Department of Conservation, Conservation Services Program project POP 2019-02: Fish shoal dynamics in north-eastern New Zealand

Milestone 5: Final report summarising analysis of zooplankton samples collected 2019 - 2020

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NEW ZEALAND

SCIENCE
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The appended report (Exploring distributions of pelagic fish using aerial sightings data – interim report) has been prepared by **Paul Taylor** (Statfishtics Ltd) with **Chris Gaskin** (Northern NZ Seabird Trust).

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Cover image: Skipjack tuna with Buller's shearwater in foreground in pursuit of small fish. *Photo: Chris Gaskin.*

Figure 1 (above): Towing the zooplankton net through a dense school of feeding trevally from the RV *Hawere*. *Photo: Chris Gaskin.*

SUMMARY

A notable feature of north-eastern North Island, New Zealand waters are the large numbers of seabirds feeding in ‘workups’ – multispecies aggregations containing zooplankton and fish. Many seabird species are potentially dependant on prey (zooplankton and fish) advertised by and made available by the shoaling fish in workups. However, the processes that drive workup formation and dynamics are poorly understood in this region. Purse-seine fisheries in this region target fish species which form workups and may therefore be indirectly affecting seabirds which utilise workups for food. The degree to which this occurs is unknown and therefore it is important to better understand the relationship between seabird population trends and changes in abundance and distribution of workup forming fish shoals.

This study aimed to characterise the biological composition of workups by determining the associations among the presence of zooplankton, shoaling fish, and feeding seabirds. Nine fieldwork days were undertaken in the wider northern Hauraki Gulf between November 2019 and February 2020. Locations where seabirds were seen feeding were targeted for zooplankton sampling, fish captures, data collection on seabirds and fish species, underwater videography and environmental measurements. Three types of fish shoal event were defined and sampled: Mixed fish shoal, Kahawai school and Tuna school. Three types of non-fish shoal events where seabirds were feeding were defined and sampled: Current line, Krill patches, and Unknown. Zooplankton samples were subsampled as required and counted into seven groups: Copepoda, Malacostraca, Nauplii (krill), Thaliacea, Appendicularia, Fish eggs and Other. Each event type was able to defined by specific zooplankton, fish and seabird types/species and certain seabird feeding behaviours. Krill (*Nyctiphanes australis*) was found to be an important component of fish shoal events and preyed upon by both fish and seabirds. Krill was also found at high abundances at Krill patch events where fish shoaling did not occur, but seabirds were feeding on the krill.

This season’s research was curtailed by Covid-19 restrictions resulting in a large reduction in data collected and subsequent analysis. This needs to be considered when looking at data trends given in this report. There is a need to continue to develop the multi-disciplinary approach used here to fully investigate indirect effects of fisheries on seabirds in the wider Hauraki Gulf.

The appended report provides an update on analyses of fish shoal data from the aerial sightings database (aer_sight).

CONTENTS

1 STUDY AIMS

The aim of this study was to characterise the biological composition of workups by determining the associations among the presence of zooplankton, shoaling fish, and feeding seabirds. This was achieved by looking at the associations between zooplankton prey, such as krill, and their fish and seabird predators. Some key environmental parameters that potentially affect the spatial and temporal distribution of zooplankton and their predators were recorded. The abundance and composition of zooplankton in fish shoals was determined utilising a combination of zooplankton nets and underwater video to identify key species involved with triggering fish shoaling. These data were examined in relation to interannual, seasonal and spatial parameters. This report presents a summary of the analysis of zooplankton samples collected in the 2019 – 2020 sampling season and their relationships with different types of seabird feeding events. It forms a continuation of the fish shoal and zooplankton research conducted in the two previous sampling seasons (2017-2018 & 2018-2019, Gaskin 2019[1]; Gaskin & Adams 2019).

1.1 This report

This final report for the POP2019-02: Fish shoal dynamics in north-eastern New Zealand project updates the Milestone 4 interim report (Kozmian-Ledward et al. 2020). Note, some analyses not completed in 2020 will be incorporated into reporting for the current contract (BCBC2020-08) for a continuation of zooplankton sampling.

The appended report (Appendix 1) is an interim report for the second objective of POP2019-02. That is, to analyse fish shoal data from the aerial sightings database (aer_sight) and, for the study area in East Northland, Hauraki Gulf and Bay of Plenty (BOP), develop a model of temporal variability in surface schools of the pelagic shoaling finfish species targeted by the domestic purse-seine fishery in terms of relevant environmental variation as a first step in better understanding fisheries pressures on seabird population trends.

2 INTRODUCTION

2.1 Background

A notable feature of north-eastern North Island waters are the large numbers of seabirds feeding in “workups” – multi-species feeding aggregations containing zooplankton and fish. There is a need to understand the processes that drive workup formation and dynamics as many seabird species, predominantly red-billed gull (*Larus novaehollandiae scopulinus*), white-fronted tern (*Sterna striata*), Australasian gannet (*Morus serrator*), fairy prion (*Pachyptila turtur*), Buller’s shearwater (*Puffinus bulleri*), and fluttering shearwaters (*Puffinus gavia*), are potentially dependent on shoaling fish to drive prey to the sea surface, making them accessible as a food source. There is poor knowledge of both the relationship between the diet of surface-foraging seabirds, and what prey items are being made available to seabirds from workups. This is limiting our understanding of the mechanisms through which any changes in the distribution and/or abundance of workups may be driving seabird population changes (population status and annual breeding success). For several seabird species that interact with workups, their recent population abundance data are also incomplete or unknown which limits our assessment of population trends over time.

North-eastern North Island waters also support extensive purse-seine fisheries, due to the presence of the large shoals of fish. Fish species include kahawai (*Arripis trutta*), trevally (*Pseudocaranx georgianus*), skipjack tuna (*Katsuwonus pelamis*), jack mackerel (*Trachurus declivis*), blue mackerel (*Scomber australasicus*), saury (*Scomberesox saurus*), pilchard (*Sardinops sagax*) and anchovy (*Engraulis australis*). By targeting fish species which are also part of workups utilised by various seabird species; purse-seine fisheries potentially negatively impact these seabird populations. However, the degree to which this may occur is unknown, therefore it is important that we better understand the relationship between seabird population trends and changes in abundance and distribution of fish shoals. Note that in this report, fish ‘shoal’ and ‘school’ are used somewhat interchangeably. Technically, the term ‘shoal’ refers to a loose aggregation of fish, sometimes comprising different species, whereas a ‘school’ is a group of fish of the same species swimming together in synchrony.

2.2 Seabird feeding associations

Zooplankton occupy a key position in the pelagic food web (Fig. 2), transferring the organic energy produced by phytoplankton to higher trophic levels such as fish, seabirds, and baleen whales (Harris et al. 2000; Frederiksen et al. 2006). Zooplankton abundance and diversity are determined predominantly by oceanographic (e.g., temperature, upwelling zones) and biological factors (e.g., predation) which result in a large amount of spatial and temporal variability (Zeldis & Willis 2015).

Pelagic crustaceans such as krill, amphipods and copepods are often targeted as prey by seabirds particularly at those times when they occur at high densities near the sea surface. For example, on Canada’s West coast, the seasonal surface aggregations of *Neocalanus* sp. (large-bodied copepod), form an important food source for breeding Cassin’s Auklets (*Ptychoramphus aleuticus*) (Bertram et al. 2017). In Australian waters, the coastal krill *Nyctiphanes australis* and the pelagic amphipod *Paraprone clausi* have been noted as important prey for short-tailed shearwaters, *Ardenna tenuirostris*, when these zooplankters swarm at the surface during the summer (Montague et al. 1986). Seabirds may prey on zooplankton directly, as in the above examples, or indirectly by feeding on small pelagic planktivorous fish.

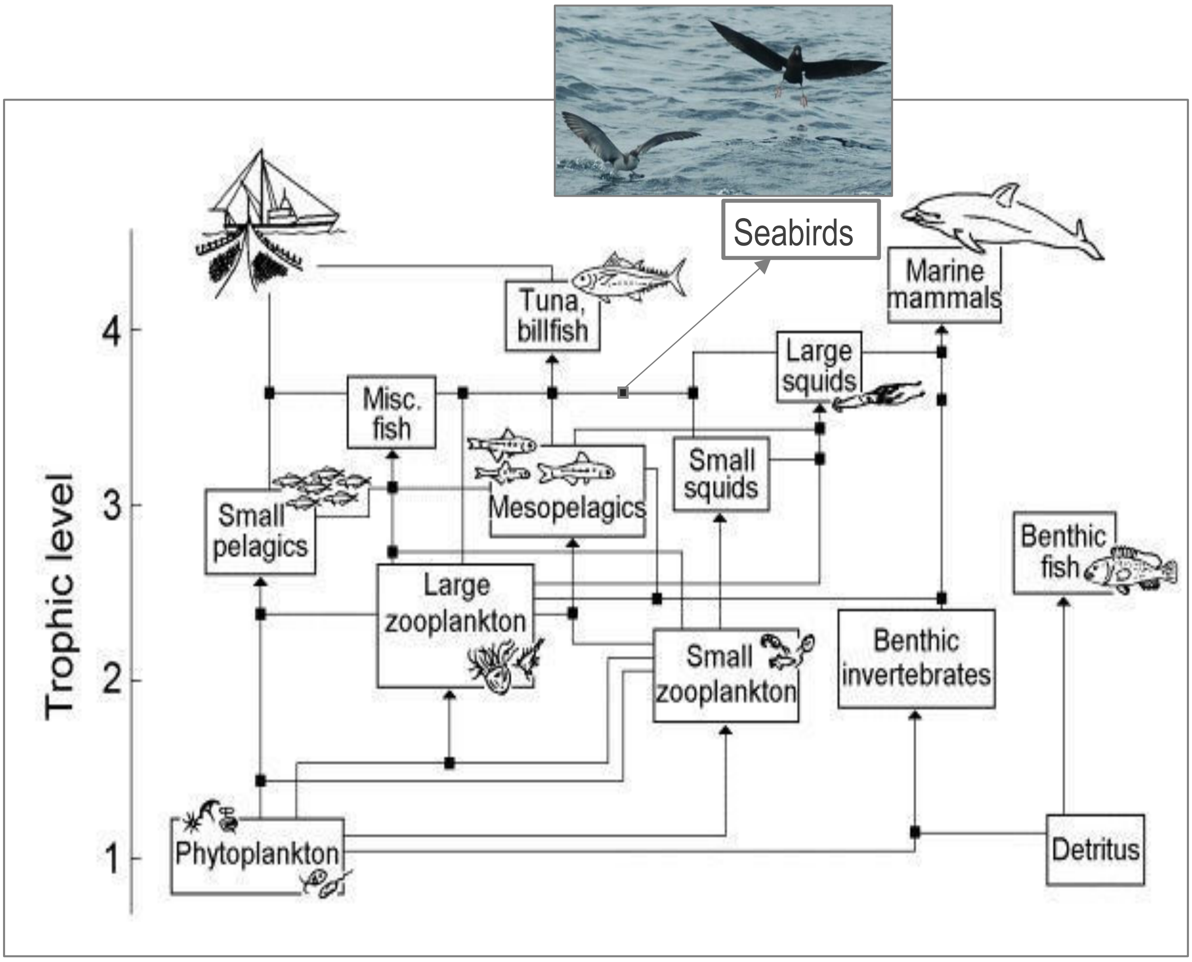


Figure 2: Generalised food web showing trophic levels and interactions between zooplankton, pelagic fish, seabirds, fishing, and other functional groups. *Modified from http://www.personal.kent.edu/~mkeatts/marinefoodwebs.htm with photo by Lily Kozmian-Ledward.*

In north-east North Island, NZ, the previous years of research and observations related to this project have determined prey types of various seabird species feeding in association with surface shoaling fish schools (Table 1). Of the zooplankton, *N. australis* (krill) appears to be an important prey for many seabirds including Buller's and fluttering shearwater and white-fronted terns. Australasian gannets feed on a variety of planktivorous fish species that include krill in their diet. Krill are also targeted by larger shoaling fishes such as kahawai, trevally and skipjack tuna. Analysis of stomach contents of kahawai and trevally in last season's work (2018-2019) found that the predominant prey was krill (Gaskin & Adams 2019).

Table 1. Summary of seabird prey items described in previous studies by NNZST and associates. Field observations include direct identification of prey captured/carried at sea and at colonies, and later analysis of photographs taken. Regurgitations and faecal samples were obtained from seabirds in their colonies.

Seabird	Prey types	Samples	References
Buller's shearwater	Krill, squid, fish. Scraps from marine mammal feeding (false-killer whales, pilot whales, pelagic bottlenose dolphins, fur seal).	Regurgitations, field observations.	Gaskin (2019[2]), Gaskin & Adams (2019), Kozmian-Ledward et al. (2019[1]).
Fluttering shearwater	Pelagic crustaceans, predominantly krill. Juvenile/larval fish. Scraps from marine mammal feeding (false-killer whales, pilot whales, pelagic bottlenose dolphins)	Regurgitations, field observations.	Gaskin & Adams (2019), Kozmian-Ledward et al. (2019[1]).
Fairy prion	Pelagic crustaceans, predominantly krill. Juvenile/larval fish. Scraps from marine mammal feeding.	Regurgitations, field observations.	Doyle & Adams (2019[2]), Gaskin & Adams (2019), Kozmian-Ledward et al. (2019[1]).
Australasian gannet	Arrow squid, anchovy, pilchard, saury, redbait, jack mackerel, blue mackerel, flying fish, kahawai.	Regurgitations, field observations.	Adams (2019), Gaskin (2019[2])
Red-billed gull	Potential krill (also opportunistic foragers on intertidal and land-based food sources).	Regurgitations (pellets), field observations.	Gaskin (2019[2]), Kozmian-Ledward et al. (2019[1])
White-fronted tern	Small fish (anchovy, potential pilchard, sardine), potential krill, juvenile squid	Dropped prey, faecal samples – DNA analysis, field observations.	Doyle & Adams (2019[1]), Gaskin (2019[2]), Kozmian-Ledward et al. (2019[1]).
Flesh-footed shearwater	Saury. Scraps from marine mammal feeding (false-killer whales, pilot whales, pelagic bottlenose dolphins)	Field observations.	Gaskin (2019[2])
Black petrel	Scraps from marine mammal feeding (false-killer whales, pilot whales, pelagic bottlenose dolphins)	Field observations.	Gaskin & Adams (2019)
Cook's petrel	Scraps from marine mammal feeding (false-killer whales).	Field observations.	Gaskin & Adams (2019)
White-faced storm petrel	Zooplankton. Scraps from marine mammal feeding (false-killer whales, pelagic bottlenose dolphins, fur seal).	Field observations.	Gaskin & Adams (2019)

Observations made during previous years of zooplankton sampling trips and on other seabird research trips have identified various types of seabird feeding events associated with fish shoal activity (Table 2). Other types of events can also be characterised where fish shoals are not involved but there is prey available to seabirds (Table 3). At these feeding events, seabirds utilise a variety of feeding techniques depending on the prey being targeted (Fig. 3). Numbers of seabirds attending these events will vary considerably from tens of thousands to a few hundred, even just tens on occasions. Despite these observations, there is still poor knowledge of the diet of surface-foraging seabirds and what prey items are being made available to seabirds from fish workups.

Table 2. Seabird feeding events involving fish shoals (modified from Gaskin 2017). Definition of seabird species codes given below.

Event type	Fish species	Seabird species	Activity
Mixed fish shoal	Trevally (often the dominant fish species), kahawai, blue maomao, kingfish. Can be just trevally schools.	BUSH, FLSH, FAPR, RBGU, WFTE (plus sometimes SOSH, FFSH, STSH, WFSP, COPE, GRNO)	Tightly packed, very active dense schools, sometimes with several schools merging to form very large schools. Birds either forage in the wake of the schools, or sometimes feed ahead of and around the schools. Fish will erupt explosively if disturbed either from below (e.g. predatory fish) or from above (e.g. birds flying low over school). Shearwaters and prions have been filmed diving in the wake of school activity.
Kahawai school	Kahawai	FLSH, WFTE, RBGU, FAPR	Fast-moving schools, birds moving in ‘leap-frogging’ formations, shearwaters plunging and diving. Also, tightly packed schools separate from trevally schools in the same vicinity.
Saury school	Saury	AUGA, FFSH (BLPE, SOSH)	Shearwaters and gannets diving on saury. Can occur in association with common dolphins.
Jack mackerel school	Jack mackerel	AUGA	Schools most commonly identified by gannets coming to the surface with prey. Fish occasionally seen breaking the surface.
Blue mackerel school	Blue mackerel	AUGA, FLSH, BUSH, FAPR	Very eruptive mobile schools, one minute here, the disappearing to appear somewhere else.
Baitfish shoal	Pilchard, anchovy, koheru	AUGA, FLSH, BUSH (FFSH, WFSP, COPE)	Often tightly packed schools, sometimes forming spinning ‘bait balls’ close to the surface. Birds plunging/diving and pursuing prey underwater. Can occur in association with common dolphins.

Tuna school	Skipjack tuna	BUSH, FLSH, AUGA, RBGU, occasional WFTE	Fast-moving fish sometimes jumping clear of water. Shearwaters following at speed, leap-frogging from one emergent feeding area to the next.

Table 3. Other types of events where seabirds are observed feeding in the absence of fish shoal activity. (modified from Gaskin 2017).

Event type	Seabird species	Activity
Krill patches	BUSH, FLSH, FAPR, CODP, WFSP, SOSH	Mainly krill and salps with birds actively feeding from the surface, often well-spread, occasionally across several sq. kms.
Current lines	FAPR, FLSH, WFSP	Current lines containing planktonic crustaceans, salps and juvenile fish. Birds actively feeding without prey being visible at the surface.
Common dolphins	FLSH, AUGA, FLSH, BUSH	In contrast to baitfish shoal activity – more sedate feeding activity by the dolphins (with occasional surges). Attendant birds on the surface peering below, sometimes diving in pursuit of prey, or flying to where new action takes place.

Seabird codes developed by NNZST: AUGA: Australasian gannet, **BLPE**: black petrel, **BUSH**: Buller's shearwater, **CODP**: common diving petrel, **COPE**: Cook's petrel, **FAPR**: fairy prion, **FFSH**: flesh-footed shearwater, **FLSH**: fluttering shearwater, **GRNO**: grey noddy, **RBGU**: red-billed gull, **SOSH**: sooty shearwater, **STSH**: short-tailed shearwater, **WFSP**: white-faced storm petrel, **WFTE**: white-fronted tern.

2.3 Study area

The study area is located off the north-east North Island, including the northern Hauraki Gulf (Fig. 4). This includes most of the areas where research work was conducted in previous years projects (INT2016-04 and POP2017-06) and extending out to include the waters around Kawau, Te Hauturu-o-Toi/Little Barrier Island and Aotea/Great Barrier Island. Research on seabird feeding associations and diet has been conducted in this area for several years due to the islands here being important breeding areas for 27 species which forage in the surrounding waters (Gaskin & Rayner 2013; Forest & Bird 2014).

The wider Hauraki Gulf area is a highly productive marine ecosystem whose productivity is influenced by both wind and current driven circulation. Offshore winds during spring cause upwelling of cool, nutrient rich waters, which, together with increasing daylight, promote high levels of phytoplankton production (Booth & Sondergaard 1989; Sharples & Greig 1998). During the summer, the Gulf and the coast are influenced by the warm, nutrient-poor surface waters of the East Auckland Current (EAUC), which are pushed inshore by easterly winds (Chang et al. 2003; Sharples 1997). The EAUC, combined with downwelling caused by the onshore winds, reduces primary productivity during late summer and autumn (Chang et al. 2003). Physical barriers such as headlands and islands enhance local upwelling, together with tidal currents in the Jellicoe, Cradock and Colville Channels that can attain up to 3 knots (Black et al. 2000; Royal NZ Navy Hydrographic Office Chart NZ53). Sea Surface Temperature (SST) typically ranges from 12.5 to 22 ° C across the Hauraki Gulf (Paul 1968). A full summary of oceanography of the region is provided in the earlier Milestone 2 report for this contract (Taylor & Gaskin 2020).

Figure 4. Study area in the northern wider Hauraki Gulf.

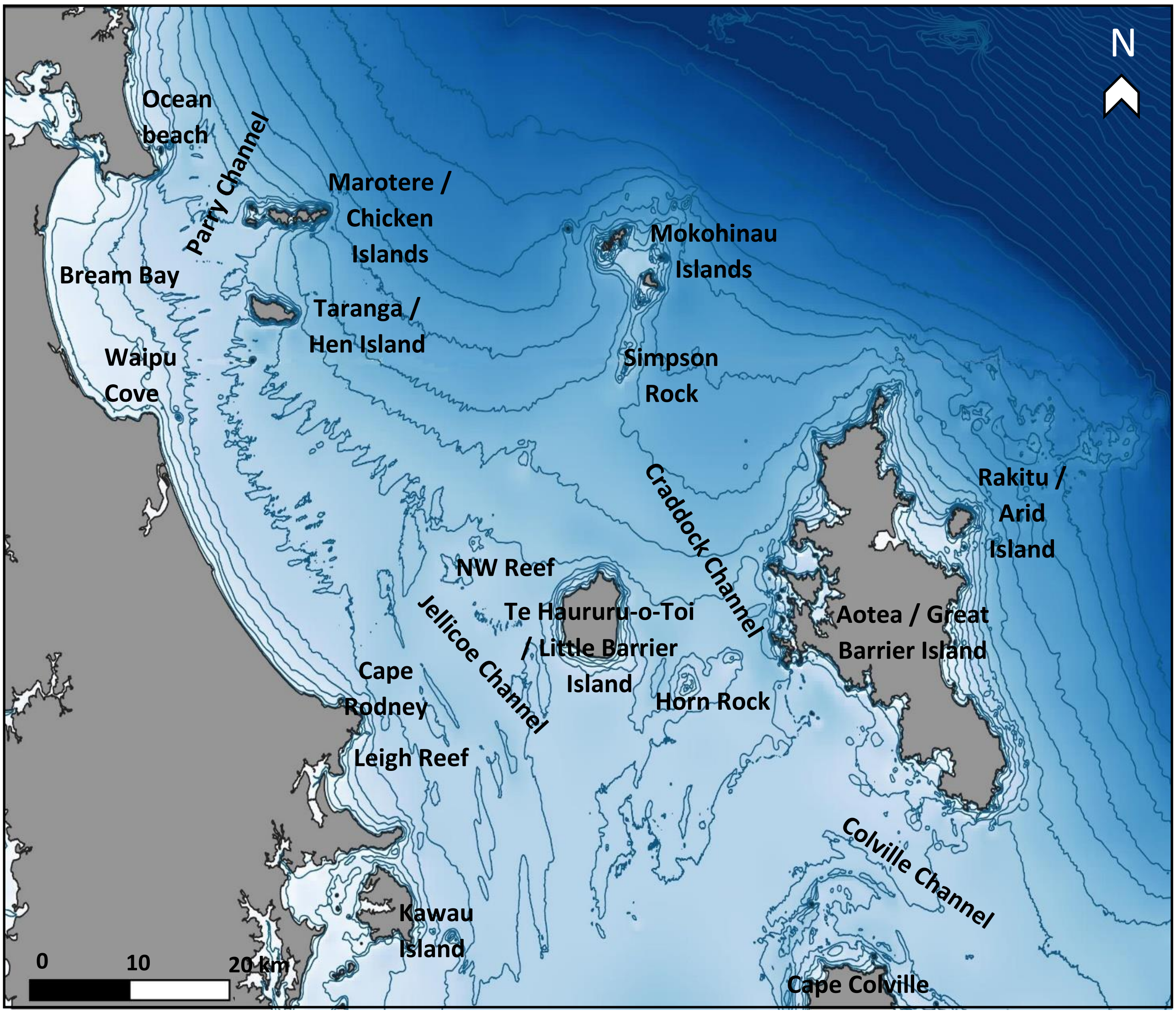
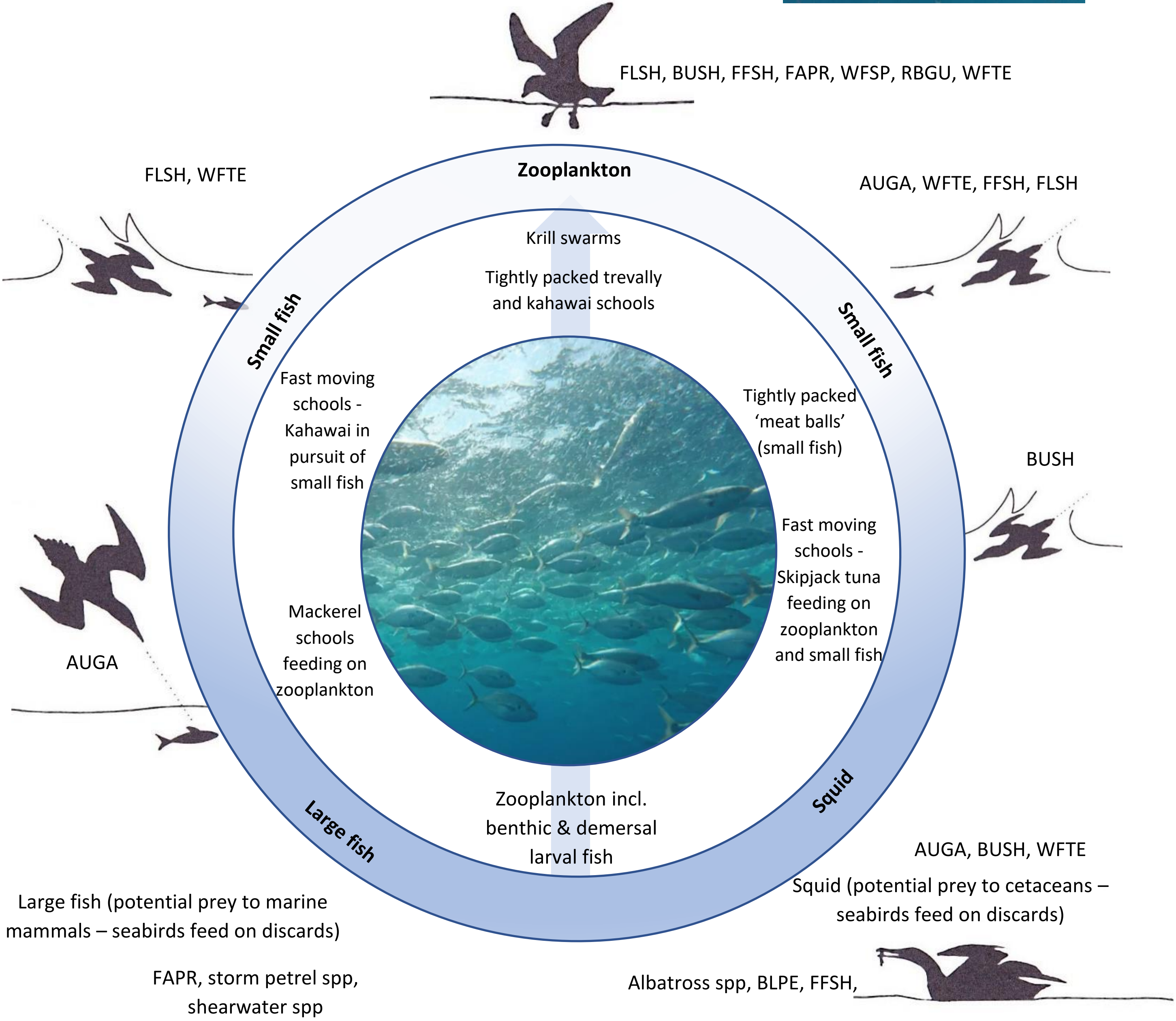


Figure 3 (following page): Feeding associations observed over this three-year study (2017 – 2020). Photos (clockwise from top left): Buller's and flesh-footed shearwaters feeding on krill patches; small fishes feeding on krill; NZ fur seal (*Arctocephalus forsteri*) feeding on a john dory (*Zeus faber*) with attendant fairy prion and Cook's petrel; pilot whales (*Globicephala melas*) with flesh-footed shearwaters (*Puffinus carneipes*). Seabird code definitions are given above.


FLSH, BUSH, FFSH, FAPR, WFSP, RBGU, WFTE
FLSH, WFTE
Zooplankton
AUGA, WFTE, FFSH, FLSH
Krill swarms
Tightly packed trevally and kahawai schools
Small fish
Small fish
Fast moving schools - Kahawai in pursuit of small fish
Tightly packed 'meat balls' (small fish)
BUSH
Fast moving schools - Skipjack tuna feeding on zooplankton and small fish
Mackerel schools feeding on zooplankton
AUGA
Zooplankton incl. benthic & demersal larval fish
Large fish
Squid
AUGA, BUSH, WFTE
Squid (potential prey to cetaceans – seabirds feed on discards)
Large fish (potential prey to marine mammals – seabirds feed on discards)
FAPR, storm petrel spp, shearwater spp
Albatross spp, BLPE, FFSH,

3. METHODS

The proposed methodology for Objective 1 of the fish shoal dynamics in north-eastern North Island project was detailed in the Milestone 1 report (Kozmian-Ledward et al. 2019[3]). The methodology was generally conducted as proposed, but with a few modifications, some of which were due to the Covid-19 pandemic. Due to Covid-19, trips scheduled for late March, April and early May 2020 were not undertaken. These dates coincide with chick-rearing stages for Buller's shearwater, one of the key study species for the Indirect Effects projects (INT2016-04, POP2017-06 and POP2019-02).

The final design of the "high-speed" zooplankton net was different from that described in the proposed methodology (Kozmian-Ledward et al. 2019[3]). Instead of a nested net, the new net was made to the same design as the old "low-speed" net, but with a coarser mesh (1.32 mm versus 0.25 mm) to enable faster towing speeds. It was determined that a nested net would not have worked in this application. The high-speed net was not available until January 2020 due to difficulties in obtaining the high strength precision mesh and delays with the net construction.

Instead of broadly categorising zooplankton sampling locations into "workup" and "no workup" as was done in the previous years of work and proposed in Milestone 1, events were categorised into several more detailed types based on seabird and fish activity described by Gaskin (2017) (Tables 2 & 3). These included event types where seabirds were feeding but surface shoaling fish were not present. Figure 5 shows the various inter-linked factors from which data was collected and analysed for this project. The methods for each type of data collection and analysis are given below.

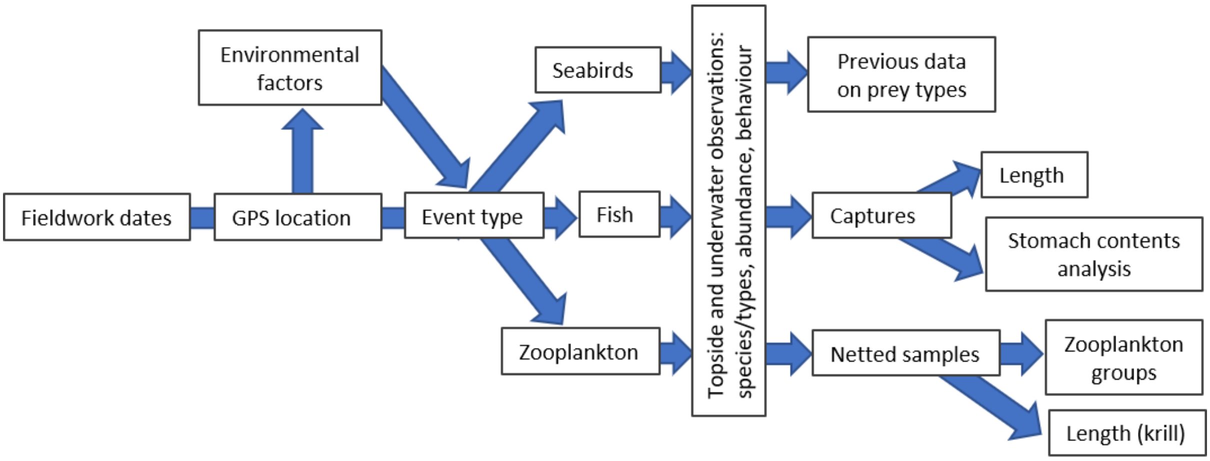


Figure 5: Flow diagram outlining the various inter-linked factors from which data was collected and analysed in this project.

3.1 Field methods

Nine fieldwork days were conducted between 22 November 2019 and 28 February 2020. Figure 6 shows the fieldwork dates and vessel tracks for each day. Day trips were conducted from the charter vessel *El Pescador* (1 day) and the volunteer vessel *Waimania* (3 days) out of Marsden Cove and Omaha respectively. Two multi-day trips (of 2- and 3-days duration) were conducted from the research vessel *Hawere* from Ti Point. The RV *Hawere* is a 15 m research vessel run by the

University of Auckland's Leigh Marine Laboratory. Using this bigger vessel allowed us to do overnight trips and this combined with fast vessel speed meant that a large area could be covered to search for fish workup and seabird feeding activity. Four to five team members including the skipper were on these trips, including a dedicated fisher, providing sufficient personnel to undertake the various research tasks. The large back deck/cockpit provided a good working space for sample collection and a small RIB could be stowed and easily deployed without inhibiting plankton net deployment.

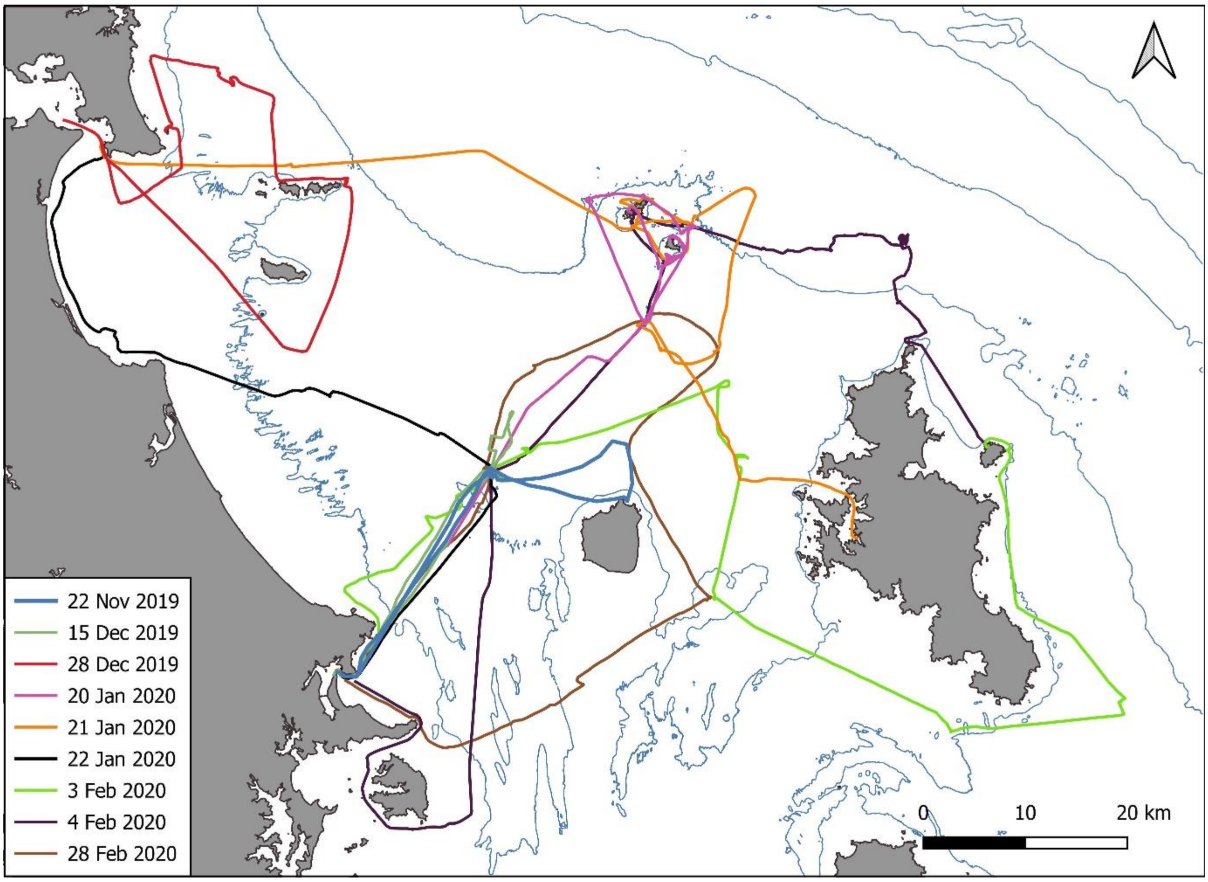


Figure 6: Vessel track-lines for each fieldwork day conducted. Note, an evening passage was undertaken between the Mokohinau Islands and Port Fitzroy, Great Barrier Island, on 20 January 2020 but is not shown on the map due to it occurring mostly in the dark when workups could not be observed or sampled.

Research trips this season were conducted primarily for this project and therefore the sampling work was not opportunistic as it had been previously – i.e., working in with other at sea surveys, island transfers and seabird birdwatching trips. The field methodology was generally conducted in a similar way to the previous two seasons (2017-2018, Gaskin 2019[1] and 2018-2019, Gaskin & Adams 2019) but extended to include additional variables described in Milestone 1 and detailed below.

The vessel route was determined by searching for seabird feeding/foraging activity, and where fish activity was observed occurring at or near the surface of the sea. While underway, observers continually scanned the horizon using binoculars and naked eye to search for workups by looking for the presence of seabirds, marine mammals, or disturbances at the sea surface by shoaling fish. Specific locations were targeted where workup activity has been previously located such as Leigh Reef, Northwest Reef, Simpson Rock, Mokohinau Islands, Taranga/Hen and Marotere/Chicken Islands, and Parry Channel/Bream Head area. Finding workups can be challenging and the use of high-speed vessels plus the extended range of the RV *Hawere*, together with utilising calm conditions (Beaufort 3 or less) where possible, increased chances of finding multiple workups in a day. Events where there was no surface fish shoaling activity, but birds were feeding such as surface krill patches and current lines (i.e., flow lines visible at the surface, and sometimes with accumulations of algae and other natural debris such as feathers and vegetation) were also opportunistically sampled while looking for workups. Searches for workup activity and subsequent sampling were only conducted during daylight hours. The vessel track was recorded on a handheld GPS (Garmin GPS 72H), at 1-minute intervals except for the first survey trip (22 November 2019) where it was recorded at 5-minute intervals.

On arrival at an event, the position and time were recorded together with information on the type of activity occurring. Fish species were recorded where possible with their behaviour, for example if they were forming dense shoals feeding at the surface or the activity was quieter and mostly sub-surface. The species of seabirds were recorded, approximate numbers and their behaviour. The presence of other marine megafauna (e.g., cetaceans, mobulid rays) were recorded. High resolution photographs were taken where possible of the activity and species present. Dorsal fin identification photos of Bryde's whales (*Balaenoptera edeni*) and bottlenose dolphins (*Tursiops truncatus*), together with location and behavioural information from these events were sent to Assoc. Prof. R. Constantine (University of Auckland) who curates fin ID catalogues for these species. Zooplankton sampling was conducted, and fish were caught during feeding events - further details on these methods are described below. The floating underwater camera rig was deployed at many events to identify fish species in the shoals and to record activity occurring underwater. Where an event was spread over a wide area, more than one observation/data collection was often made and designated a, b, c etc.
Oceanographic data was recorded at many events; a YSI meter was used to measure the SST and salinity, and water clarity was measured using a Secchi disc to the nearest meter. Water samples were taken for chlorophyll-*a* determination with two replicate samples taken at various events/sites. For each replicate, 1 L of seawater was filtered through a 0.45 µm, cellulose nitrate filter (25 mm diameter). Filters were kept frozen at -20 °C until they could be analysed in the laboratory.

3.2 Zooplankton sampling

The patchy nature of zooplankton, particularly for the mobile swarming species, such as krill, results in the potential for a large amount of variability among samples, even among replicate samples taken at the same event. Most of the zooplankton sampling was undertaken by horizontal surface net tows (just below the sea surface) using conical plankton nets towed approximately 30 m behind the vessel (n = 48) (Fig. 7). Conical zooplankton nets have been used for decades worldwide and remain the most used zooplankton sampling device, especially from smaller vessels due to their ease of use and low cost. More complex or larger zooplankton sampling devices generally require large vessels to operate them. Large nets can help to reduce the variability among zooplankton samples through the greater spatial scale of sampling, however, the larger samples are correspondingly more difficult to process and evaluate. The use of zooplankton nets in this study to conduct horizontal surface tows through fish workups is a relatively novel method however. Two additional samples were collected using a fine mesh hand net (150 µm mesh) and one vertical haul was conducted using a zooplankton net. A zooplankton net capable of being towed at faster speeds was designed and built for this season's work and the old 'low-speed' net was also used at times. The duration of the zooplankton tows was generally 5-6 min (~250 – 550 m distance) with the start and finish time recorded to the nearest minute

The new high-speed net has a mesh size of 1.32 mm and mouth diameter of 750 mm and was towed at around 5 knots. The rationale for having a net that could be towed at a faster speed was to be able to sample the patchy and mobile swarming zooplankton more effectively. With a greater tow speed and therefore manoeuvrability compared to the old net, it was hoped that it would be easier to position the net to pass through the areas of greatest activity and reduce potential net avoidance by larger and more agile zooplankton such as krill. Due to the new net not being available until January 2020, the old net was used exclusively throughout trips in November and December 2019.

The old low-speed net has a mesh size of 0.25 mm and mouth diameter of 780 mm and was towed at around 2 knots. Both plankton nets were used with a flowmeter (General Oceanics 2030R) mounted in the centre of the net mouth. The addition of the flowmeter this season meant that the volume of water passing through the net mouth was recorded, therefore allowing the number of individual zooplankton per cubic meter of filtered water to be calculated. The flowmeter was not available on two days of sampling due to a malfunction on the flowmeter's rotor.

As in the previous season (2018-2019), a tow camera was integrated into the bridle of the net to film any activity at the net mouth. The tow camera consists of a GoPro Hero+ inside a PVC tube, closed at one end, open at the camera end with buoyancy and lead integrated to provide a steady tow. The low-speed net had a tow camera for all trips, but the high-speed net did not have a dedicated tow camera fitted until the last trip when a second dedicated tow camera was made.

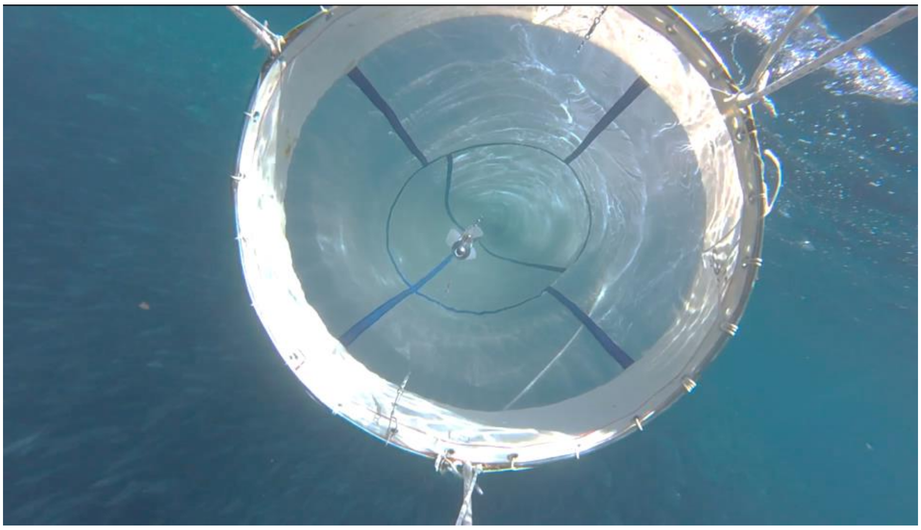


Figure 7: Plankton net with flowmeter, videoed from net camera attached to bridle. Schooling fish are visible in lower left background. *Screenshot from videography: NNZST.*

Due to the inherent temporal and spatial variability in seabird feeding events, a non-stratified approach was taken with the collection of zooplankton samples in order to maximise variety in sample collection with the limited fieldwork days available due to budget constraints. Generally, one plankton tow was conducted per event encountered. On several occasions however, more than one tow was conducted and with the different nets to compare performance. Control tows were only conducted in relation to Mixed fish shoal events and done in one of two ways; either in the vicinity of a previously sampled event where activity was no longer occurring, or as an isolated sample collection where no activity was occurring at locations where activity had been seen on previous days/times.

On the completion of a zooplankton tow, the sample was washed down into the cod end of the net and then transferred to a fine sieve to remove excess water. On several occasions, the sample was so large it had to be transferred to a bucket or fish bin for processing (Fig. 8). The total volume of the sample was recorded, and a sub-sample taken (typically 300 ml) if the sample was large. Samples for enumeration were preserved in 100% ethanol. Samples were also taken for energy and macronutrient analysis and were kept frozen at -20 °C for later analysis.

Figure 8: Krill emptied from the zooplankton net into a 10 L bucket. *Photo: Lily Kozmian-Ledward*.

3.3 Fish captures

Fish were caught on rod and line (with bait and/or lures) from workups to obtain stomach contents and muscle tissue samples (Fig. 9). It had been anticipated that the high-speed net might capture some small 'bait' fish as well as zooplankton, but, aside from larval and small juvenile fish, this did not happen. This may have been due to these fishes not being present at events sampled, or fish avoiding the net. Fishing was undertaken by a dedicated person on the trips undertaken on the RV *Hawere* only as this vessel had sufficient space on the working deck. Fishing was either conducted from the main vessel or from a small outboard powered RIB. When fish were caught, those required for sampling were euthanised immediately by pithing with a spike into the brain cavity. Any other fish caught were returned immediately back to the sea. The length (fork length) and species of all fish landed was recorded. All manipulations were conducted in accordance with the Animal Ethics (AE) permit detailed below and data on fish catches will be reported to the AE Committee. The stomach contents of each fish were immediately removed and stored in 100% ethanol at room temperature for later laboratory analysis. Many of the fish captured had empty or nearly empty stomachs despite being caught where they were presumably feeding. It is possible that they regurgitated their stomach contents between being hooked and landed on the boat. A small sample of fish muscle (approx. 10 g) was also removed for later stable isotope or energetic analyses and stored at -20 °C.

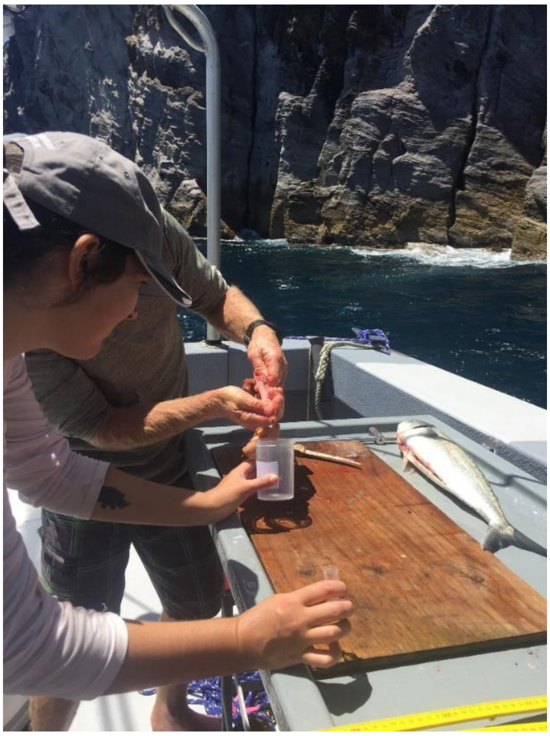


Figure 9. Collecting a stomach sample from a caught kahawai. *Photo: Chris Gaskin.*

Fish captures were covered under the following permits:

- Special Permit 679, Fisheries New Zealand which allows the taking of marine life for the purpose of research.
- Animal Ethics Application 14829, AgResearch with the maximum number of fish captured and killed during the whole research period capped at 440. The total number of fish caught during this season was 18 with one released alive and 17 killed.

3.4 Laboratory methods

All samples were stored and processed at the Leigh Marine Laboratory (University of Auckland). The laboratory processing of the zooplankton and fish stomach content samples was done in the same way as the 2018-2019 season (Kozmian-Ledward et al. 2019[2]), with zooplankton samples being sub-sampled as required and counted into seven taxonomic groups: Copepoda, Malacostraca, Krill nauplii, Thaliacea, Appendicularia, Fish eggs and Other (Kozmian-Ledward et al. 2019[2]). A summary of the taxa details of zooplankton included in each of these groups are given in Appendix 1 of Kozmian-Ledward et al. (2019[2]). Larval fish were extracted during the counting process for later identification by Dr. T. Trnski (Auckland Museum). High-resolution photographs of various zooplankton types and larval fishes are presented in Appendices 2 and 3 of Kozmian-Ledward et al. (2019[2]). Microplastics were also removed from samples. The filters containing the chlorophyll-*a* samples were kept at -20 °C until they were analysed using the spectrophotometric laboratory methods and equations from Parsons et al. (1984) to determine the amount of chlorophyll-*a* amount in mg/m^3.

From each sample containing krill, 10 individuals (if present) were randomly selected, photographed and the length (anterior eye to telson)) measured from the photos using the open-source program Image J (Schindelin et al. 2012). These small sample sizes were measured to provide a snapshot of potential trends in krill size and therefore life-cycle stage over the sampling season.

3.5 Data analysis

The raw counts for each zooplankton group per sample were corrected for the degree of sub-sampling (in the field and the laboratory) and for the volume filtered by the net, by converting the flowmeter readings using the following equations. Abundances were then expressed as number of zooplankton per m^3 of seawater sampled.

Equation 1: Distance = Difference in counts x Rotor constant (26,873) / 999999

Equation 2: $\text{Volume, m}^3 = \{3.14159 \times (\text{Net mouth radius})^2\} \times \text{Distance}$

To allow comparison with previous years data (and for those samples taken this year without flowmeter data), the proportional abundance (as a percentage of the total count of individuals) was also calculated for each zooplankton group per sample.

3.5.1 Categorical analysis

Categorical analyses were undertaken to determine statistically significant ($P \le 0.05$) associations between zooplankton, fish, seabirds and physical variables. Data for these analyses were derived from those sampling events for which the full suite of data was available, i.e., zooplankton tows with a flowmeter in addition to seabird and fish observations. For each sampling event, the abundance of each zooplankton group was standardised as the number of organisms per m^3 water filtered by the zooplankton net. The species of seabirds and fish present at each sampling event were categorised as primary (most abundant) or secondary (present in good numbers but not the most abundant) based on visual observations of birds from the vessel and fish from the underwater video recordings.

Seabird species present at sampling events and included in the analyses are listed below with their scientific name and identification code:

- Australasian gannet, *Morus serrator* (AUGA)
- Black petrel, *Procellaria parkinsoni* (BLPE)
- Buller's shearwater, *Puffinus bulleri* (BUSH)
- Cook's petrel, *Pterodroma cookii* (COPE)
- Diving petrel, *Pelecanoides urinatrix* (DIPE)
- Fairy prion, *Pachyptila turtur* (FAPR)
- Flesh-footed shearwater, *Puffinus carneipes* (FFSH)
- Fluttering shearwater, *Puffinus gavia* (FLSH)

- Little penguin, *Eudyptula minor* (LIPE)
- Red-billed gull, *Larus novaehollandiae* (RBGU)
- Short-tailed shearwater, *Puffinus tenuirostris* (STSH)
- Sooty shearwater, *Puffinus griseus* (SOSH)
- White-faced storm petrel, *Pelagodroma marina* (WFSP)
- White-fronted tern, *Sterna striata* (WFTE)

Fish species present at sampling events and included in analyses:

- Albacore tuna, *Thunnus alaunga*
- Blue knifefish, *Labracoglossa nitida*
- Blue maomao, *Scorpis violacea*
- Juvenile fish spp.
- Kahawai, *Arripis trutta*
- Kingfish, *Seriola lalandi*
- Koheru, *Decapterus koheru*
- Mackerel spp.
- Pink maomao, *Caprodon longimanus*
- Snapper, *Chrysophrys auratus*
- Two-spot demoiselle, *Chromis dispilus*
- Trevally, *Pseudocaranx dentex*
- Skipjack tuna, *Katsuwonus pelamis*

The physical variables: depth, distance from shore, seabed slope, and rugosity were obtained from a bathymetry raster (NIWA NZ bathymetric grid at 250 m resolution) and coastline layer (LINZ Topographic dataset). GIS layers for seabed slope and a ruggedness index (Riley et al. 1999) were created from the bathymetric raster using tools in QGIS (version 3.10; QGIS Development Group 2020). GIS layers were sampled using QGIS to obtain data on each physical variable at the GPS position for which each event was first encountered. Tidal information was calculated to the nearest hour +/- high water from each event start time using Auckland tide times (LINZ).

On account of the truncated field season resulting in a relatively small number of sampling events in relation to the number of different response variables that we were attempting to compare; only associations between zooplankton, fish and seabirds could be included in the analyses described below. Consequently, comparisons of the biological response variables (fish, birds, zooplankton) with the physical variables (depth, distance from shore, seabed slope etc) were excluded from the final analyses to retain sufficient statistical power. Permutational multivariate analyses of variance (PERMANOVA) using distance matrices were performed using Vegan (version 2.5-6; Oksanen et al. 2019) to identify any significant differences between the zooplankton and for each category of birds and fish. Significant differences ($P \leq 0.05$) were detected for the categories, secondary birds, primary fish, and secondary fish. A generalized linear model (GLM) using Quasi-Poisson was then used to identify the significant interactions within these categories and the resulting data were explored using emmeans (version 1.4.3; Lenth 2019). All statistical analyses were run in R Studio® (version 3.6.1; R Core Team, 2018).

3.5.2 Prey selectivity of fishes

Where fish were caught in conjunction with zooplankton tows, Ivlev's selectivity index (Ivlev 1961) was used to compare the relative proportions of zooplankton groups between fish gut contents and the surrounding waters as measured from the associated zooplankton net sample from the same sampling location. Where more than one zooplankton tow was undertaken at a relevant sampling event, the relative proportions of the zooplankton groups present were combined by averaging before comparing them to the fish gut contents from that event.

Ivlev's selectivity index was calculated using the formula below:

$E_i = (r_i - P_i) / (r_i + P_i)$

Where, E_i is the Ivlev's selectivity index, r_i is the relative abundance of prey *i* in the gut of the fish caught and P_i is the relative abundance of the prey in the water at the event sampled. Observed values range from -1 to 1, where -1 indicates prey avoidance, 0 indicates that a prey type is being ingested at the same proportion as it is found in the environment, and 1 indicates a preference for a specific prey type.

4 RESULTS

Nine survey trips were conducted between 22 November 2019 and 28 February 2020 covering an area between Kawau Island, Bream Islands, Mokohinau Islands, Great Barrier Island and Little Barrier Island (Fig. 6).

4.1 Seabird feeding events

Fifty-two seabird feeding events were recorded over all survey trips. Thirty-five were surface fish shoal events (Mixed shoal, Kahawai school or Tuna school) (Table 2, Fig. 10), and 17 were of other event types (Common dolphin, Current line, Krill patches or "Unknown") (Table 3, Fig. 12). Occasions where cetaceans were seen with no seabird association (bottlenose dolphins, n = 3; Bryde's whales, n = 2; common dolphins (*Delphinus delphis*), n = 1) were recorded but not included in this analysis.

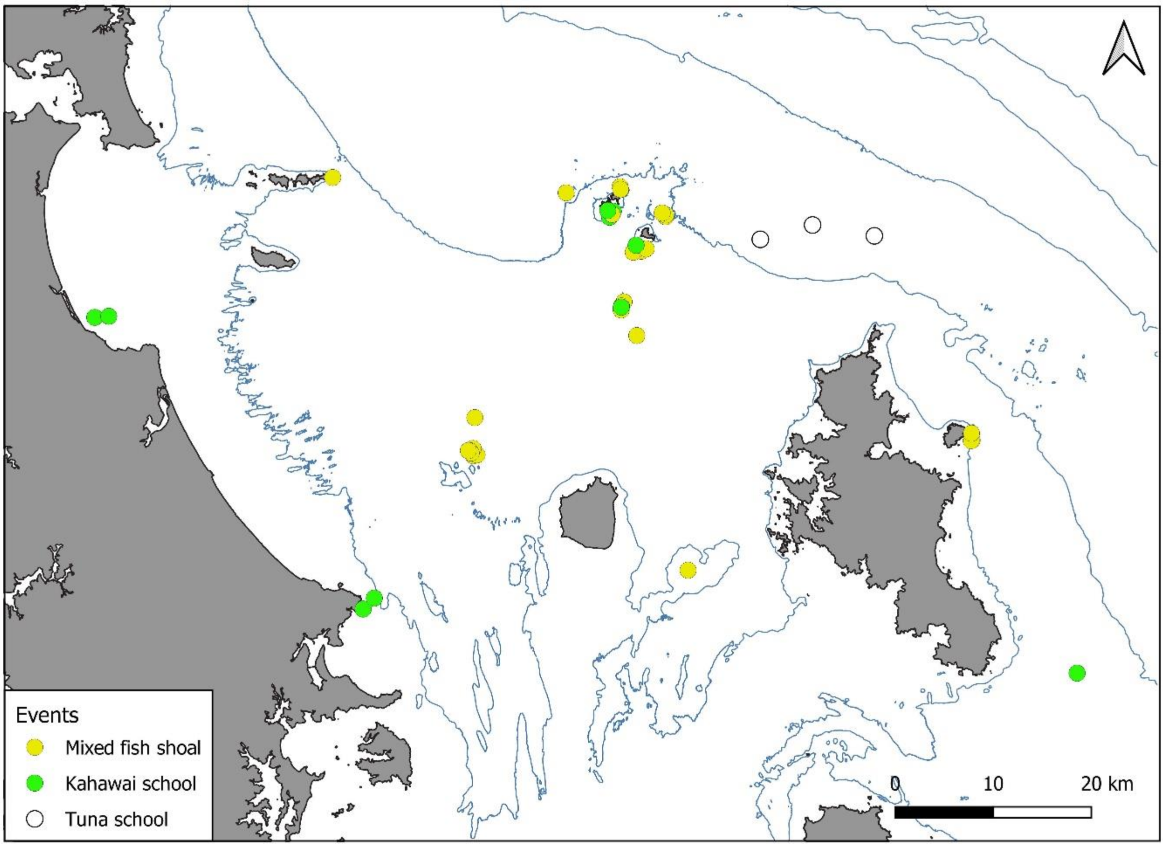


Figure 10. All seabird feeding fish shoal events encountered during the field research period.

Mixed fish shoal events

Twenty-four Mixed fish shoal events were found throughout the research period, all located at least 12 km away from the mainland (Figs. 10 & 11). Key areas were the Mokohinau Islands and Northwest Reef with shoal events also found at Horn Rock, Arid Island and Coppermine Islands. These locations are all in areas of current flow around islands or over underwater reefs and pinnacles. Activity ranged from highly dynamic with multiple fish shoals and large numbers of birds feeding to small quieter shoals that were easily disturbed by the boat. The seabird and fish species present and their activity generally followed that described in Table 2. Additional fish species observed were: pink maomao, blue knifefish, koheru, juvenile fish spp., and two-spot demoiselle.

Figure 11. Kahawai and trevally in a Mixed fish shoal. *Screenshot from videography: NNZST.*

Kahawai school events

Ten Kahawai school events were found throughout the research period (Fig. 10). Nine schools were in depths of 10 – 50 m, near the mainland coast (off Leigh and Waipu Cove), at Northwest Reef and in the Mokohinau area. An additional school was found in deeper water (~ 80 m) in the Colville Channel. As with the Mixed fish shoal events, fish and seabird dynamism varied between events. Seabirds present and their activity generally followed that described in Table 2, however mackeral spp. were also observed

Tuna school event

A single Tuna school event was found in February 2020, north of the 100 m depth contour, with widespread and scattered activity, extending at least 15 km along the track line (Fig. 10). Three separate observations (data recordings) were made over the course of an hour, while travelling through the scattered school. The tuna here were a mixture of albacore and skipjack, rather than just skipjack described in Table 2, however, the activity was similar. Most of seabirds were Buller's shearwaters, chasing prey at or just below the water's surface (cover image). The birds were moving in groups or individually, in frenetic dashes prompted by either the tuna breaching or something unseen at the surface. Whatever the prey (small fish, crustaceans or even squid), they must have been visible to the birds.

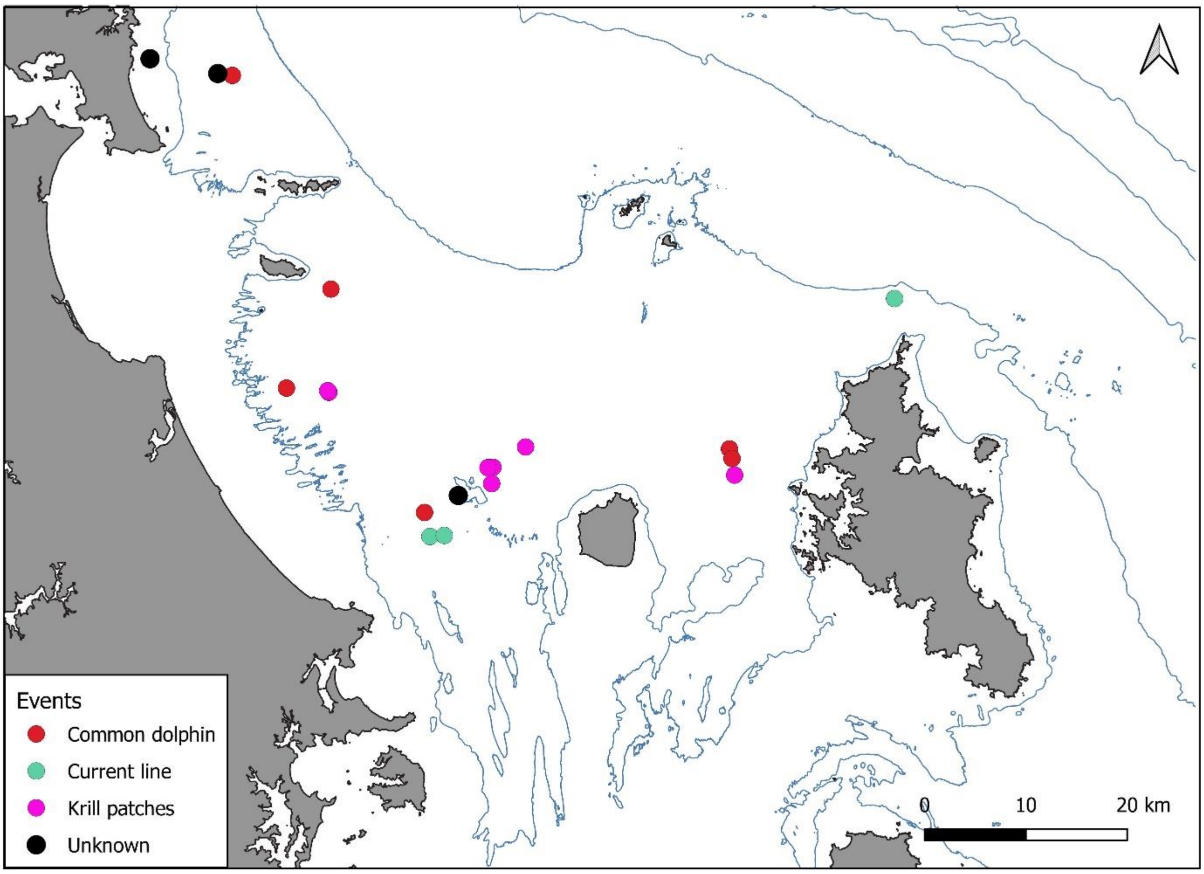


Figure 12. All other seabird feeding events encountered during the field research period.

Common dolphin events

Five Common dolphin events were encountered from late December 2019 onwards, all in areas greater than 50 m depth and in open water (Fig. 12). Dolphin activity was generally sedate, with some feeding activity with seabirds following, sometimes spread over a wide area, and tended to comprise groups of less than 50 dolphins. Seabird species associating with the common dolphins included fluttering, flesh-footed, Buller's and short-tailed shearwaters and gannets.

Current line events

Three Current line event were encountered throughout the research period, all on calm days in the Jellicoe Channel and off northern Aotea/Great Barrier Island, both are areas of higher current flow (Fig. 12). White-faced storm petrels were the most common bird present, feeding on unknown small prey. Other seabird species present at times were fairy prions, Buller's and flesh-footed shearwater.

Krill patch events

Six Krill patch events were encountered in late January and early February 2020, all in areas of current flow, and during calm conditions (Fig. 12). Krill could be seen at the surface over large areas with scattered fluttering, Buller's and flesh-footed shearwaters feeding while sitting on the water. On one occasion (22 January 2020) there were large numbers of birds, mostly Buller's shearwaters, spread across a wide area in very calm conditions, feeding in scattered small groups (< 10), pecking at the krill at the surface (Fig. 13). Small fish (mackerel spp.) could be seen at times also feeding on the krill (Fig. 14). On one occasion near Northwest Reef (3 February 2020), a manta ray (*Mobula birostris*) was observed feeding on the krill – doing 'somersaults' at the surface and was also detected by the underwater camera rig swimming beneath a krill patch (Fig.15).

Figure 13. Buller's shearwaters feeding on krill. *Photo: Chris Gaskin.*

Figure 14. Small mackerel spp. feeding on krill at the surface. *Screenshot from videography: NNZST.*

Figure 15. Manta ray swimming beneath a krill patch just below the surface. *Screenshot from videography: NNZST.*

Unknown events

On three occasions, the seabird feeding activity observed did not fit any of the previous categories and no fish were seen at the surface. These events were classified as “Unknown”. On 28 December 2019, two Unknown events were encountered off Ocean Beach where fluttering shearwater were undertaking prolonged dives, potentially pursuing small fish (Fig. 12). Fish were seen mid-water on the depth sounder. On 3 February 2020 in the Jellicoe Channel, Buller’s shearwaters were feeding at the surface and Australasian gannets were diving.

4.2 Environmental measurements

Sea surface temperature ranged between 19.3 – 22.7 °C and showed a general increase during the research period (Fig. 16C). A much lower SST than others (on that day) was recorded at E59 (20.6 °C, Colville Channel, 3 February 2020) together with low water clarity (11 m) (Fig. 16B) and high chlorophyll-*a* concentration (0.76 mg/m^3) (Fig. 16A), indicating the upwelling of cooler, nutrient-rich water here. A slightly higher SST than others (on that day) was recorded at E31 (20.0 °C, Maori Rocks, 20 January 2020) together with a higher water clarity and low chlorophyll-*a* concentration (0.21 mg/m^3) which may indicate the influence of warm, nutrient-poor EAUC water. This same pattern was also seen at E59 (Simpson Rock, 28 February 2020). Unfortunately, the salinity measurements taken were later deemed to be inaccurate due to incorrect instrument calibration and therefore are not presented here.

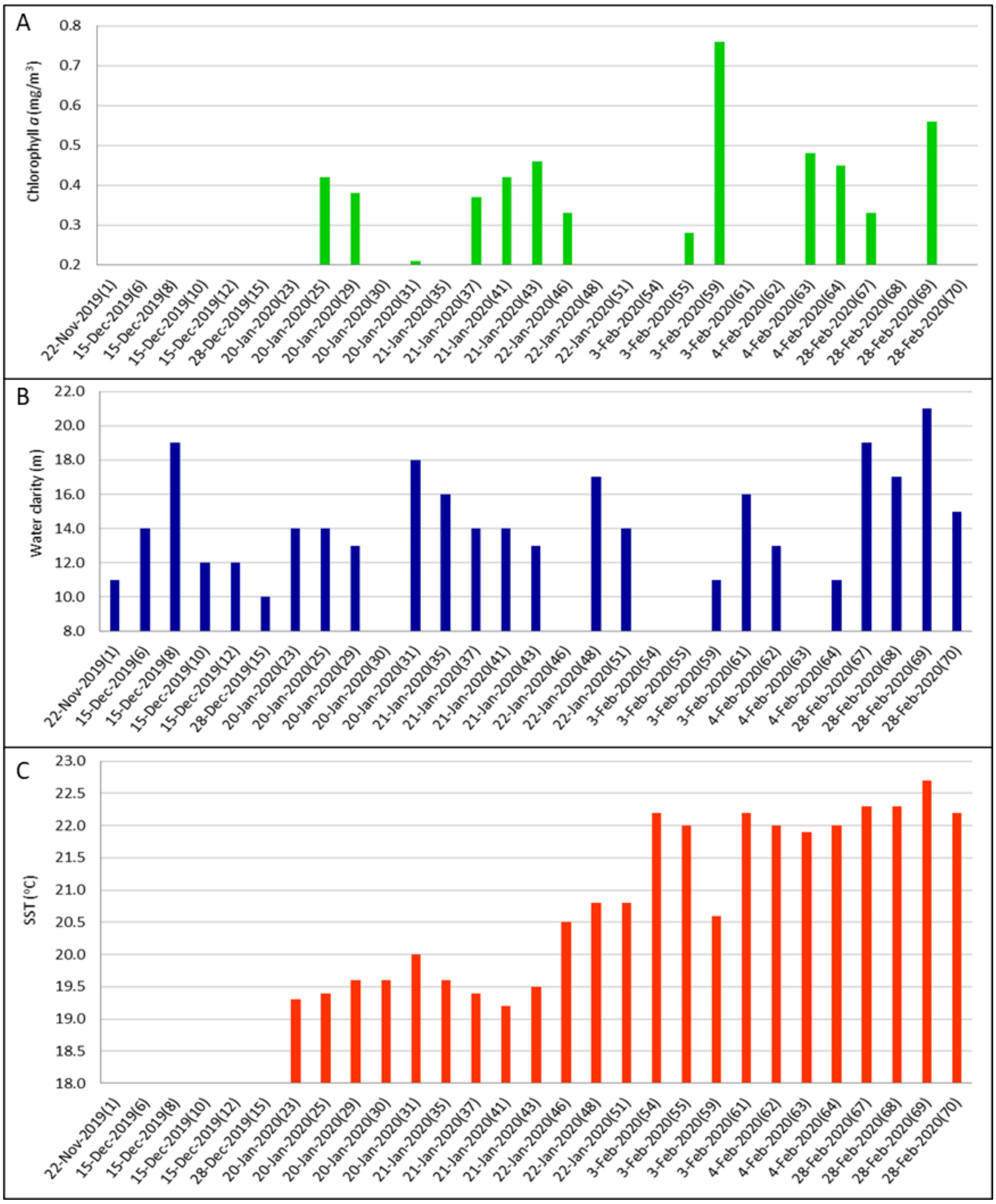


Figure 16. Environmental readings taken at event locations; from top: A. chlorophyll-*a*, B. water clarity and C. SST. Note that the y-axes do not start at zero in order to present all graphs together on a single page. The full suite of environmental readings were not recorded at all events and these are left blank in the graphs.

4.3 Zooplankton samples

A total of 50 zooplankton samples were collected at 33 seabird feeding events and at eight control sites (Table 4). Samples were taken at three types of fish shoal events (Figs. 18, 19, 20, 21): Mixed fish shoal (n = 21), Kahawai school (n = 9) and Tuna school (n = 1). Zooplankton samples were also taken at three other event types (Figs. 22, 23, 24): Krill patches (n = 8), Current lines (n = 2), and Unknown (n = 1). Of the control tows undertaken, four were direct controls to zooplankton tows conducted in Mixed fish shoals, and four were indirect controls i.e., done in areas where Mixed fish shoal activity had been seen on previous occasions. Twenty-four samples were taken in total using the low-speed net and 23 with the high-speed net. Additionally, two samples were collected with a fine-mesh hand net and one via a vertical haul from 30 m depth using the low-speed net.

General observations across all zooplankton samples:

- Copepoda present in 68% of samples, generally low proportions/abundances.
- Malacostraca present in 96% of samples, often at high proportions/abundances. Krill at various life stages often the most common, also decapod shrimp larvae, stomatopod larvae, amphipods, crab megalopa and zoeae.
- Nauplii (krill) present in 22% of samples, at both low and high proportions.
- Thaliacea present in 100% of samples, often at high proportions/abundances. The majority were salps of varying sizes.
- Appendicularia present in 8% of samples, generally at low proportions/abundances.
- Fish eggs were present in 56% of samples generally at low proportions/abundances.
- Zooplankton in the Other group were present in 66% of samples, generally at low proportions/abundances. Other zooplankton included siphonophores, arrow worms, cladocera, pteropods, barnacle and echinoderm larvae, and larval fish.

As would be expected, the coarser mesh of the high-speed net resulted in generally lower catches of the smaller zooplankton in the following groups: Copepoda, Nauplii, Appendicularia, Fish eggs and Other.

Table 4: Summary of zooplankton samples: event type and sampling method.

Event type	Number of events sampled	Number of zooplankton samples				
		Low-speed net	**High-speed net**	**Hand net**	**Vertical haul**	**Total**
Mixed fish shoal	16	11	10	0	0	21
Kahawai school	8	4	5	0	0	9
Tuna school	1	0	1	0	0	1
Krill patches	5	2	3	2	1	8
Current line	2	2	0	0	0	2
Unknown	1	1	0	0	0	1
Control	8	4	4	0	0	8
Total	41	24	23	2	1	50

4.3.1 Fish-shoal events.

Mixed fish shoal events

Twenty-nine zooplankton samples were taken using either the high- (n = 10) or low-speed net (n = 11) at 16 of the 24 Mixed fish shoal events encountered (Table 4, Fig. 17). Relative abundance was calculated for all samples (Fig. 18) and abundance (number of zooplankton per m^3) for 21 samples (as samples from 22 November 2019 and 28 December 2019 had no flowmeter data) (Fig. 19). At four fish shoal events (E1, 3, 15, 25), up to three replicate samples were taken. Direct control samples were taken for four events (E1, 15, 25, 31). Four indirect control samples were also taken (E-6, 8, 67, 70).

Samples were generally dominated by either Malacostraca (predominantly krill) or Thaliacea (predominantly salps). Malacostraca were generally more abundant in samples taken between 28 December 2019 and 3 February 2020 with 79% of these samples containing a relative proportion between 50 and 98% Malacostraca. Abundance calculations for the same timeframe give values up to 458.7 Malacostraca ind. per m^3. Locations with high proportions/abundances of Malacostraca were various sites around the Mokohinau Islands, eastern side of Coppermine Island and north-east side of Arid Island. The maximum Thaliacea abundance sampled over the whole fieldwork season was 116.2 ind. per m^3.

Two samples, both taken with the low-speed net, were dominated (% abundance) by Nauplii (Northwest Reef, 22 November 2019). Abundance of Copepoda was generally low across the fieldwork season (max. 22.4 ind. per m^3). Appendicularia was abundant in one sample only, with 128.8 ind. per m^3 at E-33 (20 January 2020 at Maori Rocks). This event also had the highest abundance of Fish eggs for all Mixed fish shoal events (23.1 ind. per m^3). All other samples had < 3.3 ind. per m^3 of Fish eggs. Zooplankton abundance from the Other category were all low; ≤ 0.4 ind. per m^3.

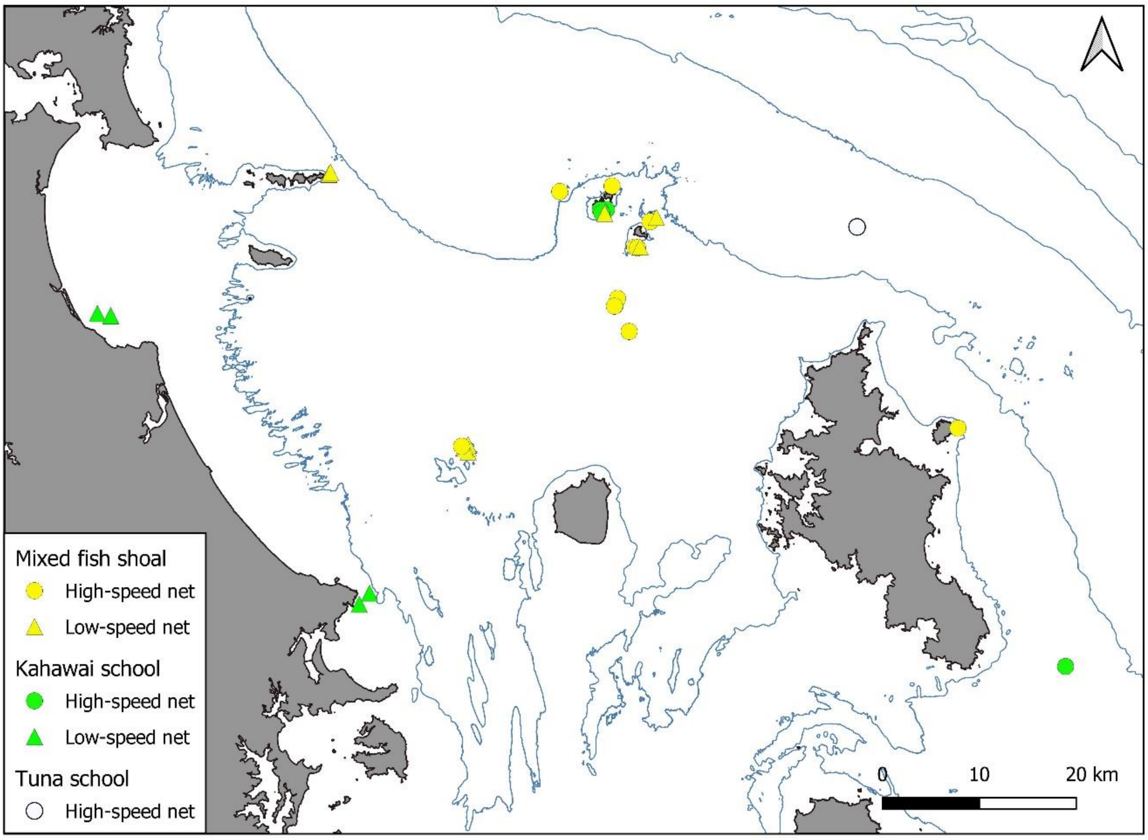


Figure 17: Location of zooplankton samples taken at fish shoal events with sampling method defined.

All the control samples whether indirect or direct, had less Malacostraca than samples taken at Mixed fish events. Of the direct controls, two had flowmeter data (E25 & 31) and can be compared by abundance values. At E-25 the mean abundance of the three zooplankton tows conducted at fish shoal activity was 269.9 ind. per m^3 while the control tow only contained 5.9 ind. per m^3. For E-31 there were much less Malacostraca overall, but still a far lower abundance in the control tow; 40.8 versus 0.1 ind. per m^3. For the other two direct controls (E1 & 15), only relative abundance data can be compared but in both cases the control percentage was much lower than the corresponding samples taken the fish shoal activity. The indirect control samples were taken in the region of Northwest Reef (E6, 8, 67) and Horn Rock (E70). All had low total abundances of zooplankton (≤ 23.0 ind. per m^3) and low abundances of Malacostraca (≤ 1.0 ind. per m^3) compared to the majority of the samples taken in Mixed fish shoal events.

At four Mixed fish shoal events (E1, 3, 15, 25), multiple zooplankton tows were undertaken (Figs. 18, 19). All replicate tows showed broadly similar compositions but had the greatest variation in proportions/abundances of Malacostraca and Thaliacea. An exception to this were the samples taken at E-3 (Northwest Reef, 22 November 2019) with the low-speed net. Both samples contained very high relative abundances of Nauplii and low abundances of Malacostraca, but the Malacostraca (krill) comprised the greatest wet biomass.

At E-25, tows were conducted with both the low- (n = 1) and high-speed net (n = 2) and this enabled a direct comparison between the net types. The low-speed net captured a higher total abundance of zooplankton: 630.0 versus a mean of 183.1 ind. per m^3 with the high-speed net tows. The abundance of Malacostraca captured by the low-speed net was more than double that of the mean of the two high-speed net samples. Indirect comparisons of other low- and high-speed net samples from Mixed fish shoal events also shows generally higher abundances of Malacostraca captured by the low-speed net.

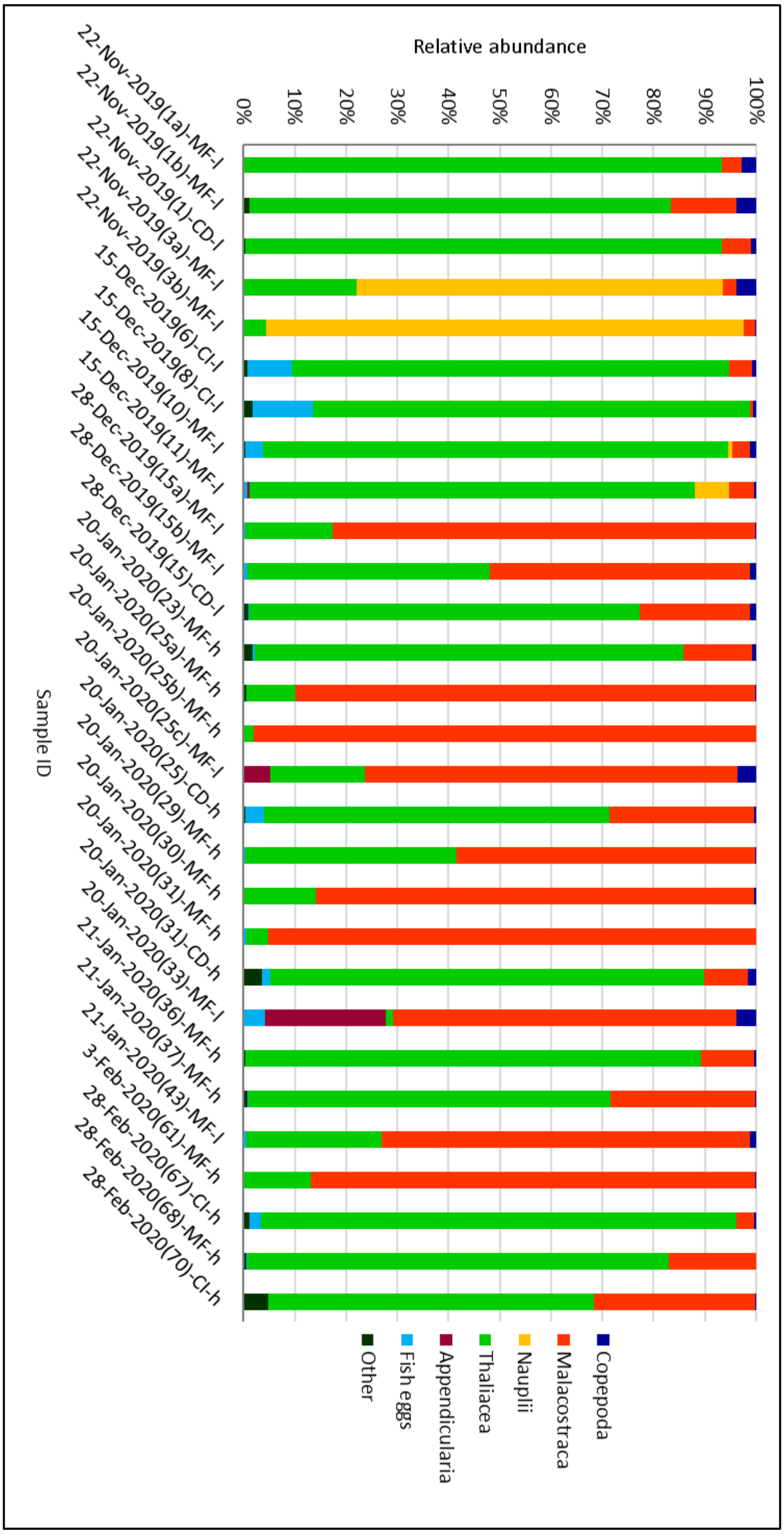


Figure 18: Relative abundance of zooplankton groups in samples taken from Mixed fish shoal and Control events. The sample ID gives the date, event number (in brackets), event type (MF – mixed fish, CD – direct control, CI – indirect control) and sampling method: h – high-speed net, l – low-speed net). Where more than one sample was taken at an event this is designated as a, b, etc.

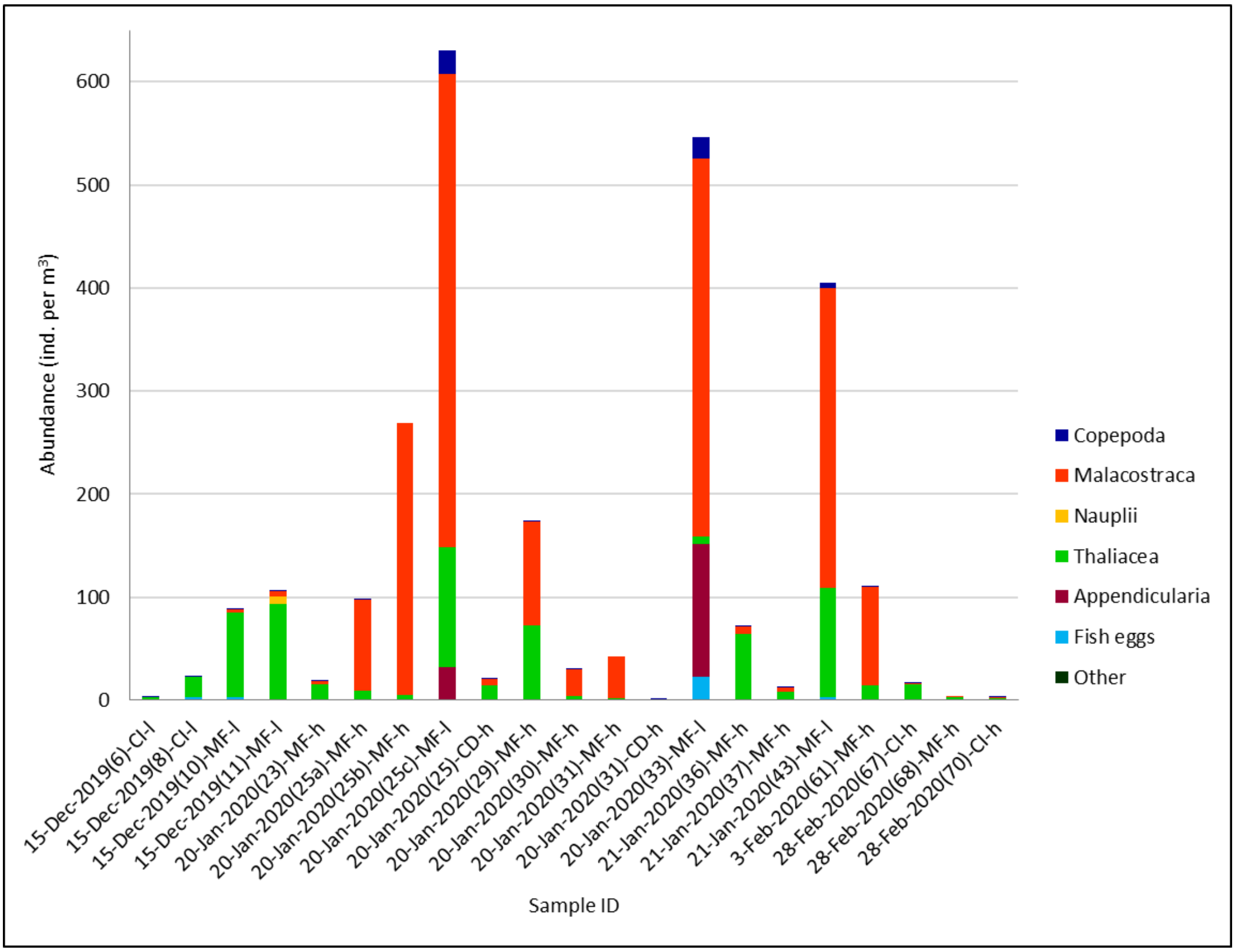


Figure 19: Abundance of zooplankton in each group for samples collected in Mixed fish shoal and control events. The sample ID gives the date, event number (in brackets), event type (MF – mixed fish, CD – direct control, CI – indirect control) and sampling method: h – high-speed net, l – low-speed net). Where more than one sample was taken at an event this is designated as a, b, etc.

Kahawai school events

Nine zooplankton samples were taken using either the high- (n = 5), or low-speed net (n = 4) at eight of the 10 Kahawai school events encountered (Table 4, Fig. 17). Relative abundance was calculated for all samples (Fig. 20) and abundance (number of zooplankton per m^3) for eight samples (as the sample from 22 November 2019 had no flowmeter data) (Fig. 21).

Samples were generally dominated by Thaliacea (max. 3670.8 ind. per m^3) and had low abundances of Malacostraca (max. 4.6 ind. per m^3) and the other zooplankton groups, except for that from E-4 (Leigh Reef, 22 November 2019) that contained a large volume of Malacostraca (krill), comprising 71.8% of the sample relative abundance. Comparing the performance of the two different nets shows that the low-speed net captured higher abundances of zooplankton, mostly Thaliacea.

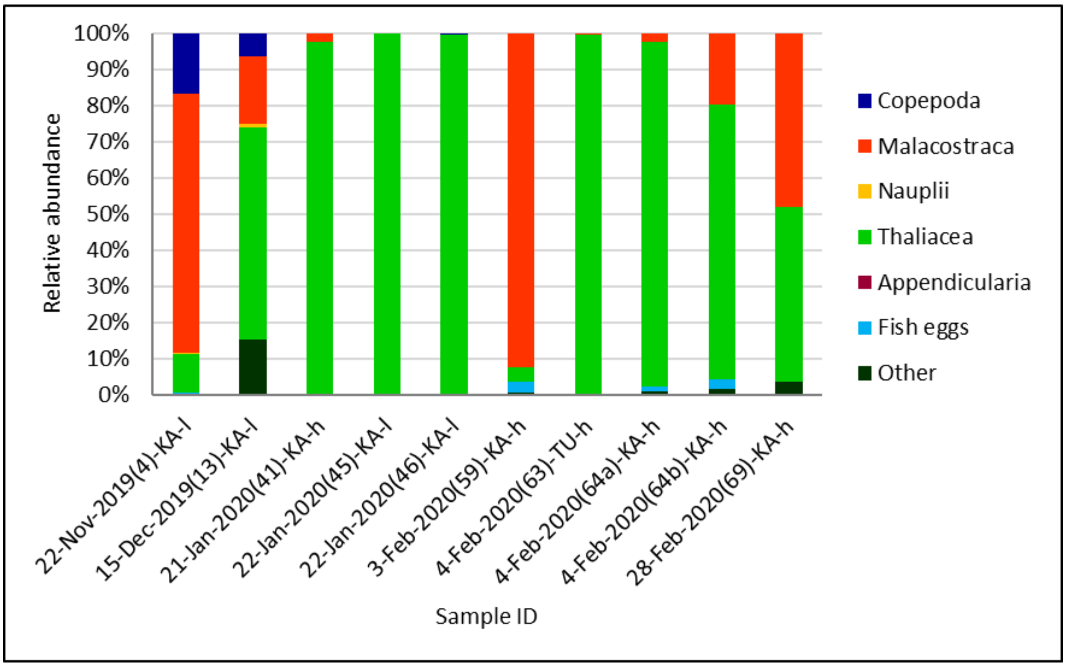


Figure 20: Relative abundance of zooplankton groups in samples taken from Kahawai and Tuna school events. The sample ID gives the date, event number (in brackets), event type (KA – Kahawai school, TU – Tuna school) and sampling method: h – high-speed net, l – low-speed net). Where more than one sample was taken at an event this is designated as a, b, etc.

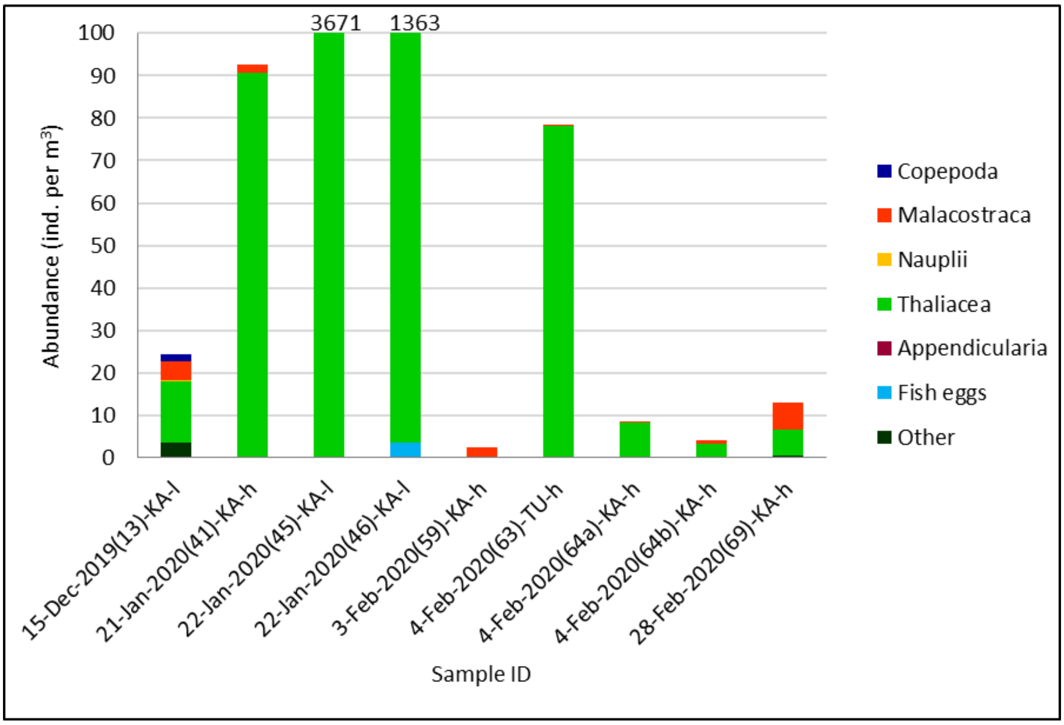


Figure 21: Abundance of zooplankton in each group for samples taken in Kahawai and Tuna school events. The total abundance of Thaliacea for E32 and 33 samples are given at the tops of the columns due to their much higher abundances. The sample ID gives the date, event number (in brackets), event type (KA –

Kahawai school, TU – Tuna school) and sampling method: h – high-speed net, l – low-speed net). Where more than one sample was taken at an event this is designated as a, b, etc.

Tuna school event

One zooplankton sample was taken with the high-speed net at the single Tuna school event (Figs. 20 & 21). The sample contained mainly Thaliacea (78.1 ind. per m^3), and a low abundance of Malacostraca (0.4 ind. per m^3). No other zooplankton groups were present in the sample.

4.3.2 Other events

Krill patch events

Eight zooplankton samples were taken at five of the six Krill patch events encountered (Figs. 22, 23, 24). Of these, five were via net tows: three with the high-speed net, and two with the low-speed net. All these samples (except for the high-speed tow at E55), had low abundances of Malacostraca (≤ 2.7 ind. per m^3) and were mainly comprised of Thaliacea. At E-55 (Northwest Reef region, 3 February 2020), a huge sample of Malacostraca was obtained with the high-speed net, approximately 7 L wet volume and 10,631.1 ind. per m^3, predominantly krill. This was by far the greatest abundance of Malacostraca obtained during this research season. This sample also contained the highest abundance of Nauplii – 16.4 ind. per m^3. Two samples (E35, 54a) were taken with a hand-net, scooping zooplankton directly from krill patches. Both samples were comprised predominantly of krill with one also containing a high proportion of Nauplii. One vertical haul was undertaken using the low-speed net (Northwest Reef, 3 February 2020) and contained mainly Copepoda and Thaliacea.

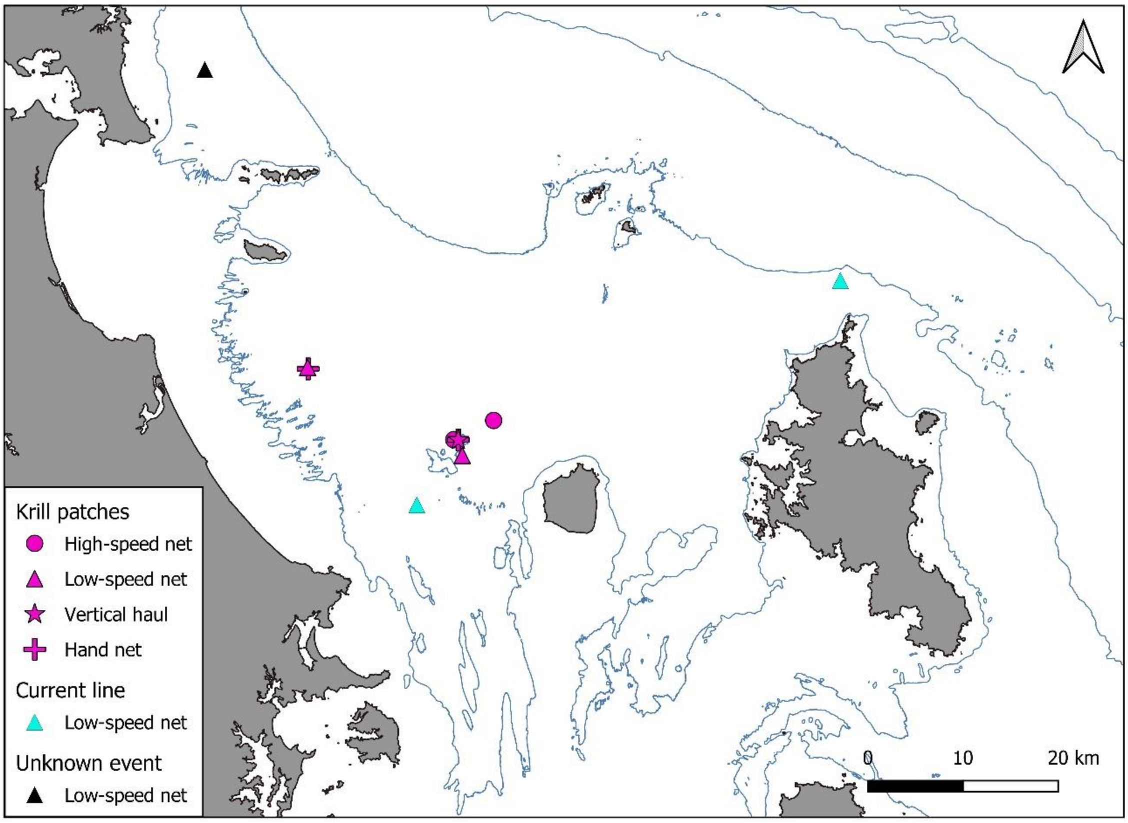


Figure 22: Location of zooplankton samples taken from non-fish shoal events with sampling method defined.

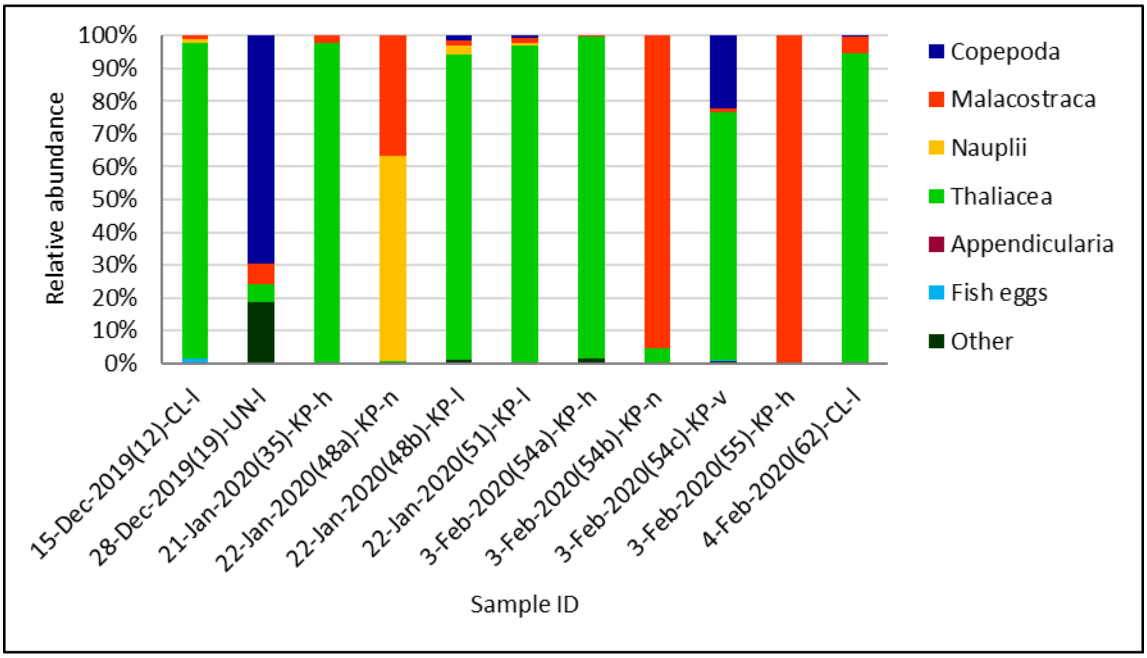


Figure 23: Relative abundance of zooplankton groups in Current line (CL), Krill patch (KP) and Unknown (UN) events. The sample ID gives the date, event number (in brackets), event type and sampling method: h – high-speed net, l – low-speed net, n – hand net, v – vertical haul. Where more than one sample was taken at an event this is designated as a, b, etc.

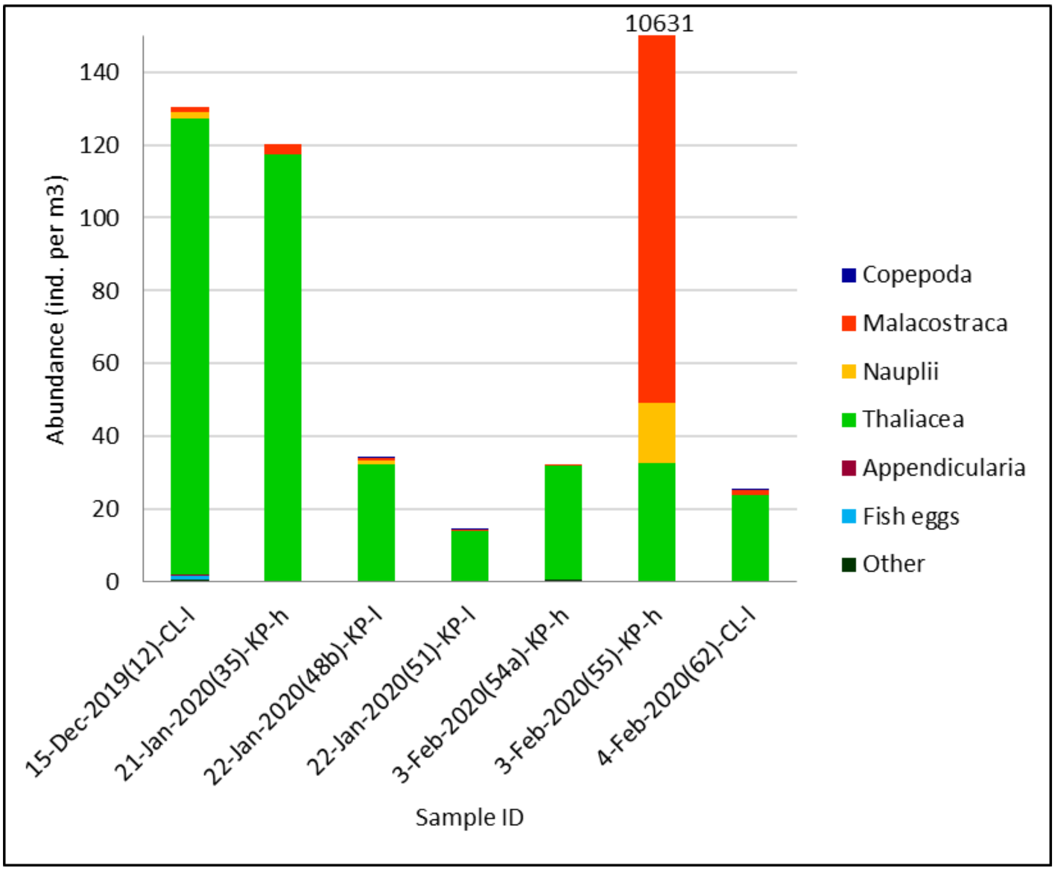


Figure 24: Abundance of zooplankton per group for samples collected in Current line (CL) and Krill patch (KP) events. The total abundance of Malacostraca in the E55 sample is given at the top of the column due

to its much greater abundance. The sample ID gives the date, event number (in brackets), event type and sampling method: h – high-speed net, l – low-speed net. Where more than one sample was taken at an event this is designated as a, b, etc.

Current line events

Two samples were taken with the low-speed net at two of the three Current line events encountered (Fig. 22). Both samples were relatively small in terms of overall abundance of zooplankton: 130.3 and 25.2 ind. per m^3, with Thaliacea the prominent group (Figs. 23, 24).

Unknown events

One sample was taken with the low-speed net from 1 of the 3 Unknown events encountered (Fig. 22). The sample contained a high proportion of Copepoda (69%), a relatively high proportion of Other (19%) - comprised entirely of echinoderm larvae - and low proportions of Malacostraca, Thaliacea and Fish eggs (Fig. 23).

4.4 Categorical analysis

No significant associations were identified for any combination of three variables from zooplankton, bird and fish categories. Significant differences ($P \leq 0.05$) were only detected for the categories, secondary birds, primary fish, and secondary fish.

Among secondary bird species found at sampling sites, both BUSH and SOSH were found more frequently at sites characterised by a higher abundance of Malacostraca when compared to FFSH. WFTE were found more frequently at sites characterised by a higher abundance of Thaliacea when compared to FAPR, FFSH, FLSH and SOSH (Table 5).

Table 5: Statistically significant relationships between zooplankton groups and secondary bird species.

Zooplankton Group	**Secondary Birds**	**P value**
Malacostraca	FFSH < BUSH	< 0.002
Malacostraca	FFSH < SOSH	< 0.0001
Thaliacea	FAPR < WFTE	< 0.005
Thaliacea	FFSH < WFTE	< 0.05
Thaliacea	FLSH < WFTE	< 0.02
Thaliacea	SOSH < WFTE	< 0.005

Among primary fish species present at sampling sites, mackerel spp. were found more frequently at sites characterised by a higher abundance of Malacostraca when compared to trevally. Kahawai were found more frequently at sites characterised by a higher abundance of Thaliacea when compared to trevally (Table 6).

Table 6: Statistically significant relationships between zooplankton groups and primary fish species.

Zooplankton Group	**Primary Fish**	**P value**
Malacostraca	Trevally < Mackerel spp.	< 0.0001
Thaliacea	Trevally < Kahawai	< 0.0001

Among secondary fish species present at sampling sites, kahawai and blue maomao were found more frequently at sites characterised by a higher abundance of Malacostraca when compared to juvenile fish species. Mackerel spp. were found more frequently at sites characterised by a higher abundance of Thaliacea when compared to blue maomao, juvenile fish spp. and kahawai (Table 7).

Table 7: Statistically significant relationships between zooplankton groups and secondary fish species.

Zooplankton Group	**Secondary Fish**	**P value**
Malacostraca	Juvenile fish spp.< Blue maomao	< 0.0005
Malacostraca	Juvenile fish spp. < Kahawai	< 0.0001
Thaliacea	Blue maomao < Mackerel spp.	< 0.05
Thaliacea	Juvenile fish spp. < Mackerel spp.	< 0.025
Thaliacea	Kahawai < Mackerel spp.	< 0.0001

Collectively, these results indicate that Malacostraca (mostly krill) and Thaliacea (salps) play a role in influencing the occurrence of some fish species and seabirds. As primary fish species present at sampling events, mackerel spp. was strongly associated with higher abundances of krill, while kahawai were associated with higher abundance of salps. White-fronted terns were consistently present as a secondary species where salps were more abundant.

4.5 Krill length

The total number of krill measured in net hauls from each day of sampling varied from 10 to 100 individuals and was dependent on the number of zooplankton samples taken per day that captured krill. Ninety-two percent of samples contained krill. Of those with no krill, two were from Kahawai school events and two from Krill patch events. Mean krill length across the field season approximates a bell-shaped curve with date, increasing to a maximum of 10.93 mm on the 20 and 21 January 2020 and a minimum of 7.43 mm on 28 February 2020 (Fig. 25). The mean krill length values for both of the first two days of sampling are not consistent with this curved trend, with the mean krill length from the 22 November 2019 potentially being high and/or the mean from the 15 December 2019 being comparatively low. Overall, there was a large variation in the length of krill over the field season and a relatively small number of krill measured so any trends may be the result of other factors. Krill that were < 6 mm length were present in zooplankton samples on most days, however, krill of > 14 mm length were less common in samples taken during February 2020.

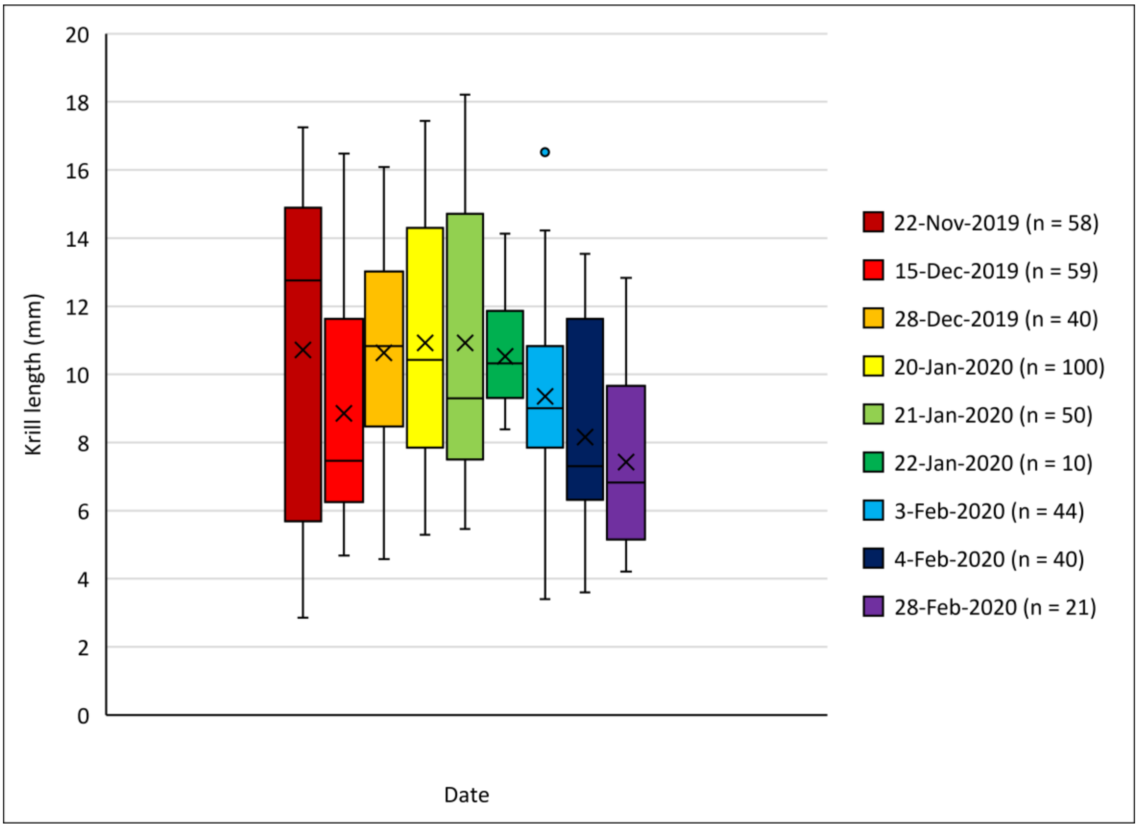


Figure 25: Box plots of krill length grouped by sampling trip date. The number of krill measured from each day is given in brackets in the legend.

The number of krill measured at each type of sampling event varied from 10 to 211 krill and was dependent on the number of zooplankton samples taken that captured krill at each type of event (Fig. 26). Over the entire sampling season, the greatest number of zooplankton samples were taken at Mixed fish shoal events and the least at Tuna school and Unknown events. There is a general trend for krill length to vary in relation to event type; larger krill (> 10 mm) were more often found at Mixed fish shoal, Tuna and Unknown events. For example, on average the length of krill for all Mixed fish shoal events was generally larger (mean = 10.93 mm) than for all the Control events (mean = 8.52 mm). However, as with the krill length data grouped by trip date, there was large variation in krill lengths for event type categories. Overall, a larger sample size would be required in order to obtain more representative data on spatial and temporal differences in krill size.

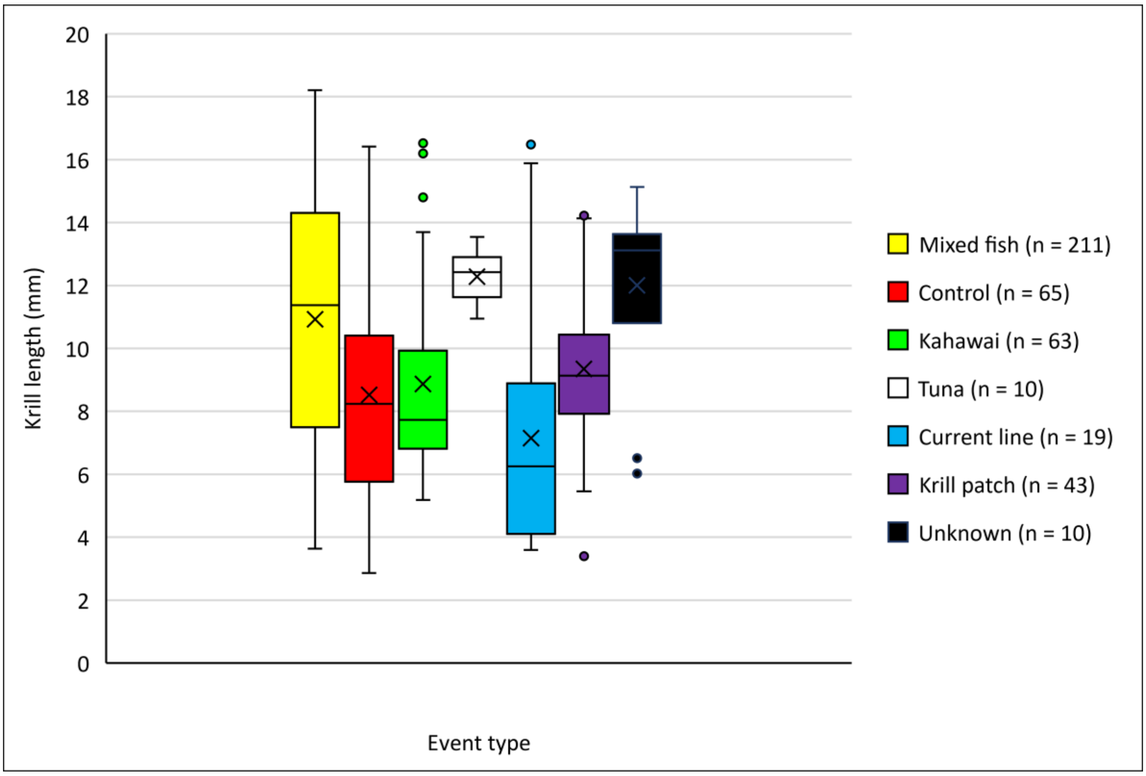


Figure 26: Box plots showing krill length grouped by event type. The number of krill measured from each event type is given in brackets in the legend.

4.6 Fish stomach contents

Seventeen fish comprising five species, were caught from four different event types (Table 8):

- 3 trevally
- 3 snapper
- 6 kahawai
- 2 kingfish
- 3 albacore tuna

Out of these, 16 fish were retained, and 12 stomach content samples were obtained (four fish had empty stomachs). Ten of these stomach samples were obtained in conjunction with zooplankton samples. One fish (an under-sized kingfish) was released alive. With this small number of fish captures, the data obtained will not be very representative.

Table 8: Fish species caught in different event types between 20 January and 3 February 2020.

Fish ID	Event type	Fork length (mm)	Stomach contents sample	Zooplankton samples collected at this event
20-Jan-2020(E25)-Trev1	Mixed fish shoal	447	Y	Y
20-Jan-2020(E25)-Trev2	Mixed fish shoal	410	Y	Y

20-Jan-2020(E25)-Snap1	Mixed fish shoal	342	Y	Y
20-Jan-2020(E25)-Kaha1	Mixed fish shoal	515	Y	Y
20-Jan-2020(E25)-Kaha2	Mixed fish shoal	526	Y	Y
21-Jan-2020(E37)-Trev3	Mixed fish shoal	395	Y	N
21-Jan-2020(E42)-King1	Mixed fish shoal	650	N	N
21-Jan-2020(E42)-King2	Mixed fish shoal	960	N	N
22-Jan-2020(E46)-Kaha3	Kahawai school	320	Y	Y
22-Jan-2020(E50)-Snap2	Control	500	N	Y
3-Feb-2020(E54)-Snap3	Krill patches	450	N	Y
3-Feb-2020(E57)-Kaha4	Mixed fish shoal	550	Y	N
3-Feb-2020(E61)-Kaha5	Mixed fish shoal	500	Y	Y
4-Feb-2020(E63)-Alba1	Tuna school	500	Y	Y
4-Feb-2020(E63)-Alba2	Tuna school	490	Y	Y
4-Feb-2020(E63)-Alba3	Tuna school	500	Y	Y
4-Feb-2020(E65)-Kaha6	Kahawai school	540	N	N

4.7 Prey selectivity by fishes

Three trevally were caught at two separate sampling events, both categorised as Mixed fish shoal events (Fig. 28). All trevally showed a negative selectivity for prey in the Copepoda, Thaliacea and Appendicularia groups and a positive selectivity for prey in the Malacostraca group (predominantly krill). Trevally 1 and 2 also had a positive selectivity for prey in the Other group (just one arrow worm found in the gut in both cases).

Four kahawai were caught at three separate sampling events, with three caught at Mixed fish shoal events and one (Kahawai 3) caught at a Kahawai school event (Fig. 29). At the Mixed fish shoal events, the kahawai had a positive selectivity for prey in the Malacostraca group (predominantly krill). The kahawai from the Kahawai school event had a strong selectivity for prey in the Other group (juvenile fish). At this particular sampling event, no juvenile fish were caught in the zooplankton sample from this site; the sample was comprised almost entirely of Thaliacea.

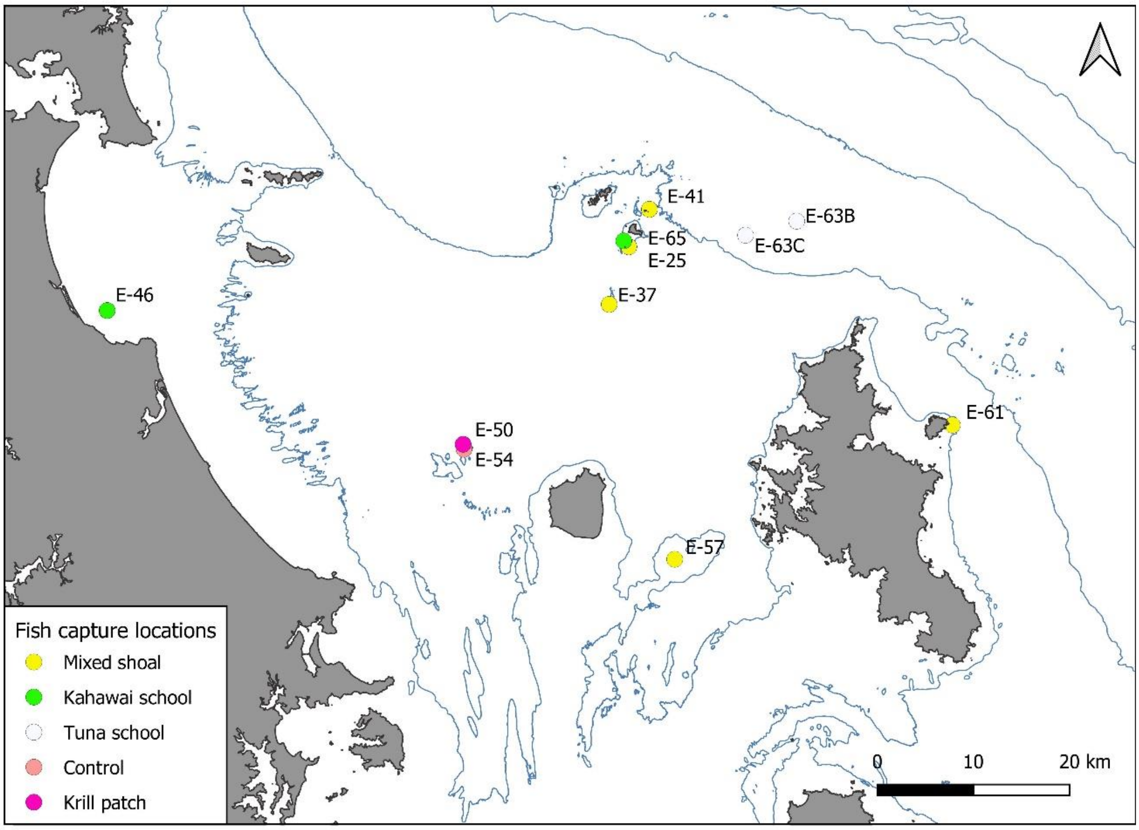


Figure 27: Location of fish captures with event type and number. Refer to Table 8 to see fish details relating to each event number.

Three albacore tuna were caught at a single Tuna school event that covered a wide area (Fig. 30). All of the albacore showed a strong positive selectivity for Malacostraca (krill and mantis shrimp larvae) and Albacore 1 also had a strong positive selectivity for prey in the Other group (juvenile fish and squid).

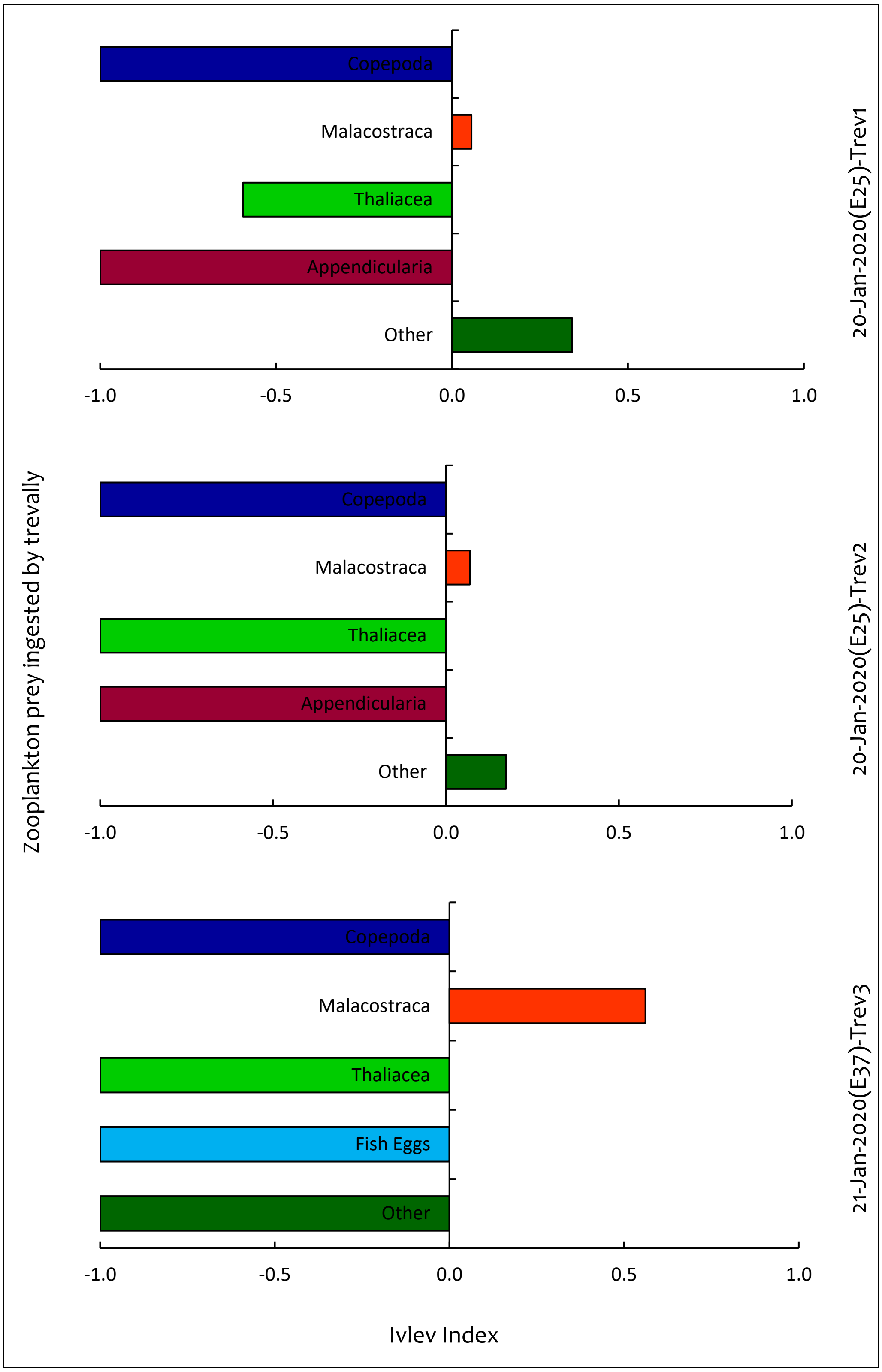


Figure 28: Ivlev Index of trevally caught in conjunction with zooplankton tow samples. The fish sample ID (at right) gives the date of capture, the event number, and individual fish number.

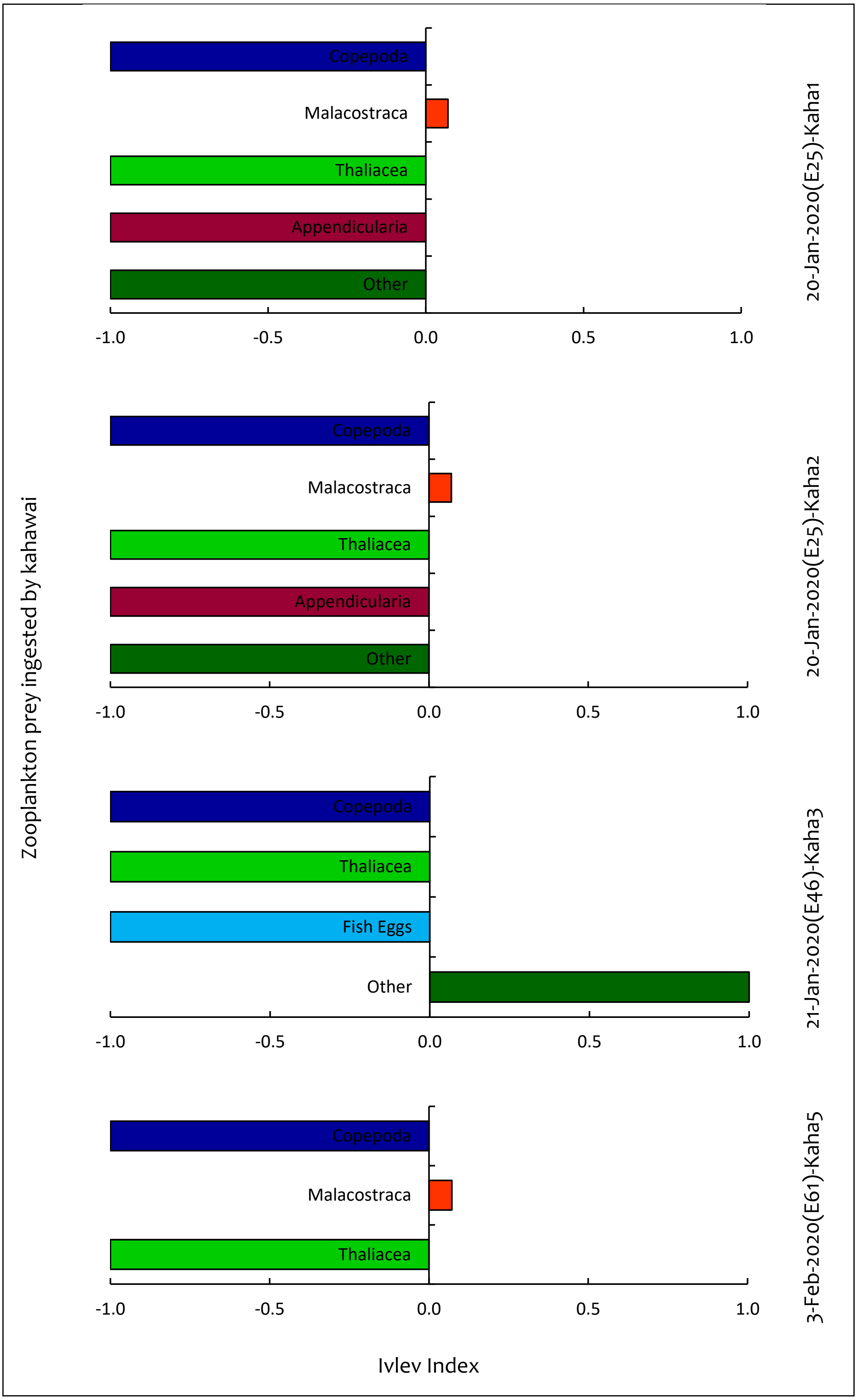


Figure 29: Ivlev Index of kahawai caught in conjunction with zooplankton tow samples. The fish sample ID (at right) gives the date of capture, the event number and individual fish number.

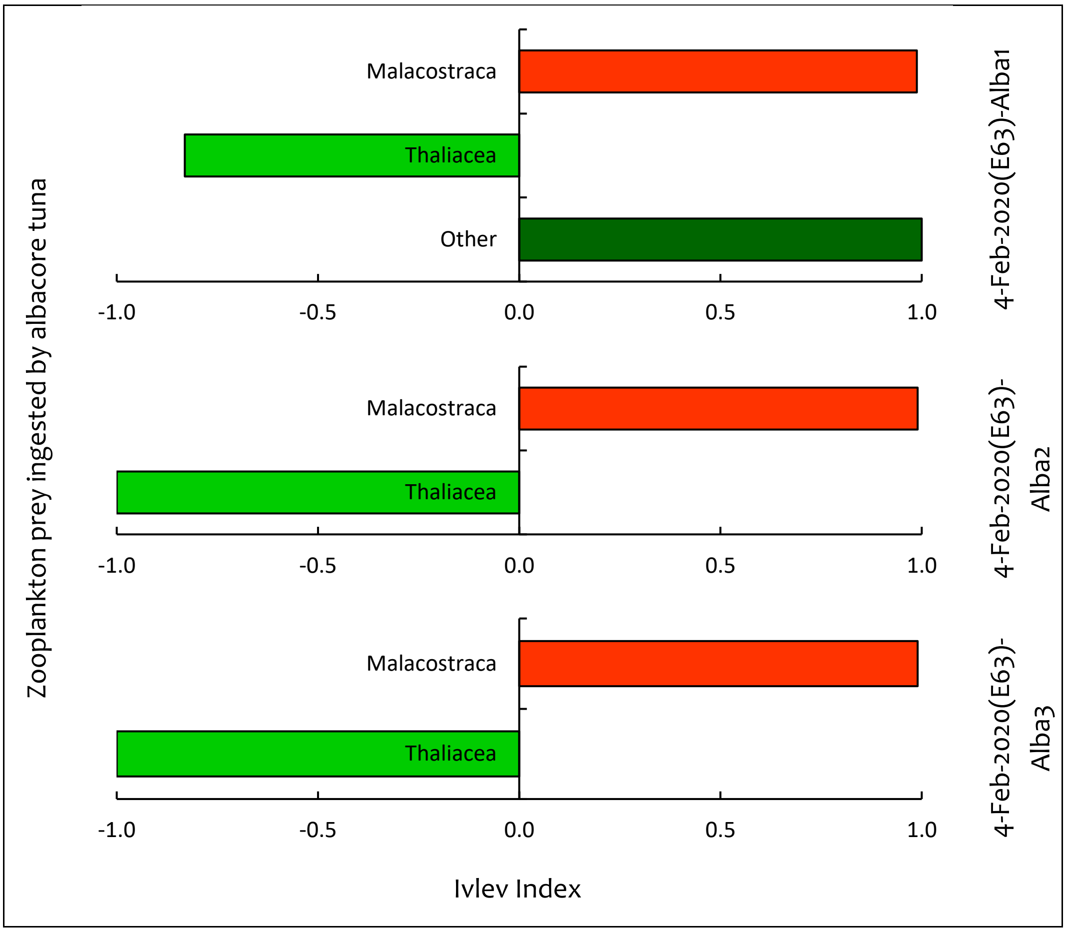


Figure 30: Ivlev Index of albacore tuna caught in conjunction with zooplankton tow samples. The fish sample ID (at right) gives the date of capture, the event number and individual fish number.

5 DISCUSSION

The general hypothesis of this study is that fish shoals drive krill and other prey species to the surface making them more readily available to surface feeding seabirds. The alternative hypothesis is that krill aggregate at or near the surface in areas of upwelling or current flows which fish shoals target, providing visual and potentially olfactory cues to seabirds. In both cases, when fish schools come across the krill patches (in high enough concentrations) they go into 'feeding mode', massing even more tightly together and potentially further concentrating the krill; in turn their feeding activity advertises krill presence to predators. The commotion, and potentially smell and sound of the fish feeding at the surface act as cues for seabirds that there is abundant prey available. However, krill were also found to aggregate in areas away from fish shoals and were targeted by seabirds cued by other visual signs besides surface shoaling activity and potentially also olfactory signs. For example, in very calm conditions, even the riffles caused by small fish attacking krill swarms from below (Fig. 14) advertise the krill presence to birds foraging in the area.

5.1 Shoal events

Of the three types of fish shoal event seen this research year (2019-2020), the highest abundances of potential seabird zooplankton prey (krill and other Malacostraca) were generally sampled from Mixed fish shoal events. These events occurred in locations where islands or underwater pinnacles rise from deeper water; key locations being the waters surrounding Northwest Reef and the Mokohinau Islands. Mixed fish shoal events also tended to be the most dramatic in activity, sometimes with the shoals covering a large area, with fish breaking the surface at times and large numbers of seabirds feeding in association. While trevally tended to be the dominant fish species seen, kahawai, kingfish, and snapper were also caught from or below these shoals. Stomach contents from the trevally and kahawai were almost entirely comprised of krill. Control zooplankton tows all contained low abundances of Malacostraca, indicating that the fish shoal activity occurred at small spatial scales in relation to the presence of krill.

The Kahawai school events occurred both near the mainland coast and locations affected by current flow and/or upwelling, such as around the Mokohinau Islands and Leigh Reef. They were not as commonly found as the Mixed fish shoal events. The kahawai appeared to be feeding on one of two prey types at these events; small fish at the events off Waipu Cove (indicated by a stomach contents sample) and likely krill at the locations in areas of current flow and/or upwelling. Fish and seabird activity were more scattered at the Waipu Cove events while at the other events the kahawai were often tightly massed, feeding near the surface with more dynamic seabird activity occurring. However, zooplankton samples taken at these events, generally contained low abundances of Malacostraca, possibly due to the net 'missing' dense areas of krill.

The Tuna school event had a different type of activity to the other fish shoal events, with the tuna and seabirds scattered over a large area in deeper water (c. 110 m). The albacore tuna stomach contents samples were comprised of predominantly krill. However, the zooplankton tow sample only captured a small amount of zooplankton, mostly Thaliacea. This could have been due to the net missing a patch of zooplankton or due to the krill at this type of event being more dispersed. From the aggressive behaviour of the foraging seabirds (contrasting with 'pecking' behaviour at krill swarms, it is likely small fish were the prey here for both the tuna and seabirds.

Fish catches were only undertaken on the multi-day research trips conducted on the RV *Hawere* as this larger vessel provided space for a dedicated fisherman. Several of the fish caught had empty stomachs when examined and it is possible that they regurgitated the contents during capture. Other fish stomachs contained only small amounts of prey. Overall, the amount of data collected on fish stomach contents was relatively small and this needs to be accounted for when examining the data.

5.2 Krill patches or swarms

Patches of krill (or krill swarms) at the sea surface, sometimes occurring scattered over large areas, with no shoaling fish associated, were found on several occasions associated with seabirds feeding. In calm glassy conditions, the krill activity was extenuated by small or juvenile fish attacking the swarms from below and disrupting the surface, providing visual cues for seabirds. There was also a distinct smell at these events which would provide olfactory cues for Procellariiformes (e.g., shearwaters, petrels, and prions) who have a highly developed sense of smell (Nevitt 2008). The krill species here, *N. australis*, only occurs in coastal waters of south east Australia and New Zealand and is known to be an important prey for many species of fish, seabirds, and cetaceans (Bary 1954; O'Brien 1988; McClatchie et al. 1989). *N. australis* is known for daytime surface swarming activity, but the reasons for this behaviour are not clear. It has been suggested that they may; 1) congregate at the surface to feed, 2) be driven to the surface by predators, 3) be passively brought to surface by currents or upwelling, 4) actively come to the surface to satisfy internal demands related to maturation or reproduction (Komaki 1967). Swarming in *N. australis* (and other krill species), has been found to often be highly coordinated with individuals showing parallel orientation and reacting to external stimuli (e.g., predators, stationary obstructions) as a unit, in a similar way to fish schools (O'Brien 1988). Dense patches of krill are formed, surrounded by areas of water with no krill. This patchiness, together with their potential reactive movements to avoid vessels and sampling gear, can make representative sampling of krill difficult.

5.3 Other types of events

As previously noted (Gaskin 2018), seabirds feeding in association with cetaceans were observed on several occasions during this project, adding further data on this important feeding behaviour for a number of species. However, with the focus in this report on fish school dynamics, discussion of these associations is not included here. It should be noted that trials with plankton tows during POP2017-06 yielded little in terms of specimens and few clues to the exact nature of cetacean foraging other than prey, and discarded prey material that was seen at the water's surface.

Other events where seabirds were observed feeding were at current lines. White-faced storm petrels were the most common seabird species here, 'dancing' on the sea surface while feeding on prey.

5.4 Analyses

Due to the relatively small number of sampling events this field season as a result of Covid-19 restrictions, physical parameters were not able to be used in the categorical analyses and this also limited the statistical power to detect possible differences using a three-way comparison between zooplankton, fish and seabirds. However, significant relationships were determined between the zooplankton and some secondary bird species, zooplankton and some primary fish species, and between zooplankton and some secondary fish species. The analysis may be able to be further expanded by using data from all three years of this study to deliver greater statistical power for the comparisons. Zooplankton abundance and diversity are determined predominantly by oceanographic (e.g., temperature, upwelling zones) and biological factors (e.g., primary productivity and predation) which result in a large amount of spatial and temporal variability (Zeldis & Willis 2015). However, the detailed mechanisms of the drivers of this spatial and temporal heterogeneity in relation to availability of seabird prey in the wider Hauraki Gulf has not been modelled.

Krill are an important food source for both seabirds and fishes (Gaskin et al. 2019). In this study, *N. australis* was seen swarming at the surface during the day, particularly at Mixed fish shoal and Krill patch events. The reason for this surface swarming behaviour during the day, which makes them highly vulnerable to predation by seabirds and fish, is not fully understood (O'Brien 1988). It is thought that mature krill may aggregate at the surface for reproductive reasons (Mauchine & Fisher 1969). Mature females of *N. australis* range in length from 9.8 – 17.0 mm and males from 12.0 – 16.0 mm (Barry 1954; Brinton et al. 2000). Krill of these sizes, including females carrying eggs as well as metanauplii (i.e., the first free-swimming stage) were found most at Mixed fish shoal events throughout the field season. However, smaller krill occurred at these events also, indicating other reasons for surface swarming behaviour.

Analysis of krill lengths from zooplankton samples showed some broad trends in krill size as described in the results. However, to confirm these trends greater numbers of individual krill need to be measured and greater account taken of other potentially influencing factors, such as location of sampling. More data is required to obtain more definitive results on krill populations associated with bird and fish feeding events.

Mixed fish shoal events were dominated by trevally and kahawai and these shoals sometimes occurred over large areas, particularly in the vicinity of the Mokohinau Islands. The gut contents of both kahawai and trevally captured from these events were comprised predominantly of krill. From underwater video observations, krill could often be seen in dense patches near the waters surface. Fairy prions and Buller's shearwaters tended to be the most common bird species at these events. A previous study of the gut contents of these two seabirds found that, particularly for fairy prions, krill was an important prey type (Kozmian-Ledward et al. 2019[1]).

By far, the greatest abundances of krill were found at Krill patch events (in the absence of shoaling or workup activity), with the highest abundance in one zooplankton sample being 10,631 krill per m^3. The predominant fish present at these events were mackerel spp. and juvenile fish spp. When compared with a study on *N. australis* in Tasmania (O'Brien 1988), the krill abundance is still relatively low. Krill densities of 3000 to > 450,000 individuals per m^3 were measured in Tasmania and the biomass of an individual swarm could exceed 100 kg wet weight. However, because of the highly patchy nature of krill occurrence, sampling can be highly variable in the numbers of krill captured. This was illustrated at two Krill patch sampling events where no krill at all were captured in the net tow despite the krill swarm being clearly visible at the surface from the sampling vessel and recorded using underwater cameras; the net had missed the krill patches Conducting a greater number of replicate zooplankton tows at each event would likely average out some of the sample variability but the extra time taken to do this then reduces the area that can be covered on each fieldwork day. The large amount of time taken to process samples in the laboratory also needs to be considered within the time and budget allocation for this project.

There have been no previous studies in the wider Hauraki Gulf (or indeed New Zealand) that sample zooplankton in relation to seabird foraging and our use of zooplankton nets to conduct surface horizontal tows through fish workups appears to be novel in this regard. Previous studies on zooplankton in the wider Hauraki Gulf pelagic realm are few and far between (e.g., Jillett 1971; Zeldis & Willis 2015). For example, Jillett (1971) used a Clarke-Bumpus sampler to conduct three replicate oblique hauls at a single station in the Jellicoe Channel at monthly intervals for 14 months. Zeldis & Willis (2015) conducted single vertical hauls using a zooplankton net at multiple stations from the inner Hauraki Gulf to the outer continental shelf and repeated this over several multi-day research voyages. Carroll et al. (2019) conducted systematic zooplankton sampling in a study examining the diet of Bryde's whales in the Hauraki Gulf, using DNA extraction techniques to examine community composition in relation to the species composition of whale faecal matter. Due to the importance of *N. australis* in the diet of various seabird and fish species (as well as baleen whales and mobulid rays) in the wider Hauraki Gulf region, more research is recommended on the distribution, lifecycle, behaviour, effects of environmental factors, and whether commercial fishing of fish species which prey on krill has a positive or negative effect on krill abundance.

5.5 Inter-annual comparisons

In the previous years of this zooplankton research, fish shoal activity was not characterised into 'event types' but instead into two broad categories: "workup" and "no workup". This, combined with the lack of quantitative data on zooplankton abundance (no flowmeter), meant that statistical differences between zooplankton composition and abundance for workup and non-workup samples were hard to determine. General observations of the data suggested that Malacostraca were more abundant at workup events, but this was not statistically defined. This season's work has shown that there are characteristics between different types of seabird feeding events, zooplankton and fish present, and between zooplankton and some secondary fish species in terms of bathymetry and oceanographic factors which should be explored further.

Sampling methods in the previous two research years differ slightly from this year. In the current year, two net types were used and predominantly surface tows were conducted, whereas in the previous years, both vertical hauls and surface tows were conducted, all with the fine mesh, low-speed net. Despite these differences, some general comparisons can be made between zooplankton samples among the years. Higher proportions and greater species diversity of Copepoda were obtained in previous years which could be due to several reasons; 1) smaller copepods would have been less likely to retained in the high-speed net due to its coarser mesh, 2) copepods may be more common deeper in the water column, 3) copepods were generally more common in spring and autumn, i.e., seasons not sampled in this current year. The Malacostraca and Thaliacea groups appear to occur in generally similar relative proportions throughout the years. However, without the abundance data in the previous years this is not quantifiable. For the Nauplii group, last year, barnacle nauplii were included in this group and were common in samples taken in May. This year, only krill nauplii were included in this group. Given their small size (< 0.6 mm), nauplii would have not been readily retained by the 1.32 mm mesh of the high-speed net. However, in one sample taken with the high-speed net at a Krill patch event, a high abundance of nauplii was retained, possibly due to the extremely high numbers of krill captured blocking the net mesh to some degree. Appendicularia were not common in samples this season compared to the previous seasons. In the 2017-2018 research season, Appendicularia were present in 93% of samples, compared to only 8% this season. This could be due again to greater numbers being taken by vertical hauls. There were no samples dominated by fish eggs this year as there had been in previous years. Egg size range measured from last year was 0.78 – 1.38 mm (n = 11), mainly smaller than the high-speed net mesh. Inter-annual differences in zooplankton sample composition could also be due to climatic variability between years

This study reinforces observations made during previous research (INT2016-04 and POP2017-06) that seabirds adopt a range of feeding associations with respect to prey, and importantly the way prey is made available. Seabird science continually emphasises the role of seabirds as indicator species for marine ecosystem health (Furness & Camphuysen 1997; Tasker et al. 2000, Wagner & Boersma 2011). Fisheries can reduce the abundance of forage fish and may also change the community structure of fish schools resulting in smaller and less frequent workups reducing food availability. Depending on the level of dependence of seabirds on these foraging opportunities, this could result in impacts to populations of seabirds. Taking an ecosystem approach is required to understand this dynamic system (Hebshi et al. 2008; Maxwell & Morgan 2013). Our research has focussed on a suite of species that we have identified as key for the study of fish schools/shoaling fish in north-east North Island waters and potential indirect adverse effects (Gaskin 2017; Gaskin et al. 2019[1]).

This season's research was curtailed by Covid-19 restrictions on vessel activities resulting in a large reduction in data collected and subsequent analysis. This needs to be considered when looking at data trends given in this report. There is the need to continue to develop our multi-disciplinary approach to fully investigate indirect effects of fisheries on seabirds through the study of these species, complemented by ongoing investigation into fish school dynamics and seabird diet, foraging distribution and behaviour utilising GPS or satellite tracking, and breeding success. Details on recommendations are given below for expansion and improvements to this research.

6 RECOMMENDATIONS

General

- Zooplankton sampling timed to link to seabird breeding cycles is required over multiple years and across each full season (September to May) to cover multiple species.
- This year's study demonstrated the significant advantages of using a high-speed dedicated research vessel for sampling, enabling large areas to be covered and multiple seabird-feeding events to be sampled much more efficiently during periods of good weather. While much more effective, the use of such research vessel comes with significantly more cost.
- Conduct further literature research on the methodology and outcomes of international studies examining pelagic food webs involving surface fish shoals and seabird foraging to compare with this current project.

Complementary research (seabirds)

- Connect at-sea sampling with areas of sea identified by GPS tracking of seabird species as important feeding grounds. Despite relatively small sample sizes, preliminary GPS tracking of four key indicator species (Buller's and fluttering shearwaters, fairy prions and Australasian gannets) undertaken separately from this project, have confirmed at-sea observations of occurrence around key bathymetric features and highlighted other important foraging locations within the wider Hauraki Gulf region.
- To identify key feeding grounds a comprehensive integrated tracking programme using remote GPS loggers downloading to base stations set up in colonies is recommended for multiple years starting with the four indicator species we have identified (Buller's and fluttering shearwaters, fairy prion and Australasian gannet). Additional species could include flesh-footed shearwater, black petrel, little penguin, and northern diving petrel.
- Furthermore, tracking of flesh-footed shearwaters (Kirk 2017) and black petrels (Bell et al. in prep.) together with observations of this species feeding in association with cetaceans highlights the need to examine those relationships more closely.
- Stable isotope analyses from blood and feather samples, and opportunistic diet sampling collected through all key stages of their respective breeding cycles for all seabird species studied to detect any annual changes in prey and foraging area.

Complementary research (bathymetric features)

- Reefs, pinnacles, and groups of islands can be highly productive areas attracting many fish species. Plankton biomass may be increased in these areas possibly because of local enhancement of productivity. The communities overlying or between significant bathymetric features, i.e., known areas for work up activity and seabird aggregations, should be investigated to fully understand fish school dynamics and their importance to seabirds.

Event sampling

- In general, a full suite of data for biological variables (zooplankton, fish, seabirds) should be made at each event to allow for full comparisons of all variables.
- The floating camera rig should be deployed at all sampling locations to ground-truth topside observations of fishes. Ideally, additional GoPro's to be mounted, one at the top of the rig above water to film topside activity of seabirds and fishes, and one at the bottom of the rig pointing straight down into the water to record any fish activity beneath the rig.
- Oceanographic data recording – measurements of SST, salinity, water clarity and chlorophyll-*a* to be taken at all sampling events. Ideally have dedicated YSI meter that is known to be calibrated correctly for each trip. A more efficient method of filtering seawater for the chlorophyll-*a* samples is required than the very slow syringe method used to date. For example, a portable vacuum filtration unit.
- The use of the flowmeter is invaluable for standardising zooplankton sampling and needs to be retained.
- Seabird data collection needs to be standardised to include primary species, secondary species, abundance, and behaviours.

- Consider conducting multiple replicate zooplankton tows at each event to take greater account for zooplankton patchiness.
- Control zooplankton tows to be undertaken with more frequency.

Fish captures

- Increase fish sampling at different types of event and for different species to determine how fish diet varies with zooplankton composition and with fish species. Stomach contents show what is in the water and may include things that have avoided the zooplankton net, such as small fish. They also indicate fish are being highly selective so there should be more fish sampling in different types of event and for different species to determine how fish diet varies with zooplankton composition and with fish species.
- Develop an effective technique for the capture of bait fishes that can be integrated into the sampling programme because no bait fish samples were obtained through the sampling this season either through fishing efforts, or in the zooplankton net.

Captures of birds at sea

- Capture of key indicator Procellariform species to collect regurgitations to establish direct links of seabird diets to the zooplankton. Net guns have been developed as an effective tool for capturing seabirds at sea for research purposes (Gaskin in prep.).

Zooplankton lab analysis

- With greater knowledge of key dietary items for seabirds, the categories for zooplankton sampling should be revised to reflect their relative importance to seabird diet.
- Continue to expand the macro-photography of specimens and work towards a zooplankton identification guide for northern North Island region.

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Many thanks to Imogen Lloyd for her help with processing the zooplankton samples in the lab and assistance in the field. Thanks to the Leigh Marine Laboratory for providing excellent resources and lab space. Thanks to the vessel skippers: Brady Doak RV *Hawere*, James Ross *Waimania*, and Trevor Jackson *El Pescador*. Thanks to Kerry Lukies, Peter Mitchell, and Rod Neureuter for being excellent field assistants.

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APPENDIX

Exploring distributions of pelagic fish using aerial sightings data (interim report)

This report has been prepared by **Paul Taylor** (Statfishtics Ltd) with **Chris Gaskin** (Northern NZ Seabird Trust) for the Department of Conservation (DOC), Conservation Services Programme (CSP) and managed by DOC marine science advisor Dr. Karen Middlemiss.

December 2020

Figure 1 (this page): Purse seiner in operation, Bay of Plenty 1979. View from spotter plane. *Photo: Michael Guthrie (pilot)*

OVERVIEW

Overall objective

To analyse fish shoal data from the aerial sightings database (aer_sight) and, for the study area in East Northland, Hauraki Gulf and Bay of Plenty (BOP), develop a model of temporal variability in surface schools of the pelagic shoaling finfish species targeted by the domestic purse-seine fishery in terms of relevant environmental variation as a first step in better understanding fisheries pressures on seabird population trends.

Tasks in progress this period

This report aims to provide an update on work currently being carried out, which was begun after the interim report dated 12 August 2020. The current work is of an exploratory nature, to analyse certain aspects of the data as a preliminary to beginning the analysis proper outlined in the objective above.

- Investigate the links between environmental features and distribution of fish schools from *aer_sight*.
- To continue examining changes in schooling aggregations over time i.e., size of schools, tonnage of sightings, number of schools.

Ongoing development of the methodology to complete the first of these tasks is of prime importance. This requires several steps. In particular during this period has been development of a method for projecting observations from the *aer_sight* database onto the same coordinate space as the raster-based environmental variables (see interim report dated 10/03/20) and code for manipulating the data as raster stacks within R. Completion of these tasks still requires some work.

Underlying these tasks is the need for reliable data from *aer_sight*. Direct access to the database has been available for previous work contracted by NIWA (e.g., Taylor, 2014; Taylor & Doonan, 2014), but is not possible for the current work, so extracts must be requested from Fisheries NZ. Exploratory data analysis is necessary to ensure that the expected content of data provided is received. This process of data access has been complicated by the general level of unfamiliarity with the *aer_sight* database and the constraints Fisheries NZ necessarily impose on the data to satisfy privacy terms for contributing fishers. Consequently, discussion and several variations on an evolving data request have been required to produce the current dataset.

The analysis described here under the second task above explores the hypothesis that the aggregation size of surface schooling pelagic finfish species has decreased appreciably over the years since the advent of the purse-seine fishery in 1975–76. The analysis was not designed to provide biomass estimates, only to investigate possible changes in aggregation size of the various species, so no standardisation was performed. A simple approach was taken to determine whether there were any obvious changes through time with the data treated as samples of school size. The analysis did not include mixed schools of these species, but focused on sightings of mono-specific or single-species schools. To maximise the basis for detecting changes in size, the dataset included sightings from the entire northeast coast, from North Cape to East Cape.

Sightings are mainly of 8 species: the coastal schooling species trevally (*Pseudocaranx dentex*), blue mackerel (*Scomber australasicus*), three species of jack mackerel (*Trachurus declivis*, *T. murphyi*, and *T. novaezelandiae*), and kahawai (*Arripis trutta*), and the highly migratory species skipjack tuna (*Katsuwonas pelamis*); sightings of blue maomao (*Scorpis violaceus*) have also been reasonably high, though at a much lower rate than the other species listed here.

This work is preliminary to the main modelling work which has been discussed in previous interim reports. In that work the aerial sightings data will be used in a two-step modelling process to fit an offset model

(McCullagh & Nelder, 1989; Venables & Ripley, 2002; e.g., Clapcott et al, 2010; Sólymos et al, 2013), with step-1 being application of a boosted regression tree (BRT) (Elith et al, 2008) approach to perform the modelling investigating the relationship between sightings and environmental variables, followed by step-2 as application of a BRT or a generalised linear model (GLM) to apply the offset model and estimate the year effects. In the latter, the fitted values from step-1 will be included in the step-2 fitting as an offset. The BRT in step-1 requires observations to include absences and methods reviewed by Elith et al., (2006) (e.g., Ferrier 2002) will be used to generate appropriate pseudo-absences within the area of interest.

Previous use of the aer_sight data has been in producing stock indices for use in stock assessments of kahawai and trevally (Taylor, 2014; Taylor & Doonan, 2014). This work was limited to the Bay of Plenty, mainly because there were fewer records collected further north in east Northland. Data management approaches in the current work is investigating various strategies to overcome this issue, such as the pooling of data over several years or including more flights, perhaps from more pilots than considered previously.

NB: This work will be continued and combined with the new contract BCBC2020-08 Fish School Dynamics.

Data selection

A dataset was created in R (R Core Team (2019) based on the revised extract of schools data from the *aer_sight* database. For each sighting, spotter pilots record details that include species composition, the total number of schools, tonnages of the smallest and largest schools (= range of school sizes), as well as the geographical position of the sighting. These were included in the dataset along with date and area (east Northland and Bay of Plenty); annual and "decadal" references (1976–83, 1984–93, 1994–03, 2004–13) were also created. The dataset was restricted to the six senior pilots contributing to the database (pilot codes 1, 2, 6, 9, 50, 87: see interim report dated 12/08/20) and to the eight main species, although sightings of the three jack mackerel species are included as the singular species, jack mackerel because they are not always recorded separately by the spotter pilots.

Also included in the dataset was the calculated sighting tonnage. The three measures related to sighting size recorded by the spotter pilots are minimum school size (*ton_min*), maximum school size (*ton_max*), and number of schools in the sighting (*num_of_schools*). These measures are combined to provide a simple estimate of the size of the sighting as the calculated tonnage (*ton_tot_calc*):

$$ton\_tot\_calc = num\_of\_schools((ton\_min + ton\_max)/2)$$

Examining school size and number of schools

Some exploratory analyses were carried out to characterise the descriptors of sighting size, *ton_max* and *num_of_schools*. These included a plot of ton_max on ton_min (Figure 1), box and whisker plots of ton_max by species for each of the senior pilots (Figure 2), ton_max by species for the two areas (Figure 3), ton_max by decade for each species in the two areas (Figure 4), num_of_schools by species for the two areas (Figure 5), num_of_schools by decade for each species in the two areas (Figure 6) and calculated tonnage by species for the senior pilots.

The two measures, ton_min and ton_max express the range of sizes in the sighting. Figure 1 is a summary of data for all sightings of the main species by the senior pilots and shows that the majority of ton_max values are less than 100t. The skewness in the data is a feature of the *aer_sight* data and is strongly evident in the plots shown here.

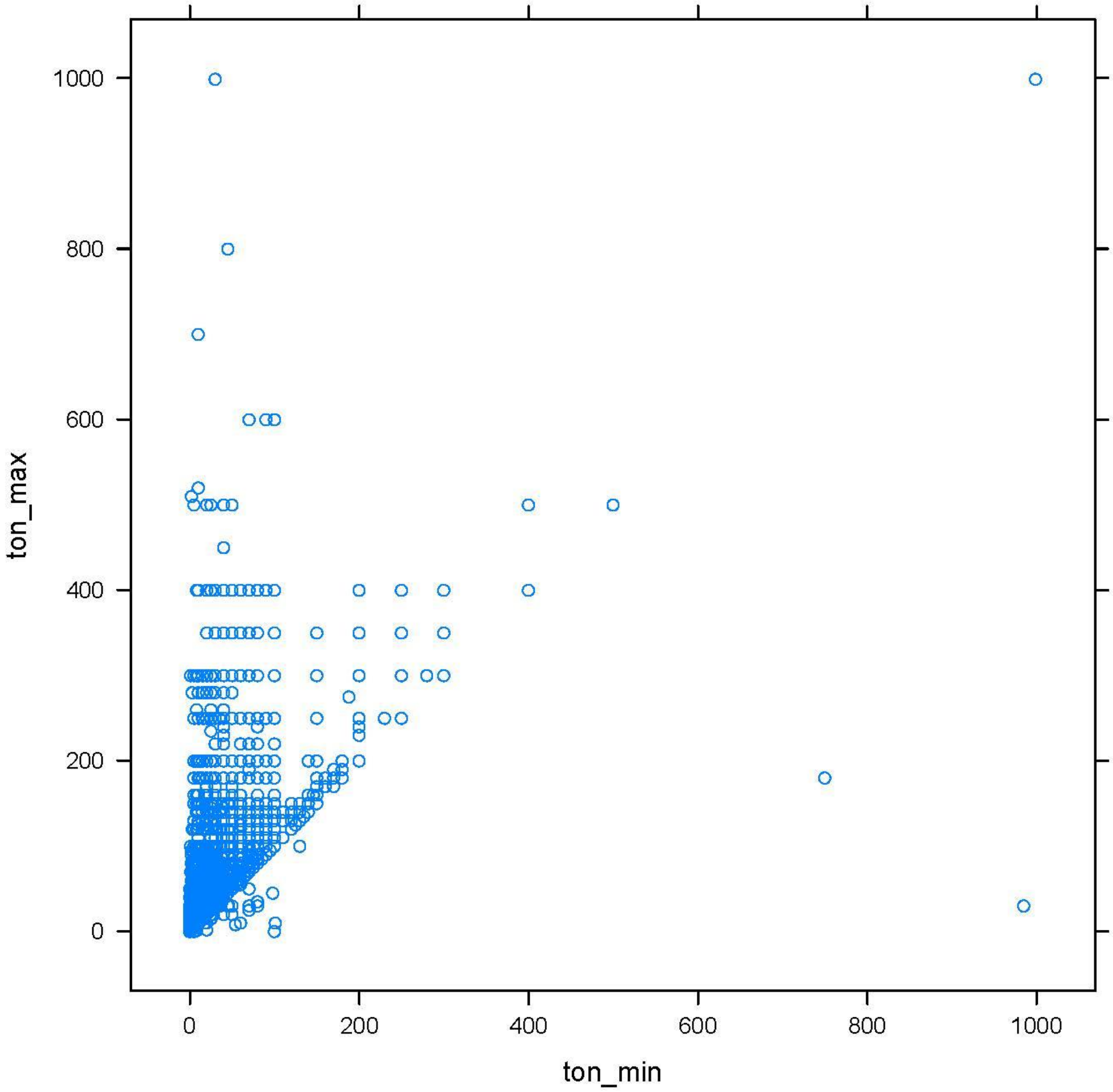

Figure 1: Maximum tonnage on minimum tonnage. Source: Fisheries NZ *aer_sight* database.

Pilots #2 and #9 have collected data over many years. Pilot #9 appears to have a cut-off value for ton_max of about 500t (Figure 2), a feature that is not evident in the data from Pilot #2. The distribution for blue maomao (BMA) is quite different for pilot #9 compared with the other 4 pilots recording observations. Generally the between-pilot patterns of medians and interquartile ranges are similar for the other 5 species, although there are some clear differences e.g., interquartile range of blue mackerel (EMA) for Pilot #9.

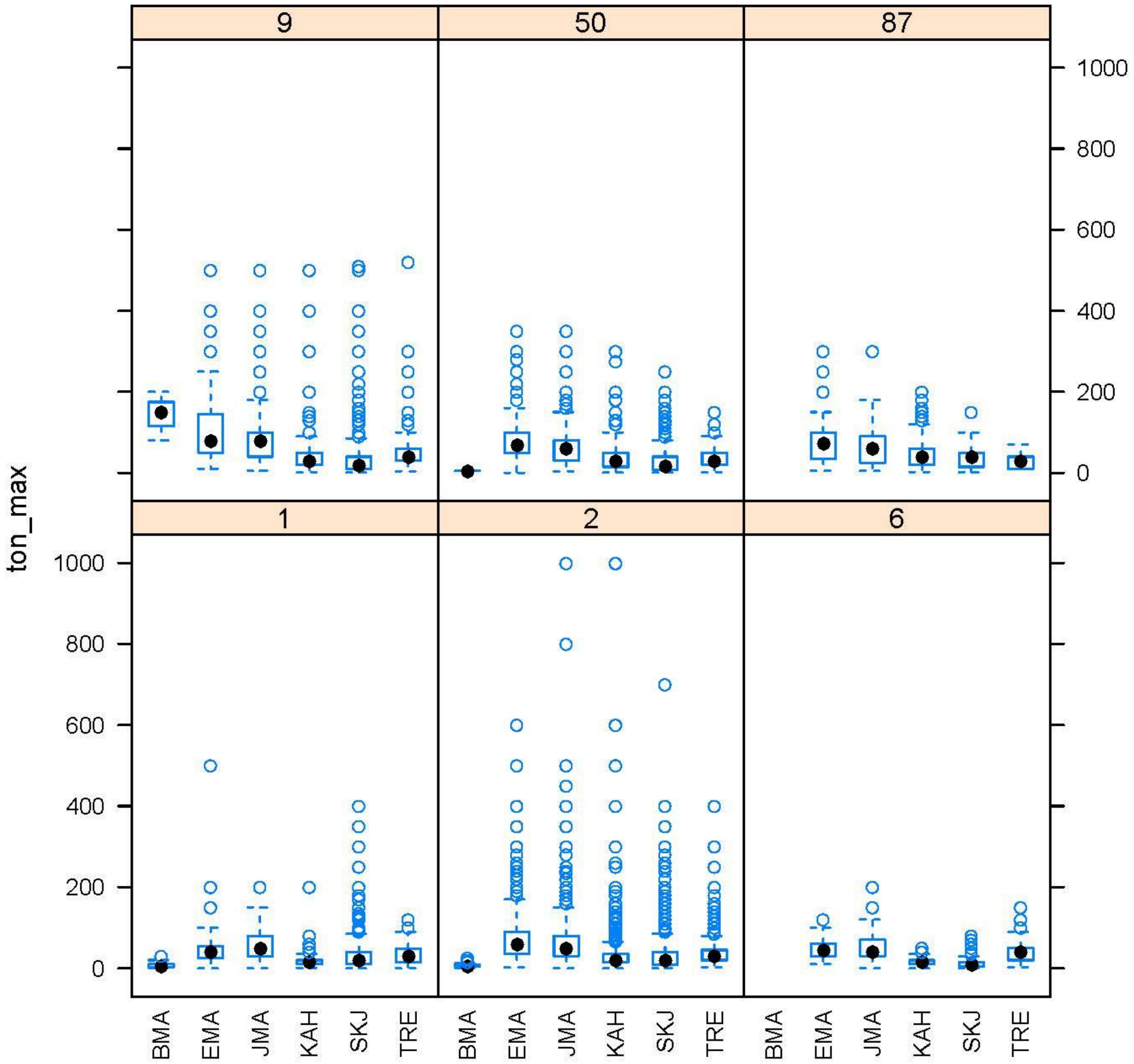

Figure 2: Maximum tonnage by the main species for the senior spotter pilots. Source: Fisheries NZ *aer_sight* database.

The median pattern for ton_max is also similar between the two areas, BOP and ENL (Figure 3), although maximum school size of EMA may tend to be higher in ENL. Apart from 4 sightings in the BOP with ton_max > 600t (2 for blue mackerel, and 1 each for kahawai (KAH) and skipjack tuna (SKJ), the overall spread in the two areas is similar. However, the distribution of ton_max for kahawai is clearly different in the two areas.

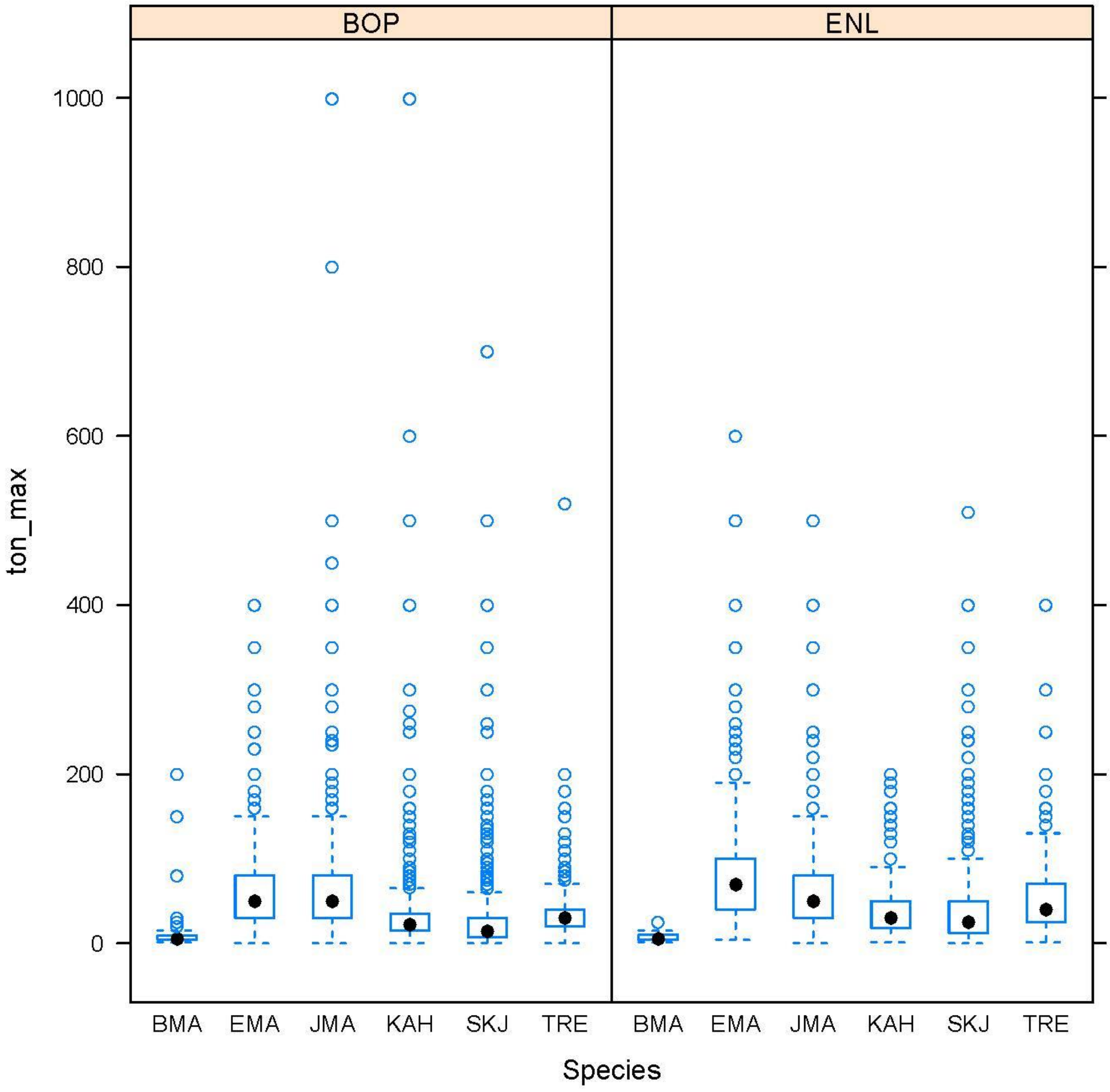

Figure 3: Maximum tonnage by species for the two areas, Bay of Plenty (BOP) and east Northland (ENL). Source: Fisheries NZ *aer_sight* database.

Adding the time factor "decade" (Figure 4) reveals a little more. The higher variability of ton_max for blue mackerel in ENL is largely from decades 2 and 3; otherwise the patterns are similar for this species between the two areas. The pattern of decadal medians is similar for jack mackerel (JMA) in the two areas. The interquartile ranges for kahawai are similarly tight for the two areas and through time, although there is much wider variation in the recorded larger ton_max values in the BOP. The patterns for skipjack are fairly consistent between the two areas and through time. There is little actual difference in the trevally (TRE) distributions between the two areas.

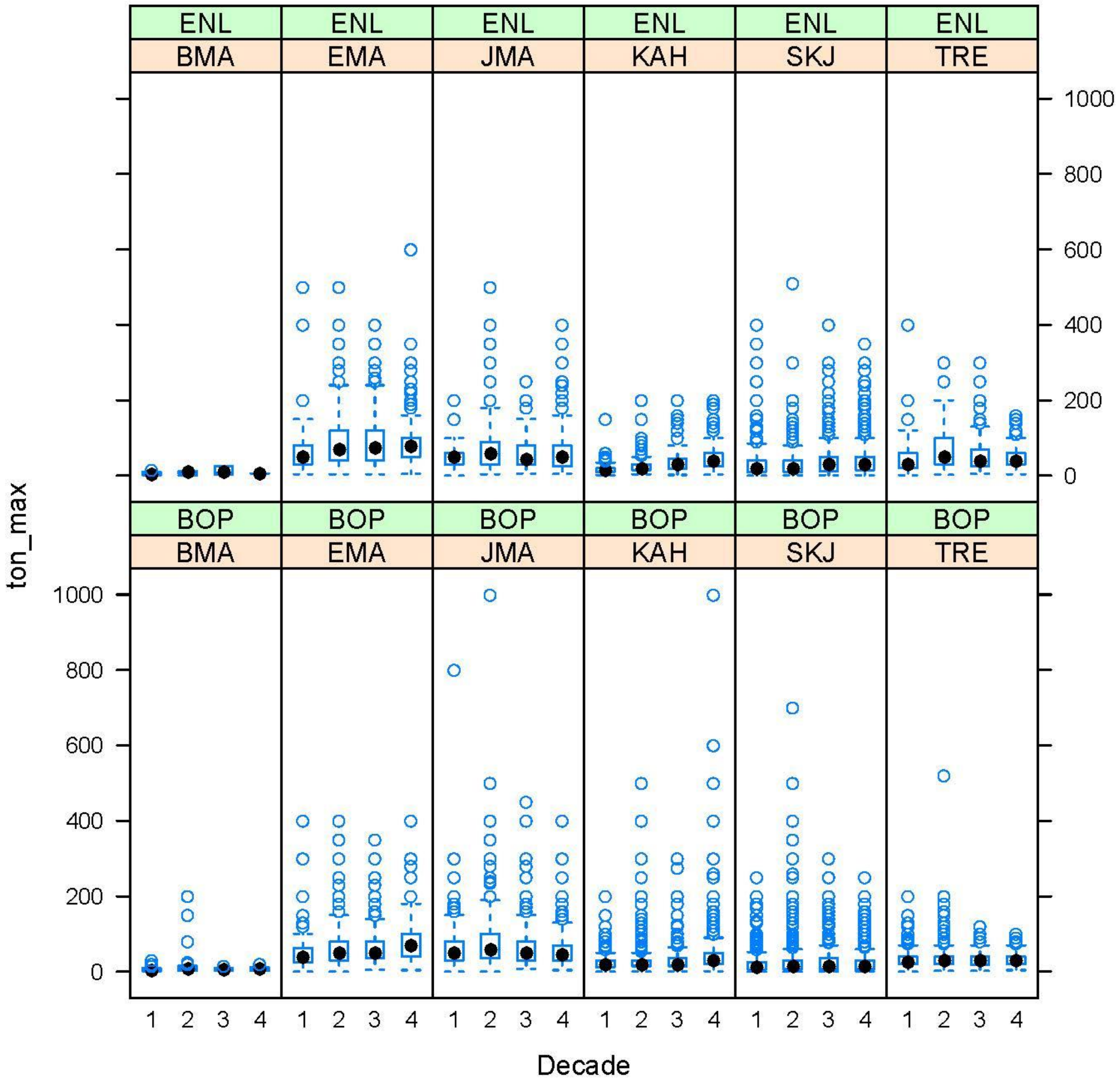

Figure 4: Maximum tonnage by decade (1976–83, 1984–93, 1994–03, 2004–13) for each species in the two areas, Bay of Plenty (BOP) and east Northland (ENL). Source: Fisheries NZ *aer_sight* database.

Because of the low values for the majority of the data and the degree of skewness for 3 species, jack mackerel, kahawai and skipjack tuna in the BOP, the plots of num_of_schools are a little more difficult to read (Figure 5). This skewness represents a much larger variations for this factor in the BOP. Highest degree of skew in ENL is for skipjack, which is the species more often targeted in that at area.

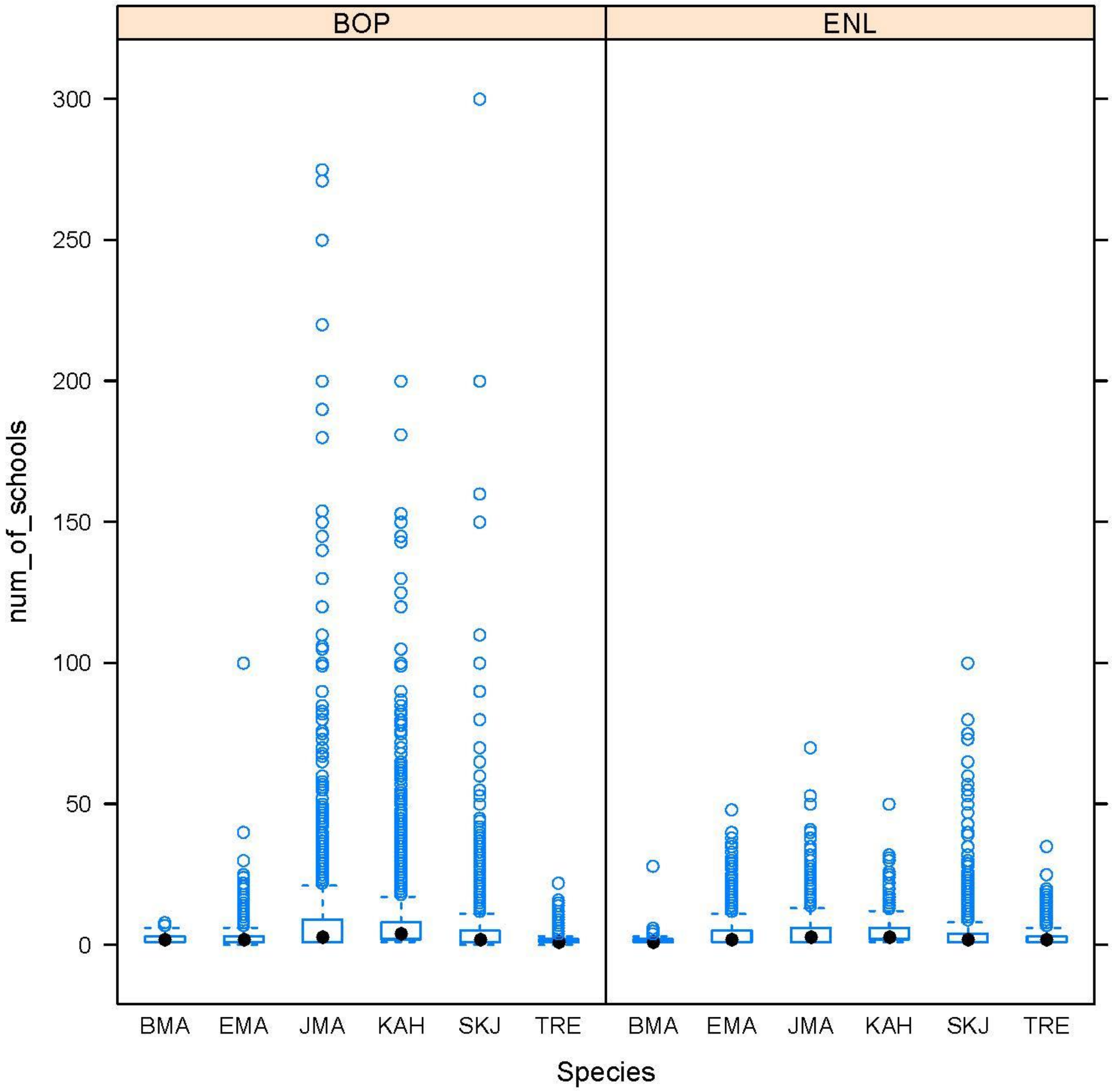

Figure 5: Number of schools by species for the two areas, Bay of Plenty (BOP) and east Northland (ENL). Source: Fisheries NZ *aer_sight* database.

The higher numbers of schools recorded for skipjack are most evident in the third decade (1994–03) (Figure 6). Generally the higher values in the BOP for jack mackerel, kahawai and skipjack continue throughout the time series, although there are some variations e.g., the fourth decade for jack mackerel.

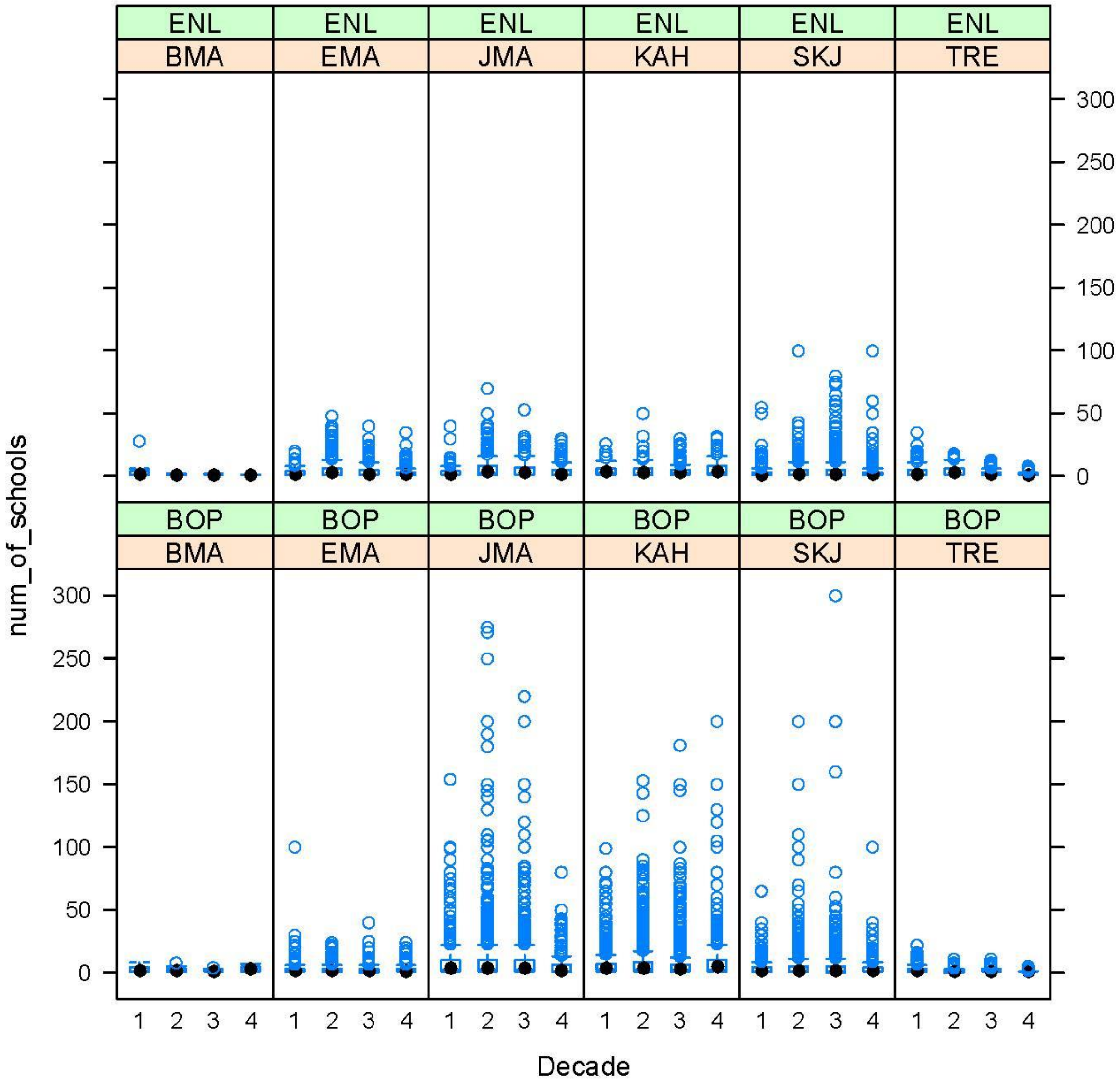

Figure 6: Number of schools by decade (1976–83, 1984–93, 1994–03, 2004–13) for the main species in the two areas, Bay of Plenty (BOP) and east Northland (ENL). Source: Fisheries NZ *aer_sight* database.

Estimates of ton_tot_calc are calculated from ton_min, ton_max and num_of_schools. In two cases the values are very high (Figure 7), suggesting that one or more of the contributing values are incorrect. Several other variations between pilots are of interest: the jack mackerel distribution for Pilot #9 is considerably wider than for the other pilots (apart from the gross outlier for Pilot #2); similarly for KAH/Pilot #50 and SKJ/Pilot #2.

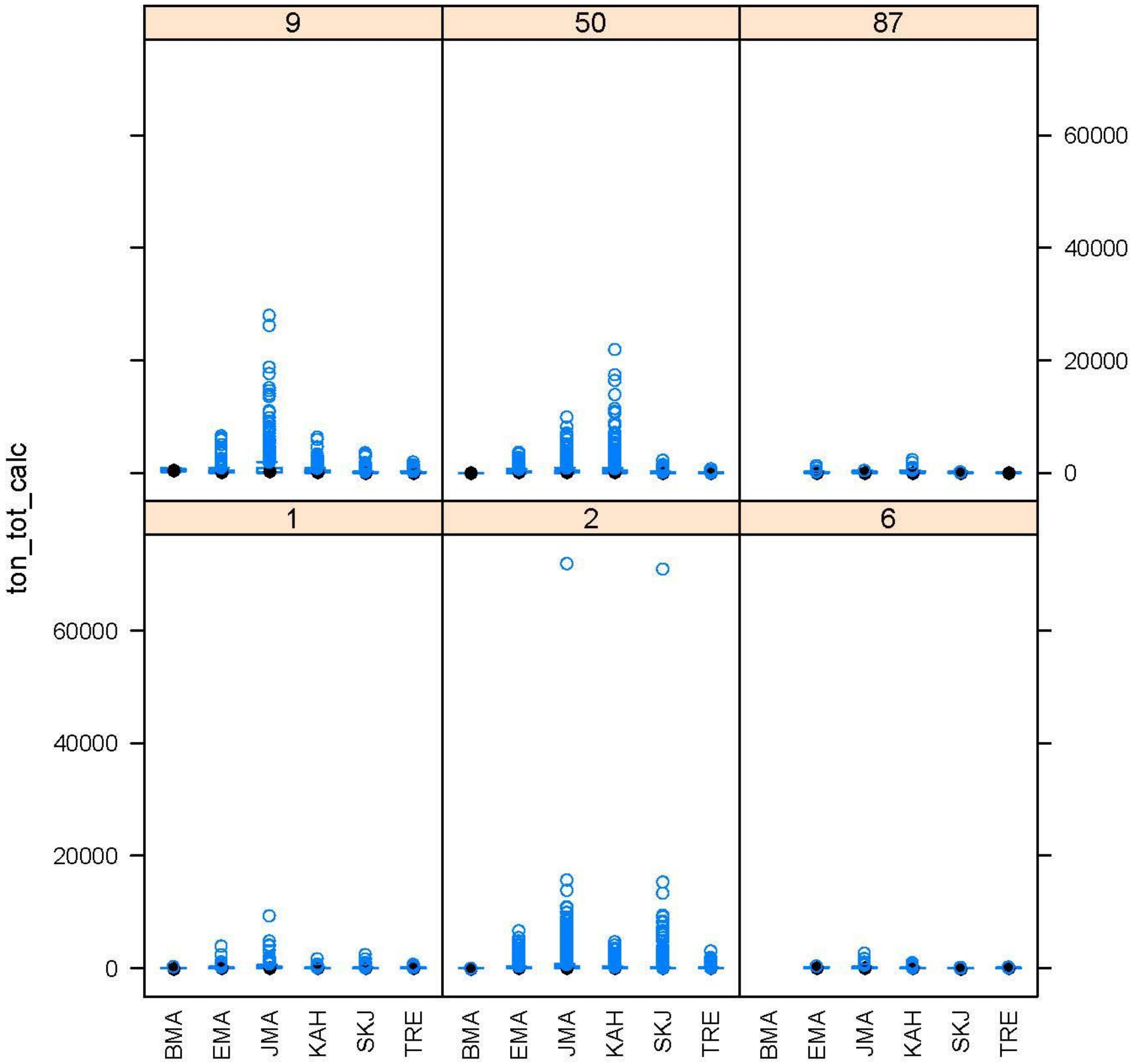

Figure 7: Calculated tonnage by species for the senior pilots. Source: Fisheries NZ *aer_sight* database.

Examining changes in school size, number of schools and calculated tonnage

Methods

The dataset referred to previously was separated by species and the measures of school size (ton_max, num_of_schools and ton_tot_calc) were examined for trends using the time series analysis package TTR. Two aspects of the time series of raw data for these measures were investigated: 1) the likelihood of trend through the sequence and 2) a difference between the first half of the sequence (before 1995) and the second half of the sequence (after 1994). These were examined for five of the main species: blue maomao (BMA) was omitted from these analyses because of a high frequency of missing data.

For the time series analyses, sequences of monthly means of the three measures were created for each species. To provide perspective two series were produced in each case: a series for all pilots and a series for Pilot #2. Missing data were replaced by the preceding value, which was repeated in the case of multiple missing values. For the statistical testing, values of the particular measure for all sightings of a given species in all years were included.

For the examination of trend, the linear model in R (lm) was used to produce t-test/p-value for the time variable (year) which provided the test for the null hypothesis (no trend in the sequence) vs the alternative. In each case a test for normality in the distribution of the sequence was carried out using the R function qqplot to determine whether applying the linear model was appropriate.

For the comparison of the first and second halves of the sequence, data for the species and measure of interest were selected as being either <1995 or >1994 and the t-test applied. Once again, normality was tested using qqplot.

Results

Generally, the time series plots were highly variable. The clearest indication of a positive trend was for ton_max and kahawai (Figure 8) and the clearest negative trend was for number of schools and trevally (Figure 9), the latter also suggested in the ton_tot_calc plot for trevally (Figure 10). Other trends are a little more subtle. For example, the ton_max curve for jack mackerel (Figure 8) shows an increase from 1985 which peaks and declines from about 1992. This trend is also evident in the num_of_schools plot for jack mackerel (Figure 9), although it begins a little later in the sequence.

The results of the linear model and t-testing are shown in Table 1. Empty cells are where simple data transforms would not comply with the normal assumption. All successful transformations were logarithmic. Note that the trend estimates for jack mackerel are both negative, which reflects the trend in Figure 8, though perhaps not so clearly the curve in Figure 10. The highest positive estimates are for both kahawai cases and for ton_max/blue mackerel which also reflect the curves in Figure 8 (ton_max) and Figure 10 (ton_tot_calc).

Note that in some cases however, the lack of normality in the testing data precluded carrying out the testing, while a clear trend is evident in the time series plot. This is perhaps clearest in the blue mackerel plot for ton_tot_calc (Figure 10). In this case it is interesting to note that the t-test on the first-half vs second half of the data (sequence halves) tested significant at the 0.05 level on normal data.

Table 1: Estimates and significance levels (SL) from the trend analysis and comparison of sequence halves. **Source: Fisheries NZ *aer_sight* database**

Analysis (statistic)	Sighting measure	SKJ	TRE	EMA	JMA	KAH
Trend (estimates)	ton_max	6.27e-3	9.193e-3	1.306e-2	-3.613e-3	1.810e-2
	num_of_schools					
	ton_tot_calc		†	7.123e-3	-19361e-2	1.964e-2
Trend (SL)	ton_max	0.001	0.001	0.001	0.001	0.001
	num_of_schools					
	ton_tot_calc			0.001	0.001	0.001
Sequence halves (SL)	ton_max	0.001		0.001	0.001	0.001
	num_of_schools			0.05	0.001	
	ton_tot_calc		0.001		0.001	0.001

†estimate = -1.176e-2 with no transformation or 7.024e-4 with a log transformation; the original distribution is closer to normal; neither are significant.

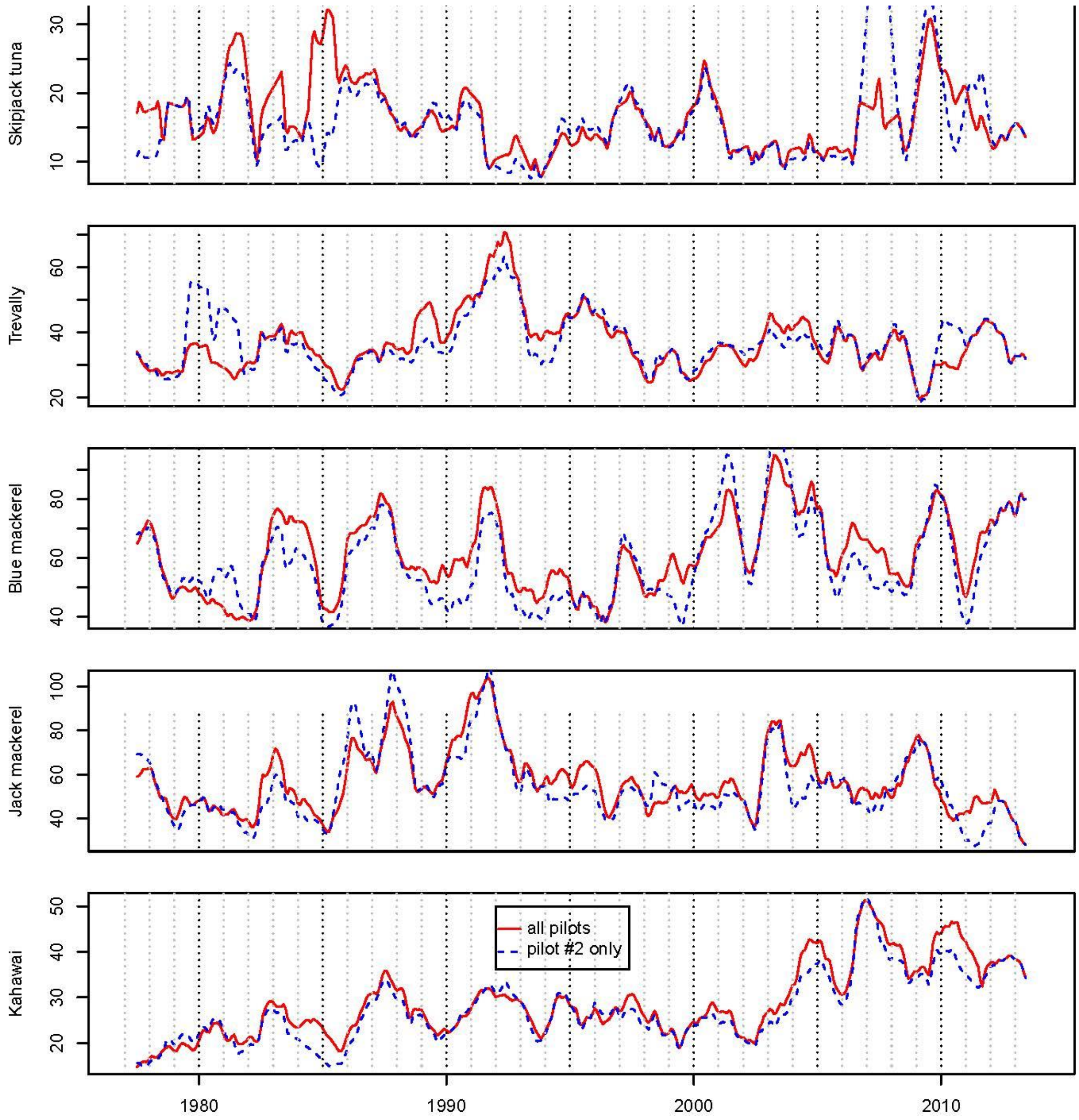

Figure 8: Time series plots of maximum sighting tonnage. Source: Fisheries NZ *aer_sight* database.

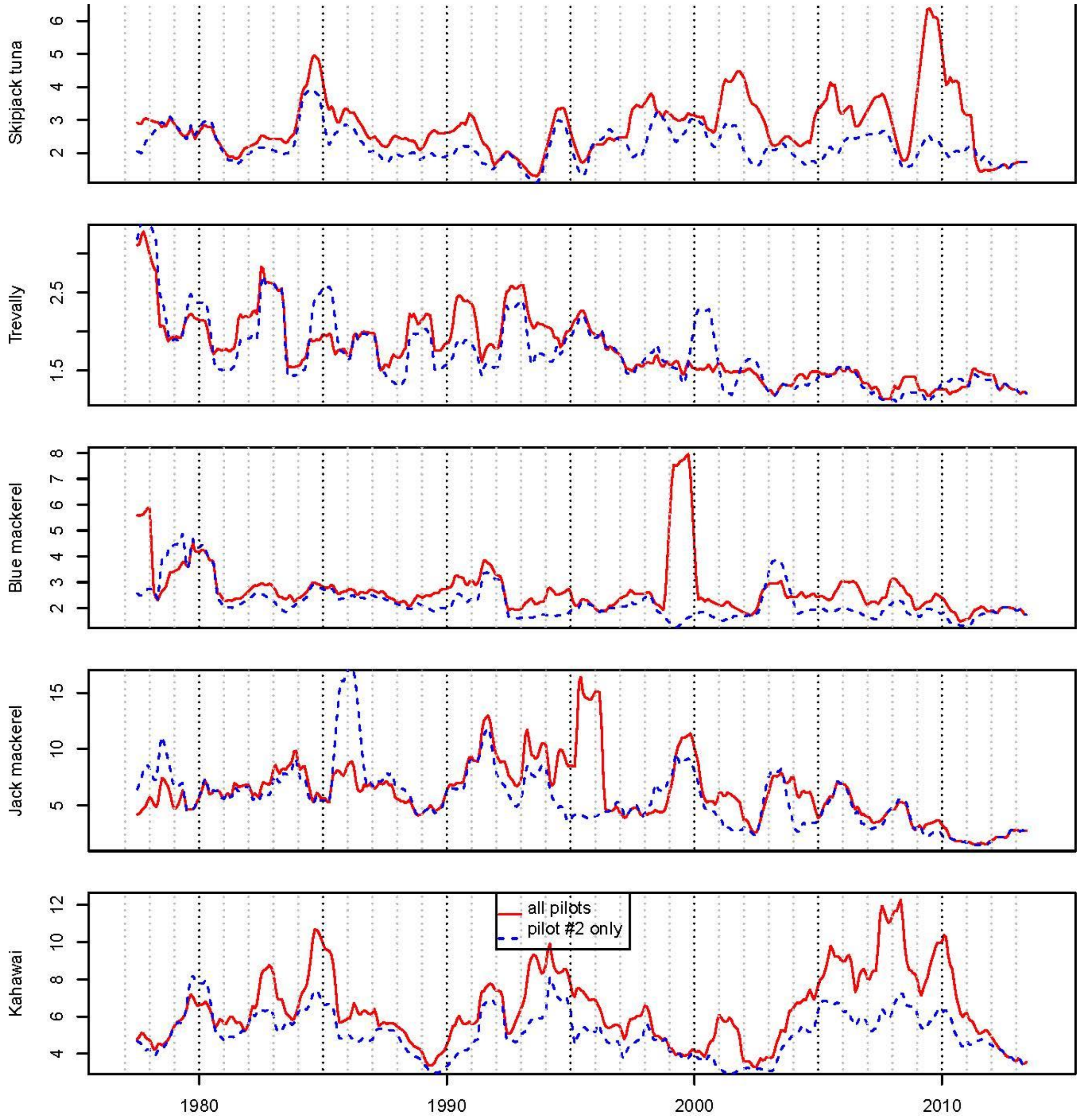

Figure 9: Time series plots of the number of schools by sighting for each of the main species. Source: Fisheries NZ *aer_sight* database.

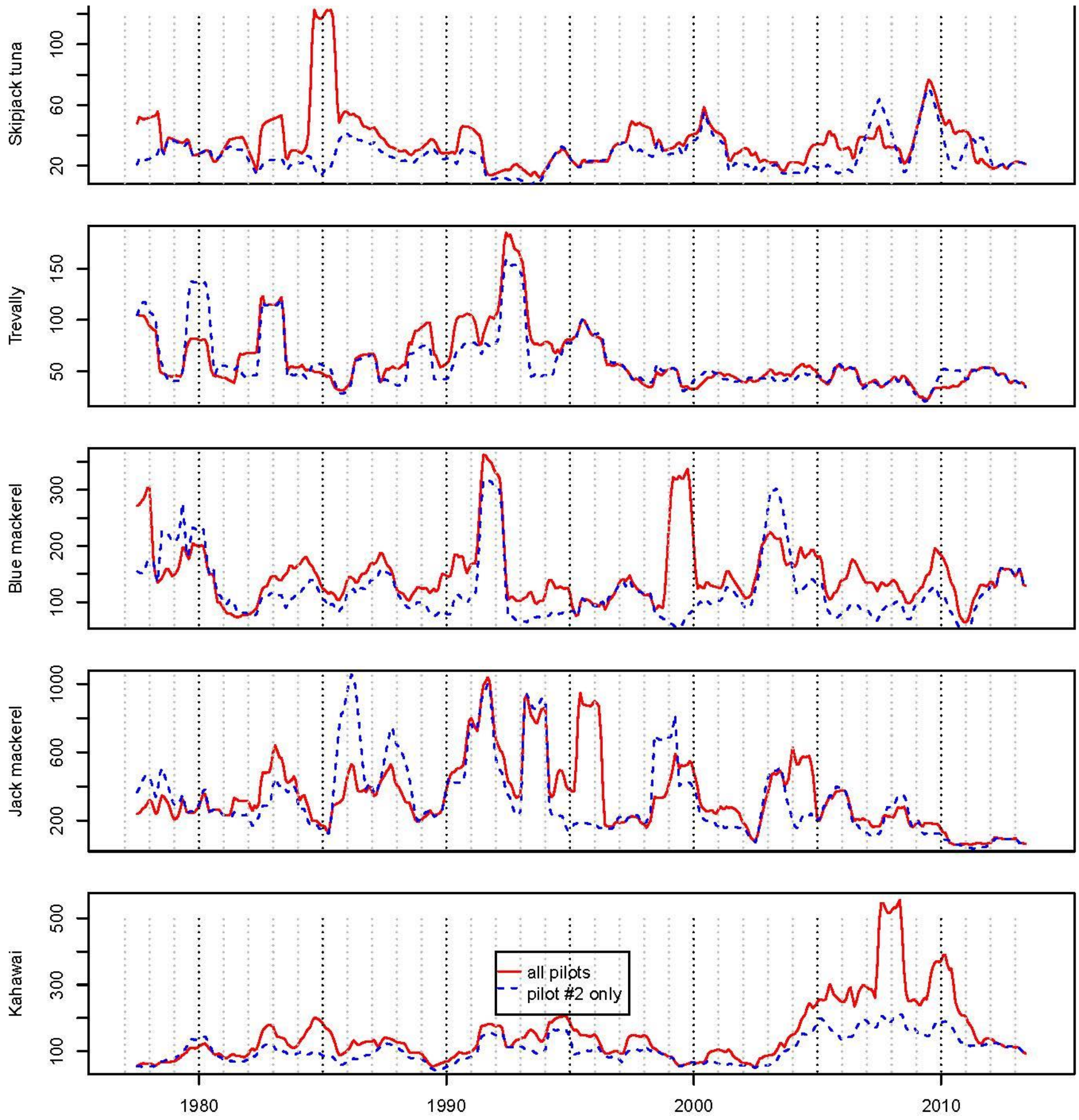

Figure 10: Time series plots of maximum sightings tonnage for each of the main species.

Discussion

The aim here was to examine whether there was any obvious evidence to support the hypothesis that school size in surface schooling finfish species had declined over time since the advent of the purse-seine fishery. Although there is clear evidence of downward trends in the measures of school and sighting size, it is also clear that time series plots of the measures are highly variable. Moreover, in the case of kahawai for example, a clear positive trend is evident in at least one of the measures, possibly as a result of the management of this species.

There are other patterns that are interesting. One example is that of the calculated tonnage for trevally, where the high variability that is a feature of the first half of the series is reduced considerably and accompanied with what appears to be a reduction in calculated tonnage of the sighting as well as num_of_schools. The lesson here, perhaps, is that this is not reflected in the ton_max time series, indicating that it is the number of schools that is more revealing in this case.

Generally, the analyses presented here are useful groundwork in understanding the information contained in the *aer_sight* data.

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