vessels had visited over the timeframe of the dataset, and whose (directional) edges represented movement frequencies between vessel sources and destinations. These networks visualise and enable quantification of the entire domestic 'reach' of GBI / GMI, both 'upstream' (i.e. nationwide locations where vessels had visited *prior to their voyage to GBI / GMI*) and 'downstream' (i.e. nationwide locations where vessels travelled to *following their departure from GBI / GMI*).[5]

[4] This was carried out based on the known distribution of marina berths and moorings across Aotearoa New Zealand and the occupancy rates provided by facility operators.

[5] The AIS dataset was thus able to identify visits to GMI made by vessels that also visited GBI. However, it was unable to identify visits to GMI by vessels that had not also visited GBI during that year. The Survey dataset was able to do both.

3.3.2. *Networks to identify potential anchorage events of vessels departing from nodes where exotic* Caulerpa *is established*

One of our key objectives was to determine which destinations along the coast of the Northland Region may have received vessels from upstream locations where exotic *Caulerpa* is known to be established. We assumed that during this process, exotic *Caulerpa* may have become entrained in anchoring gear upon vessels' departures from infested locations and inadvertently released (introduced) while the vessels anchored at subsequent destinations. To quantify this potential, we developed constrained, 'downstream' networks using the following logic:

i. We constrained the datasets to only those vessels that had (over the data period) resided in locations where exotic *Caulerpa* is known to be established. These locations were:
   - Whangaparapara Harbour, Blind Bay and Tryphena Harbour at Great Barrier Island (both datasets)
   - Great Mercury Island (captured in the Survey dataset only)
   - Omakiwi Cove, Northland (Survey dataset only).

   While our data cannot tell us whether entrainment of exotic *Caulerpa* in a vessel's anchoring gear had actually occurred, our analyses assume that it *may have occurred* given the biology of the species and the fact that these locations are popular anchorages for recreational and other vessel types.

ii. Following their departure from 'infected locations', these vessels were 'tracked' for 10 days, which is the period exotic *Caulerpa* is thought to remain viable while entrained in anchoring gear.[6] In the case of the AIS data, tracking was mapped using the time-stamped vessel location data. The survey data were not time-stamped but contained the destinations vessels had visited following their departure from infested nodes, as well as the time spent at each destination.

iii. If during this 10-day period vessels visited and resided at any destinations that were *not* commercial marinas or mooring fields (where vessels presumably would not drop anchor), then these visits were classified as an anchoring event during which exotic *Caulerpa* fragments may have been released. In the case of the AIS data, vessels had to have been stationary for at least 1 hour in order for the visit to qualify as a potential anchoring event. Anchoring events were explicit in the survey data, which also included the time (number of days) spent at each destination.

[6] https://www.mpi.govt.nz/biosecurity/exotic-pests-and-diseases-in-new-zealand/pests-and-diseases-under-response/exotic-caulerpa-seaweeds-at-great-barrier-great-mercury-kawau-island-and-bay-of-islands-te-rawhiti-inlet/

While our data cannot tell us whether release of exotic *Caulerpa* had actually occurred during a vessel's visit to 'downstream' locations, our analysis assumed that this *may* have occurred given the biology of the species and the fact vessels anchor if they are unable to use a mooring or berthing infrastructure. In this sense, these data should be interpreted as potential anchoring and / or potential risk for exotic *Caulerpa* introductions.

iv. If vessels departing infected locations (see (i) above) anchored at multiple 'downstream' destinations over this 10-day period, we classified *each visit* as a potential introduction event of exotic *Caulerpa*. This was done using the following assumptions / reasoning: first, the relationship between fragment viability and time spent in transit (within the anchor locker) is unknown, and for this reason, we assumed fragments remained 100% viable for the entire 10-day period; second, it is also unknown whether *all* fragments potentially entrained in anchoring gear are released during the first anchoring event; therefore, we assumed there was the same potential for release at all anchoring events within the 10-day period.

For the time-stamped AIS data, it was straightforward to track vessels and their residencies at 'downstream' locations. For the survey data, we estimated transit time based on distance and average travel speeds. We first calculated the distance between a vessel's successive departure and destination locations. We then assumed an average cruising speed of 5 knots over 8 hours per day, which is realistic for sailing yachts. This allowed us to calculate the transit time between successive destinations, including residency periods, up to the 10-day limit.

3.3.3. Response variables to assist surveillance prioritisation

Following the tracking process described above, we summed the potential anchoring events that had taken place in each location along the Northland coast. We then calculated the percentage of the potential introduction events that occurred at each site, relative to the Northland coast. This was done to (i) enable direct spatial comparison between the two datasets, and (ii) focus the results based on the estimation of relative, but not of absolute, risk.

Here, the relative strength of potential introductions can be interpreted as an analogue of 'potential propagule pressure', which is an established risk indicator for the establishment of invasive species (Hedge et al. 2012) and, in the case of this study, suitable as a metric for supporting decisions around prioritisation of surveillance efforts.

4. RESULTS

4.1. Domestic 'reach' of Great Barrier Island and Great Mercury Island

Over the 12-month period, the 454 vessels in the AIS dataset had resided at a total of 273 domestic locations (network nodes) that ranged from near Cape Reinga / Te Rerenga Wairua in the north to Stewart Island / Rakiura in the south, and also included some of Aotearoa New Zealand's sub-Antarctic islands (Figure 1). A total of 3,776 distinct connections linked coastal locations, and 13,576 voyages had occurred along these connections (Figure 1). The recreational vessels in the Survey dataset had visited 178 domestic locations that also spanned the length of Aotearoa New Zealand but did not include offshore islands. This network contained 1,854 connections, along which 14,784 vessel voyages had occurred. Along the Northland coast, locations around the outer and inner Bay of Islands, the Tutukaka coastline, and Whangaroa, Whangaruru and Whangārei Harbours were the most frequently visited locations for vessels from both datasets (208–850 visits per location).

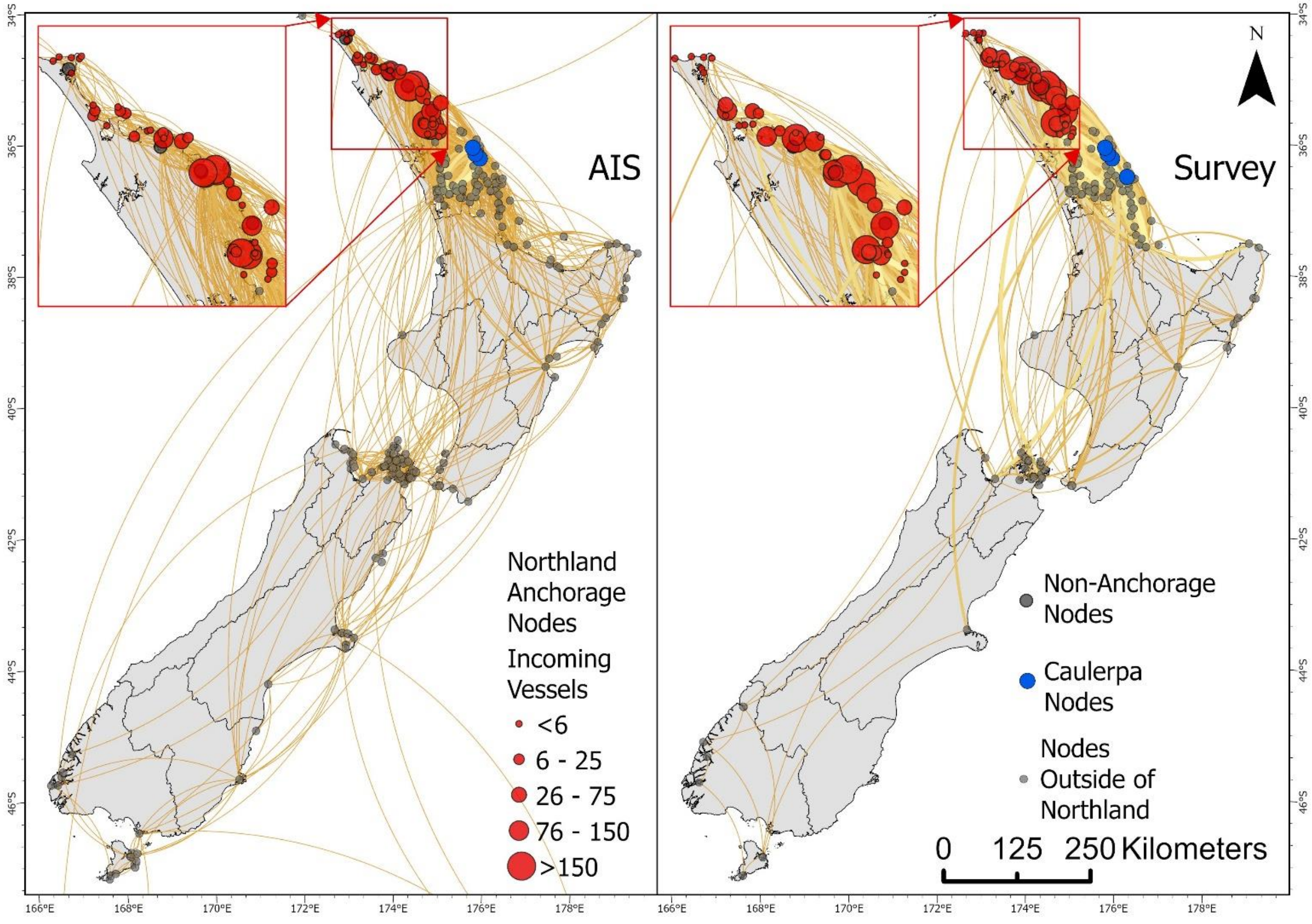

Figure 1. Maximum reachability networks for Great Barrier Island (GBI) and Great Mercury Island (GMI) developed from the Automatic Identification System (AIS; left panel) and Survey datasets (right panel). Circles represent coastal locations (nodes) where vessels had resided after or before visiting GBI or GMI. Red circles depict locations along the Northland coast; circle diameter scaled according to vessel visits received. Orange arcs represent connections between locations (edges between nodes) and linewidth is scaled to number of vessels. Directionality of the vessels is implied by the bend of the arc, following a clockwise direction. The blue dots are locations with known populations of exotic *Caulerpa*.

4.2. Potential anchoring events along the Northland coast

'Downstream networks' created for both datasets indicate numerous anchoring events may have occurred along the Northland coast by vessels that had departed locations with established exotic *Caulerpa* populations within the previous 10 days. The AIS dataset (restricted to vessels departing from exotic *Caulerpa* populations around GBI, Whangaparapa Harbour, Blind Bay and Tryphena Harbour) indicated a total of 90 potential anchorage events in 18 Northland locations (Figure 2). The downstream network developed from the Survey dataset (including vessels departing locations with existing exotic *Caulerpa* populations at GBI, GMI and Omakiwi Cove) suggests that 4,000 anchorage events may have occurred at 36 Northland locations.

Potential anchorage events occurred around 'mainland' bays and estuaries, coastal islands (e.g. Hen Island, Moturoa Island), and marine protected areas (e.g. Poor Knights Islands Marine Reserve, Whangārei Harbour Marine Reserve) (Figure 2). The inner Bay of Islands, and Te Rawhiti Inlet in the outer Bay of Islands had the highest 'relative *Caulerpa*[7] risk', having received 20% (AIS dataset) and 31% (Survey dataset) of the total number of anchorage events recorded for the Northland Region, respectively. For each network, the 10 locations with the highest relative *Caulerpa* risk captured approximately 92% of the total Northland-wide risk associated with anchorage events (Figure 3).

[7] Relative *Caulerpa* risk refers to exotic *Caulerpa.*

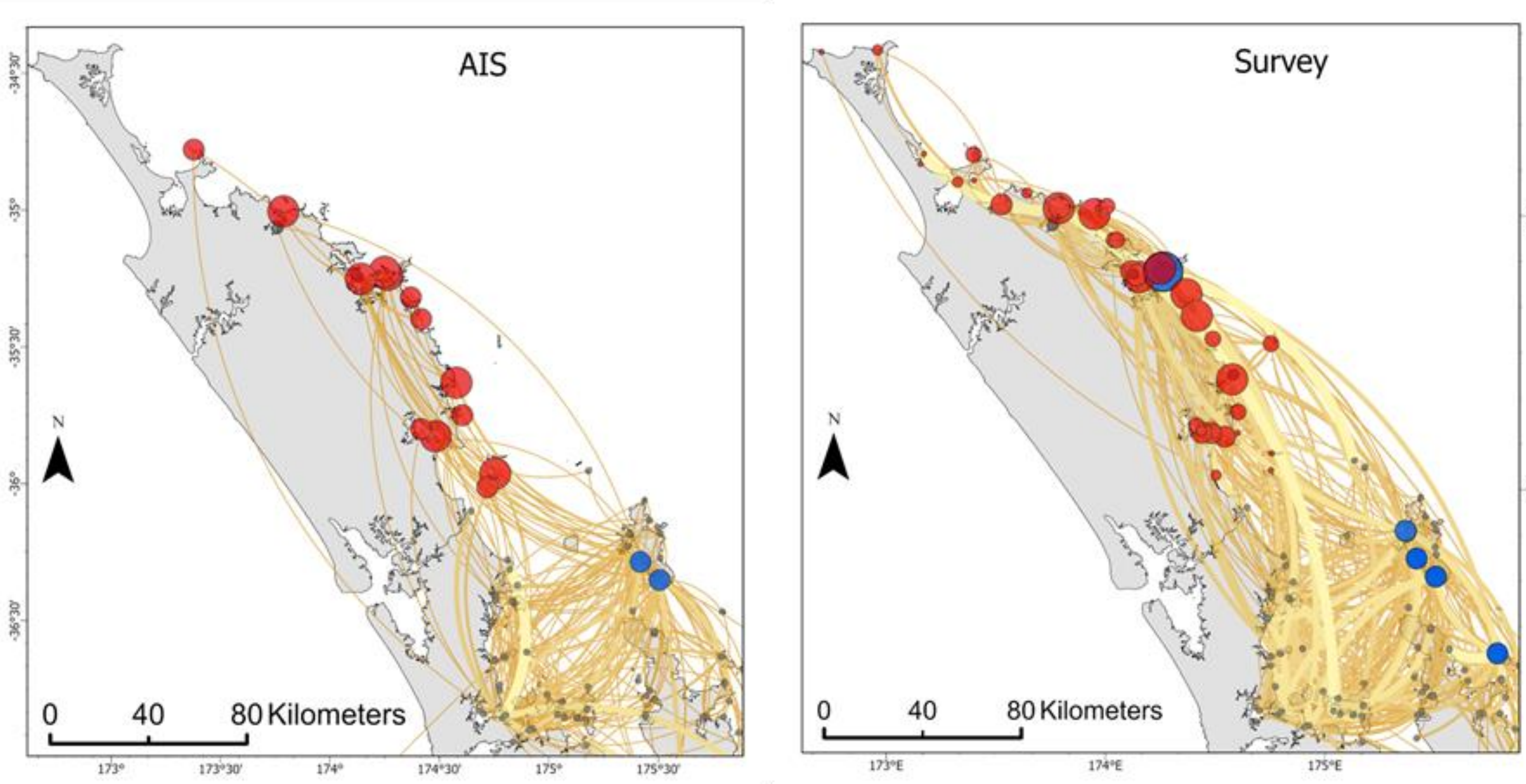

Figure 2. Potential anchoring events along the Northland coast of vessels that had departed locations with known populations of exotic *Caulerpa* (blue circles) within the 10 previous days. Nodes where potential anchoring events occurred (red circles) are sized according to their relative risk, i.e. the proportion of the total number of Northland anchorage events that occurred at each location. Left panel is for the Automatic Identification System (AIS) data network and the right panel for the Survey data network.

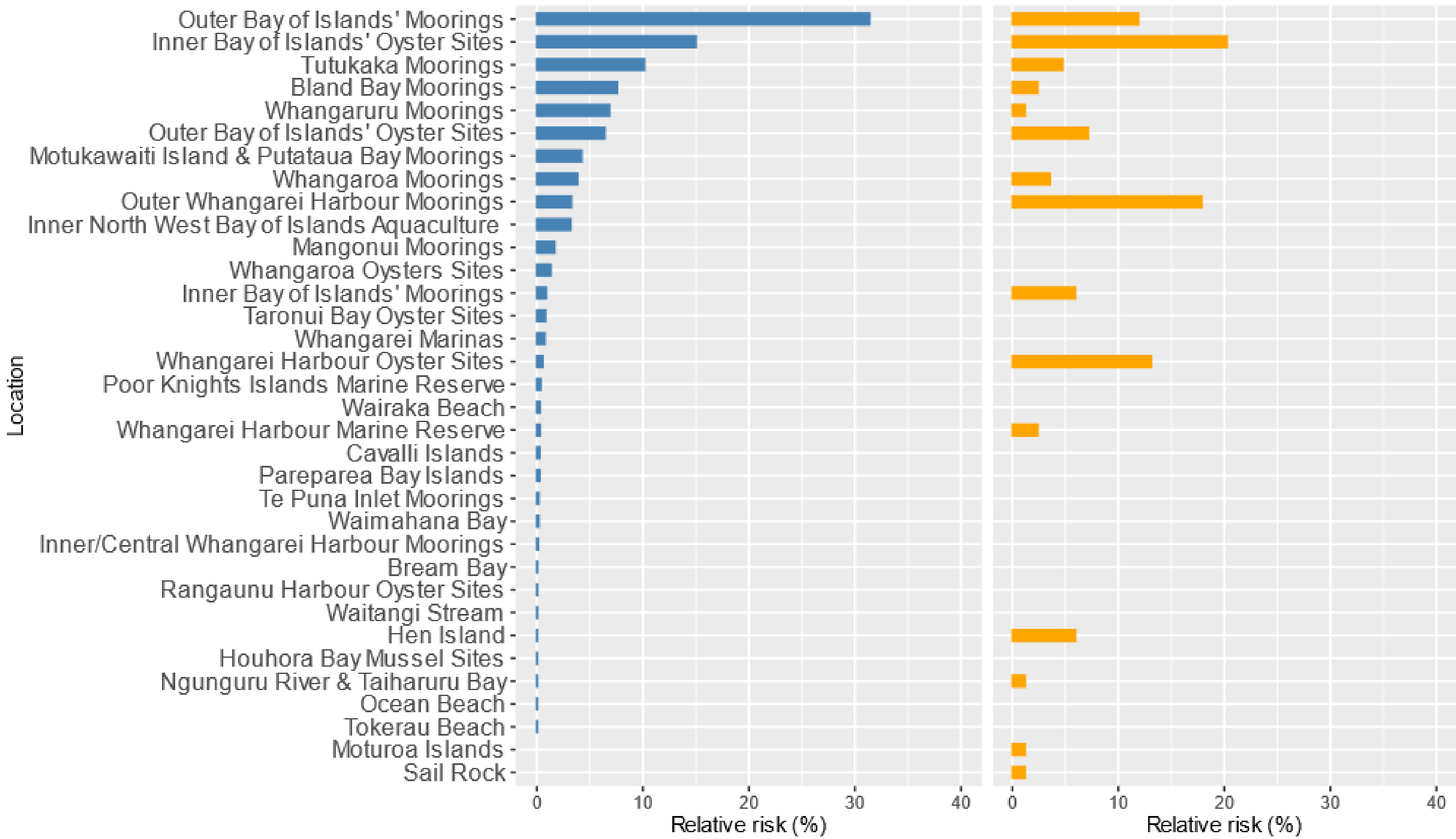

Figure 3. Relative *Caulerpa* risk (% of total Northland-wide anchorage events) of Northland Region locations (nodes) within the 10-day downstream networks. Left panel is for the Survey dataset and right panel is for the Automatic Identification System (AIS) dataset.

The 10 Northland locations with the highest relative *Caulerpa* risk within each network resulted in a list of 13 priority sites (Table 1). Of these, seven locations (Outer Bay of Islands Moorings; Inner Bay of Islands Oyster Sites; Tutukaka Moorings; Bland Bay Moorings; Outer Bay of Islands Oyster Sites; Whangaroa Moorings; Outer Whangārei Harbour Moorings) were shared between the two networks. Both networks featured three additional priority sites (AIS: Whangārei Harbour Oyster Sites; Inner Bay of Islands Moorings; Hen Island; Survey network: Whangaruru Moorings; Motukawaiti Island & Putataua Bay Moorings; Inner Northwest Bay of Islands Aquaculture) that were of lower relative importance or absent in the other network (Table 1).

Table 1. Top 10 nodes from each network with respect to relative *Caulerpa* risk.

	Survey network		AIS network	
Node	**Rank**	**Relative risk**	**Rank**	**Relative risk**
Outer Bay of Islands Moorings	1	31%	4	12%
Inner Bay of Islands Oyster Sites	2	15%	1	20%
Tutukaka Moorings	3	10%	8	5%
Bland Bay Moorings	4	8%	10	2%
Whangaruru Moorings	5	7%		
Outer Bay of Islands Oyster Sites	6	6%	5	7%
Motukawaiti Island & Putataua Bay Moorings	7	4%		
Whangaroa Moorings	8	4%	9	4%
Outer Whangārei Harbour Moorings	9	3%	2	18%
Inner NW Bay of Islands Aquaculture	10	3%		
Whangārei Harbour Oyster Sites			3	13%
Inner Bay of Islands Moorings			6	6%
Hen Island			7	6%

5. DISCUSSION AND RECOMMENDATIONS

The network models developed from our AIS and survey datasets illustrate the high level of connectedness of two ‘remote locations’ – Great Barrier Island and Great Mercury Island – with approximately 300 coastal locations around wider Aotearoa New Zealand.

5.1. Priority locations for surveillance

Our downstream analyses identified and quantified potential anchorage events along the Northland coast that occurred within 10 days of vessels having departed locations with known populations of exotic *Caulerpa*. Potential anchorage events were detected for a total of 34 locations, with approximately 92% of all anchorages having taken place in the top 10 locations of each of the two networks. Te Rawhiti Inlet and Omakiwi Cove – the locations where established populations of exotic *Caulerpa* were discovered in early May 2023 – received the highest proportion of potential anchorage events (31%) within the survey network. The inner Bay of Islands, only approximately 15 km away, had the highest proportion of anchorage events (20%) across the AIS network.

The identity and relative risk of 'anchorage locations' can be used by NRC to guide the design of a regional surveillance programme for exotic *Caulerpa*. Below are some key considerations relating to our analyses and results:

i. Our analyses were only based on vessel movements and did not consider environmental aspects of locations where anchorage events may have occurred. We recommend that local knowledge, and information on the habitat preference and environmental tolerances of exotic *Caulerpa* are used to scrutinise our list of anchorage locations. This may (or may not) result in some locations being 'discarded' based on unsuitable environmental conditions.

ii. Our analyses did not consider the likelihood of exotic *Caulerpa* entrainment or release via anchoring, or a decay function of exotic *Caulerpa* survival over time when transported in anchor lockers. This information currently does not exist. Instead, based on a precautionary approach, we assumed that entrainment and release may have occurred at every visit and survival was 100% over the 10-day period.

Consequently, these results should be viewed as <u>relative</u> *Caulerpa* risk, based on the relative number of potential anchoring events detected along the Northland coast. This is not to be confused with the <u>absolute</u> risk of exotic *Caulerpa* establishment, which is influenced by numerous additional biotic and abiotic factors.

With limited time and financial resources for surveillance, we recommend that priority be given to locations that had the highest relative number of anchorage events, while also considering their environmental and habitat suitability. In addition, a stratified approach could be considered that includes multiple locations across low, moderate and high relative *Caulerpa* risk. This approach may reduce the effect of not understanding the absolute risk associated with low vs high numbers of anchoring events.

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