Foraging ecology and habitat suitability of the critically endangered New Zealand Fairy Tern or Tara Iti (*Sternula neresis davisae*) in Northland, New Zealand

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(Jacob Ball)

Thesis abstract

This thesis aimed to improve scientific knowledge of the critically endangered New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) (hereafter; NZFT) foraging ecology, measuring three key elements; (1) Behavioural time budget analysis; (2) Spatial interactions; (3) Dietary analysis through stable isotopes.

Current knowledge of NZFT behaviour has been limited to observational and ad-hoc approaches. Coordinated behavioural observations occurred on 13 individuals (21% of population) throughout the 2021/22 breeding season in Mangawhai, New Zealand. A mean foraging trip length of 17 ± 1 min was determined for adult provisioning NZFT, during which they spent 97% of their time performing foraging related behaviours. I observed 17 flight paths and 25 dive locations outside of the estuary in coastal marine environment. Estuarine habitats accounted for less foraging trips than expected, suggesting the importance of other habitats.

With the human population of Mangawhai predicted to increase over the next 30 years, I aimed to understand the current spatial use of Mangawhai estuary and surrounding areas by NZFT and people providing a baseline to support future management. Spatial data collection on dive and resting locations, and activities of humans were undertaken using GIS over the 2021/22 breeding season. Kernel density maps were compared through visual analysis and supported territorial foraging theory. Peak human presence occurred during the fledging period of NZFT chicks, highlighting need for management of human activities within Mangawhai estuary.

This study used stable isotopes $\delta^{13}C$ and $\delta^{15}N$ to provide analysis into NZFT diets using chick feathers. Thirty-one feathers were obtained from four breeding seasons and analysis undertaken following previous methods (Ismar et al., 2014). Reference fish samples (n = 52) were obtained from Mangawhai estuary and Bream Bay, New Zealand. I found a higher proportion of marine prey in 2022 than other years, however, this was not statistically significant. Marine foraging was not shown to influence chick survival.

Findings from my thesis highlight the role of the marine environment as an integral part of NZFT foraging habitat during breeding, complementary to estuarine foraging territories. Furthermore, my thesis results provide key baseline data for this species, emphasizing potential impact of increased human pressure.

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Ethical approval was required and obtained for all methods outlined within this thesis from both The Department of Conservation and Massey University Ethics Committee.

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1. Introduction and thesis background

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1.1. Estuarine and coastal systems

Estuaries are transitional, ephemeral, unique, and highly diverse ecosystems influenced by many environmental factors, but most notably from the mixing of freshwater and saltwater (França et al., 2012; He et al., 2021; Ray, 2005a). The rate of mixing within an estuary is defined by the topography and is currently classified into three categories; 1) Salt-wedge estuary; 2) Fjord, and 3) Shallow, partially mixed estuary (Chapman & Wang, 2001). Furthermore, both the topography and bathymetry of these estuarine groups influences the role energy sources – wind and wave - have on the characteristics of the estuary.

Due to the role of tidal influences and riverine inputs estuaries provide a naturally rich area for wildlife (Elliott & Mclusky, 2002; Lotze et al., 2006). Sediment beds provide an area for a rich benthic community, in turn benefiting bird communities (Elliott & Mclusky, 2002; Whelan et al., 2003). Estuaries are also important habitats for fisheries for all life stages due to the influences of tide for transport, food availability, and reproduction (Trnski, 2001). The role of estuaries for fish further increases diversity of this habitat supporting piscivorous bird species such as Terns (Mcdowall, 1976; Shin & Han, 2019; Vasconcelos et al., 2009).

Ecosystem services are processes that are naturally occurring within healthy environments that benefit human populations (Barbier et al., 2011; Boerema & Meire, 2017). Estuarine and coastal habitats represent opportunity for a wide range of ecosystem services such as provisioning of water and fish, flood and storm protection, water purification, trapping of pollutants through sedimentation, and cultural and recreational benefits (Boerema & Meire, 2017). The value of these habitats is therefore greater than just an ecological value and must be protected to provide human benefits.

Estuarine and coastal ecosystems are primarily under pressure from urbanisation and coastal developments, leading to disruption of natural processes within these ephemeral environments (Barbier et al., 2011; de Freese, 2008; Donald & Mclusky, 2004). Coastal environments within New Zealand have seen population growth within coastal communities, causing an intensification of development and urbanisation (Bryan et al., 2008; Brunsdon, 2020). New Zealand estuarine systems are under great threat from not only urbanisation, but from an increase in recreation within these environments (de Freese, 2008; Macdiarmid et al., 2012). Recreation causes disturbance to species occupying estuaries, causing displacement and ecological imbalance, in turn reducing the capacity for estuarine ecosystem services.

Marine systems are largely influenced through ocean currents, nutrient inputs, and temperatures (Hopwood et al., 2018; Lévy et al., 2018; Miller et al., 2018) as such productivity can be highly ephemeral (Putman, 2018). Many species dependant on this resource have adapted foraging strategies to overcome the unpredictability of food availability within this environment, through efficient travelling strategies, deep diving, and generalist foraging (Caldwell et al., 2020; Connan et al., 2019; Putman, 2018). A range of species are however at a greater risk of food scarcity due to breeding strategies such as, central-placed foragers (Houston, 1985; Houston & McNamara, 1985). As such, many marine seabirds are long-lived species with a reduced reproductive output often only producing one or two chicks a season, thus allowing flexibility within times of food scarcity, and maximising reproductive opportunity (Crawford et al., 2010; Pelletier & Guillemette, 2022).

1.2. Terns

Terns (Sternidae) are a geographically wide-ranging family with 39 species consisting of 8 currently recognised genera, occupying a broad range of habitats, from inland to marine, and tropical to polar (Egevang et al., 2010; Fijn et al., 2017a; Mauco & Favero, 2005; Paiva et al., 2008; Treadgold, 2000; Urmy & Warren, 2018). Tern species using these varying habitats target a diversity of prey items, from invertebrates taken by the black-fronted tern (*Chlidonias albostriatus*) in braided river systems (Keedwell, 2005) to fish, invertebrates, and molluscs in arctic tern (*Sterna paradisaea*) (Hall et al., 2000). However, most species are largely piscivorous (Green, 2017; Molina & Marschalek, 2003). Species across the family are mostly colonial nesting in diverse environments, from ground nesting on open low-lying habitats (Fijn et al., 2017a) to rocky outcrops (Barre et al., 2012) to trees in the case of the white tern (*Gygis alba*) (Vanderwerf & Downs, 2022). The greatest threat to tern populations globally is from habitat loss and degradation through coastal developments, draining of wetland habitats for agriculture, and loss of nesting habitat through sea level rise (Erwin et al., 2011; Travis, 2003). Erwin et al. (2011) found a 96% reduction in nesting common terns (*Sterna hirundo*) over a 13-year period in Tangier Sounds, Virginia due to habitat loss from water encroachment.

The role of weather and the ephemeral nature of marine productivity causes all tern species to be at great risk from long-term changes within marine fish populations. Climate change may therefore be pivotal in the long-term survival of many tern species due to changes in sea surface temperatures (Devney et al., 2010; Quiring et al., 2021; van Rijn et al., 2017). Sea surface temperatures have been linked to fish size through a phenomenon known as the temperature-size rule (van Rijn et al., 2017). This may prevent smaller bodied terns (*Sternula sp.*) and breeding terns from finding appropriately sized prey for themselves or chicks (Marinao et al., 2019; Quiring et al., 2021; Villard et al., 2020) and prevent opportunity for niche separation, increasing interspecific competition.

Tern breeding success is highly dependent on a reliable food source, as such insufficient food availability, or inability to successfully forage can lead to nest failure (Green, 2017; Moore et al., 2000; Scopel & Diamond, 2018a; Urmy & Warren, 2018). Weather is known to affect water properties and conditions, most notably wind speed is shown to have a direct relationship with wave action (Dunn, 1973; Young & Ribal, 2019). Fish foraging species such as terns are known to alter foraging behaviour with changing weather conditions, often reducing foraging rate during adverse weather conditions due to increased energetic costs, however, foraging optimality has been shown to improve with wind speed to a point in some tern species (Mcgarrigle, 2017; Stienen et al., 2000). The relationships between weather and foraging availability may cause limits to foraging terns alongside seasonal variations in prey availability.

Optimal foraging theory (herafter; OFT) outlines how species foraging behaviour is influenced by a range of ecological factors to provide a foraging strategy that has a net energy gain (Cowie, 1977; Macarthur & Pianka, 1966). Estuarine species such as NZFT may fit OFT due to the ephemeral nature of this habitat and patchy prey distributions (Chapman & Wang, 2001; Trnski, 2001). NZFT may undertake prey switching during fluctuations in prey availability from tidal, seasonal, or weather factors (Prokopenko et al., 2023). OFT may therefore provide a role in understanding foraging optimality through habitat choice and foraging behaviour within this species and should be considered.

1.3. Fairy Terns

Fairy Terns are a species found within the sub-family sternidae belonging to a genus of 6 species – sternula (Dunlop, 2018). Three subspecies of Fairy Tern are known, being endemic to Australasia; Australian Fairy Tern (hereafter; AFT); New Caledonian Fairy Tern (hereafter; NCFT) and New Zealand Fairy Tern (hereafter; NZFT) (Dunlop, 2018; Ismar et al., 2014; Parrish & Honnor, 1997).

Small morphological differences occur between subspecies; however behavioural differences are distinct, the current ecological conditions suggesting that NZFT are solitary breeders (Parrish & Pulham, 1995; Treadgold, 2000). Migration between subspecies has to date not been recorded, suggesting populations should be genetically unique. Baling & Brunton (2022) describe a single unique haplotype within NZFT and NCFT populations showing an absence of interbreeding between Australasian subspecies. These findings highlight the need to manage NZFT populations as an endemic species.

The NZFT, or tara iti has a current population of less than 40 individuals including approximately 9 breeding pairs (Pulham, *pers obs*.; DOC, 2022), making it the rarest indigenous breeding bird in New Zealand. It is classified as an endangered species, with a 'Category A' priority for conservation action by DOC(Jeffries & Brunton, 2001). Species management began in 1983/84, and intensive management began with the first species recovery plan in 1997 (Parrish & Honnor, 1997) being revised in 2006 (Hansen, 2006) with the aim of preventing extinction and increasing population size.

1.3.1. New Zealand Fairy Tern

1.3.1.1. Breeding Ecology

Previous evidence suggests that NZFT breed widely at coastal sites around the North Island of New Zealand within the early 20th century, however, NZFT are now confined to the lower half of the Northland Peninsula (Gill, 2007). Breeding is limited to four sites: Waipū spit, Mangawhai spit, Pākiri and the South Kaipara Head (Hansen, 2006; Harris et al., 2019). Pressure from habitat loss and degradation, introduced predators, anthropogenic disturbance, and genetic bottlenecking are considered the causes of the current conservation status and decline (Zimmerman et al., 2011). Small populations have a greater extinction risk due to effects from stochastic events and inbreeding, the need for detailed knowledge to support intensive management is therefore vital for continued species recovery.

The NZFT breeding season occurs from September to February, nesting occurring from October to January. Courtship feeding is believed to be the predominant driver behind pair bonds, other courtship behaviours include flight displays and vocalisations. NZFT breed within shell patches above the mean high tide mark within open sand dune habitat (i.e. free from vegetation) (Ferreira et al., 2005; Parrish & Pulham, 1995; Zimmerman et al., 2011). Nesting scrapes are made by both sexes, often many scrapes are created and maintained prior to laying. Up to 2 eggs are laid at 2-3 days apart, incubation lasting 22-25 days and fledging occurring within 22-23 days (Parrish & Pulham, 1995). A total of 3 clutches may be laid within a season, however, if first attempts successfully raise chicks no further nesting attempts are made. Pairs commonly change between breeding seasons and occasionally within breeding seasons. Males provide most of the parental care, teaching, and provisioning of fledglings. Immature birds reach sexual maturity at 2/3 years.

1.3.1.2. Foraging Ecology

Sternula terns are known to feed within coastal and estuarine zones globally and require central place foraging for breeding success (Bell, 1990; Houston & McNamara, 1985; Paiva et al., 2008; Ratcliffe et al., 2008). NZFT have been shown to forage on goby (Gobiidae) and flounder (Rhombolosiidae) within coastal shallows and estuarine tidal pools, predominantly on a changing tide (Ismar et al., 2014). Isotopic analysis has suggested adults may also supplement diet with shrimp (Ismar et al., 2014).

Ismar et al. (2014) also showed a strong dependence on Goby's for chick rearing within individuals, whilst also suggesting oceanic prey play a role within food provisioning in chicks. Other allopatric species are known to use deeper coastal waters for foraging (Fijn et al., 2017a), furthermore, Dunlop et al. (1988) has observed AFT foraging over the continental shelf, and observations have shown NZFT flying offshore presumably to forage (Ball, *pers obs*., Southey, *pers comm*., Pulham, *pers comm*.), however, little study has been undertaken on the importance of this habitat. This food resource may play a critical role in development of eggs and chicks due to the high levels of oils and fats within marine fish tissues. If NZFT are found to use offshore sites, this may influence current fisheries management strengthening protection for coastal and oceanic species dependant on the Hauraki Gulf.

1.4. Stable isotope analysis

Stable isotope analysis (hereafter; SIA) is a relatively new dietary analysis technique within ecology. It is reliant on the variations found within isotopic signatures of dietary items, and thus consumer tissues (Inger & Bearhop, 2008). A range of isotopic ratios are used within a broad spectrum of ecological fields such as; carbon, nitrogen, sulphur, oxygen, and hydrogen (West et al., 2006). These isotopes provide the opportunity to record differences in movements of nutrients, compounds, particles, and organisms throughout an environment to measure changes in life histories, dietary composition, and species habitat relationships (Inger & Bearhop, 2008; West et al., 2006) . Analytical comparisons between signatures of potential consumer foods - reference prey - with signatures of the consumer allow an understanding to be drawn into habitat and resource use where there is great enough variance (Forero et al., 2005; Herrera et al., 2003).

Two isotopic ratios are primarily used within avian ecology to determine habitat resource use and to determine trophic segregation: isotope ratios of carbon (^{12}C to ^{13}C, shown as $\delta^{13}C$) and nitrogen (^{14}N to ^{15}N, shown as $\delta^{15}N$) (Inger & Bearhop, 2008). Hilton et al. (2006) showed by comparing $\delta^{13}C$ signatures obtained from body feathers over a 160 year period that declines in rockhopper penguin (*Eudyptes chrysocome*) populations are related to changes in primary productivity, finding a decrease in $\delta^{13}C$ across 7 locations through time series comparisons. Furthermore, Bearhop et al. (1999) showed a link to freshwater foraging within Cormorants (*Phalacrocorax carbo*) through both $\delta^{13}C$ and $\delta^{15}N$ signatures of feathers recorded throughout the year. Other isotopes are less frequently used but provide opportunity for analysis into other key relationships; for example, Connan et al. (2019) used oxygen isotopes to determine the role of resource portioning within a sub-Antarctic bird community.

While SIA is a powerful tool knowledge of the natural history of a species is crucial to allow methods to be applied appropriately. Furthermore, the role of temporality within stable isotopes must ensure that tissues must be temporally similar for effective comparison, and scientific discretion should be applied within conclusions in its absence (Inger & Bearhop, 2008). Within species where ecological conditions and qualitative data are available, SIA can provide an effective tool to infer dietary compositions and foraging habitats (Inger & Bearhop, 2008).

1.5. Study Sites

1.5.1. Mangawhai

My primary study site was Mangawhai (-36.104663, 174.606264), east coast Northland, a 4.6km^2 mesotidal estuarine lagoon comprised of intertidal mudflats, shifting sand bars, converging channels, and mangroves within the upper reaches and shallow edges, contained by a 2.5km sandspit with a narrow channel at the northern tip (Zimmerman et al., 2011) (Figure 1.1). Two estuarine arms are present within the upper Mangawhai estuary, reaching North to the Molesworth causeway and West towards Insley Street causeway. The spit is bounded by ocean to the east and by the estuary on the west, connecting to Te Arai dunes, Mangawhai forest, and Tara

Iti golf club on the Southern end. The spit was classified as a wildlife sanctuary in 1953 by the Department of Internal Affairs, the estuary is also classified as an internationally important site for birds by the Important Bird Area Programme (Northland Regional Council, 2020).

During the 1980's the spit was breached due to a storm event, creating two inlets and an island. Management within the 1990's closed off the new inlet and dredging reopened the Northern inlet recreating the original harbour (Treadgold, 2000). Sand fencing is still present, and dredging continues today for recreational access within the estuary on the western shoreline of the spit. The spit is largely devoid of vegetation apart from the northern tip where grasses, rushes and some tree species dominate, the rest of the spit is a mosaic of ephemeral shell patches and mobile sand with *Demoschoenus spiralis* and *Spinifex hirsutus* throughout. Management of invasive weed species such as *Cortaderia jubata* and *C.selloana* and *Lupinus arboreus* is undertaken by the Department of Conservation (hereafter; DOC) and Tara Iti golf course.

Mangawhai has a diverse range of sea and shorebirds that nest and roost on the spit and the surrounding estuary. Annual colonies of caspian terns (*Hydroprogne caspia*) and white-fronted terns (*Sterna striata*) are found on the North-eastern end of the spit. Northern New Zealand dotterel (*Charadrius obscurus aquilonius*) and variable oystercatcher (*Haematops unicolor*) nest throughout the spit, and small nesting populations of banded dotterels (*Charadrius bicintus*) and pied stilts (*Himantopus leucocephalus*) exist on the northern end. Large colonies of red-billed gulls (*Chroicocephalus novaehollandiae scopulinus*) and black backed gulls (*Larus dominicanus*) are also found on the northern end and black-billed gulls (*Chroicocephalus bulleri*) often roost within colony fringes. The spit is also used by non-breeding waders such as bar-tailed godwit (*Limosa laponica*), red knot (*Calidris canutus*), wrybill (*Anarhychus frontalis*) and sanderling (*Calidirs alba*) (Ball et al., 2021; Treadgold, 2000). Mangawhai is also a stronghold for the New Zealand Fairy Tern with 6 breeding pairs using the spit within the 2020/21 season. Three main NZFT breeding sites are found on the spit, two of which are artificial (North Bund and Dredge), and one natural (South Sea Valley) (Figure 1.1.).

Mangawhai has a low human population, however, it increases dramatically depending on the seasons. Mangawhai estuary is used by public for a range of recreational activities such as kitesurfing, water skiing, jet skiing, swimming, surfing, hiking, horse riding, and mountain biking. Public activity is monitored by DOC rangers aiming to reduce public impact on all breeding birds and increase public education and awareness (Treadgold, 2000).

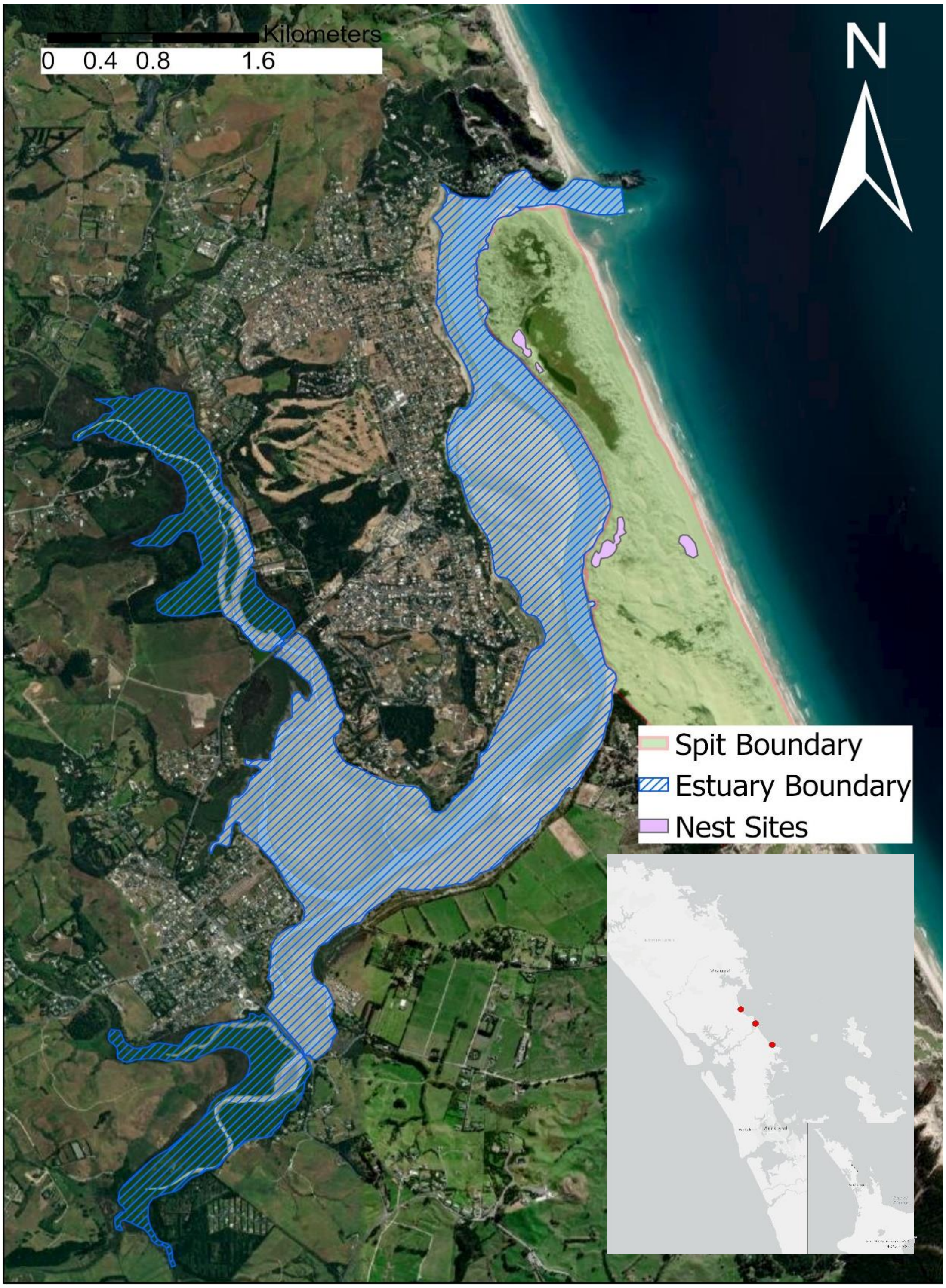


Figure 1.4.; Mangawhai site including the estuary, spit, and nesting location of New Zealand Fairy Tern/tara iti (*Sternula nereis davisae*).

1.6. Aims & Objectives

The current population status and lack of previous study into the complexities surrounding the NZFT highlight a need for further scientific research to inform active population management of this species for recovery. Many questions surrounding dietary composition, foraging limitations, and habitat use remain and are vital to determine how this species uses the landscape. Here I intend to build on previous research improving the understanding of spatial use, behaviour, and dietary composition within NZFT – the flow and direction of this thesis are visualised through Figure 1.4.

Chapter 2; Foraging behavioural analysis and inferences of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*)

Within this chapter I provide a time budget analysis of chick provisioning adult NZFT during foraging trips within Mangawhai estuary using coordinated behavioural observations on known breeding pairs. I provide evidence to support the role of different habitats as a foraging resource within this population, highlighting the importance of previously overlooked foraging habitats.

Objectives:

(1) Quantify the foraging time budget of chick provisioning adult NZFT, thus providing baseline information for this species.
(2) Expand the current knowledge on the role of estuaries and marine coastal habitats for breeding NZFT populations.

Chapter 3; Spatial use and interactions of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) within Mangawhai estuary, Northland, New Zealand

Here I provide analysis into how NZFT use habitat throughout the breeding period focusing on Mangawhai estuary, using spatial data collection methods. I provide evidence to support current ecological theories on NZFT, while further understanding the relationship with the marine environment within this species. Furthermore, I examine the potential for spatial overlap between NZFT and human activities, providing analysis into potential human impacts on this species.

Objectives:

1. Provide a baseline of spatial information for future studies to determine how habitat relationships may change over time within NZFT.
2. Provide meaningful management objectives which support coexistence between humans and NZFT.

Chapter 4; Investigating the roles of estuarine versus marine foraging by New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) through Stable Isotope Analysis.

Stable isotope analysis has been undertaken within NZFT before, however, previous studies did not explore the role of the marine environment. Here I use the same techniques and methods from previous research to explore that relationship looking into annual variation and highlighting the importance of the marine environment for this species. Furthermore, I isolate key questions for future research to understand the complexities of feeding within this species.

Objectives:

1. Build on previous knowledge of NZFT diets through SIA providing evidence required for future management of this species.
2. Explore how dietary composition changes between seasons within NZFT.
3. Address key areas for further research for further knowledge into marine resources by NZFT.

Chapter 5; Conclusions

Here I provide a summary of this thesis on the key findings, approach taken, limitations and future recommendations from this study.

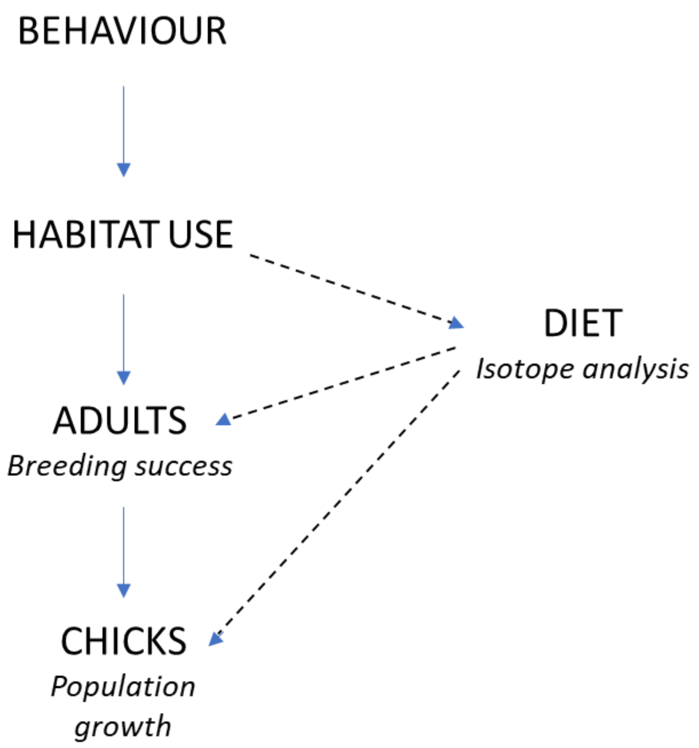


Figure 1.4; Flow diagram highlighting thesis relevance to New Zealand Fairy Tern /Tara iti (*Sternula nereis davisae*) conservation and the potential influences/findings my study may have on the potential for breeding success and species recovery.

2. Foraging behavioural analysis and inferences of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*)

Jacob Ball

2.1. Abstract

Behavioural time budget analysis is a valuable tool that allows analysis into animal behaviour, energy expenditure, breeding variability, habitat use, and individual plasticity. The New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) (hereafter; NZFT) is potentially New Zealand's rarest indigenous breeding bird with around 40 individuals. Current knowledge of NZFT behaviour is limited to observational and ad-hoc knowledge. I used coordinated observations to determine the foraging behaviour, foraging trip length, and foraging time budgets of chick provisioning adult NZFT through focal continuous sampling. Furthermore, I made observations to imply the role of estuarine environments for this species. Observations occurred on 13 individuals (21% of population) throughout the 2021/22 breeding season in Mangawhai, Northland, New Zealand. A mean foraging trip length of 17 minutes ±1 minute was determined for adult provisioning NZFT over which time they spent 97% of time performing foraging related behaviours. Foraging was largely undertaken by males and provided an appropriate proxy for feeding rates to chicks. Foraging was found to vary with weekdays, mean foraging trip length increasing over weekend days. Estuarine habitats were utilised less than expected for foraging trips suggesting other habitats may be of importance, supported by analysis of foraging area determined through trip length. This study has shown that NZFT may be use a wider range of habitats for foraging than previously thought. I suggest that further study is undertaken to determine what other habitats are of importance to this species and how NZFT use the habitats within foraging ranges determined in this study.

2.2. Introduction

The New Zealand Fairy Tern or Tara iti (*Sternula nereis davisae*) (hereafter; NZFT) is potentially New Zealand's rarest indigenous breeding bird with a current population estimate of 40 individuals and 12 breeding pairs (DOC, 2022). This critical population level means the NZFT are currently classified as Threatened – Nationally Critical and have a Category A priority for conservation action from The Department of Conservation (hereafter; DOC) (DOC, 2022; Jeffries et al., 2016). Part of the intensive management by DOC involves unique colour banding of individuals that provides the opportunity to easily identify all known individuals in the population.

Current management of the NZFT population involves nest manipulations, breeding observations, predator control, public awareness and disturbance control, and more recently captive rearing (Ferreira et al., 2005; Parrish & Honnor, 1997). A wide range of other management options exist within species recovery such as supplementary feeding and landscape scale protection (Cade & Temple, 1995; Casazza et al., 2016; Pakanen et al., 2014). While intensive manipulations have been shown to be effective for extinction prevention of endangered species, it is most effective when applied alongside other species conservation actions, such as ecosystem protection(Cade & Temple, 1995). NZFT rely on a diversity of landscapes for foraging that remain unprotected. A greater understanding of habitat used by NZFT breeding populations will provide a case for future protection on a landscape scale, improving likelihood of population recovery.

A critical study by Ismar et al. (2014) highlighted the role of the estuarine environment for foraging NZFT 8 years ago. Further observations of individuals within estuarine environments would provide insights into any changes over the last decade and confirm the ongoing significance of estuaries to foraging NZFT. Although, NZFT are known to consistently use estuarine environments for foraging, there is no published data on the role of marine environments for NZFT. Within Australian Fairy Tern (*Sternula nereis nereis*) (hereafter; AFT) the ocean plays a significant role supporting nest provisioning by adults (Dunlop, 2018; Greenwell et al., 2021) suggesting it could be a reliable source for NZFT. Therefore, expanding the scope of observations during the breeding season to include marine coastal systems, will increase our understanding of the importance of these habitats to NZFT chick provisioning.

Under current ecological conditions NZFT appear to rely heavily on individual foraging territories, seemingly as a reliable source of food throughout the breeding season. This is a unique behaviour among the Fairy Tern sub-species (*Sternula nereis*) however, it may be linked to the variation in foraging habitat between species. Both AFT and New Caledonian fairy tern (*Sternula nereis exsul*) are known to use a wider range of habitats for foraging than NZFT, most notably they have a stronger reliance on the marine environment (Barre et al., 2012; Greenwell et al., 2021; Ismar et al., 2014; Paton & Rogers, 2009). Paiva et al. (2008) highlighted that estuarine environments may be important to the allopatric little tern (*Sternula albifron*s) due to estuarine channels condensing available prey, thus improving foraging potential.

Other Terns are known to have adopted territorial behaviour under similar ecological pressures within similar habitats. Nisbet (1983b) suggests that common terns (*Sternula hirundo*) develop a detailed understanding of their feeding territories, allowing an increase in foraging efficiency, even when food may seem equally accessible within other locations. Furthermore, he found an increased food delivery rate and a higher quality of food item within territorial birds. Nisbet (1983b) showed that individual terns within the same species can adopt a wide range of foraging strategies.

Like most tern species NZFT are single prey loaders, as defined by Orians and Pearson (1979) within the bounds of central placed foraging (Houston, 2000; Houston & McNamara, 1985), NZFT therefore have a strong dependence on foraging habitats close to nesting locations. The foraging strategy undertaken by NZFT alongside current species management provides a unique opportunity to investigate foraging behavioural time budgets using basic observation techniques, where more intrusive methods are not available due to the current conservation status.

The exploration of time budgets can allow analysis into a broad range of avenues such as animal behaviour, energy expenditure, breeding variability, habitat use, and individual plasticity (Buttemer et al., 1986; Kurup & Kumar, 1993; Pöysä, 1991). Litzow et al. (2003) showed that time budgets can be used to effectively determine variation in breeding strategies between populations of pidgeon guillemots (*Cepphus columba*) due to shifts in prey availability, furthermore, Collins et al. (2016) showed that energy expenditure from time spent foraging within kittiwakes (*Rissa tridactyla*) was highly variable due to sitting on the water surface. Findings such as those by Collins et al. (2016) & Litzow et al. (2003) highlight the importance of determining behavioural time budgets to allow analysis into species constraints. Therefore, there is the ability for time budgets to determine insights into habitat preferences, imply energetic requirements, and infer health of

NZFT populations. However, caution must be implemented to prevent the introduction of bias within study design (Pöysä, 1991).

In this chapter I address two key objectives (1) To quantify the foraging time budgets of chick provisioning adult NZFT thus providing baseline information for this population, and (2) to expand our current knowledge on the roles of estuaries and marine coastal habitats within breeding NZFT populations.

2.3. Materials and Methods

2.3.1. Study site and study preparation

I focused this study on the primary breeding location of this species, Mangawhai, Northland, New Zealand. Despite the overall low population size of NZFT, multiple nesting birds occur at Mangawhai hence observations of multiple individuals can be recorded. Three other breeding sites (Waipu, Pakiri, and Papakanui) are known, however, time constraints meant observations of these birds was beyond the scope of this study.

Mangawhai estuary is a 4.6km^2 mesotidal estuarine lagoon comprised of intertidal mudflats, shifting sand bars, converging channels and mangroves within the upper reaches and shallow edges (Zimmerman et al., 2011). The estuary is contained by a 2.5km narrow sandspit where all Mangawhai NZFT nests are located within three primary locations. Mangawhai estuary is home to a wide range of waders, gulls and fish species, with large shellfish beds and mudflats providing unique and rich habitat. The fish diversity is primarily made up of smaller species such as goby (*Favonnigobius sp.*), juvenile flounder (*Rhombelosa sp.*) and mullet (Mugilidae).

Due to limitations stipulated through licencing agreements and a research partnership with DOC, observations were focused on the estuary over the 2021/22 breeding season. Territorial surveys were undertaken during October 2021 when NZFT foraging territories are clearly defined (Southey, *pers comm.*). Nine territories (15 individuals) were found of which 6 territories were associated with breeding pairs (Appendix; Table 2.3.). Continuous monitoring of territorial boundaries was undertaken throughout the breeding season to record any changes that may influence data collection methods (Appendix; Figure 2.7.). ESRI ArcGIS Pro was used to digitise foraging territories.

All observations were undertaken using Hawke Vantage 8x42 binoculars and a Vanguard Endeavor spotting scope (Ө82mm) with a 20-60x zoom eyepiece. Digital photography was also used as images could be reviewed and lighting corrections made when post processing. Digital photography was particularly useful to determine individuals in flight as NZFT hang their legs after ascending from a dive, hence unique band combinations could be identified. Photographs were made using a Nikon D750 with a Tamron G2 150-600mm lens using manual exposure and autofocus.

A single observation location was chosen for each territory (Appendix; Figure 2.7.). These locations met the following criteria: the whole territory was visible, known flight paths were visible, colour bands could be read or determined through photography, and where the observer could safely be located during all tidal states.

A range of behaviours were predetermined before sampling began (Appendix; Table 1). Clear definitions were given to each behaviour to allow distinction between behaviours and future replication. Eight behaviours were described covering the range of known behaviours within NZFT and an 'other' category was defined to allow abnormal or unknown behaviours to be recorded (Burger & Gochfeld, 1991a; Molina & Marschalek, 2003).

2.4. Data collection & Analysis

2.4.1. Observation methods

Observations were split across two observers: nest observers and territory observers. Nest observations were undertaken by DOC staff, and they provided information to me with NZFT arrivals and departures at the nests whenever it was possible for them to do so. I undertook all foraging territory observations. This coordination enabled me to determine foraging durations of focal birds. When there were multiple active nests with chicks, observations on nests were selected at random. Observations were undertaken throughout all daylight hours, however, a slight bias for morning hours was introduced due to role requirements from DOC nest observers.

Communication between observers was undertaken through a combination of handheld UHF radios and mobile telephones when radio signal was deemed too poor for clear consistent communication. When using mobile telephones, calls were preferred to SMS messaging to allow as real-time communication as possible. A radio communication application was later used as a substitute to mobile telephone communication as it provided a preferable alternative when radio signal was deemed too poor.

Nest observers identified individuals at the target nest through individual colour band combinations prior to beginning an observation period. Sexes were chosen at random and were determined by the first identified individual to leave the nest/nest site. Once an individual left the nest site this bird became the focal individual for that observation period. While nest observers were situated at the nest the territorial observer was situated at the associated territory for that nest. The nest observer communicated departure from the nest site to the territorial observer to begin an observation period.

2.4.2. Foraging trip length

An observation period was dictated by the length of time an adult bird would forage. For all observation data collected, I determined overall time budgets and foraging trip lengths. A start time was defined as the time the individual left the nest or nest site, and an end time by the time the target individual returned to the nest or nest site. Multiple sequential foraging trips were undertaken on the same nests where possible and continued until nest observers were no longer present. Foraging time was determined to the nearest minute.

Foraging time budgets focused on foraging for chick rearing and therefore data collection occurred from the time the first chick hatched at Mangawhai until all chicks from all nests had fledged. Hatching was defined as a exiting a shell completely (day 0) and fledging was defined as a bird leaving the natal nest site through flight. Chick age was recorded in days aged from every new day irrespective of the time of day they hatched.

2.4.3. Foraging trip length analysis

Foraging time was log10 transformed prior to data analysis. A series of comparisons were drawn between foraging time; individuals, territory, tidal state, distance travelled, weekday, and abiotic conditions. Comparison of means and standard errors were used to provide descriptive analysis of relationships between groups. A range of statistical analyses were used such as ANOVA, t-test, and Wilcoxon rank sum test where appropriate.

A paired t-test was used to determine differences between sexes and foraging time and pairwise comparisons were used to determine differences between foraging times in individuals. Pairwise comparisons were undertaken on 7 individuals.

2.4.4. Behavioural sampling strategies

Focal sampling was used, recording both continuous and instantaneous sampling on target individuals. A dictaphone was used to collect data allowing continuous observations of target birds. An interval timer set to 1-minute intervals begun at the departure time of the foraging bird to provide an audio queue distinguishing between minutes of the recording and allowing instantaneous sampling to be recorded every minute. Both methods were recorded to evaluate differences between the two methods on foraging NZFT. Continuous behaviours were recorded as a frequency of occurrence over the foraging trip and broken into 1-minute blocks within instantaneous sampling. As such, a proportional sample of how often behaviours were performed was recorded.

2.4.5. Behavioural classifications

Behaviours were recorded into 10 categories combining both state and event behaviour types: *Resting, Aggression, Courtship, In flight, Foraging, Dive, Dive attempt, Out of view, Out of Sight* and *Other* (Appendix; Table 2.4.). Behaviours were recorded every time a change in behaviour was seen from a target individual. Where the water surface could not be seen i.e. a bird was foraging within vegetation, then dives were not recorded and the behaviour was recorded as out of view/ In these cases notes were taken to indicate if dive-like behaviour occurred (as a distinct from 'Dive attempt' or 'Dive').

2.4.6. Behavioural sampling

Flights where no bird was seen, or where discrepancy was seen between observers were removed from the data set prior to analysis (n=28). Count data was used to show the frequency of occurrence for a behaviour and standardised as a proportional representation of each foraging trip. To determine the proportional occurrence of behaviours for NZFT, a mean value was determined for all foraging trips recorded to provide an analysis of mean proportional occurrence of behaviours within a provisioning adult NZFT foraging trip.

$$\left(\frac{\text{Behaviour } x^{1}}{\Sigma \text{ (Counts of all behaviours)}} \right) \text{ X } 100$$

2.4.7. Travel Time

While ‘Out of Sight’ behaviour is related to time taken for individuals to travel to the foraging location it also encompasses any time a bird is out of sight and therefore cannot be directly used to determine travel time. To evaluate time taken for a target bird to travel to the foraging location, the time taken to arrive from the nest to the foraging location, and the time taken for a bird to leave the foraging location and return were used to determine the travel time. A mean value was determined for each foraging trip. Observations where a direct flight was not apparent as well as where detection was immediate were excluded from the analysis. Distance was determined to the central point of a foraging territory to provide a singular value for all foraging trips associated with each individual territory. Accuracy was determined to the nearest mean minute and average speed determined for all trips in m/s with an error of 60 seconds.

2.4.8. Estuarine use by NZFT

Presence or absence of NZFT was also recorded when any NZFT was seen or heard irrespective of it being the target individual. This was to understand what conditions may affect the use of Mangawhai estuary by NZFT, using presence/absence as a measure of environmental suitability for foraging NZFT. Data was grouped through presence and absence i.e. a bird seen or not seen. Mean foraging trip length was compared between the two groups through a paired t-test to analyse the importance of estuaries for NZFT. A further comparison in percentage rate of detection was made between the two groups over the 6 tidal categories suggesting preference. A chi-squared analysis was undertaken to determine significant differences between groups.

2.4.9. Chick age

Chick ages were defined for each day using the hatching date and the date of the observation. Within 2-chick nests a mean value for chick age was determined to provide a singular value for each nest as individual chicks could not reliably be identified. Chick ages were grouped into 6-day periods (0-6, 7-12, 13-18, 19-24, 25-31) for comparison of foraging trip length between groups. 6-day periods were chosen as to provide a more equal variance between groups allowing improved statistical robustness whilst still being relevant to NZFT life history. An ANOVA was used to determine if there was significant variation in mean foraging trip length between chick age groups.

2.4.10. Weekday comparison

Data were grouped by weekday (Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, and Sunday) to determine the influence of weekday on foraging trip length. Data collection days were undertaken at random, however, Tuesday was underrepresented within the data (n=4). Mean foraging trip length was determined for each day and a compared visually and statistically. Kruskal-Wallis analysis was used to determine the between means and a Tukey HSD analysis undertaken for pairwise comparisons. A comparison between weekend and weekdays means was made through a paired t-test.

2.4.11. Territoriality

NZFT behaviours were used to determine territorial boundaries between resident males. Males more commonly perform territorial behaviours; therefore, territories were delineated through male behaviours. Key behaviours include, posturing, aggressive vocalisations, flight displays and chasing of conspecifics (Appendix; Figure 2.8). Prior to egg laying individuals flight pathways were determined from the breeding site to each territory to ease detection of individuals during observations.

A comparison between territories occupied by breeding pairs (1,3,4,6,8) was undertaken using ANOVA and Wilcoxon-rank sum. The variation between territories was also used as a proxy for comparison between individuals as sample size of individuals prevented meaningful analysis.

2.4.12. Abiotic parameters

Environmental conditions were also measured to understand the influence on behaviour. The conditions measured included: wind speed, wind direction, wave height, last high tide time and height, cloud cover, turbidity, wave height, air temperature, and rain. Wind speed was determined using a handheld anemometer recording an average over 10 seconds at 1.8m (± 0.1m) above ground level. Wind direction was determined using visual cues and a compass. Wave height was determined on the Beaufort scale independently of wind speed as other factors may influence wave height (Jefreys, 1925). A Land information New Zealand tide table was used to determine tide time and read from Marsden point to allow for standardisation with other data from separate locations in this research. Cloud cover was recorded as percentage cover on all visible sky. Rain was determined as present or absent (yes or no). All environmental conditions were recorded at the start and end of an observation period and median values drawn providing a singular value for each observation.

Frequency of wind directions (north, northeast, east, southeast, south, southwest, west, northwest) were recorded at the start and end of each observation. A median direction was determined to provide a prevailing direction over that observation. Wind directions were also grouped into two dominant directions: southwest (south, southwest, and west) and northeast (north, northeast, and east).

Tidal categories were divided into high, high outgoing, low outgoing, low, low incoming, and high incoming. A tidal cycle takes 12 hours and 25 minutes, to determine the variation between groups 12 hours and 25 minutes was divided by 6 and added to the recorded last high tide time to determine the tidal category at the time of observation. Tidal category means were compared through Kruskal-Wallis and Tukey HSD to determine pairwise comparisons and differences in mean foraging times between tidal states.

2.4. Results

2.4.1. Basic Results

Over the 2021/22 NZFT season 5 breeding pairs formed at Mangawhai, producing 11 eggs, 8 of which hatched. These five breeding pairs held distinct foraging territories in the Mangawhai estuary. The first egg hatched on the 16/12/2021. The final egg laid in this study hatched on the 31/12/2021.

A total of 103 observations were made over the chick rearing period in the 2021/22 breeding season. Of these 88 included full foraging events in which the focal individual was tracked from leaving the nest to returning to the nest. Nine observations did not include a known time of return to the nest. Observations occurred from the first hatching day of 15/12/2021 until the last fledging date of 30/01/2022.

Behaviours were defined based on detailed descriptions from Ornithological Society New Zealand NZFT observers and DOC staff. Over the pre-sampling period, NZFT were observed to have individual flight paths often flying high, direct, and avoiding passing over other NZFT territories (Appendix; Figure 2.7). The nature of these flight paths improved reliability for identifying individuals. Both males and females used these flight paths, however, there was an observational difference seen between sexes, with females observed to have flight paths less dependent on territorial boundaries.

2.4.2. Foraging trip length

Foraging trip length was recorded as the continuous time a focal bird was observed leaving a nest, ending when the bird returned to the nest. From 15th December 2021 until 30th January 2022 foraging observations were made on nine individuals from five different nests. Four males and five females were observed over this time and foraging times, foraging budgets, and abiotic factors were measured. Overall, 88 foraging trips were recorded over the 2021/22 breeding season (male = 68, female = 33). Of these, NZFT were seen on 44 of them. Of the 44 trips where NZFT were detected, the focal bird was directly identified for 6 foraging trips and inferred based on flight paths, observer correlations, and foraging territory for the remainder. There was no difference in foraging trip lengths for birds that were observed foraging versus birds that were not observed foraging.

Mean foraging trip length was similar for males (18 minutes) and females (17 minutes), and 17 minutes overall. The longest foraging trip for a male was 1 hour and 4 minutes and the shortest was 1 minute. The longest foraging trip for a female was 41 minutes and the shortest was 4 minutes. Of the nine incomplete foraging trips removed from analysis (male n = 6, female n = 3) the greatest time spent away from the nest was 1 hour and 35 minutes.

Foraging trip length was found to vary between chick age groups, showing a downward trend in time spent on a foraging trip as chick age increased; $\bar{x} = 21.7 \pm 1$ min for chicks 0-6 days (n=19), and $\bar{x} = 11$ min ±1 for chicks were aged 25-31 days (n = 11) (Figure 2.1.). There was no apparent sex difference in foraging times. The largest difference in foraging between sexes was found when chicks were 7-12 days old and males foraging trip length was a $\bar{x} = 13.2 \pm 1$ mins longer than females (Figure 2.1).

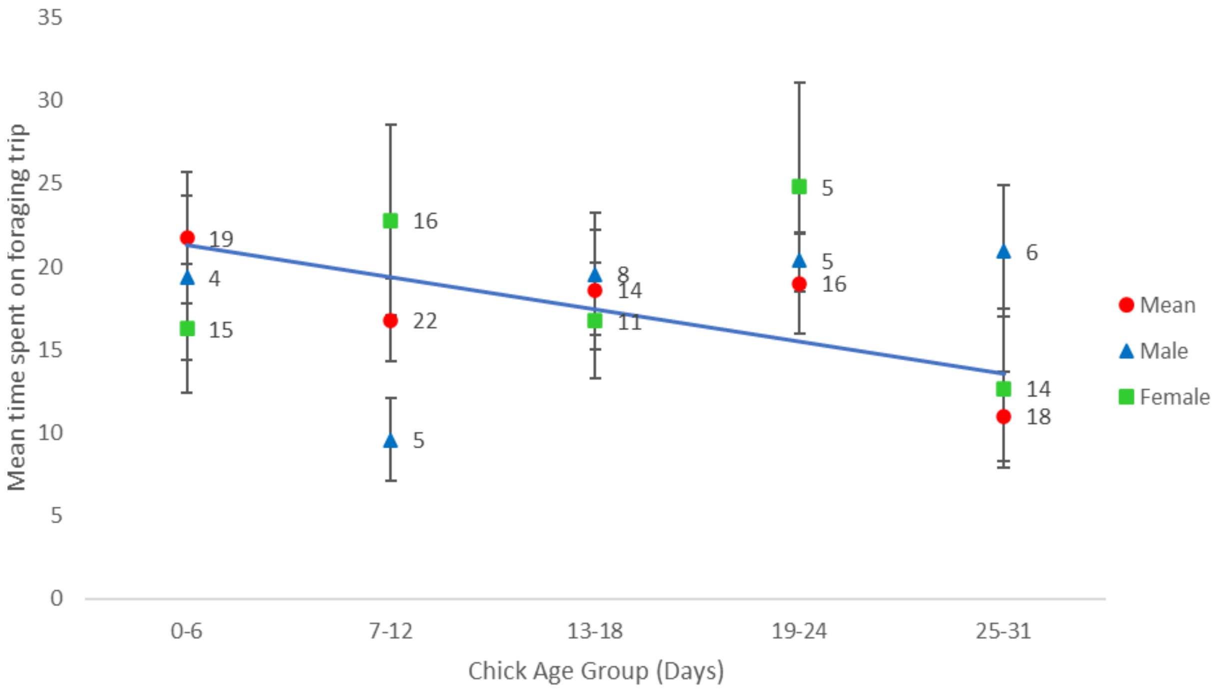


Figure 2.1; Comparison between mean foraging trip length (mins) and chick ages (days) within provisioning adult, male and female New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand.

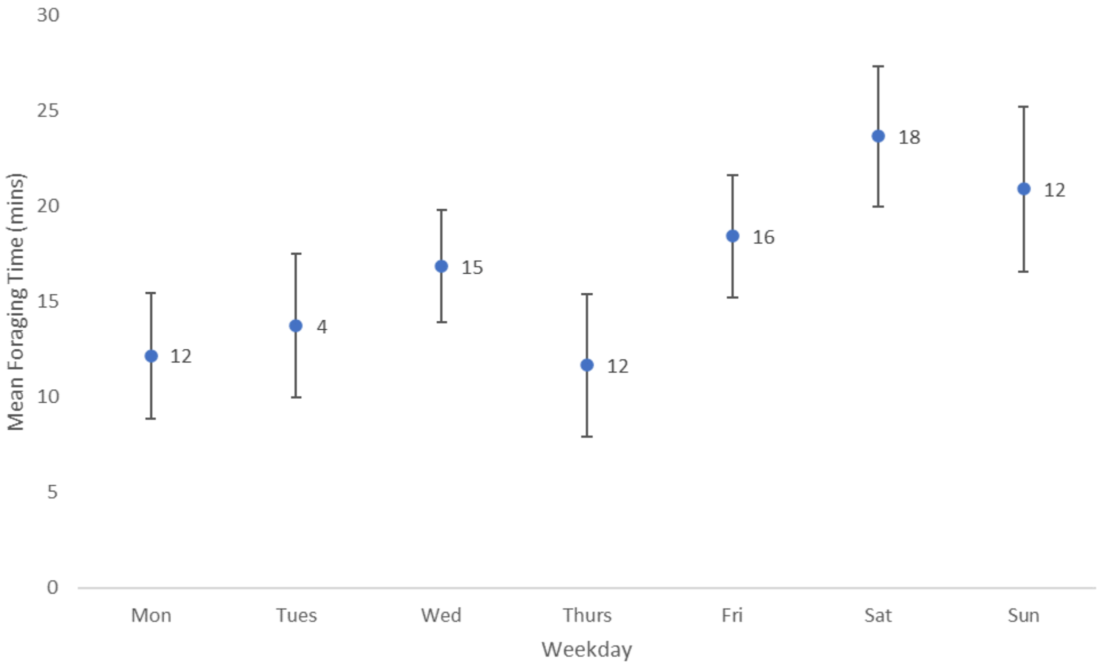


Figure 2.2; Comparison of mean time spent on a foraging trip between weekdays within provisioning adult New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand. Standard error bars displayed; n values display as labels.

Foraging trips were found to vary with weekday, a greater foraging trip length (x̄ = 22 ± 1 mins) was found over weekend days, compared to weekdays (x̄ = 15 ± 1 mins) (Figure 2.2). Detection rate of NZFT was similar throughout the days of the week and weekend days were not found to influence likelihood of detection.

2.4.2.1. Territory

Generally, I found positive correlation between foraging trip length and increasing distance between the foraging territory and nest site (i.e. from territory 6 to territory 1) (Appendix; Figure 2.7). However, the longest foraging durations were found for territory 8, the closest territory to the nesting site.

A significant difference in mean foraging trip length was found in pairwise comparisons between territory 6 and 3, 6 and 1, and 6 and 8 (Wilcoxon rank sum, $df = 4, p = <0.05$). Within other territories there was little disparity between foraging time between males and females, neither spending a significantly different length of time foraging ($t = 1.0085$, $df = 67.57, p = >0.05$) (Figure 2.3). The greatest foraging trip length was observed for male W-KM (x̄ = 29.7 ± 1 mins) and the shortest foraging trip length was also a male BK-M (x̄ = 9.6 ± 1 mins) (Figure 2.3). Territory 4 had the fewest observation periods due to access difficulties.

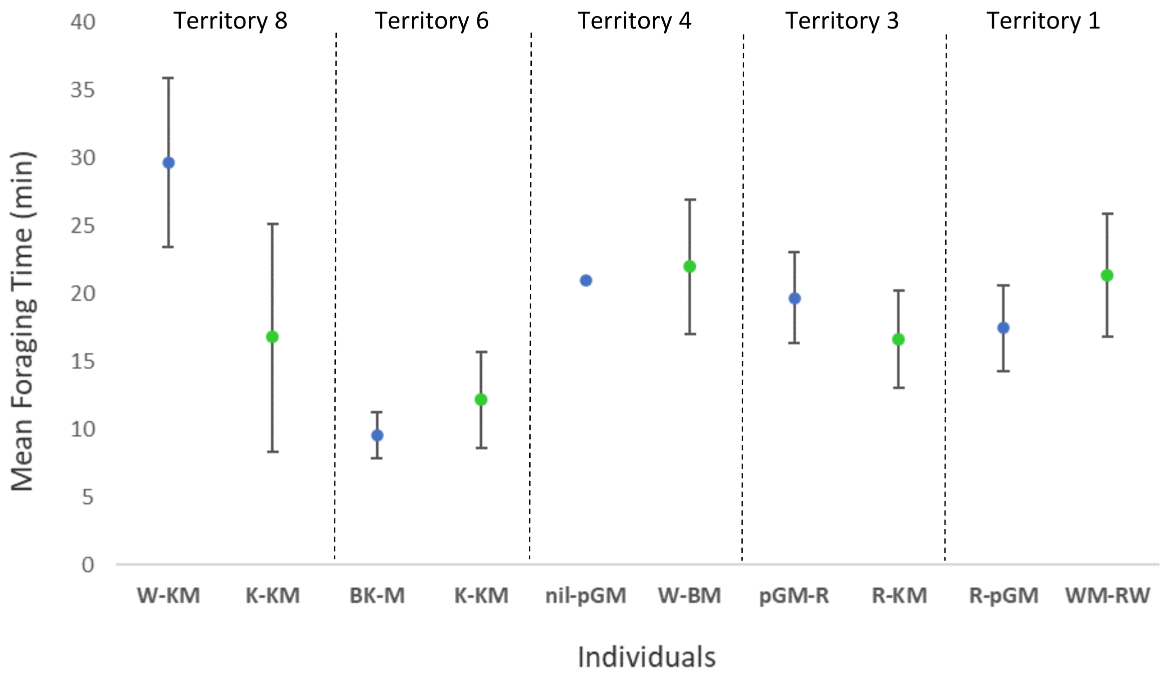


Figure 2.3; Comparison between individuals in mean foraging trip length within provisioning adult, male (Blue) and female (Green) New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand. Individuals grouped by pair groups, territories, and sex. Standard error bars displayed.

2.4.2.2. Tidal influence

I found a small difference in mean foraging trip length between low (n=61) and high (n=21) but it was not significant (*t = 0.65582, df = 46.02, p= >0.05*). The longest foraging trip length was found on an incoming high tide (n=3) (Figure 2.4) and the shortest over an incoming low tide (n=25). No difference was found between an incoming low tide and an outgoing low tide (n=36).

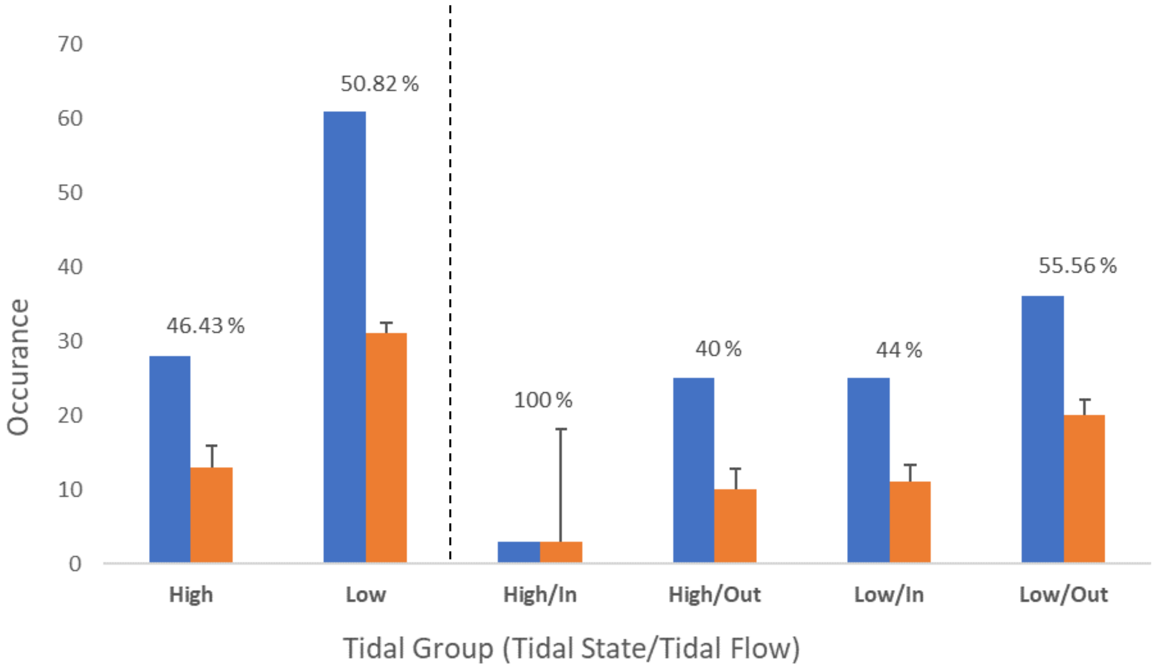


Figure 2.4; Occurrence of detection of NZFT over tidal categories within New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand. The total observations undertaken during each tidal category are shown (blue) with a percentage of observations where NZFT were detected (orange) and displayed as a label. Standard error bars displayed. High (n=21), Low (n=61), High/In (n=3), High/Out (n=25), Low/In (n=25), Low/Out (n=36).

2.4.4. Foraging behavioural time budget

Behavioural foraging observations were undertaken from 15th of December 2021 till the 29th of January 2022 on 6 individuals from 4 different nests over the breeding season within Mangawhai estuary totalling 521 minutes of observation (n=27). Males were observed more frequently than females (n=25 and n=2, respectively). Majority of nests observed for contained a 2-chick nest (n=26), and one had a 1-chick nest. The mean foraging trip length was 18 minutes ± 0.01 min, the minimum time was 3 minutes, and the maximum foraging time was 50 minutes.

A continuous sampling method was used to determine behavioural time budgets. Twenty-six foraging trips from 6 individuals (n=6) were used in the time budget analysis. Foraging time varied greatly from 50 ±2.67 minutes to 3 ±2.67 minutes ($\bar{x}$ = 19.46 ±2.67 minutes) (Table 2.1). *Foraging* behaviour was found to have the greatest frequency of occurrence (46.22%) and courtship was found to occur the least often (0.29%) (Table 2.1).

When grouping behaviours into those related to foraging (*Foraging, In Flight, Dive, Dive attempt*) and those unrelated (*Aggression, Courtship, Resting* and *Other*) and excluding the category *Out of View*, it is found that NZFT spend 98.7 % of a mean foraging trip performing foraging related behaviours, whereas <2% was spent performing behaviours unrelated to foraging.

Table 2.1; Observation time budget analysis of provisioning parent New Zealand Fairy Tern (*Sternula nereis davisae*) (n=6) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand. Mean frequency of occurrence for each behaviour is shown as well as the proportional percentage of time a behaviour is performed over a mean foraging trip. Data was collected using continuous data collection methods.

Calc	*n*	*Foraging Time*	*Out of View*	*Foraging*	*In Flight*	*Dive*	*Dive Attempt*	*Aggression*	*Courtship*	*Resting*	*Other*
Mean	26	**19.46**	**1.65**	**18.35**	**9.27**	**8.00**	**1.92**	**0.15**	**0.12**	**0.23**	**0.00**
%	-		**4.17**	**46.22**	**23.35**	**20.16**	**4.84**	**0.39**	**0.29**	**0.58**	**0.00**
SE		2.67	0.36	2.79	1.30	1.29	0.50	0.11	0.06	0.19	0.00
Min		3.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00
Max		50.00	7.00	55.00	26.00	27.00	10.00	2.00	1.00	5.00	0.00

2.4.4.1. Influence of chick age on Behaviour

Foraging behaviour grouped by chick age showed a similar pattern in behavioural time budgets (Figure 2.5). *Foraging* behaviour occurred most frequently when chicks were between 19-24 days old (n=2) and the lowest occurred when chicks were between 25-31 days of age (n=9). Rates of *Foraging* behaviour increased as chick age increased from 0-6 days (15.64%) to 19-24 days (23.49%), however foraging trip length was not found to vary between groups. Rare behaviours (*Dive attempt, Aggression, Courtship, Resting*) were found to vary slightly between groups, however low occurrence rates prevented meaningful analysis.

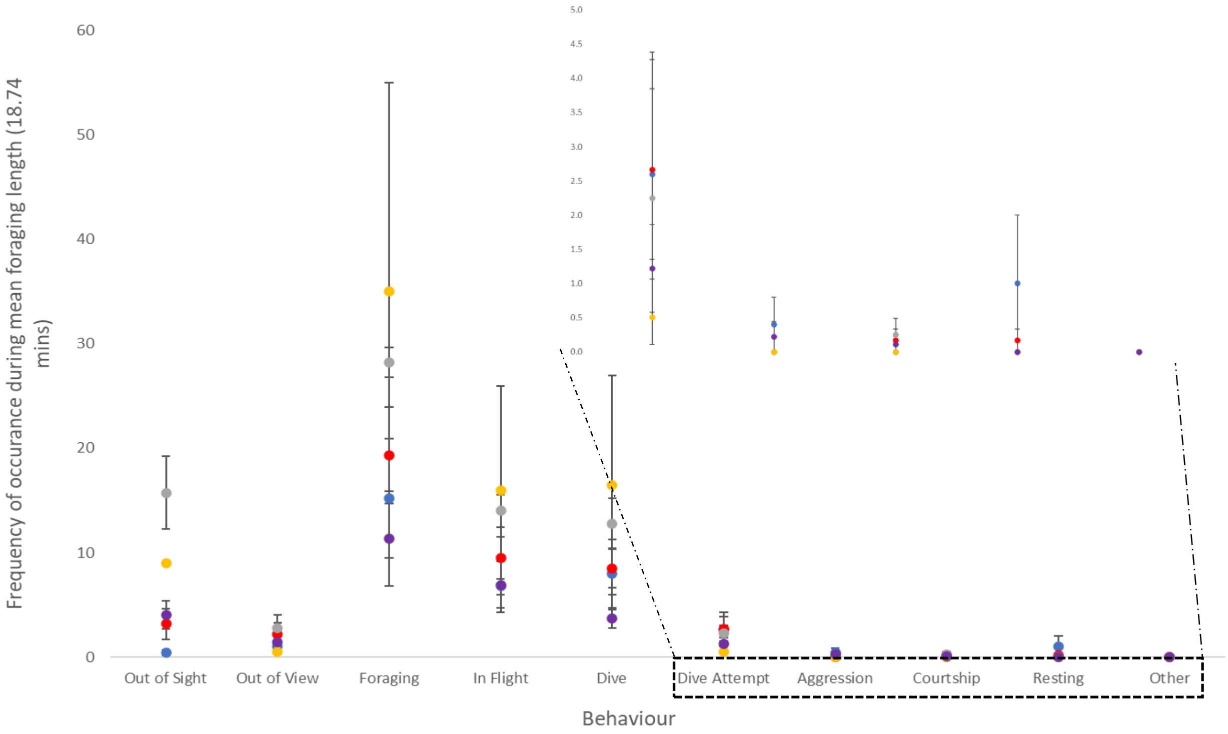


Figure 2.5; Mean frequency of performed behaviours by adult provisioning New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) (n=6) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand. A comparison between chick age groups (0-6 (n=6) (Blue), 7-12 (n=6) (Red), 13-18 (n=7) (Grey), 19-25 (n=1) (Yellow), 26-31 (n=7) (Purple)) are shown for all behaviour categories. Data was collected using continuous observation.

2.4.6. Estimating foraging range

14 foraging trips from 5 individuals were used to determine mean travel time (x̄ = 5 minutes 28 seconds ±60 seconds) and mean time spent *Foraging* (x̄ = 8 minutes 51 seconds ± 60 seconds). Using the central point of a foraging territory as a measure for distance allowed a calculation of flight speed range (8.4m/s to 14m/s). Using mean value of flight speed (10.38m/s) (Table 2.2) the mean distance a NZFT may travel when assuming continuous flight is 10.59km ±5.68km (Figure 2.6). Within the longest recorded foraging trip of 64 minutes, the individual could have travelled a mean distance of 39.86km ± 21.39km with the same assumptions (Appendix; Figure 2.12).

Table 2.2; Foraging time and flight speed travelled for provisioning adult New Zealand Fairy Terns (*Sternula nereis davisae*) (n=5) within the 2021/22 breeding season in Mangawhai, Northland, New Zealand.

Foraging Time (s)	*n*	*Mean Travel Time (s)*	*Mean Time Foraging (s)*	*Mean Speed (m/s)*	*Min Speed (m/s)*	*Max Speed (m/s)*
550.7 ±60	14	327.6 ±60	531 ±60	10.38	8.38	13.95

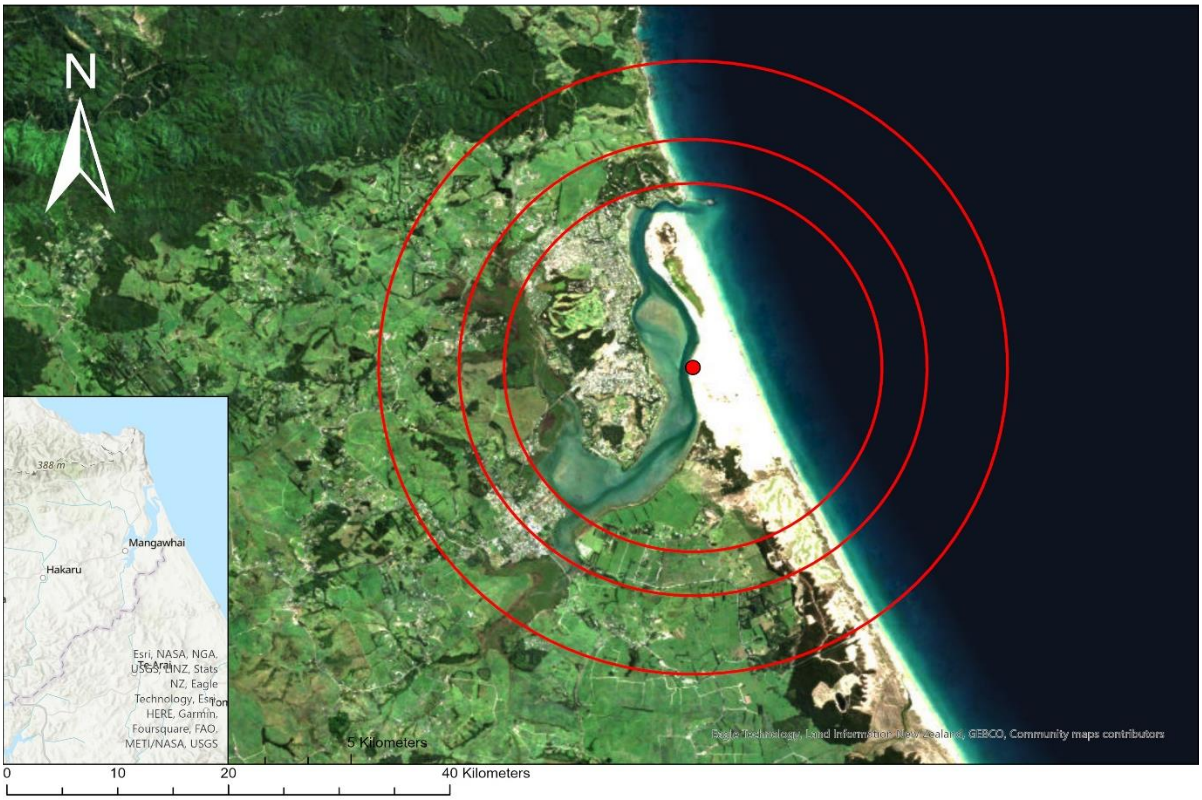


Figure 2.6; Area available to foraging New Zealand Fairy Tern/tara iti (*Sternula nereis davisae*) when traveling at minimum (inner circle), mean (middle circle), and maximum (outer circle) flight speeds.

2.5. Abiotic conditions

Abiotic conditions remained stable over the sampling period. The minimum wind speed record was 0m/s recorded on multiple dates and the maximum was 7.6m/s on 18/1/2022 with a mean wind speed of 3.1m/s (n=44). Wind speed was consistent throughout the study period and mean values were greater in January than December, with a difference of 0.25 m/s. Wind direction was recorded for 89 observations, the prevalent wind direction was SW (n=39) with a changing wind direction seen throughout most observation periods (n=79). The next most prevalent wind direction was Northly (n=7), no statistical difference was found between foraging times and all wind directions (TukeyHSD, *df = 3, p = >0.05*).

A mean estuarine water clarity value of 53.37cm ±2.73 (n=66) was found over the data collection period, the minimum clarity was 11cm and the maximum was over 100cm. Clarity was found to be comparable between months, however, it was slightly greater in January (n=43) than in December (n=23), with an increase in water clarity of 1.48cm. I compared clarity between territories and found an increase in mean clarity with proximity to the mouth of the estuary (territory 1 to territory 8). I found a significant difference in water clarity between the two most separated territories 1 and 8 (TukeyHSD, *df = 4, p = <0.05*).

Within the estuary, I measured a mean wave height of between Beaufort 1-2 (n=62) over the data collection period. A negligible difference in wave height was found between January (n=42) and December (n=20). When comparing wave heights between all territories a significantly greater wave height was found between territory 6 and territory 1 (TukeyHSD, *df = 4, p = <0.05*). A mean wind speed of 2.56m/s ±0.19 (n=79) was found over the data collection period. Wind speed also varied little between January (n=45) and December (n=34) with a difference in means of 0.24m/s. There was no significant difference in wind speed between territories (TukeyHSD, *df = 4, p= >0.05*).

Over the data collection period the mean air temperature was 20.25 ± 0.16 °C (n=55). The mean temperature was warmer in January than December, with a mean difference of 0.87 °C. A mean cloud cover of 60 ± 3 % (n=58) was found over the data collection period, with December (n=15) having a 16% greater mean cloud cover than January (n=43).

2.6. Discussion

2.6.1. Foraging trip length

This study was able to accurately determine mean foraging trip lengths for NZFT within Mangawhai, from a large percentage (21%) of the total current population (DOC, 2022) allowing a meaningful analysis. Mean foraging trip lengths fit the theory of central placed foraging, furthermore, fitting the role of single-prey loaders (Bogliani & Massara, 1990; Houston & McNamara, 1985). This study also highlighted the potential for large variation in foraging trips, suggesting that chick provisioning NZFT may use separate resources for different foraging uses i.e., chick provisioning and self-provisioning, like other seabirds (Elliott et al., 2008; Ropert-Coudert et al., 2004).

2.6.1.1. Weekend comparison/People

A range of influences were analysed within this study to determine how foraging trip length varied such as weekday, chick age, and tidal influence. The influence of human disturbance on estuarine bird species has been well documented, particularly within species which rely on this habitat after long migrations (Fitzpatrick & Bouchez, 2010; Pienkowski, 1992). Variations in foraging trip length between weekdays shown in this study may be linked to anthropometric influences. Mangawhai's human population is greatly influenced through seasonality, increasing over the summer period including weekends (Brunsdon, 2020). Population influxes over weekends may explain variation in foraging lengths between weekdays and weekends. Furthermore, anthropogenic influence is not evenly spread throughout the estuary, the accessibility and sediment type of the lower estuary provides a higher attraction for recreation, alongside a greater area for water sports and recreation. Variation in foraging trip length between territories reflects this as territory 8 had a greater mean foraging trip length than all other territories while being situated closest to the nesting site, disagreeing with the predicted hypothesis.

2.6.1.2. Foraging Trip variation in chick age

Mean foraging trip length was found to vary with chick age, and while not a direct relation of feeding rate, it may be used as an effective proxy (Davoren & Montevecchi, 2003). The general downwards trend in length of foraging trip as chick age increased may be linked to two key influences. Gape size limits prey size within NZFT, as chick age increases so does gape size, thus allowing a reduction in time required to locate suitable prey (Hulsman, 1980; Tern & Shealer, 1998), and increasing efficiency by provisioning NZFT (Fernández et al., 2011; García-Navas et al., 2012) (Fernández et al., 2011; García-Navas et al., 2012). Furthermore, the role of energetic demands from aging chicks would increase requiring higher feeding rates. Watson et al. (2012)Watson et al. (2012) found that feeding rates increased with chick age in Rosette Terns (*Sterna dougallii*) supporting the findings in this study. Future implications of prey fluctuations or changes to habitat through indirect or direct actions may influence future breeding success within NZFT.

2.6.1.3. Tidal influences

The role of tide within all Terns has been well documented(Becker et al., 1993; Ismar et al., 2014; Nisbet, 1983b; Taylor, 1975), multiple studies highlighting Terns favouring a changing or lower tide. I also found that NZFT have a slight preference for a lower tide or a changing tide, the strongest preference was seen for a high decreasing tide. This may be due to an increased fasting period over the higher tide, thus, a decreasing high tide is the first opportunity to forage.

Furthermore, the role of tidal movement may influence prey distributions pulling prey into channels and leaving tidal pools where concentrations of prey may exist. Tidal direction may also influence the detectability of prey items as they must move to counter act the role of the tidal force and remain within locally to their territory (Locatello et al., 2021).

The greatest influence tide may have on NZFT are the types of prey items NZFT select. NZFT in estuaries mostly forage for demersal fish species, but do not have the ability to undertake deep plunge dives like other coastal foragers (Greenwell et al., 2021; Hamer et al., 2001). The depth of water can therefore act as a limitation on foraging for this species and prevent all prey from being targeted. It is therefore reasonable to suggest that NZFT may favour a lower or decreasing tide as this allows individuals to effectively target demersal fish species, a large proportion of their estuarine diet.

2.6.1.4. Territoriality

Seabirds such as Gannets (*Morus sp.*) are known to use foraging area fidelity to improve foraging efficiency (Ropert-Coudert et al., 2004), territoriality replicates this and may also be used to increase foraging efficiency while reducing competition. NZFT are known to show rare foraging behaviour within Terns (Sternidae), in that males occupy estuarine foraging territories (Baling, 2008; Zimmerman et al., 2011, Southey, pers comm., 2021). This behaviour has previously been observed within other terns such as sandwich terns (*Sterna sandviscensis*) and common terns (*Sterna hirundo*) (Nisbet, 1983a; Stienen et al., 2000). Nisbet (1983b) found that common terns adapt foraging behaviour throughout the breeding season depending on the spatial distribution of suitable prey species. He also found males display territoriality behaviour within courtship and defending throughout chick rearing, very similar to current NZFT behavioural expressions. While current knowledge of NZFT foraging shows a strong reliance on foraging territories, there have not yet been the required ecological pressures to influence a territorial foraging strategy, notably from an increase in population density. It is likely that, as ecological condition's change, the foraging strategy may likewise adjust, affecting previous estimations of carrying capacities and species management strategy.

2.6.1.5. Habitat use

On numerous occasions, NZFT were known to have departed the nest on a foraging trip but not visit their estuarine territory, implying foraging is occurring in a separate habitat. Mangawhai is a spit is surrounded by water on the east, north and south sides, thus providing many foraging opportunities. The role of marine foraging has been largely overlooked within NZFT, my study suggests it is a potentially important foraging location for NZFT, as it has been found within AFT (Dunlop et al., 1988; Greenwell et al., 2021). Furthermore, the role of other inland water sources may be of greater importance to NZFT than previously thought. Inland lakes have previously been shown as a resource within foraging NZFT (Harris et al., 2019; Preddey & Pulham, 2017), and highlights the potential diversity of this species to adapt to different to water systems (Cotin et al., 2011; Greenwell et al., 2021).

The method used within my study was dependant on the role of territoriality in the estuary by NZFT. While this was found to be the most common foraging location there is potential that a bird travelling to its foraging territory may utilise a nearby unoccupied territory to forage. Nisbet (1983b) suggested however that common terns (*Sterna hirundo*) actively avoided foraging within competitors' territories, suggesting that individuals learnt the distribution of prey items within their territory, thus improving the efficiency of foraging making foraging within competitor's territories unbeneficial.

When analysing the relationship between foraging time and chick age, two key outliers were found within the 25-31 age group. These outliers showed an increased time taken to forage for a pair (a male and female from the same nest). This foraging event took 45 minutes for the male and 36 minutes for the female to finish the foraging trip both occurring on the same day 16th of January 2022 over the high tide period. During this time tidal surges were also occurring within the associated foraging territory due to a large volcanic eruption from the Hunga Tonga – Hunga Ha'pai volcano (Amores et al., 2022). This highlights the potential influence of natural events on breeding birds, while nests may not be damaged, an increased foraging time if prolonged may lead to nest abandonment and therefore reproductive failure.

2.6.1.6. Sex Roles

Previous observations have highlighted a potential sex role within NZFT, suggesting males undertake most of the foraging activity (Parrish & Pulham, 1995; Preddey, 2008). This study found that when using foraging trip length as a proxy for foraging effort there was no significant difference between sexes. Furthermore, it highlights that both sexes are travelling similar distances implying use of the same resource.

While there is no significant variation in foraging trip length, there is a large variance in number of observations between sexes with males recorded on 33 more foraging trips than females. Due to the randomised methods used when selecting a target individual within this study, this suggests that males have an increased foraging effort within the chick rearing period than do females, supporting previous research (Parrish & Pulham, 1995; Watson et al., 2012).

2.7. Behavioural time budgets

Determining time budgets can allow a detailed understanding of foraging efficiency and strategy, energy expenditure, population health, and behavioural analysis (Delius, 1988; Ropert-Coudert et al., 2004; Tremblay et al., 2003; Tripet et al., 2002; Weathers et al., 1984; Wolf et al., 1975). While a wide range of behavioural inferences require multiple populations to understand behavioural change (Tripet et al., 2002), baseline data provides opportunity for future comparisons within the same populations. No previous study on NZFT has effectively determined foraging time budgets within the species. With large-scale habitat changes occurring within Mangawhai (Brunsdon, 2020), baseline data is essential for future comparisons. My study effectively determined the foraging time budget of NZFT.

Findings in this study show that *Foraging* behaviour accounts for the majority of performed behaviours in chick provisioning NZFT. Within a functional population you would expect a greater amount of time given to performing rare behaviours such as resting or courtship (Kitaysky et al., 1999; Swennen et al., 1989). Foraging behavioural time budgets have however been largely understudied, therefore the influences of this remain ambiguous. Furthermore, within this study behaviour was not recorded at the nest site, individuals may prefer to rest or perform courtship displays near offspring where chicks can be protected (Burger & Gochfeld, 1991b; Riechert & Becker, 2017).

Furthermore, time spent foraging greatly reduces amount of time devoted to performing other potentially key behaviours. In current ecological conditions territoriality ensures that NZFT have a reliable food source, additionally, courtship is crucial in affirming pair bonds, thus both behaviours increase the chance of producing viable offspring (Riechert & Becker, 2017). With a current male bias within the population performance of these other behaviours is even more critical and may currently be a greater influence on chick rearing success (Burger & Gochfeld, 1991b).

2.8. Distance

Within foraging times not all trips were observed until the target bird returned to nest. The greatest length of these trips was a male observed away from the nest for greater than 1 hour and 35 minutes. This occurred over a low rising tide when foraging is thought to be optimal for NZFT within the estuarine environment (Ismar et al., 2014). This occurred within an individual whose foraging habitat is found at the western tip of the estuary and therefore may have suitable foraging habitat for a shorter time. If a continuous flight was undertaken by this foraging male, then there is potential for it to have travelled greater than 67.83km over this foraging trip. This trip occurred when parental pressures may have been lessened as the chick age was greater than 25 years old but, highlights that foraging NZFT may be using other resources and have a broader habitat use than previously thought.

2.9. Abiotic conditions

Adverse weather is known to have a strong effect on nesting birds, both directly and indirectly, in particular NZFT are highly vulnerable due to their breeding strategy (Ramos, Maul, Ayrton, et al., 2002; Scopel & Diamond, 2018a, 2018b). The 2021/22 season had low variation in abiotic conditions due to stable weather, preventing meaningful analysis into effects of abiotic conditions on foraging NZFT.

The influence of precipitation on the water surface was predicted to influence foraging. While limited data was obtained for meaningful analysis into the effects of rain on foraging, the longest foraging trip recorded was during a heavy rain event when water clarity was beyond 100cm. This finding may suggest precipitation is a large influence on foraging ability. Previous studies have found an increase in density of plunge diving species such as foraging Terns within areas of high-water opacity (Henkel, 2006; Holbech et al., 2018). While this seems an unlikely correlation, water opacity is associated with high energy output and high amount of organic material, in turn attracting a higher density of fish (Stephenson et al., 2012). This study alongside previous research suggests that rain events may be of greater detriment to NZFT foraging ability than water clarity. (Stienen et al., 2000; Taylor, 1983). Further research into the role of weather conditions and influences of weather on foraging resources would be greatly beneficial to improve management strategies offsetting energetic demands on individuals.

2.10. Future directions

More recent studies on time budget analysis are undertaken using GPS trackers providing accurate and reliable data on the same parameters undertaken within this study (Cairns et al., 1987; Fauchet et al., 2021; Fijn et al., 2017b). Furthermore, GPS trackers provide constant location data, providing further answers to questions surrounding resource portioning and resource use within birds. Previous studies have shown the scientific benefit to GPS tracking within sternula terns (Fijn et al., 2017c; Kokubun et al., 2015; Whittier & Leslie, 2005). The limitations within GPS tracking have until recently been the size and weight, as adult NZFT only weight ~70g (DOC, 2022) the potential impacts of GPS would have to be approached cautiously ensuring there was no negative impact. Previous studies into the effect on breeding arctic terns found no impact to chick provisioning within birds fitted with a GPS and a leg flag (Seward et al., 2021). There is potential for GPS to be ethically applied to NZFT allowing invaluable data to determine habitat use, habitat importance, and behavioural time budgets of NZFT.

Small terns are known to be selective foragers over the chick rearing period and often target size appropriate prey, rather than species (Brenninkmeijer et al., 2002). The role of gape size within NZFT makes understanding prey availability crucial to successful recruitment within this species. Greenwell et al. (2021) found that prey size differed between courtship (adult provisioning) and chick provisioning in AFT, furthermore, roseate terns are known to select size appropriate prey for chicks (Martins et al., 2004). The availability of prey within Mangawhai was not recorded within this study, however, future research should evaluate how fish populations change in both size structure and availability. Influences on estuarine prey availability would currently prevent the successful conservation of this species.

2.11. Conclusion

This study has provided previously unexplored factors within NZFT foraging ecology, providing a baseline understanding of foraging trip length, foraging rate, and foraging time budget analysis for this species. As the human population increases within Mangawhai there is potential for it to influence foraging NZFT, having a baseline understanding of both time budgets and foraging trip lengths can provide insights into the ability for the species to effectively locate prey. This will provide a further tool to assess future population health, environmental resource management and aid in improving population recruitment.

Furthermore, this study has highlighted unexplored questions into habitat use by NZFT through the role of foraging distance. This study suggests that the marine environment may play a greater role than previously believed. When compared to other sternula terns this may not seem surprising, however, previous literature has highlighted on the dependency for estuarine habitat within NZFT. This may highlight a potential for adaptation within this species and increase known habitat suitability of NZFT influencing future management actions.

2.7. Appendix

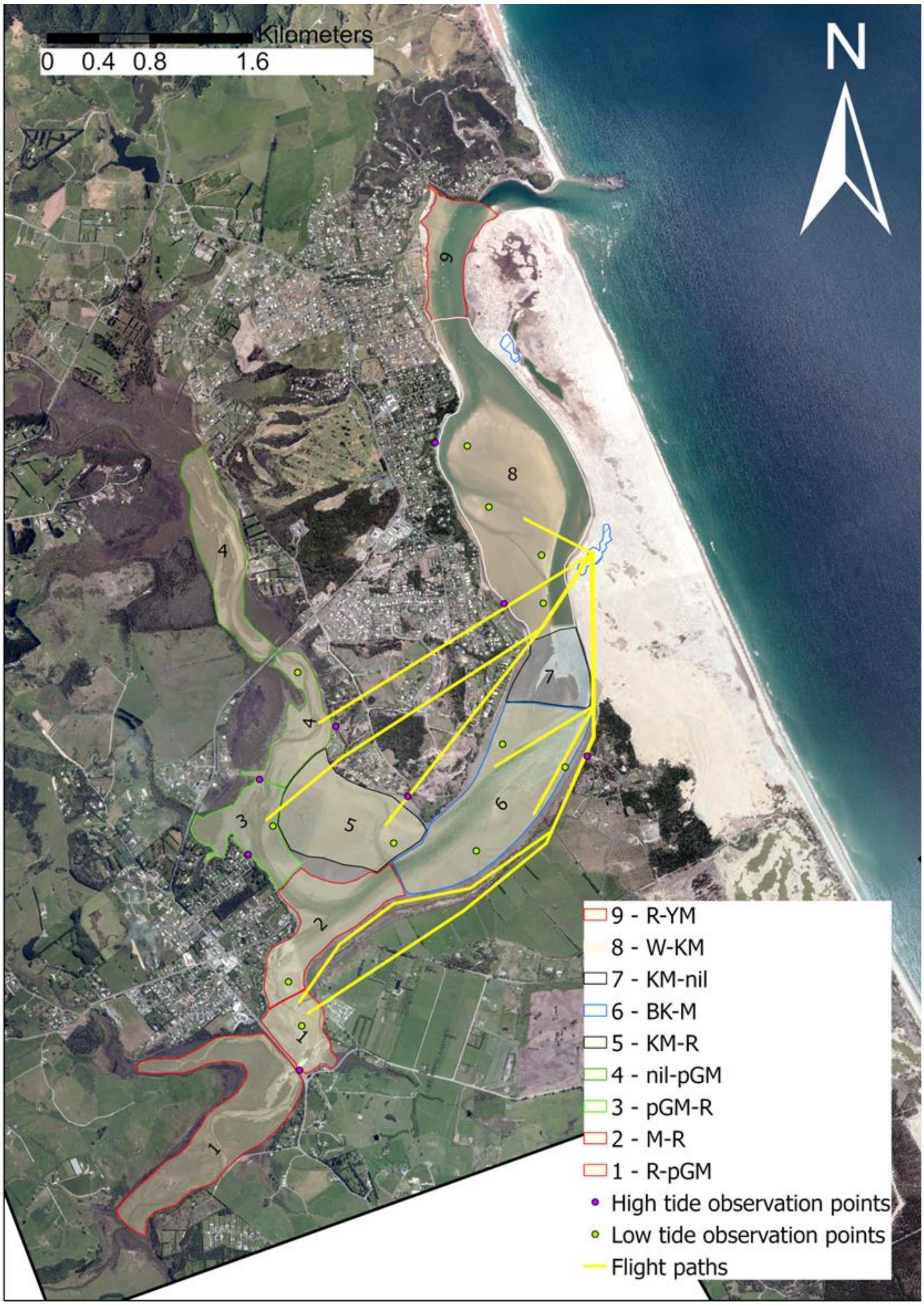


Figure 2.7; Map showing territories of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) males over the 2021/22 breeding season within Mangawhai estuary, Northland New Zealand. Known flight paths of individuals are shown. Observation points for data collection over the study period are shown for both high and low tide.

Colour Band	Sex	Territory	Pair

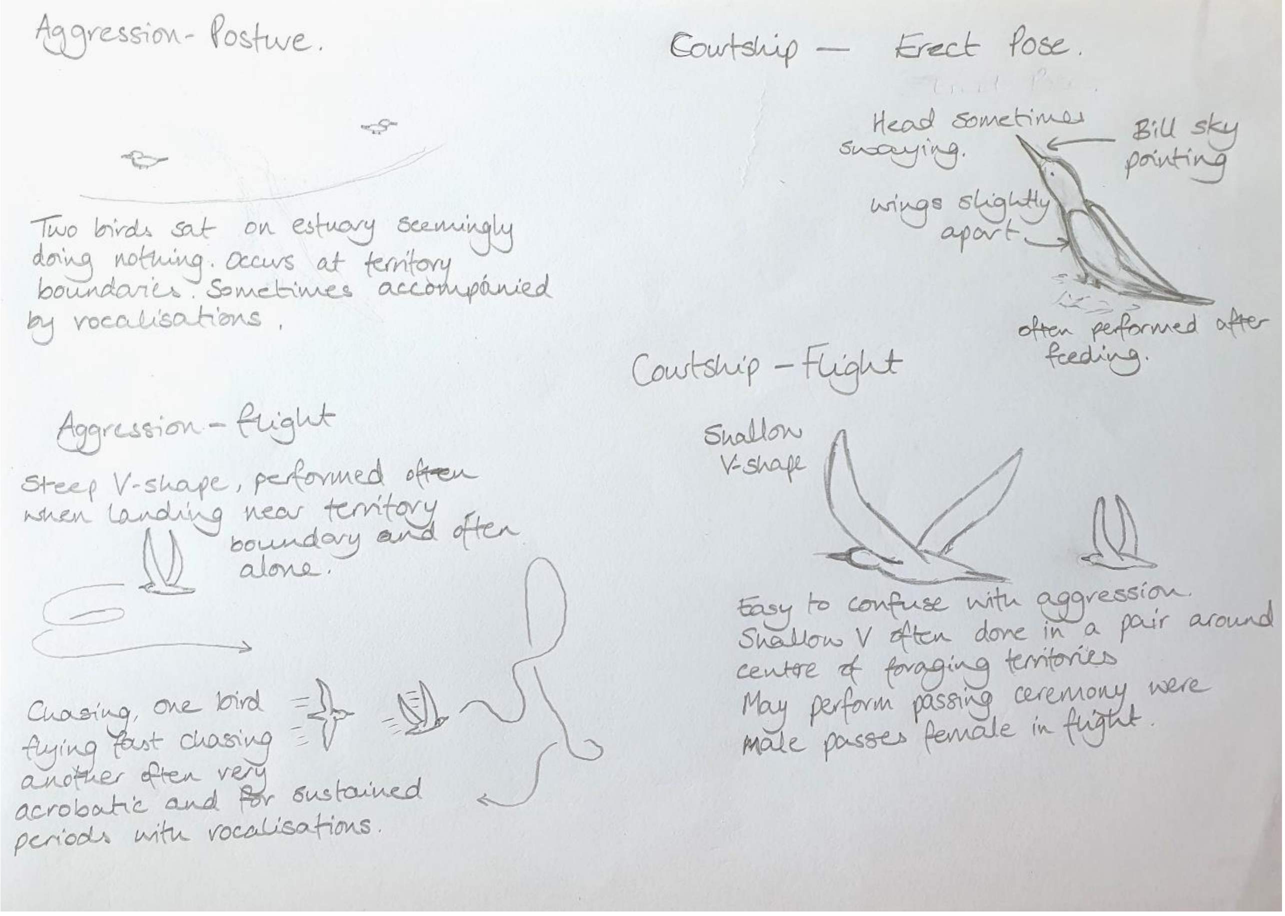
Table 2.3; List of NZFT individuals monitored throughout the 2021/22 breeding season at Mangawhai estuary, Northland, New Zealand.

W-KM	M	8	K-KM
R-pGM	M	1	WM-RW
pGM-R	M	3	R-KM
KM-R	M	5	pGY-pGM
KB-M	F	6	BK-M
W-BM	F	4	Nil-pGM
K-KM	F	8	W-KM
WM-RW	F	1	R-pGM
R-KM	F	3	pGM-R
KM-Nil	M	7	-

Table 2.4; List of behavioural categories and descriptions of classifications used during behavioural observations on foraging New Zealand Fairy Tern (*Sternula nereis davisae*) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand.

c

Behaviour Code	**Behaviour**	**Description**
R	Rest	Bird is on the ground, not alert either sleeping or resting. Eyes can be open but a lower posture showing a resting position. This includes any preening behaviour and eye to the sky.
A	Aggression	Bird is alert and being aggressive, accompanied by aggressive vocalisations. May be in flight or on the ground, if on the ground will be posturing and alert, head up may be accompanied by vocalisations, may look like a stand off between two birds.
C	Courtship	Bird is engaged within a courtship behaviour. This only includes courting within the ground through posturing, fish feeding or through other behaviours. Flight courtship is not included.
IF	In Flight	Bird is in flight not foraging. This includes any other time the bird is in flight where the head is not pointing downwards. This may include traveling, courting or disturbance.
F	Foraging	Bird is in flight flying with head pointing down 'scanning' for potential prey. Bird may also be hovering during this time. This does not include diving for prey.
D	Dive	Bird has performed a dive for prey breaking the waters surface. Often falling from height in a steep dive, however may be a more shallow dive and only bill may break the water. Both are classified as a dive.
DA	Dive Attempt	Bird has performed the same behaviour described within a dive, however, the water surface was not broken and the bird pulled up out of the dive.
OV	Out of View	Bird still present but can't be seen.
OS	Out of sight	Bird is not present and can't be seen.
O	Other	Any other behaviour not listed or included within these descriptions.



Aggression- Posture.

Two birds sat on estuary seemingly doing nothing. Occurs at territory boundaries. Sometimes accompanied by vocalisations.

Aggression - flight

Steep V-shape, performed of~~ten~~ when landing near territory boundary and often alone.

Chasing, one bird flying fast chasing another often very acrobatic and ~~for~~ sustained periods with vocalisations.

Courtship — Erect Pose.

Courtship - Flight

Easy to confuse with aggression. Shallow V often done in a pair around centre of foraging territories May perform passing ceremony were male passes female in flight.

Figure 2.8; Diagrams of behaviour observed within New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) highlighting both aggression and courtship behaviours.

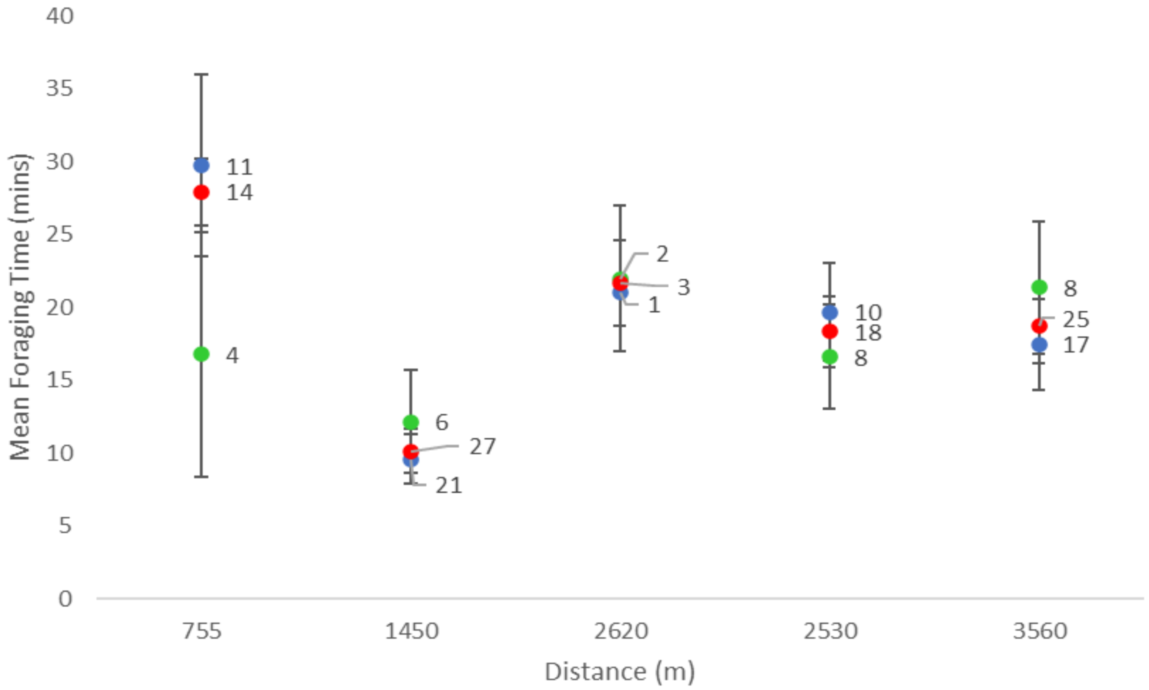


Figure 2.9; Comparison between mean distance to territory and chick ages within provisioning adult, male (blue), female (green), and mean values (red) of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand. Standard error bars displayed; n values displayed as labels.

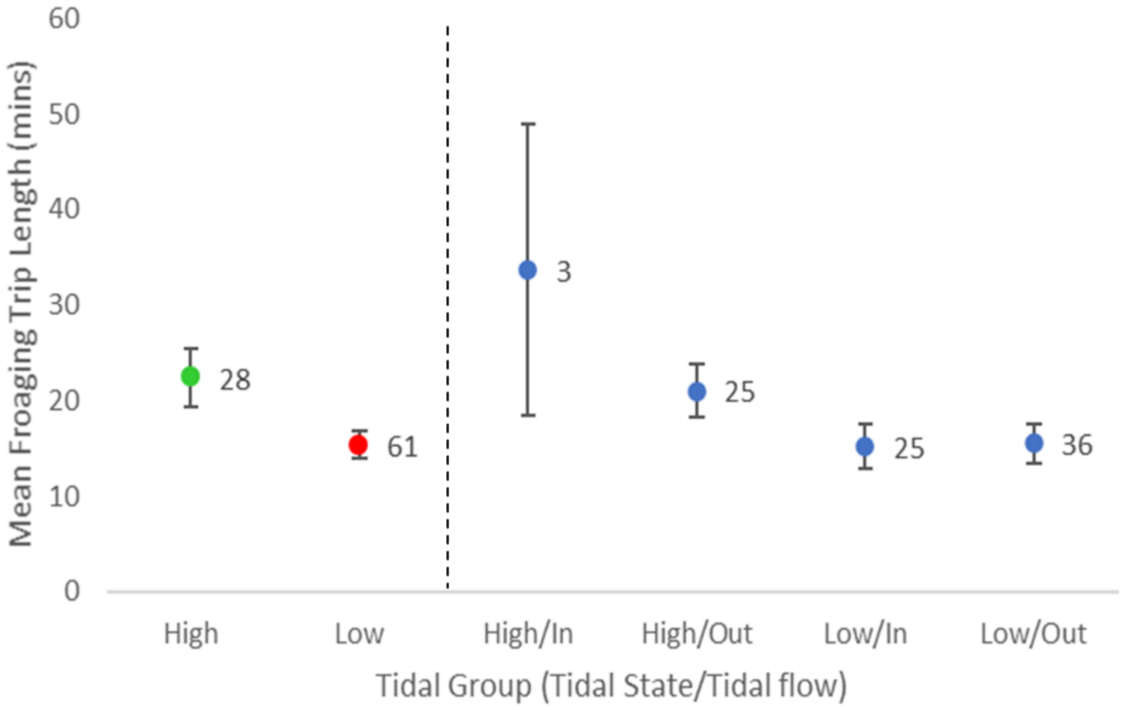


Figure 2.10; Variation in length of mean foraging trip length over different tidal categories within provisioning adult, male and female New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) over the 2021/22 breeding season in Mangawhai, Northland, New Zealand. Standard error bars displayed; n values displayed as labels.

Table 2.5; Recorded abiotic factors within foraging trips displaying minimum, maximum, and mean values.

Factor	Min	Max	Mean
Wind Speed (m/s)	0.9	7.6	3
Clarity (cm)	11	100	47.4
Wave height (beaufort)	0	3	2
Cloud Cover (%)	10	100	57
Air temperature (°C)	18.5	23	20

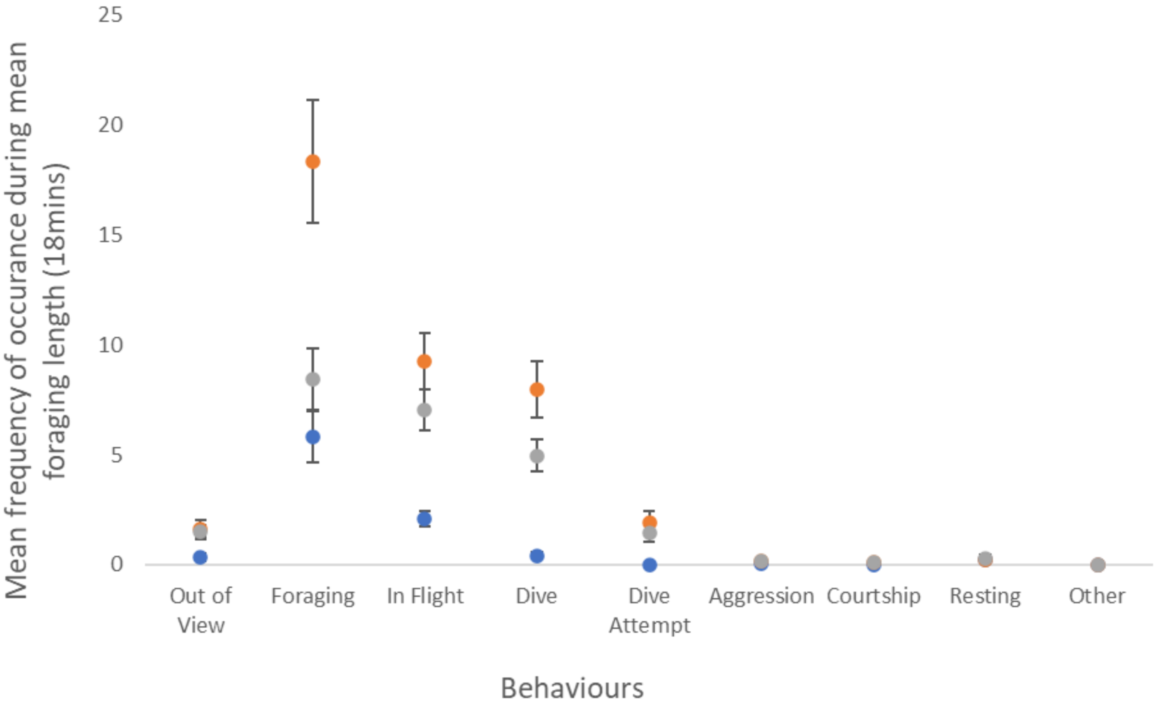


Figure 2.11; Variations in behavioural observations of adult foraging New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) between four main behavioural categories compared with each observation method – Instantaneous sampling (blue), continuous sampling (orange), 0/1 sampling (grey), over different chick age groups (0-6, 7-12, 13-18, 19-24, 25-31).

Figure 2.12; Distances breeding New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) may travel when determining distance on maximum return trip foraging time (inner circle) and maximum time away from nest (outer circle).

3. Spatial use and interactions of New Zealand Fairy Tern/Tara iti (Sternula nereis davisae) within Mangawhai estuary, Northland, New Zealand

Jacob Ball

3.1. Abstract

Estuaries are ephemeral, dynamic, and extreme environments that provide refuge for a wide range of species. Coastal change from development has threatened this habitat globally both indirectly and directly. A wide range of avian species are greatly reliant on estuarine habitats for foraging locations, including the New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) (hereafter; NZFT) which remains dependent on this habitat throughout its life history. The human population of Mangawhai is predicted to increase over the next 30 years, potentially influencing NZFT populations through disturbance, infrastructure, and coastal development. My study aimed to understand the spatial use of Mangawhai estuary and the surrounding areas by NZFT to provide a baseline and influence future management. Spatial data collection on dive locations, resting locations, and activities of human locations were undertaken using ESRI ArcGIS FieldMaps® over the 2021/22 breeding season. Locations were recorded within Mangawhai estuary, Mangawhai spit, and Te Arai stream mouth to improve the understanding of other habitats for NZFT. Kernel density maps were produced for visual analysis and were found to support territorial foraging theory within NZFT. Resting was found to occur by both non-breeding and breeding individuals throughout the estuary. Dog walking was found to have a high risk as most occurrences were off-lead (79.23%) and not classified as under control (71.11%). Peak human presence occurred during fledging period of NZFT chicks. This highlights a need for management of human activities within Mangawhai estuary to protect this habitat for NZFT. 17 flight paths and 25 dive locations were recorded within the marine environment, highlighting NZFT's ability to utilise the marine environment, however, the true extent and locations of foraging could not be determined. My study has shown the need for local scale protection to ensure the longevity of this species and others.

3.2. Introduction

Estuaries are ephemeral, dynamic, and exposed environments influenced by varying fractions of fresh and salt water. Currently three classifications exist; 1) Salt wedge estuary; 2) Fjord estuary; and 3) Shallow, partially mixed estuary (Chapman & Wang, 2001). Shallow, partially mixed estuarine habitats vary greatly due to different influences of fresh and salt water. Furthermore, large differences in substrate type can occur due to variation in energy throughout an estuary creating mudflats, sandflats, and deeper channel habitats (Elliott & Mclusky, 2002).

The varied structures and environmental influences caused by estuarine processes create a wide range of niches, but also a challenging environment due to the extreme changes in conditions (Chapman & Wang, 2001). This drives a preference for r-selected species type within the benthos - low species diversity, but high densities (Chapman & Wang, 2001). Upper reaches of estuarine environments can be relatively stable, caused by marginal habitats such as mangroves or salt marshes(Horstman et al., 2018). These brackish waters can provide a greater species diversity through fish nursery habitat (Horstman et al., 2018; Manson et al., 2005; Mcdowall, 1976).

Estuaries provide an important habitat for a large diversity of avian species, primarily due to the high species densities. Within New Zealand a broad range of threatened species are known to use estuaries, in particular over-wintering migrant waders (Riegen & Sagar, 2020; Veitch, 1977; Whelan et al., 2003). Human activity has caused wide scale change within the coastal environments threatening this habitat and the dependant species (Bryan et al., 2008; Galbraith et al., 2002; Lawrence et al., 2018).

While coastal change has threatened estuarine ecosystems through habitat loss and degradation (Bryan et al., 2008), further environmental pressure occurs through human recreation (Davidson et al., 1993; Keller, 1991; Osinga et al., 2012). The range of recreational activities undertaken within an estuary have varied influences on disturbance (Keller, 1991). The negative impact of dogs on wildlife within coastal zones has been well documented, particularly within unleashed free-roaming dogs (Bowes et al., 2015; Cortés et al., 2021; Kwon et al., 2021; Maguire et al., 2019). Recreational management is therefore fundamental within coastal wildlife conservation to limit disturbances.

The New Zealand Fairy Tern or Tara iti (hereafter; NZFT) is potentially New Zealand’s rarest indigenous breeding bird with a current population estimate of 45 individuals and 12 breeding pairs (DOC, 2022). This critical population level means the NZFT are currently classified as Threatened – Nationally Critical, and currently carry a Category A priority for conservation action from DOC (Department of Conservation, 2022; Jeffries et al., 2016). Part of the intensive management by DOC involves unique colour banding providing an opportunity to easily distinguish between all known individuals in the population.

NZFT are a species that rely on estuarine habitats, presumably for a reliable food source(Ismar et al., 2014). Furthermore, currently over the breeding period they appear to exhibit territorial behaviour within estuarine environments limiting the carrying capacity through intraspecific competition. Therefore, the productivity and health of estuaries associated with NZFT breeding sites are of extreme importance to ensure maximum breeding success and species survival.

The Mangawhai estuary is a shallow partially mixed estuary with an abundance of benthic and pelagic fishes, dominated by Gobies (*Favoniigobius sp.*) (Southey, *unpublished data*). Mangawhai estuary is the primary breeding location for NZFT with 6 breeding pairs occurring over the 2021/22 breeding season (Courtenay et al., 2022). Ismar et al. (2014) showed the key foraging habitats used by NZFT within Mangawhai estuary are tidal pools and channel margins, highlighting the importance of niche habitats for this species.

While Ismar et al. (2014) assessed the key foraging habitats for NZFT, there was no assessment of resting locations by the species. Furthermore, a spatial analysis into the anthropogenic use of Mangawhai estuary has not previously been undertaken. An estimated population increase of more than 100% is predicted over the next three decades within Mangawhai (Brunsdon, 2020). With the increased anthropogenic pressure predicted, a baseline survey is essential to understand spatial use of Mangawhai estuary by anthropogenic activities.

This study aims to understand spatial use of Mangawhai estuary by NZFT for both dive and resting locations, and by humans to understand any potential relationships or conflicts. Furthermore, this study aims to highlight the role that humans have within Mangawhai estuary and highlight the density of human use to; 1) provide a baseline of spatial information for future studies to determine how habitat relationships change may occur over time within NZFT, level for future studies, and 2) provide meaningful management objectives in which support coexistence between humans and NZFT.

3.3. Methods

3.4. Study Site

My study was split between three locations: Mangawhai estuary, Mangawhai spit, and Te Arai stream mouth (Figure 3.1). These locations where targeted as they were all related to the Mangawhai population and provided opportunity to determine how this breeding population uses the landscape. Sites are previously described in detail (Chapter 1; 1.2).

3.4.1. Mangawhai estuary

Mangawhai estuary is a 4.6km^2 mesotidal estuarine lagoon comprised of intertidal mudflats, shifting sand bars, converging channels, mangroves within the upper reaches, and shallow edges(Zimmerman et al., 2011). Mangawhai estuary is home to a wide range of waders, gulls, and fish species, with large shellfish beds and mudflats providing unique and rich habitat. The fish diversity is primarily made up of smaller species such as goby (*Favonnigobius sp.*), juvinielle flounder (*Rhombelosa sp.*) and mullet (*Mugilidae*).

3.4.2. Mangawhai spit

Mangawhai spit is a narrow 2.5km wildlife refuge across the entrance of Mangawhai estuary (-36.100063, 174.604705) managed by the Department of Conservation. The spit is ephemeral often shifting in structure due to influences from wind and water. The spit is used by for nesting by a wide range of shorebirds including NZFT.

3.4.3. Te Arai

Te Arai stream mouth is a small stream with an intertidal open dune habitat between the stream and the sea with ephemeral shell patches. The stream is directly bordered by grasses and further surrounded by clear felled pine forest, with regenerating native bush and open scrubland. It has previously provided nesting habitat for NZFT but is primarily used as a post breeding flocking site by NZFT (Jeffries et al., 2016; Parrish & Pulham, 1995; Zimmerman et al., 2011).

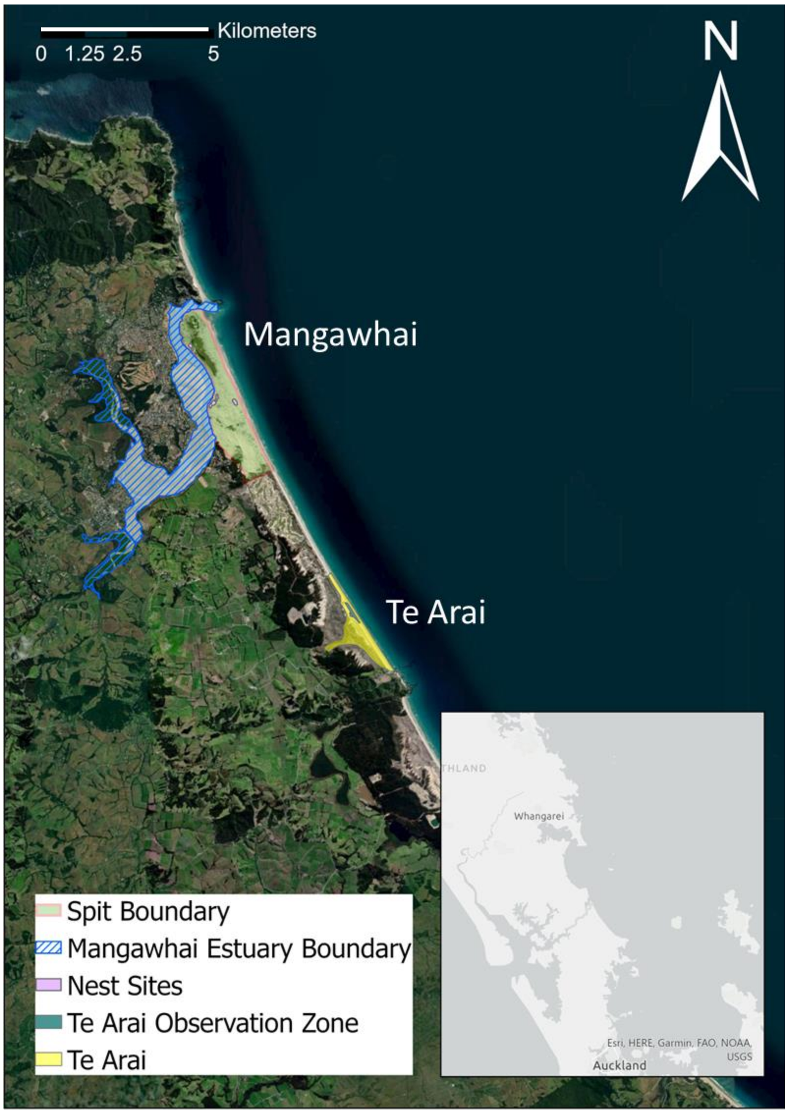


Figure 3.1; Map showing both Mangawhai and Te Arai study locations on the east coast of Northland, New Zealand.

3.5. Data collection

Data collection for my study occurred from late October 2021 until January 2022, covering the main breeding period of the NZFT (Zimmerman et al., 2011). I used ESRI ArcGIS Field Maps© to collect both spatial data and the required metrics. I recorded data on foraging locations, NZFT resting locations and human activities. Data related to NZFT was collected within Mangawhai estuary, from Mangawhai Spit and at Te Arai stream mouth, however a focus was on Mangawhai estuary.

All observations were undertaken using Hawke Vantage 8x42 binoculars and a Vanguard Endeavor spotting scope (ϴ82mm) with a 20-60x zoom eyepiece. Digital photography observations were made using a Nikon D750 with a Tamron G2 150-600mm lens using manual exposure and autofocus, and images reviewed with lighting corrections made during post processing. Digital photography was particularly useful within Mangawhai estuary and Te Arai stream to determine individuals in flight from colour bands as NZFT hang their legs after ascending from a dive.

3.5.1. Territoriality

Before I commenced observations, NZFT territories were observed, and territorial boundaries determined through detailed descriptions of NZFT aggression and courtship behaviours and experienced guidance (Southey, *pers comm.*). Courtship behaviours include courtship flights, vocalisations, flight displays, courtship feeding, and copulation. Aggressive behaviours included agonistic calls, aerial chases, flight posturing, and ground posturing (Appendix; Figure 3.7). Furthermore, identification of individuals through unique colour bands allowed a distinction between males and females, thus I was able to determine territorial boundaries and pairings. Once territories had been determined, I plotted them using ESRI ArcMap PRO and labelled the territories 1 to 9 (Appendix; Figure 3.8). Territorial ownership is primarily associated to males, as such males were targeted to determine territorial boundaries (Parrish & Pulham, 1995, Southey, pers comm., 2021).

3.5.2. Mangawhai Estuary

Mangawhai estuary was monitored from late October until early February for foraging dive locations and resting locations of NZFT. An observation location was determined in relation to the location of an NZFT individual, no closer than 25m ensuring identification could be undertaken and individuals reliably tracked whilst preventing disturbance. I use 9 observation zones: a single best viewing land-based location for each of the 9 territories. Individuals were not always clearly identified but similar observation locations were used to provide consistency. I randomised my observations across different tidal states and times. My observations stopped once fledging had occurred, and nesting birds were deemed to have left Mangawhai estuary territories.

NZFT were recorded over multiple 30-minute observation periods to account for variation in weather patterns between observations. However, foraging observations were often undertaken in consecutive periods on the same individuals. Once an individual had been targeted for a foraging observation period no other bird was observed. If the individual left the site and returned within the same foraging observation period, observations did not continue until the individual had been identified through colour bands.

During the foraging observation period, I recorded the locations of all observed dives using ESRI Arc FieldMaps® on an iPad 6 tablet. Dive locations were plotted using map orientation skills through permanent geographic features to orientate the observer, thus allowing accurate location of dives. Often-short distances (10-50m) between the observer and target individual aided accurate geospatial referencing.

Alongside spatial plotting of dive locations, I collected information on foraging direction and foraging orientation to understand the relationship of foraging with abiotic influences (Table 3.1). A compass was used to determine direction and orientation.

Table 3.1; Definitions used to determine metrics within observations of foraging New Zealand Fairy Tern (*Sternula nereis davisae*) within Mangawhai estuary.

Term	**Definition**
Foraging Direction	*The direction of travel the target individual was moving prior to performing a change in behavioural type*
Foraging Orientation	*The direction the target individual was facing using the crown and bill as a reference point*

I tried to also determine foraging success. Being single prey loaders, NZFT provide the unique opportunity to observe foraging success as fish are held within their bills (Houston, 2000; Houston & McNamara, 1985). Therefore, I could determine foraging success only when a fish was clearly seen within the bill of the individual, or behaviour clearly displayed an individual consuming a prey item. The range of target prey for NZFT is not truly known, but small prey items are often targeted to provide appropriate prey for chicks as within other species (Bogliani & Massara, 1990; Parrish & Pulham, 1995), this prevented clear distinctions being made during early chick rearing periods. Furthermore, I noted the foraging strategy and classified as, *Dive*, *Skim* or *Plunge*, to provide a suggestion of water depth.

3.5.3. Mangawhai Spit

I also used 30-minute observations periods from Mangawhai Spit of birds foraging within the marine environment from one location. To maximise these observations, I chose a sand dune vantage point based on my previous observations of NZFT flight paths between nest sites and coastline (Figure 3.6.) (-36.103218, 174.606996). When I detected a NZFT passing my vantage point, I tracked it using a spotting scope. The spotting scope was set to x45 magnification to provide a good medium between short and long-distance observations as magnifying whilst tracking a bird resulted in losing visuals on the target individual. I recorded both flight paths and the occurrence of any diving behaviour. I used Arc FieldMaps® to plot flight paths using the FieldMaps® drawing feature and I included notes associated with the flight path. I plotted dive locations after the target bird was no longer in sight to reduce the risk of losing sight of the bird. Due to my distance from the target individual, dive locations were not precise but estimates. Observer experience and cardinal direction orientation prior to each observation period allowed accuracy within plotting. I was unable to identify specific individuals as when I observed the birds they were flying below the height of my location, and they regularly fly with legs tucked into their plumage, preventing identification.

3.5.4. Te Arai Stream

I employed the same methods for observations at Te Arai as used at Mangawhai Spit. The use of Te Arai stream as a NZFT roost site provided the opportunity for me to identify individuals from colour bands. I made observations within a 380m stretch of beach (Figure 3.1). The exact roost location varied, and I made all observations from a point no closer than 25m.

3.5.5. Abiotic Metrics and methods

A wide range of abiotic metrics were collected to find a relationship between NZFT and spatial habitat use. Abiotic conditions included wind speed, wind direction, wave height, last high tide, last high tide height, cloud cover, turbidity, wave height, rain. I collected these abiotic measures at the start and end of each 30-minute observation period to account for changes within weather conditions. Median values were drawn and used for data analysis.

Wind speed was recorded using a handheld anemometer set to 10 second average wind speed held at 1.8m ± 0.1. Wind direction was determined through visual and sensory queues and a compass. The Beaufort scale (0-12) was used to determine the wave height independently of the wind speed to provide a value of water surface roughness. A Land information New Zealand tide table read from Marsden point was used to determine last high tide time and height to allow for standardisation between sites. Cloud cover was recorded within thirds, encompassing the whole sky. Rain was simply recorded as light, medium or heavy, as the level of precipitation may influence the visual ability to see beyond the water surface (Mcgarrigle, 2017). Clarity was determined using a clarity tube taken from a depth of 30-40cm at the closest water directly adjacent to the observation location. When performing observations on the marine environment or within shallow tidal pools water clarity was not recorded as this value was inaccurate and water was too shallow for an accurate determination of clarity.

Tide was categorised into 4 categories: *high, outgoing, low,* and *incoming*. If the data point was found to fall between times relevant to a category (Table 3.2), that category was assigned to that data point prior to input into GIS. All times were determined through recording of the last high tide, collected using the same tidal data.

Table 3.2; Time additions made to recorded last high tide time within data analysis methods to determine the tidal category of a dive location. Tidal time was recorded using Land information New Zealand tide table read from Marsden point.

	High	**Outgoing**	**Low**	**Incoming**
1st Cycle	±1 hr	+1 hr - +4 hr	+4 hr - +7hr	+7hr - +11hr
2nd Cycle	+11hr - +13hr	+13hr - +17hr	+17hr - +19hr	+19hr - +24hr

Wind direction was classified into the two prominent wind directions, northeast (hereafter; NE; north, northeast, east, and southeast) and southwest (hereafter; SW; northwest, west, southwest, and south).

3.5.6. Resting

I defined resting as a bird standing in place on the ground. I recorded resting locations of NZFT for Mangawhai estuary, Mangawhai spit and Te Arai stream throughout the period of my study on an *ad-hoc* basis, i.e., whenever a resting NZFT was seen due to observer time limitations. I identified resting birds using the same observation methods, ensuring to not disturb individuals.

3.5.7. Human distributions

I determined the level of human distribution within Mangawhai estuary from November until February. I made observations from 4 fixed locations within Mangawhai estuary (Appendix; Figure 3.6.), a location from which I could see the whole estuary. I conducted surveys in consecutive order from observation point 1 to 4. My surveys began from observation point 1 within 1 hour either side of low tide as this provided the greatest intertidal area for human use, and NZFT to forage and rest. I used clear geographic features to distinguish between observation zones as a means of preventing duplicate counts of people. If I detected a person within one zone and the same people were later seen in the next zone, I counted them again as a clear distinction between individuals could not always be reliably made, however, this did not occur frequently.

As an aim of my study is to understand the human distributions within Mangawhai estuary, all land-based and water-based activities were included. I classified data based on human activity as follows: *walking, running, swimming, sunbathing, dog (on lead), dog (off lead), cycling, fishing, horse, vehicle, speedboat, jet ski, sailing boat, kayak, wind surfer, kite surfer, paddleboard, drone, other*. A data point was made for each party of individuals - a party defined by clear observations where people were only interacting with people in that group. A distinction was made between dogs off and on a lead as the impacts of an unrestrained dog off may be significantly higher to wildlife (Banks & Bryant, 2007; Maguire et al., 2019). For off lead dogs I also defined the level of control, under control, or out of control. I defined under control as a dog within 2m of the owner and responsive to commands. When a dog observation was made it was inclusive of the people within that party. I included water-based activities such as, *speedboat, jet ski, sailing boat, kayak, wind surfer, kite surfer* and *paddleboard* as these activities could affect foraging and resting bird life both directly and indirectly at varying rates (Burger, 1998).

While doing the human distribution surveys, I included the same abiotic factors that I measured for NZFT observations. The abiotic factors were associated with each observation point and therefore may not be representative of weather conditions throughout the estuary.

Finally, I included two other data fields for each human activity observed: 1) general bird disturbance (yes or no) and NZFT disturbance (yes or no). A disturbance to a bird was defined as a bird actively changing behaviour within 5 seconds due to human activity.

3.6. Data analysis

Visual analysis of data was undertaken using ArcGIS through a map series of kernel densities for dive locations, resting locations, human locations, and dog locations. Kernel density mapping for both humans and dogs used count data associated with each observation point. Visual comparison and descriptive analysis allowed me to provide analysis into the relationships between NZFT and humans within Mangawhai estuary.

Abiotic factors were recorded to provide opportunity into analysis of NZFT behavioural influences. A series of chi-squared analyses with pairwise comparisons were used to compare between groups, abiotic factors, and weekdays. To understand variability in disturbance rates between human activity groups chi-squared analyses were undertaken.

Due to the large variations of factors influencing foraging within Mangawhai estuary statistical comparisons directly between foraging, resting, and human presence could not be undertaken. Further factors would be required to allow a comprehensive statistical analysis through mixed models. However, the rate of disturbance between human categories allowed analysis through a chi-squared test to determine the statistical comparison of disturbance rates between groups.

3.7. Results

Over the 2021/22 NZFT season 5 breeding pairs formed at Mangawhai, producing 11 eggs, 8 of which hatched. These five breeding pairs held distinct foraging territories in the Mangawhai estuary. The first egg hatched on the 16/12/2021. The final egg laid in this study hatched on the 31/12/2021 (Courtenay et al., 2022).

8 chicks fledged over the 2021/22 breeding season, 7 from Mangawhai the first chick fledging on 15/01/2022, fledging defined as a bird actively leaving the nest site on the wing(Courtenay et al., 2022; Wiles, 2022). Birds were actively seen within all observation locations until data collection ceased. Nesting birds were soon not seen within observation locations after fledging had occurred.

3.7.1. Dive

3.7.1.1. Basic Analysis

Between 8/11/2021 till 02/02/2022 130 observation periods were undertaken totalling 156 hours and 52 minutes. NZFT were observed for 89 hours and 52 minutes over the data collection period, 70 hours and 59 minutes in an estuarine environment – Mangawhai estuary, 18 hours and 52 minutes within a marine environment – Te Arai Stream and Mangawhai Spit.

Observations were undertaken on at least 13 individuals, accounting for 31.7% of the population at the time of study. Both males (n=10) and females (n=3) were observed. A greater number of individuals may have been monitored, however, detection limits or bird behaviour prevented reliable identification of unique colour bands.

532 Dive locations were recorded across all observation locations, within a range of environments such as tidal pools, mangroves, channels, channel margins, and marine environments. Only 25 dives were recorded from Mangawhai spit and Te Arai stream as detection limits often prevented determining dive locations or diving behaviour within the marine environment. 17 flight paths were recorded, all birds heading offshore, except 2 flight paths where birds were returning to the nesting site.

Success was only clearly determined for 63 dives or 11.9% of dives, fish being recorded as eaten on the wing on 9 occasions. The last courtship feeding event was recorded on 14/12/2021 within non-breeding birds, however, within breeding birds the last courtship feeding was seen on 01/12/2021. Observations on courtship feeding were only undertaken within the estuary and there is potential for it to have still been occurring at the nest site as individuals were seen carrying fish.

3.7.1.2. Presence

A variation was found in number of times NZFT were seen/detected over tidal categories. A lower percentage of detections occurred over a high tide than all other tidal states, with comparable rates of detection within *Outgoing, Low* and *Incoming* tidal status' (Figure 3.2). No significant difference was found between tidal categories (Pearson's chi-squared, $df = 3$, $p = >0.05$).

There was no large variation found between rates of detection of NZFT between wind directions (Figure 3.3). When grouping wind directions into prominent wind directions, (NE, n=182) and

South West (SW, n=108) there was a difference in detection rate percentage of 7.75%, NZFT being seen more frequently within a SW wind direction.

A small variation was found within percentage rate of detection between locations, however, there was no significant differences between sites (Pearon's chi-squared, *df* = 4, $p = >0.05$). When grouping into Upper (n=6) and Lower (n=3) estuary locations NZFT were detected 7.27% more within the Upper estuary than the lower. Furthermore, rates of detection were greater at Te Arai than on the Spit with a difference in detection rate of 36.6%.

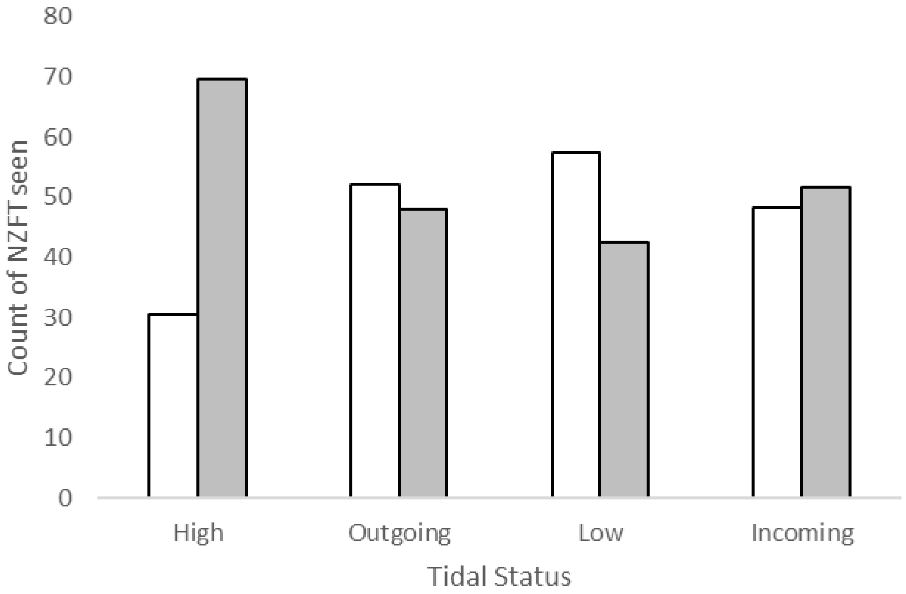


Figure 3.2.; Comparison in detections of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) against 4 tidal categories High (n=23), Outgoing (n=75), Low (n=40), Incoming (n=178) within Mangawhai estuary, Northland, New Zealand over the 2021/22 breeding season. N-values are shown as labels.

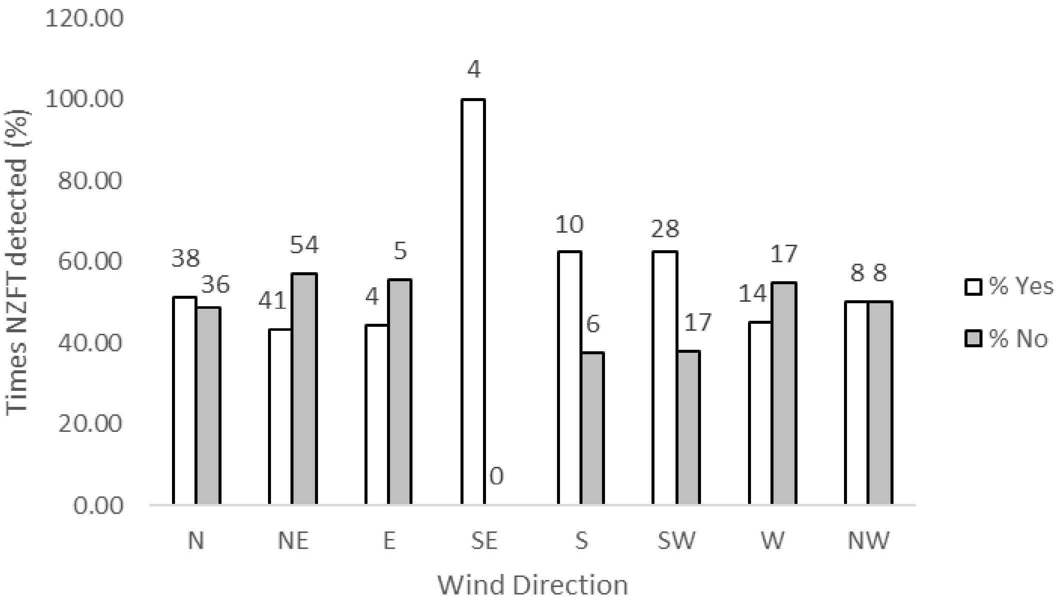


Figure 3.3.; Comparison in detections of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) against wind directions within Mangawhai estuary, Northland, New Zealand over the 2021/22 breeding season. N (n=74), NE (n=95), E (n=9), SE (n=4), S (n=16), SW (n=45), W (n=31), NW (n=16). N-values are shown as labels.

There is no obvious comparison in detection of NZFT between weekdays, with no significant differences found between all pair-wise comparisons (Pearson's chi-squared, *df* = 6, *p = >0.05*). The greatest disparity in detection was found on Friday, NZFT not detected for 64.7% of observations (Table 3.2.).

Table 3.2.; Variations between weekdays in numbers of times NZFT were detected or not detected over the data collection period on foraging New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) within Mangawhai, Northland, New Zealand over the 2021/22 breeding season.

Bird Seen	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Yes	19	41	36	22	6	17	8
No	21	53	27	30	11	14	9
n	40	94	63	52	17	31	17
% Yes	47.50	43.62	57.14	42.31	35.29	54.84	47.06
% No	52.50	56.38	42.86	57.69	64.71	45.16	52.94

3.1.3. Marine Use

Over the 2021/22 breeding season observations were recorded on marine foraging as both flight paths and dive locations. 23 observations periods were made on Mangawhai spit, the first on 30/11/2021 and the last on 11/1/2022 and 27 observation periods were undertaken at Te Arai stream starting on 15/11/2021 and the last observation occurring on 2/2/2022. 17 flight paths were observed, and 25 dives recorded. The nature of observation methods prevented accurate determination of flight distance and foraging location; however, the results highlight that NZFT use the marine environment. Flight paths were only found to occur on 4 separate dates.

The majority of flight paths were undertaken within an eastbound direction (n=10) from leaving the spit and returning individuals were found to travel in a westbound direction (n=1; Figure 3.4). Within the other 6 recorded flight paths birds were found to stay within the foreshore just beyond breaking waves and to head north. Only 3 dives were recorded from birds beyond the breaking waves, primarily due to the difficulty of keeping a clear view on the subject.

Figure 3.4.; Map showing flight paths and dive locations of New Zealand Fairy Tern/tara iti (*Sternula nereis davisae*) over the 2020/21 breeding season from Mangawhai spit and Te Arai stream mouth, Northland, New Zealand. Flight paths (red lines) and dive locations (red points) were drawn and plotted in the field using ESRI FieldMaps. Notes were recorded alongside flight paths.

3.7.2. Human Presence

3.7.2.1. Basic Analysis

Data was collected from 16/11/2021 till the 28/01/2022 throughout Mangawhai estuary with a total of 35 surveys undertaken. Greater than 3040 people were observed over this time, the most common observed activity being Walking (24.53%) and the least common observed activity being sailing (0.08%) (Appendix; Table 3.5).

A difference was found between observations locations with 40.05% of data points collected at location 1 (Appendix; Figure 3.9) Observation 1 and 2 accounted for 74.71% of all observations within Mangawhai, showing there is a large bias within spatial use of Mangawhai estuary to the lower estuary.

Human density varied over the survey period with a peak in observations occurring on the 03/01/2022 (Figure 3.5) with 612 people observed within the estuary. The lowest density of people was seen on 24/11/2021 with 4 people observed. A spike in human densities was seen on 02/01/2022 with 429 people observed, this coincides with the national Christmas holiday period (Employment New Zealand, 2022[a]). An increase in people was seen from 18/12/2021 until 07/01/2022 where a drop to 22 people was observed, then an increase was again found on 12/01/2022, 18/01/2022 and 19/01/2022. Another spike was found on the 28/01/2022 with 264 people seen again coinciding with public holidays and weekend days (Employment New Zealand, 2022[b]). January (n=9) had the highest mean count of people at 217.11 (Appendix; Figure 3.8).

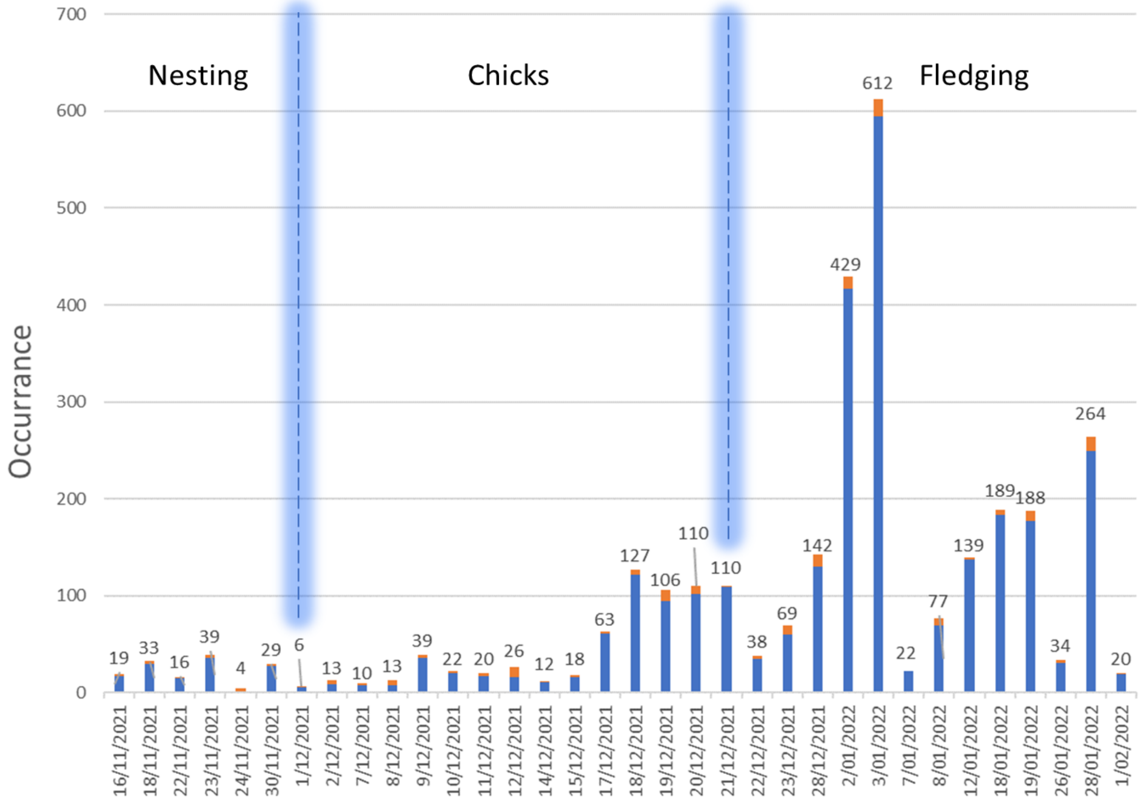


Figure 3.5; Number of people seen within Mangawhai estuary over the New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) breeding season. Dog data points (orange) are displayed separately to all other categories (blue), total data points shown in data labels. Key life history stages are shown through labels, lines representing rough boundaries. Surveys occurring at 4 individual locations throughout the estuary from the lower to upper estuary within 1 hour of peak low tide.

3.7.3. Disturbances

I recorded disturbance of birds for 13.81% of observations throughout the estuary. The highest cause of disturbance to birds was from *dogs (Off lead)* (26.23%; n = 61), however, this is potentially due to the high presence of dogs within the estuary as it was the 3rd most common recorded activity (Appendix; Table 3.7). *Horses* were found to cause a higher rate of disturbance (100%), but only accounted for 0.23% (n = 2) of observations. Disturbance was not recorded from the following activities: *jet skis, kayaks, paddle boards, wind surfers* or *runners*, accounting for 8.65% of all recorded activities.

Disturbance varied between observation locations. The highest rate of disturbance was found within observation location 4 (62.07%; n=29) and the lowest rate was found at observation location 1 (10.06%; n=537) (Appendix; Table 3.7).

Out of 140 surveys across all observation locations, I found NZFT present during 47 (33.57%) surveys. I observed NZFT being disturbed twice (0.24%) at separate locations, and I observed resting only twice (0.24%) in the estuary habitat, hence, this habitat was primarily used for foraging over the survey period.

3.7.4. Spatial use maps

3.7.5. Dive Locations

I used dive location as a proxy for foraging and found that NZFT used the entire estuary for foraging, the highest rate of dives found within the upper section of the estuary (Figure 3.6; a). I used kernel density mapping of dive locations to identify key areas used by NZFT. These maps show distinct foraging territories, supporting the hypothesis of exclusive foraging areas for breeding pairs (Figure 3.5.).

3.7.6. Resting Locations

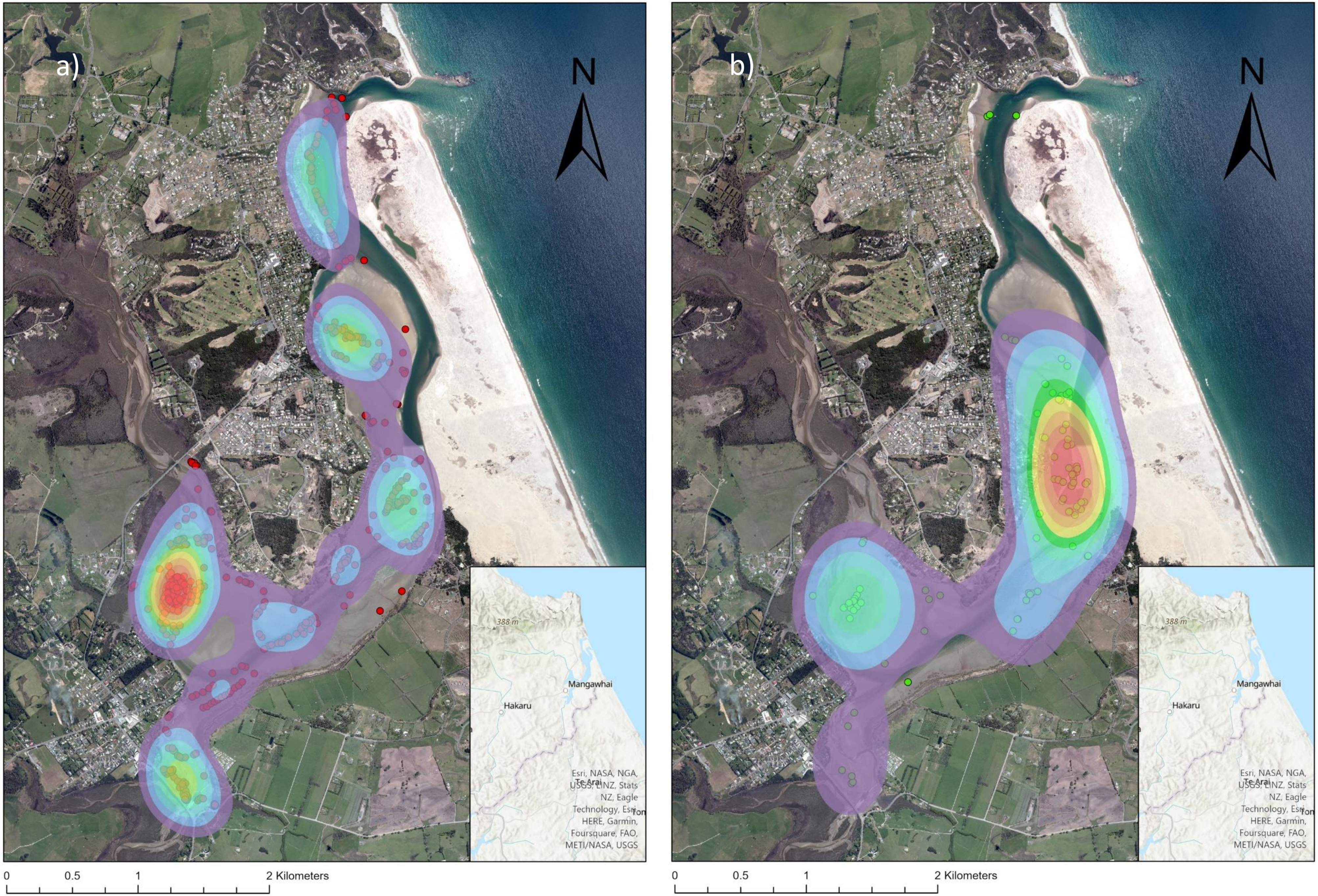
Resting was observed throughout the estuary; however, a higher density of resting was found within the mid-lower estuary, an area occupied by a non-breeding male (Figure 3.6.; b). Within resting observations three key outliers were identified at the entrance to the estuary by the same bird (R-YM), occurring in November and February.

3.7.7. Human locations

I mapped the distribution of human activities throughout the estuary (Figure 3.6; c) and I determined human density through the kernel density heat map. The whole estuary was used by people; however, the highest human density was at the mouth of the estuary. Because of the risk posed by dogs (Banks & Bryant, 2007; Lafferty et al., 2013; Maguire et al., 2019), I plotted the distribution of dogs on the map of the estuary, and I found that the whole estuary was used (Figure 3.6; d). Furthermore, I found that dogs were spread more widely than humans (Figure 3.6; d). Metrics on dogs showed that a greater number of dogs were classified as not under control when off a lead than under control, and that there was a 26.29% greater chance of birds being disturbed (Table 3.3).

Table 3.3; Number of dogs seen during observations on human distribution within the Mangawhai estuary over the NZFT 2021/22 breeding season. Metrics were taken to determine if the dog was on or off a lead, under control or had disturbed birds, results are shown in percentages.

			Under Control? (%)		**Bird Disturbed? (%)**	
	Count	**%**	**Yes**	**No**	**Yes**	**No**
On Lead	38	20.77			9.09	90.91
Off Lead	145	79.23	28.89	71.11	35.38	64.62
Total	183					


a)
N
388 m
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Hakaru
Te Arai
Esri, NASA, NGA, USGS, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, Foursquare, FAO, METI/NASA, USGS
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0.5
1
2 Kilometers
b)
N
388 m
Mangawhai
Hakaru
Te Arai
Esri, NASA, NGA, USGS, LINZ, Stats NZ, Eagle Technology, Esri, HERE, Garmin, Foursquare, FAO, METI/NASA, USGS
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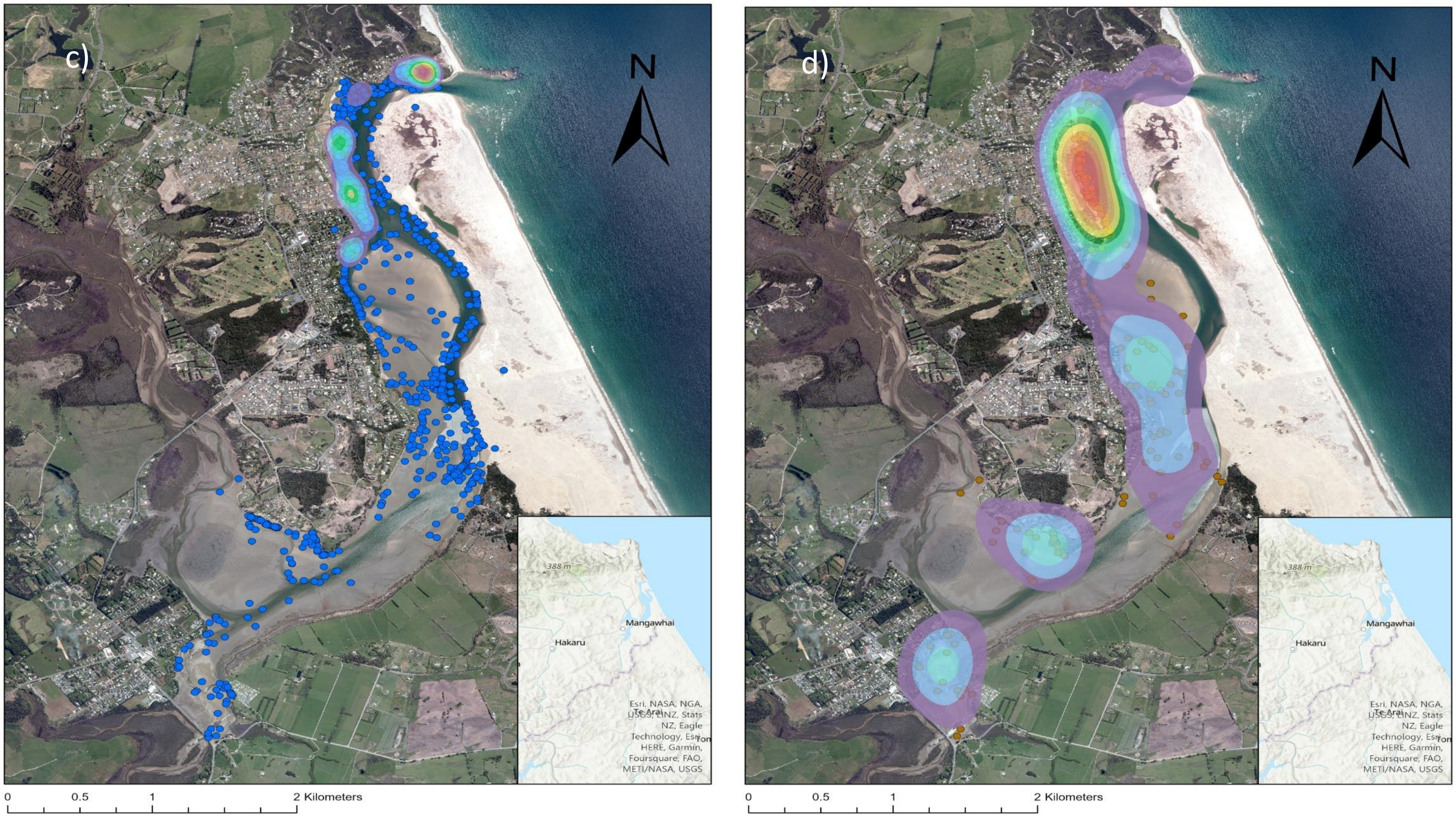


Figure 3.6; Map series visualising point data collected in Mangawhai estuary, Northland, New Zealand between November 2021 till February 2022. Locations are displayed as coloured points and 50% kernel density heat maps shown for observations on a) & b), and for count data on c) & d). a) Dive locations of New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*); b) Resting locations of New Zealand Fairy Tern/Tara iti (*Sternula davisae*); c) Human locations and density; d) Dog locations and density. All maps produced using ESRI ArcGIS Pro 2.8.3., satellite imagery from; https://data.linz.govt.nz/layer/88131-northland-04m-rural-aerial-photos-2014-2016/ Land Information New Zealand (2021).

3.8. Abiotic factors

Weather remained consistent throughout the data collection period with few adverse conditions being recorded. A maximum wind speed of 9.8 metres per second was recorded one singular event with a mean wind speed of 2.96 metres per second over the study period. Rain was recorded for 47 observations, being recorded as heavy for 8 observations. A mean wave height of 2 on the Beaufort scale was found throughout the observation period, with a maximum of 5 recorded within the sea from Mangawhai spit, the maximum recorded wave height was 4 within Mangawhai estuary. The maximum recorded temperature was 28 degrees Celsius, a mean of 22.5 degrees Celsius was recorded over the data collection period. Clarity was found to vary over the data collection period, a minimum clarity of 11cm being recorded, however, a mean clarity of 67.8cm was found.

3.9. Discussion

3.9.1. Spatial use

Previous studies have suggested a strong dependence and relationship with estuarine environments within this species (Ismar et al., 2014; Jeffries et al., 2016; Zimmerman et al., 2011). My research supports this hypothesis, but I also present evidence that suggests that marine environments may play a greater role within breeding adult NZFT as it does with other allopatric species (Barre et al., 2012; Dunlop, 2018; Greenwell et al., 2021; Paton & Rogers, 2009).

3.9.2. Dive Behaviour

This study did not find a strong relationship between wind direction and occurrence of diving behaviour. Changes in foraging behaviours associated with wind have been observed within many seabird species (Collins et al., 2020; Kruger & Garthe, 2001; Michael Reed & Ha, 1983; Stienen et al., 2000). Taylor (1983) showed that prey capture rates within the allopatric common tern (*Sterna hirundo*) and sandwich tern (*Sterna sandvicensis*) decreased with an increase in wind speed, suggestively due to water surface conditions. Furthermore, (Reed & Ha, 1983) suggested that a slight increase in wind speed improved foraging efficiency within Forester's tern (*Sternula forsteri*). The small preference found within this study suggests that like other seabirds, NZFT prefer flying into a head wind when departing for a foraging trip (Collins et al., 2020). NZFT may also use wind direction to adjust foraging locations, using sheltered areas to reduce influence of wind on water surface conditions, increasing visual ability, thus improving efficiency of foraging (Afán et al., 2021; Amélineau et al., 2014).

Ismar et al. (2014) provided an analysis into water depth requirements for estuarine foraging NZFT, suggesting that prey is predominantly gleaned from bottom substrate. I had therefore hypothesised that changes in water depth through tidal influences within the estuarine environment would influence foraging effort within this habitat. Urmy & Warren (2018) found that within both common terns and rosette terns (*Sterna dougallii*) foraging potential was greatly influenced through tidal conditions due to water depth, clarity, and prey movements. This research supported these findings highlighting that NZFT too favoured a turning tide and a lower tide, presumably due to similar influences (Brenninkmeijer et al., 2002; Taylor, 1975; Urmy & Warren, 2018).

This research successfully highlighted the role other foraging habitats may play within NZFT chick provisioning, particularly the role of the marine environment. Tidal influences within an estuarine environment prevent NZFT from continuous foraging throughout the diurnal period due to variations in water depth and prey concentrations (Paiva et al., 2008). Over periods of suboptimal foraging within the estuarine environment, the marine environment may therefore provide foraging ability for chick provisioning NZFT. Furthermore, the marine environment may play a greater role as prey is known to be of higher value nutritionally potentially influencing breeding success (Fernández Ajó et al., 2011; Greenwell et al., 2021; Li et al., 2011; Martins et al., 2004). The marine foraging observed within this study highlights the use of this environment by this species whilst highlighting the need for further study to determine the true value of this foraging resource.

Increase in detection of NZFT at Te Arai may be explained through variation in the roles of sites for NZFT. Historically Te Arai stream mouth has been well used by both non-breeding and breeding birds (Jeffries et al., 2016; Parrish & Pulham, 1995). Without a resident breeding pair over the 2021/22 season there would have been a reduced occurrence of territorial behaviour allowing non-breeding and breeding birds to use the site. Furthermore, without chick rearing adults at the site the sensitivity to threats would have been reduced allowing a greater detection of individuals from the observer.

3.9.3. Dive Locations

I found the highest rate of dives within the upper areas of the estuary; an area with three territorial boundaries and the greatest presence of NZFT. Overall dive locations supported the theory of NZFT territoriality through clear spatial distinction of dive areas. I also suggest that dive locations may occur within the core areas, in part, to reduce intra-specific competition reducing energetic demands (Marzlufi & Heinrich, 1991; Nisbet, 1983b). Alternatively, individuals may learn key foraging locations within their respective territories (Nisbet, 1983b).

My findings agree with previous research on the estuarine foraging habitats for NZFT, highlighting channel margins and tidal pools as the primary foraging resource (Ismar et al., 2014). However, a direct relationship between mangrove habitat as a potential foraging resource for NZFT has not been previously shown. I found that mangroves can be utilised by NZFT as a foraging resource. The role of mangroves within fish life cycles may highlight the potential benefit of this ecosystem for this and other coastal foraging species (Hindell & Jenkins, 2005; Manson et al., 2005). While previous research on seabird species foraging within mangroves are limited, species such as Lesser Noddy are known to nest within mangroves in part due to fish life cycles creating an abundance of prey (Surman et al., 2017). Whilst this study has shown it is not a key habitat type for NZFT, it does highlight the potential value of this habitat for this species.

3.9.4. Resting Locations

Resting location may be influenced by many different factors within NZFT. Breeding effort within all birds has high energetic demands, even greater within single-prey loader species such as NZFT (Bogliani & Massara, 1990; Markones et al., 2010). The increased energetic demand and parental drive may influence resting location choice within breeding birds. Fijn et al. (2017) showed that breeding sandwich terns (*Sterna sandviscensis*) preferred resting within locations close to nest locations over the breeding period. This may be supported by findings in this study as the highest density of resting observations were within a territory occupied by a non-breeding pair. Furthermore, individuals may choose to rest within areas not monitored within this study such as beach front.

Human disturbance on shorebird species is well known (Cortés et al., 2021; Keller, 1991; Ratcliffe et al., 2008), and has been shown to be influenced by the perceived threat and cost (Frid & Dill, 2002; Stillman et al., 2002; A. D. West et al., 2002). Mangawhai estuary is a popular location for a wide range of human activities as shown within this study. The high presence of human activity may influence breeding NZFT to avoid resting within Mangawhai estuary, alongside other key drivers.

While my research has highlighted that Mangawhai estuary is not currently used as a key resting location for breeding NZFT, the implications of this are not known. Stienen & Brenninkmeijer (2002) suggest that more distant resting locations from foraging locations may cause an increase in energetic demand for single prey loaders when provisioning for fledglings. An increase in human abundance within Mangawhai estuary may therefore implicate chick and parent bird conditions depending on NZFT tolerance to human presence.

3.9.5. Human locations

I found that human land-based use of Mangawhai estuary did not result in high levels of direct human wildlife conflict. However, passive human activities such as sunbathing may be resulting in avoidance of areas that might be otherwise available to NZFT for resting (Yasué, 2006). I found that areas were avoided by NZFT during times of high human density and utilised when density was low.

The role of dogs within anthropogenic disturbance to shorebirds is well documented (Bowes et al., 2015; Cortés et al., 2021; Kwon et al., 2021; Lafferty et al., 2013; Maguire et al., 2019). Cortés et al. (2021) showed that leashed dogs had a lower rate of disturbance, highlighting the importance of controlled dogs within important bird areas. My observations within this study further supported previous studies highlighting that human behaviour change within Mangawhai estuary would not only benefit NZFT, but all bird life.

3.9.6. Human Influence

Variation in disturbance rates seen on all birds between observation locations may be due to a variation in human densities and in part explained through Figure 7; C. A greater human density in turn creates avoidance within shorebirds due to the perceived threat from human presence (Yasué, 2006), limiting chances of disturbance events. Furthermore, foraging value changes with sediment type, thus it varies greatly within an estuarine environment (Whelan et al., 2003). Shorebirds may therefore actively avoid areas of high human density within areas of poor foraging value due to cost benefit relationships (Yasué, 2006). These influences may also be responsible for the relationships seen in this study, highlighting the need for further exploration to determine human influences on shorebirds.

I speculate that NZFT may be avoiding areas of high human disturbance due to a comparison between resting locations and human presence (Figure 7; b & c). Dive locations however, still showed high density within locations of high human density, suggesting tolerance is high when foraging within this species, like findings on little terns (*Sternula albifrons*) (Paiva et al., 2008), resting locations however play a greater role as the perceived threat may be increased (Frid & Dill, 2002; Yasué, 2006). Furthermore, Burger (1998) highlighted the role water sports may have on common tern (*Sterna hirundo*) suggesting it influenced flight paths of breeding birds. While the influence of watercraft was not directly measured on flight paths of NZFT, this study suggests similar findings to those proposed by Burger (1998) as NZFT were found to avoid foraging within key watercraft areas.

Dogs are well known to illicit a high threat response in birds, causing disturbance events or avoidance of areas (Cortés et al., 2021; Kwon et al., 2021; Lafferty et al., 2013; Maguire et al., 2019). Dogs were found to be the highest cause of disturbance (38% of all events) within Mangawhai estuary supporting previous studies. I found that dog presence was not equal throughout the estuary being lower in location 1 where human density was high (Figure 7; c & d), this finding highlights a potential risk to NZFT and may further support the low densities of resting locations within Mangawhai estuary. Furthermore, it shows that human density alone cannot be used as a proxy for dog density.

To further improve our understanding of NZFT foraging ecology a greater emphasis on marine observations should be undertaken. My current marine observations have shown that the marine environment is important for NZFT, however the role the marine environment plays could not be determined. Greenwell et al. (2021) showed a large shift within resource use in foraging AFT pre-egg laying and during chick provisioning, there is potential for NZFT to utilise these resources in a similar way. The marine environment may therefore be integral to egg development, thus reproduction and species survival.

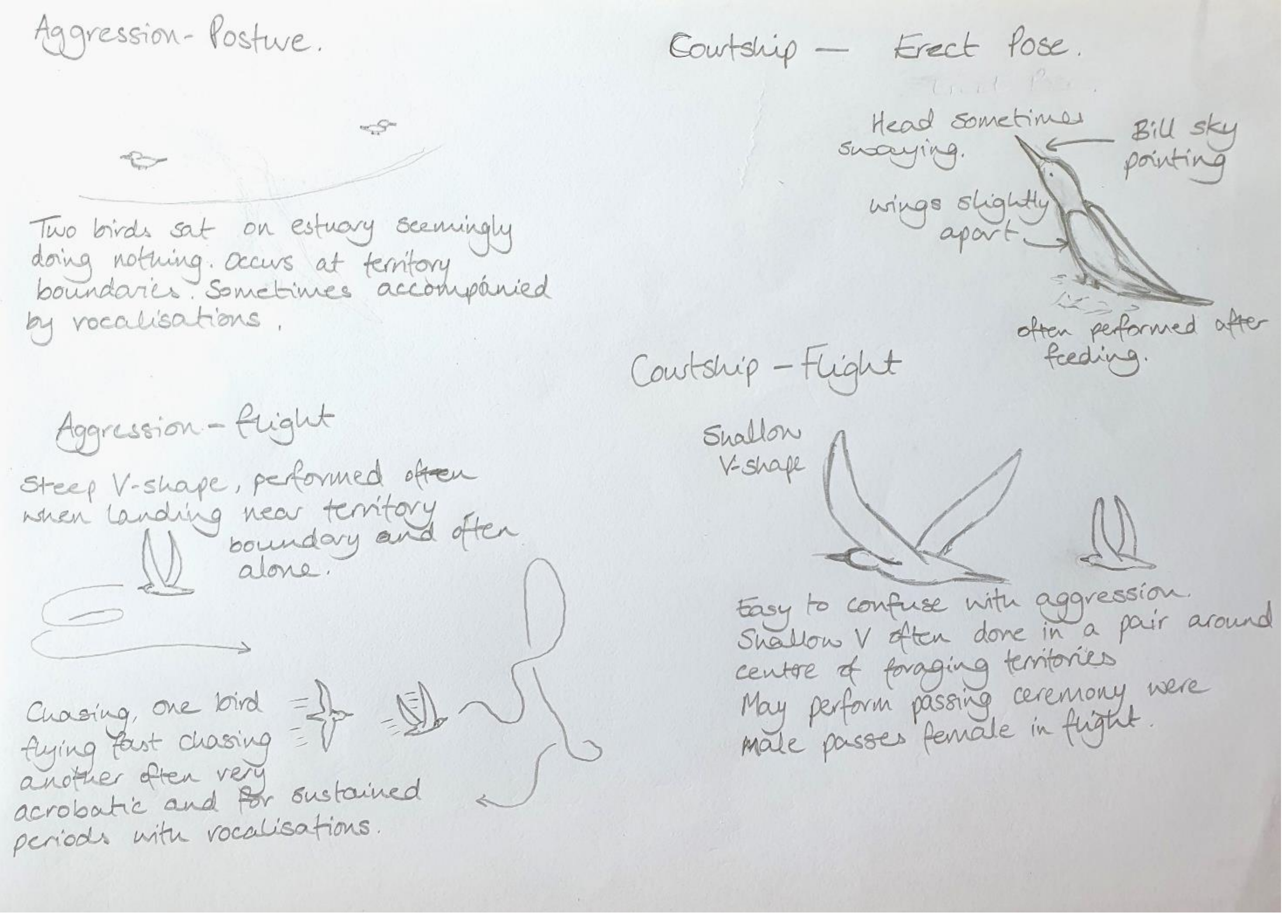
3.10. Conclusion

My research has provided key supporting evidence for previous research whilst expanding on the current understanding of the foraging ecology, particularly the use of marine environments. It has shown previously unexplored foraging relationships between both mangrove habitats and the marine environment, highlighting the need for further research to understand these relationships for the future protection of the species. Furthermore, research into the relationships between marine foraging and estuarine foraging at other breeding locations would provide an insight into species preference, suggesting if marine foraging is determined through site.

Based on my observations of NZFT within the marine environment, I suggest that other food sources may be of equal importance, especially during breeding. Furthermore, marine sources may provide a greater level of nutrition to the species (Greenwell et al., 2021). To truly understand the role of the marine environment and the broad-scale habitat requirements of NZFT further research is essential to determine if resource use changes over time; and if breeding success is affected by access to marine prey. The most accurate methods applicable to determine geospatial use would be with GPS transmitters allowing an accurate detailed understanding of habitat use by this species and allowing for further research into the role of weather and breeding success within the species.

Finally, my research has highlighted the need for future management of Mangawhai estuary to prevent damage and loss of breeding potential within this critically endangered species. Anthropomorphic pressures may be limiting the use of habitat by NZFT, and with a current growing human population, the risk of anthropogenic impacts to NZFT are increasing. I suggest that management options such as enforcing dog-leash requirements and restricting human access to key locations during NZFT breeding should be implemented within Mangawhai estuary. These measures will help ensure coexistence for not only NZFT, but other vulnerable species for which Mangawhai estuary is an important over-wintering foraging resource.

3.11. Appendix



Aggression- Posture.

Two birds sat on estuary seemingly doing nothing. Occurs at territory boundaries. Sometimes accompanied by vocalisations.

Aggression - flight

Steep V-shape, performed often when landing near territory boundary and often alone.

Chasing, one bird flying fast chasing another often very acrobatic and for sustained periods with vocalisations.

Courtship — Erect Pose.

often performed after feeding.

Courtship - Flight

Easy to confuse with aggression. Shallow V often done in a pair around centre of foraging territories May perform passing ceremony were male passes female in flight.

Figure 3.7; Diagrams of behaviour observed within New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) highlighting both aggression and courtship behaviours.

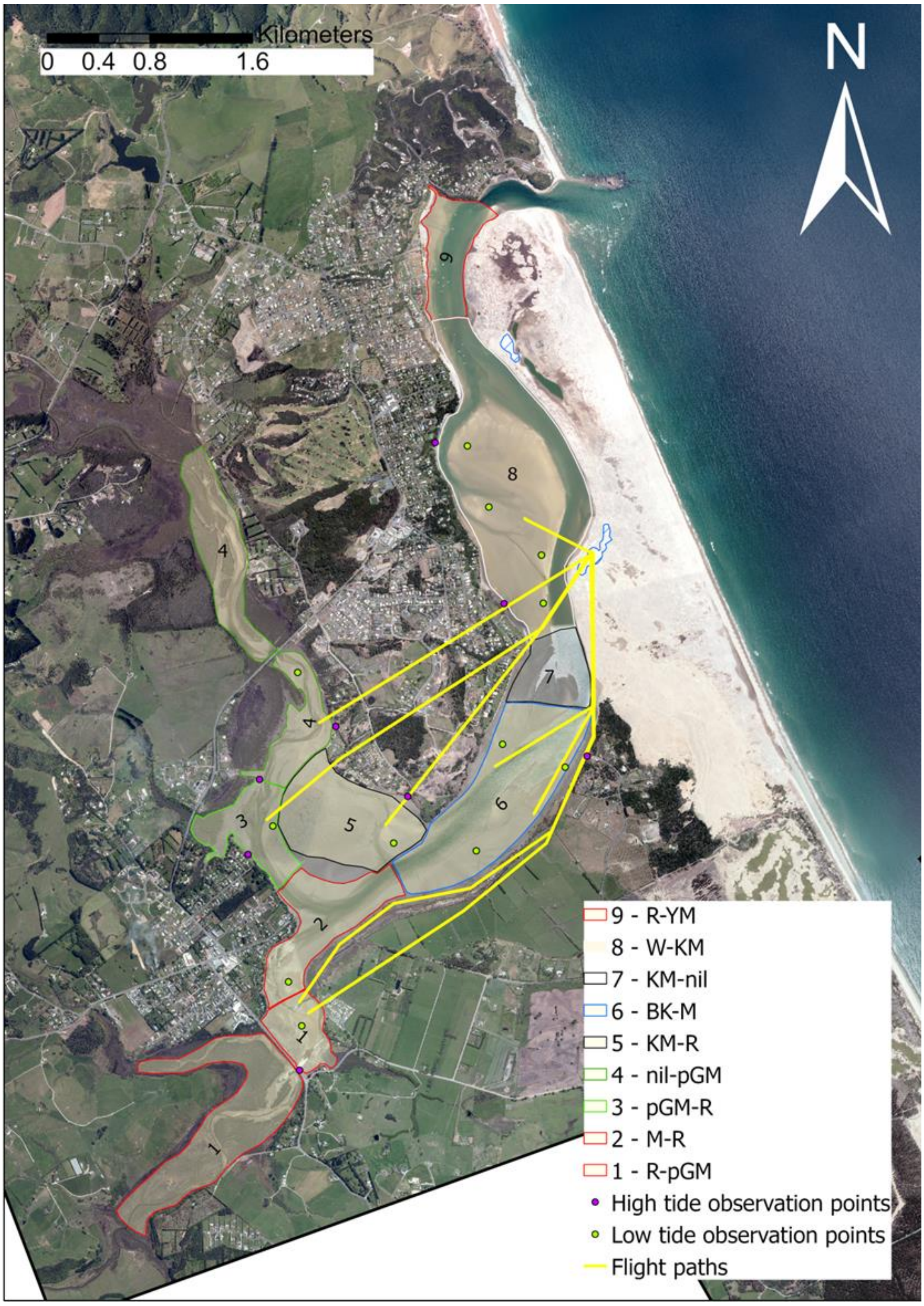


Figure 3.8; Map showing territories of NZFT males over the 2021/22 breeding season within Mangawhai estuary, Northland New Zealand. Known flight paths of individuals are shown. Observation points for data collection over the study period are shown for both high and low tide.

Table 3.4; Count of occurrence for each human activity category within Mangawhai estuary from the 16/11/2021 till 01/02/2022. Total occurrences and percentage of occurrence is shown.

Activity	Total	%
Walking	326	24.53
Sunbathing	237	17.83
Dog(Off Lead)	145	10.91
Speed Boat	131	9.86
Swimming	105	7.90
Other	81	6.09
Jet Ski	77	5.79
Fishing	70	5.27
Vehicle	70	5.27
Dog (On Lead)	39	2.93
Kayak	18	1.35
Paddle Board	9	0.68
Wind Surfer	6	0.45
Running	5	0.38
kite Surfer	4	0.30
Horse	3	0.23
Cycling	2	0.15
Sailing Boat	1	0.08
Drone	0	0.00

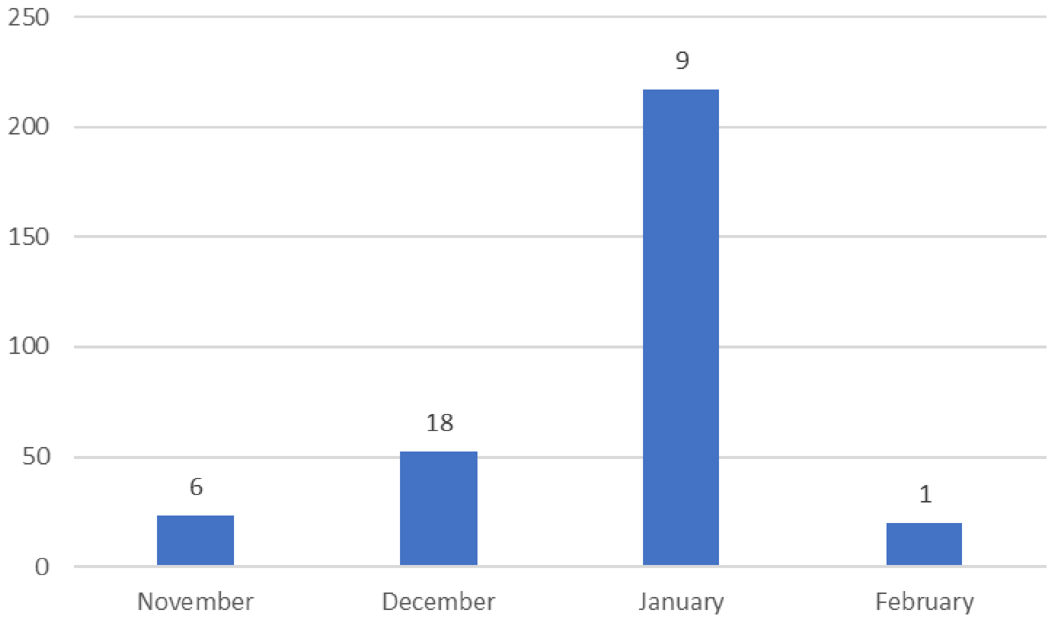


Figure 3.9; Mean count of people categorised by month within Mangawhai estuary. Data collected from 16/11/2021 till 01/02/2022 from 4 different locations throughout the estuary within 1 hour of peak low tide. Data labels show n values.

Table 3.5; Comparison of disturbance rates between observation locations from spatial recording of Human activity locations throughout Mangawhai estuary, Northland, New Zealand over the New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) 2021/22 breeding season.

Site	***n***	***Bird Disturbed (%Yes)***
1	537	10.06
2	207	14.01
3	45	42.23
4	29	62.07

Table 3.6; Disturbance rates on birds from of human activity categories recorded within Mangawhai estuary, Northland, New Zealand.

Activity	**n**	**Bird disturbed (% Yes)**
Horse	2	100
Dog (Off lead)	61	26.23
Vehicle	32	21.88
Walking	227	14.97
Speed Boat	51	11.76
Dog (On lead)	34	11.76
Swimming	65	7.69
Fishing	57	7.02
Other	59	3.39
Sunbathing	122	3.28
Jet Ski	17	0
Kayak	10	0
Paddle Board	7	0
Wind Surfer	6	0
Running	4	0

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4. Investigating the roles of estuarine versus marine foraging by New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) through Stable Isotope Analysis

4.1. Abstract

Dietary analysis of species allows an understanding of resource availability, habitat use, and spatial distribution. Stable isotope analysis is a novel technique that allows analysis into dietary composition through relative ratios of isotopes. This study used $\delta^{13}C$ and $\delta^{15}N$ to provide analysis into New Zealand Fairy Tern/tara iti (*Sternula nereis davisae*) diets using chick feathers. This study aimed to build on previous research and address changes in dietary composition between breeding seasons. 31 feathers were obtained from 4 breeding seasons and analysis undertaken following methods from previous study(Ismar et al., 2014). Reference fish samples (n = 52) were obtained from Mangawhai estuary and Bream Bay, Northland, New Zealand. Prey selection was found to vary greatly between individuals and between seasons. 2022 was found to constitute a higher proportion of marine prey than other years, however, no significant difference was found. Marine foraging was not shown to influence chick survival, suggesting multiple factors may influence survival. This study has provided evidence that the marine environment is of importance to breeding NZFT. Further study should be undertaken to understand how dietary composition changes over the breeding season and how NZFT utilise this habitat.

4.2. Introduction

To improve conservation potential of any species, an understanding of diet is vital to determine resource availability, habitat use, and spatial distribution (Lyngdoh et al., 2014; Morelli et al., 2021; Ward et al., 2012). Traditional seabird dietary analysis techniques involve invasive methods such as dissection or stomach flushing (Duffy & Jackson, 1986). Modern techniques and methods allow a wider range of dietary analysis techniques that reduce stress levels (Murray et al., 2011). While traditional non-invasive techniques exist, they are currently limited to behavioural observations, analysis of faecal matter or pellet dissection (Arim & Naya, 2003; E. C. Young, 1990), and therefore limited by species biology. Stable isotope analysis (hereafter; SIA) is a relatively new dietary analysis technique within avian ecology. It is reliant on the variations found within isotopic signatures of dietary items and thus consumer tissues (Inger & Bearhop, 2008). Analytical comparisons between signatures of potential consumer foods (hereafter; reference prey) with signatures of the consumer allow an understanding to be drawn into habitat and resource use where there is great enough variance (Forero et al., 2005; Herrera et al., 2003).

Two isotopic ratios are primarily used within avian ecology to determine habitat resource use and to determine trophic segregation: isotope ratios of carbon (^{12}C to ^{13}C, shown as $\delta^{13}C$) and nitrogen (^{14}N to ^{15}N, shown as $\delta^{15}N$) (Inger & Bearhop, 2008). Hilton et al. (2006) showed using $\delta^{13}C$ signatures that long-term declines in rockhopper penguin (*Eudyptes chrysocome*) populations were due to a reduction in marine primary productivity by using time series comparisons. Furthermore, Bearhop et al. (1999) showed a link to freshwater foraging within cormorants (*Phalacrocorax carbo*) through both $\delta^{13}C$ and $\delta^{15}N$ signatures recorded throughout the year using feathers as a temporal related sampling method. This shows the diversity of SIA in exploring ecological relationships.

While SIA is an effective tool for monitoring dietary consumption within species, caution must be taken when selecting sample tissues. Synthesis rates vary greatly between tissue types, reflecting the diet/habitat at the time of tissue synthesis (Inger & Bearhop, 2008; Sun et al., 2012). For example, blood plasma has a very high turnover rate, thus, is only relevant to dietary consumption a few days prior to sample collection (Cherel et al., 2005; Inger & Bearhop, 2008; Pearson et al., 2003), whereas feathers or bone are related to the dietary consumption from months or years prior to sampling (Nelson et al., 1998; Pearson et al., 2003).

Further caution should be undertaken to ensure that reflective sample comparisons are made. For example, Bocher et al. (2000) found that a comparison between adult feathers in two allopatric species; South Georgian diving petrels (*Pelecanoides georgicus*) and common diving petrels (*Pelecanoides urinatrix*), were ineffective in determining trophic separation, however, a comparison between chick feathers highlighted trophic segregation in foraging strategies. This highlights the importance of comparing like with like and tailoring sampling strategies to research questions (Inger & Bearhop, 2008).

Using knowledge surrounding isotope synthesis in biological material, the synthesis of feathers from yolk dependant chicks will be relevant to parental diet at the time of yolk development. This would allow analysis into comparison between dietary requirements for chicks and for egg development through a comparison of chick down feathers and 1st moult feathers, thus determining how habitat reliance changes over the breeding season.

4.2.1. New Zealand Fairy Tern

The New Zealand Fairy Tern or Tara iti (hereafter; NZFT) is potentially New Zealand's rarest indigenous breeding bird with a current population estimate of 45 individuals and 12 breeding pairs (DOC, 2022). The critical population level means the NZFT are currently classified as Threatened – Nationally Critical and currently carry a Category A priority for conservation action from DOC (Department of Conservation, 2022; Jeffries et al., 2016).

Knowledge of dietary analysis within NZFT is linked to two key studies (Ismar et al., 2014; Parrish & Pulham, 1995). Parrish & Pulham (1995) highlighted a varied piscivorous diet comprised of potentially 8 species from both marine and estuarine sources and found within the benthic and pelagic environment. Ismar et al. (2014) used stable isotopes to determine the proportions of NZFT diets over the breeding period within Northland, New Zealand. Ismar et al. (2014) determined NZFT diet to contain a mix of three key species, goby (*Favoniigobus sp.*), flounder (*Rhombosolea sp.*), and shrimp (*Palemon sp.*), suggesting a strong reliance on estuarine habitats. While this analysis provided a detailed analysis of NZFT diets, marine reference signatures were underrepresented within this study, preventing true analysis into the origin of dietary habitat in NZFT.

4.2.2. Aims

In this chapter I will aim to; (1) Build on previous knowledge of NZFT diets through SIA providing evidence required for future management of this species, (2) Explore how dietary composition changes between breeding seasons within NZFT, (3) Address key areas for further research to determine the significance of marine foraging within NZFT.

4.3. Methods

4.3.1. Feathers

Sixteen pin breast feathers and eight down feathers were plucked from 16 individual chicks during routine banding operations carried out Department of Conservation (hereafter; DOC) using certified banders under DOC ethics approval. Feathers were collected between November 2021 and February 2022, the earliest on the 6/11/2021 and latest on 8/02/2022, all when chicks were aged between 19-21 days. Feathers were removed using tweezers sterilised in 70% ethanol and stored within plastic Ziplock bags in a paper envelope. Feathers remained in a cool dark place prior to lab analysis. I was also provided with a further 15 feathers (n=31) from storage at Canterbury University, Christchurch. All feathers were subject to the same storage treatment and sample preparation.

I first washed feathers in approximately 10ml of 70% ethanol within individual falcon tubes and agitated by hand for 2 minutes. Ethanol was poured from the falcon tube into a sterilised beaker to prevent loss of any feather fragments. Falcon tubes were filled with distilled water and triple rinsed to remove ethanol residue. Between rinses distilled water was decantated into a sterilized beaker to prevent loss of feather fragments. Tweezers, beakers, and nitrile gloves were sterilized with 70% ethanol between samples. Feather material was transferred into a sterile petri-dish for drying. Drying was undertaken within a Thermoscientific© Hermatherm oven set to 50 degrees Celsius for 2 hours. Feathers were left to cool after drying for 10 minutes before being placed using sterile tweezers into sterile plastic zip lock bags and stored within a sterile sealed plastic container containing desiccant in a dark cool place.

4.3.2. Fish

Fish samples (n = 52) were collected from each individual foraging territory (n=9) (Appendix; Figure 4.1.) in November and January as dietary reference prey. These times were chosen to coincide with yolk and chick feather development, thus incorporating relevant isotopic signatures. Fish samples were collected using a 5m beach seine net with a lead weighted bottom rope and a hexagonal mesh size of 1.5mm over a 10m pull. These samples were sourced from an ongoing fish research project by another researcher at the estuary site. One individual of each species was taken from each location. Euthanasia occurred though pithing and decapitation using a sharp knife under ethics approval from Massey University. Individuals were stored individually in plastic Ziplock bags. A cooler maintained between 5-10°C was used in the field to store samples. Samples were then stored at -40°C long-term prior to processing.

Marine fish were sourced from industrial fisheries within Whangarei, Northland, New Zealand. All marine fish had been caught from Bream Bay, Northland, New Zealand in November 2021, providing a relevant spatial signature for marine foraging NZFT. Industry fisheries target fish with body lengths greater than those consumed by NZFT, however, species that had life cycles relevant to NZFT were selected. All marine fishes were stored in an industrial freezer at -40 degree Celsius prior to collection. Fish remained frozen until tissue sampling for lab analysis.

In the lab, I removed a cross section of 150mm from directly behind the gills of each fish to allow effective freeze drying and a sample of the whole fish. These samples were freeze dried for 36 hours using a Labconco FreeZone 6 Freeze Dryer. Fish were sampled whole as NZFT consume prey whole; thus, the whole signature is relevant to signatures within NZFT material. Freeze dried samples were then ground and mixed using a ceramic pestle and mortar to a fine powder. Ground samples were transferred into a small plastic bag. Equipment was sterilized with ethanol and triple rinsed with distilled water, before being air dried in between each processing.

4.3.3. Stable Isotope Analysis

Stable isotope analyses were undertaken by the National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand, using a DELTA V Plus continuous flow isotope ratio mass spectrometer linked to a Flash 2000 elemental analyser using a MAS 200 R autosampler (Thermo-Fisher Scientific, Bremen, Germany). All $\delta^{15}N$ values were blank-corrected. Blank-correction of $\delta^{15}N$ values was by the subtraction method as described by Langel & Dyckmans

(2017) and Ohlsson (2013), and was carried out prior to data normalisation. Following blank-correction, values of $\delta^{15}N$ were two point normalised using isotopic data from the daily analysis of NIST 8573 USGS40 L-glutamic acid and NIST 8548 IAEA-N2 Ammonium sulphate. Values of $\delta^{13}C$ were two point normalised using isotopic data from the daily analysis of NIST 8573 USGS40 L-glutamic acid and NIST 8542 IAEA-CH-6 Sucrose. Carbon isotope data were corrected for lipid content following equations in Fry (2002). Precision was determined by the repeat analysis of the working laboratory standard DL-Leucine (DL-2-Amino-4-methylpentanoic acid, $C_6H_{13}NO_2$, Lot 127H1084, Sigma, Australia). Data from the daily analysis of USGS65 Glycine were used to check accuracy and precision. Repeat analysis of Squid lab std provided a further check on precision.

4.3.4. Analysis

Comparisons in $\delta^{13}C$ and $\delta^{15}N$ between; all individuals, adult and chick feathers, survived the first-year vs died, and years were made primarily through visual analysis of descriptive plots with standard errors. To accompany visual plots a comparison of means was undertaken within all groups. Reference prey was grouped by species into marine and estuarine prey using known species life histories for a comparison between years. This allowed a more meaningful visual analysis to compare the role of marine foraging. A Wilcoxon rank sum test was used to compare $\delta^{13}C$ means of chicks that survived the 1st year vs died, and a t-test used to compare means in $\delta^{15}N$ of the same grouping.

4.4. Results

Based on the SI values detected, I found a wide range of prey selection within the species, suggesting a mixed diet driven by food availability (Figure 4.1). Overall, potential prey showed a wide range of both $\delta^{13}C$ and $\delta^{15}N$. Carbon ($\delta^{13}C$) ranged from -11.3344‰ to -22.8219‰ and nitrogen ($\delta^{15}N$) ranged from 8.9890‰ to 13.2376‰ (Figure 4.1). Marine sourced prey (n = 4) had a mean $\delta^{13}C$ value of -18.4010‰ (SE ± 0.4038) and a mean $\delta^{15}N$ value of 12.2214‰ (SE ± 0.3539), whereas estuarine sourced prey (n = 46) had a mean $\delta^{13}C$ value of -15.3686‰ (SE ± 0.4667) and a $\delta^{15}N$ value of 10.7356‰ (SE ± 0.1181). Juvenile marine species were found within estuarine habitat such as parore (*Girella sp.*), snapper (*Pagrus sp.*), grey mullet (*Mugil sp.*) and stargazer (*Kathetostoma sp.*), however, remained classified as estuarine species due to lifecycles of coastal fishes(Ray, 2005b).

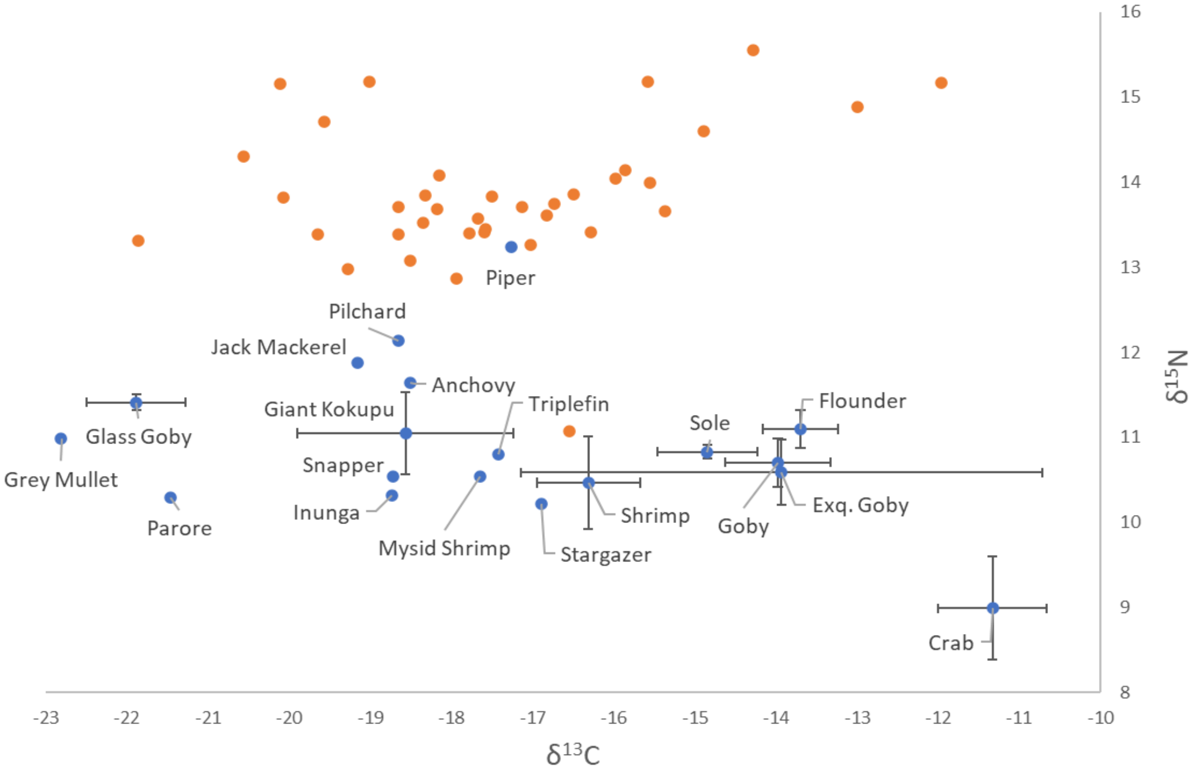

Figure 4.1; Stable isotope analysis comparison plot for δ^{13}C and δ^{15}N displaying signatures for reference prey (n=52) (blue) from Mangawhai and Bream Bay, Northland, New Zealand, and New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) feathers (n=21) (orange) over 4 years. Standard errors bars are shown where calculated.

4.4.1. Adult vs chick

The δ^{13}C values of NZFT chick feathers (n = 30) ranged from -21.8685‰ to -11.9614‰ with a mean of -17.2987 (SE ± 0.40‰). The δ^{15}N values of NZFT chick feathers ranged from 12.8666‰ to 15.5458‰ with a mean of 13.9526 (SE ± 0.13‰) (Appendix; Figure 4.5). A slight difference was found within both δ^{13}C and δ^{15}N values between down feathers (n = 8) and chick adult feathers (n = 16) of 0.0787‰ and 0.6558‰ respectively (Appendix; Figure 4.5). This result indicates a small variation in the diet foundation for egg development and chick provisioning periods. However, it suggests a slightly greater level of marine foraging is used over the egg development period. A higher value of nitrogen suggests a dietary shift towards a higher trophic level, potentially due to seasonal changes of prey over the breeding season.

4.4.2. Survival

δ^{13}C values (n = 19) for chicks that survived their first year were -16.6503 (SE ± 0.45 ‰), compared to -18.3264 (SE ± 0.43 ‰) for chicks that died within the first year. δ^{15}N values (n = 18), for surviving chicks were 13.7659 (SE ± 0.14 ‰), compared to 13.9545 (SE ± 0.25 ‰) for chicks that died. A significant difference was found in δ^{13}C between chicks that survived the first year and those that didn't (*Wilcoxon, $p = 0.009$*), suggesting a greater use of estuarine foraging within chicks that survived (Figure 4.2). However, there was no significant difference between δ^{15}N values of surviving and failed chicks (*$t = 0.6578$, $df = 24.42$, $p = 0.5168$*).

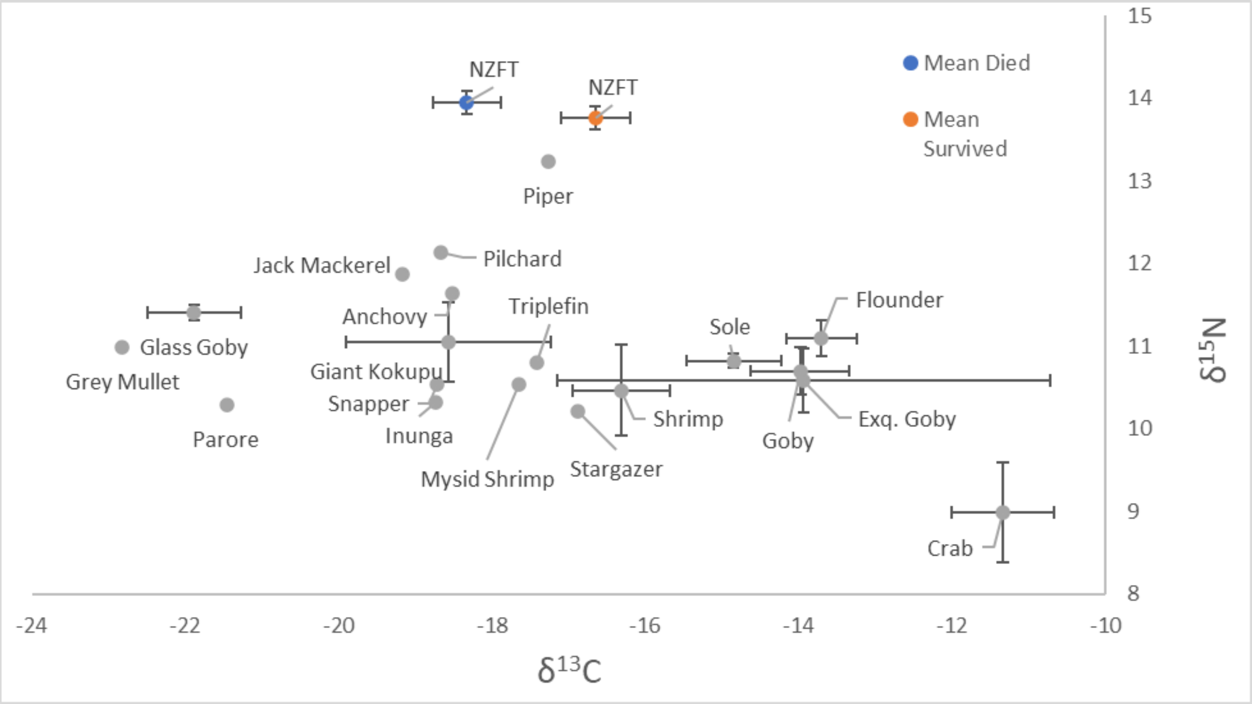

Figure 4.2; Stable isotope analysis comparison plot for δ^{13}C and δ^{15}N displaying signatures for reference prey (n=52) from Mangawhai and Bream Bay, Northland, New Zealand, and mean signatures for survived (orange) (n=20) and died (blue) (n=18) New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) chicks across 4 breeding years, 2022 (n=16), 2019 (n=6), 2017 (n=5) and 2016 (n=4). Standard error bars are shown.

4.4.3. Annual variation

The range in δ^{13}C values varied between years, from 4.71‰ δ^{13}C in 2019 (n = 6) to 7.68‰ δ^{13}C in 2017 (n = 5). Feathers from NZFT chicks in 2022 had a mean δ^{13}C value of -17.8632‰ (SE ± 0.44) and a δ^{15}N value of 14.0796‰ (SE ± 0.18), suggesting a greater proportion of marine prey within the diet (Figure 4.3). Nitrogen isotopes ranged from 0.59‰ δ^{13}C in 2019 (n = 5) to 2.68‰ δ^{15}N in

2022 (n = 16) (Figure 4.3). 2016 not only showed a broader range of diet, but it also showed a preference for estuarine foraging when compared with other years, however, small sample size (n=4) prevents meaningful analysis (Figure 4.3). Negligible variation was found in δ^{15}N values between years, suggesting trophic level is consistent throughout years.

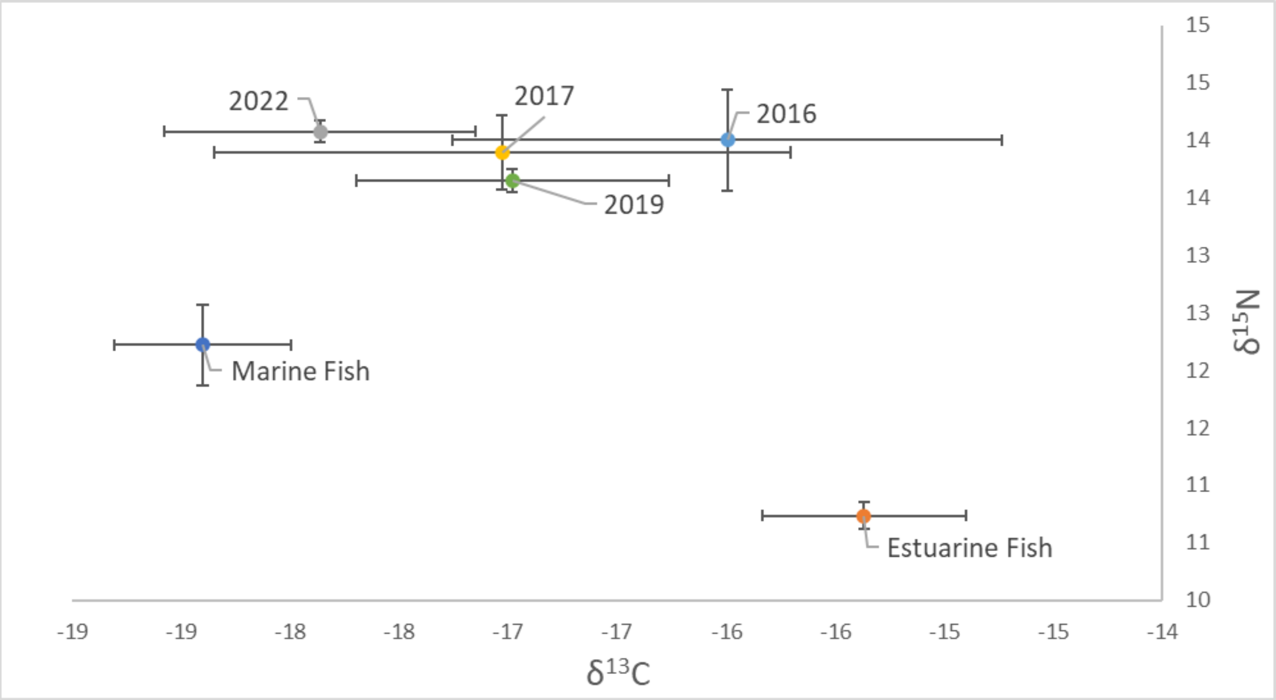

Figure 4.3; Stable isotope analysis comparison plot for δ^{13}C and δ^{15}N displaying different mean signatures for New Zealand Fairy Tern/tara iti (*Sternula nereis davisae*) feathers over 4 different breeding seasons; 2022 (n=16), 2019 (n=6), 2017 (n=5) and 2016 (n=4), and mean signatures for Estuarine sourced reference prey (orange) (n=53) and Marine sourced reference prey (blue) (n=4), from Mangawhai and Bream Bay, Northland, New Zealand. Standard error bars are shown.

4.5. Discussion

The importance of determining a wide range of reference prey within foraging SIA studies is crucial to allow correct inference on dietary composition (Inger & Bearhop, 2008). The wide range of reference prey that I sampled here provides me with a strong basis for assessing foraging habitats used by NZFT during chick rearing. While my study was limited to the collection of marine reference prey from industrial fisheries, these samples provided an appropriate marine signature to determine foraging origin within NZFT chicks. This study found NZFT forage at a greater trophic level than reference prey, this may be due to chick provisioning strategies, and variation between chick and adult feathers.

The variation in $\delta^{13}C$ signatures found within my study may not only account for annual shifts in weather patterns, but also for plasticity within individuals. Weather conditions, in particular wind, are known to have a negative effect on foraging within all tern species due to food-weather interactions (Collins et al., 2020; Dunn, 1973; Mcgarrigle, 2017; Scopel & Diamond, 2018b, 2018a; Taylor, 1983). Effects from weather events vary on different habitat types, the marine environment experiencing greater influence than estuarine environments. Wind speed is known to influence wave height within the marine environment (Thomson et al., 2013), thus impacting surface diving birds foraging potential and decreasing flight efficiency (Collins et al., 2020; Perrow et al., 2011; Taylor, 1983). Due to this, years with a greater wind speed may potentially prevent marine foraging within NZFT. Moreover, habitat use may be limited by seasonal variations in prey availability. Collins et al. (2020) concluded that prey availability had a greater influence on foraging directions within black-legged kittiwake (*Rissa tridactyla*) than did wind direction and strength. Seasonal variation within NZFT may in part be due to seasonal changes in both weather and prey availability.

Prey availability is known to change both seasonally and annually within a marine environment (Carscadden et al., 2011; Crossland, 2010). Ramos et al. (2002) found that the role of weather conditions and seasonal fluctuations in sea surface temperatures had a greater effect on breeding success within tropical roseate terns (*Sterna dougallii*), than food availability, however, the link between sea surface temperatures and fish movement and spawning may highlight causes for food scarcity (Carscadden et al., 2011). While I found that NZFT can adapt and utilise many habitats for chick provisioning, the temporal and spatial importance of these habitats is not currently known, thus influences from sea surface temperatures can only be inferred.

Individuals from a range of species are known to use foraging site fidelity or favour certain habitats (Devney et al., 2010; Hamer et al., 2001, Gaglio et al., 2018; Gilmour et al., 2018; Paiva et al., 2010). Seasonal changes in foraging habitats shown within this study may therefore be due individual plasticity. However, Devney et al. (2010) found black noddy (*Anous minutus*) – a single prey loader species - could not apply plasticity effectively to overcome food shortages. Single prey loading prevents a broader foraging habitat range due to a reduction in efficiency as a greater distance is required for the same energetic reward as multiple prey loaders(Houston & McNamara, 1985). While there may be plasticity within the NZFT population, the role of single prey loading may also prevent spatial shifts in foraging.

The differences that I found in $\delta^{13}C$ between feather types suggests similar findings to those on pre-breeding and chick provisioning foraging within Australian fairy tern (*Sternula nereis nereis*) (Greenwell et al., 2021) (Appendix; Figure 4.5.). The small sample size within this study prevented meaningful comparison between sub-species, however, it highlights the overlap in foraging ecology. Furthermore, my study too found annual variation within dietary composition, comparable to the findings of Greenwell et al. (2021). Annual difference may further indicate variation in individual prey preference or foraging location within NZFT, as it does with other allopatric species (Mauco & Favero, 2005; Ramos, 2000; Safina & Burger, 1988).

While there is a link between the role of marine foraging and prey lipid content, it has been suggested that this may play a greater role within yolk development (Greenwell et al., 2021; Li et al., 2011; Moore et al., 2000; Speake et al., 1998). An increased lipid content within prey items would, therefore, imply greater fat stores and chick conditions. Conversely within my study marine foraging was associated with a reduction in chick survival. This implies that the dietary variability of NZFT may not be the main driver behind NZFT chick survival. However, Dänhardt et al. (2011) showed that common terns (*Sterna hirundo*) actively selected higher quality food items when provisioning for chicks and consumed lower quality prey items. There is potential that NZFT are also utilising higher quality prey for chick provisioning, and therefore in the absence of high-quality prey items yolk quality and chick condition is reduced.

The broad range of isotope values found in my study for NZFT chicks indicated that NZFT use generalist foraging strategies, consistent with previous studies (Greenwell et al., 2021; Parrish & Pulham, 1995; Paton & Rogers, 2009; Ramos, 2000). The limiting factor for NZFT prey selection, as with all single prey loaders, is chick gape size (Hulsman, 1980). Estuarine habitats, especially those with mangrove habitat, are known fish nursery habitats (França et al., 2012; Hulsman, 1980), hence provide a reliable source of small prey. The relationship between correctly sized available prey and breeding has been shown within terns (Safina & Burger, 1985). The role of generalist feeding strategies may therefore allow for species such as terns to adapt their prey selection and foraging location based on seasonal shifts in suitable prey abundance, in line with optimal foraging. This may in part explain variations in dietary composition between years.

4.6. Conclusions

Shore nesting birds such as NZFT that are reliant on correctly sized prey being readily available are at greater risk from climate induced changes in fish populations. Ikpewe et al. (2021) has shown that an increase in sea temperatures affects size structures within marine fishes, known as the temperature-size rule (van Rijn et al., 2017). Current predictions suggest that Northland, New Zealand's Sea surface temperatures will increase with increases in climate temperatures (Sutton & Bowen, 2019; Sutton & Roemmich, 2010). Furthermore, the impacts of sea level rise may interfere with NZFT ecology through further loss of foraging, roosting, and nesting habitats (Galbraith et al., 2002; Ratcliffe et al., 2008). Therefore, the long-term survival of this species not only requires a detailed dietary analysis of NZFT, but also analysis into how both food availability and habitat will change with a warming climate.

The role of marine foraging has been highlighted within this study; however, the true value of this habitat cannot be explained from this pilot study. To build on this study, and to determine the true value of the marine habitat, further study should evaluate time spent within the marine environment and explore the link to breeding success. Furthermore, it should evaluate the spatial distribution and seasonal changes in habitat use of foraging NZFT to highlight key areas for landscape scale conservation.

Future study should also determine the role of storm events on marine foraging availability. Greenwell et al. (2021) highlighted large change in dietary composition within pre-breeding and breeding adult AFT, a bias for marine foraging being shown over the pre-breeding period. A comparison of signatures between years linked to weather events would highlight how NZFT may be affected by weather events and suggest the potential influences on pre-breeding condition and yolk quality.

This study has been successful in building on prior knowledge of NZFT diets. Whilst a dietary proportion analysis has not been undertaken, it has highlighted that NZFT may spend a greater amount of time foraging within a broader range of habitats than previously thought. Furthermore, this study has highlighted the generalist role of foraging within NZFT through annual variation in isotopic signatures. These findings have provided meaningful evidence to support future management of this species whilst addressing key areas for future research to further improve the conservation potential.

4.7. Appendix

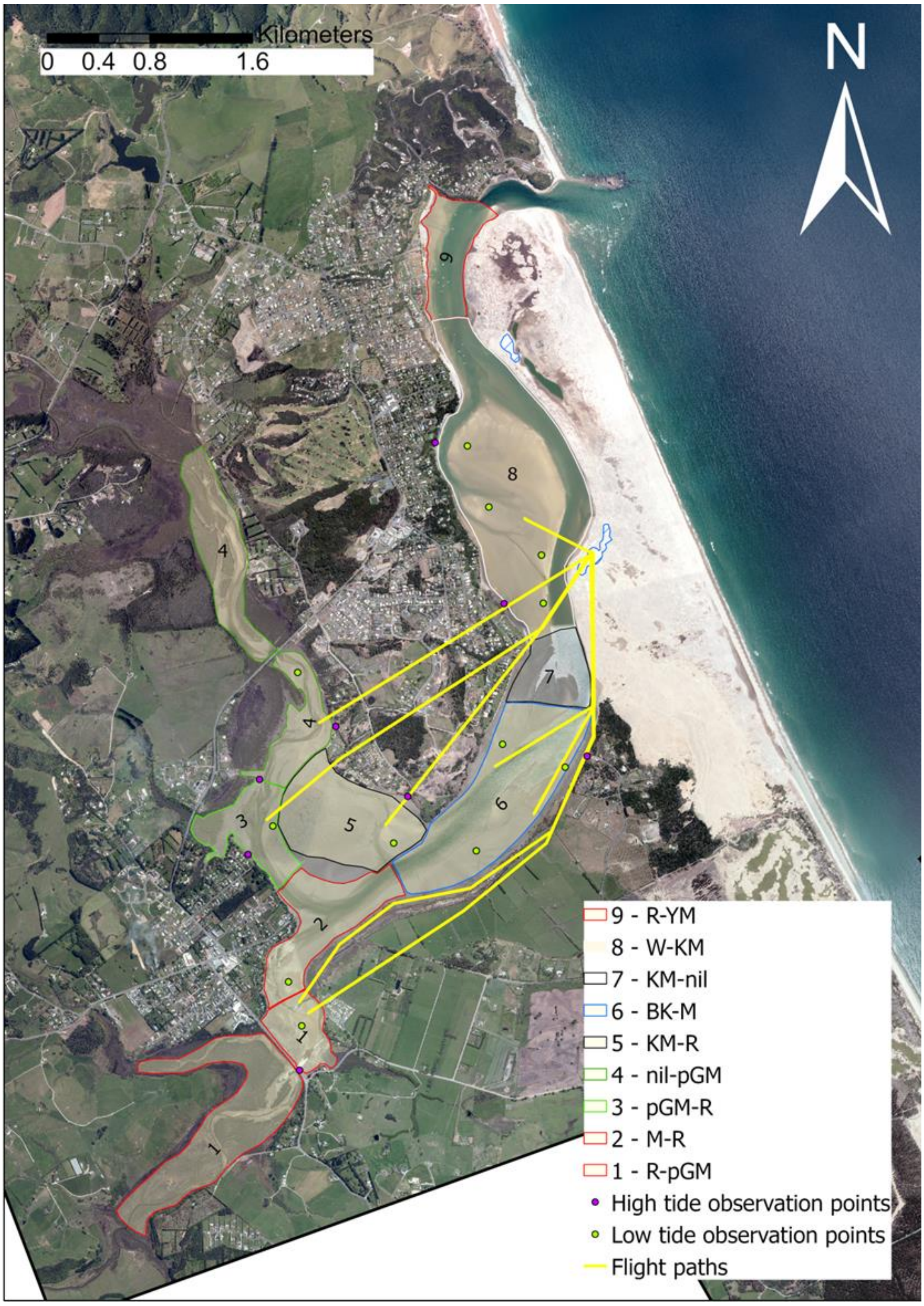

Figure 4.4; Map showing territories of NZFT males over the 2021/22 breeding season within Mangawhai estuary, Northland New Zealand. Known flight paths of individuals are shown. Observation points for data collection over the study period are shown for both high and low tide.

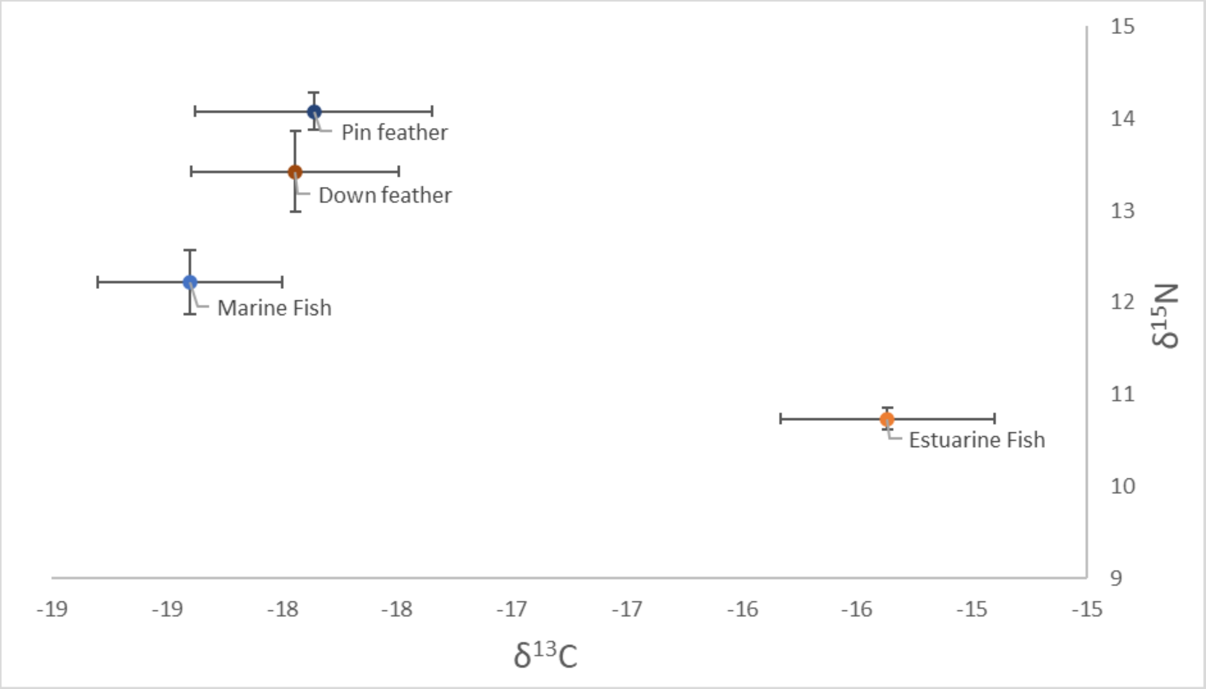

Figure 4.5; Stable isotope analysis comparison plot for δ^{13}C and δ^{15}N displaying signatures for reference prey (n=52) as Marine fish (blue) and estuarine fish (orange) and a comparison between New Zealand Fairy Tern/Tara iti (*Sternula nereis davisae*) pin feathers (n=16) (dark blue) and down feathers (n=8) (dark orange). Standard errors bars are shown where calculated.

5. Thesis Conclusions

Jacob Ball

5.1. Key findings

Previous studies have largely failed to acknowledge the role of the marine environment within NZFT (Ismar et al., 2014). The importance of the marine environment has however been shown within other Fairy tern subspecies, highlighting the likelihood of this habitat as a foraging resource for NZFT (Dunlop, 2018; Greenwell, 2021; Greenwell et al., 2021; Villard et al., 2020). My study managed to demonstrate the role of the marine environment within NZFT, suggesting it is of significant value to this species. While methods for other Fairy tern species involved mostly observational data analysis to determine marine importance, my study used observations backed up by dietary stable isotope analysis showing a clear coastal signal. While marine foraging in NZFT has been widely suspected, my study is the first to directly measure and monitor marine foraging within this species, providing a brief analysis into spatial use and annual variation.

Within the estuarine environment, NZFT are known to focus on channel margins and tidal pools when foraging (Ismar et al., 2014). Although I found evidence supporting previous research describing NZFT foraging habitat, I also found that NZFT utilise a greater range of habitats within the estuarine environment such as channels and mangroves.

Variations in foraging times between territories provided some evidence to suggest a negative impact from human presence, as the closest foraging territory to the nesting had the greatest foraging trip length. Sympatric species have been shown to alter foraging behaviour due to human pressures (Frid & Dill, 2002; Stillman et al., 2002; Yasué, 2006). Furthermore, a large spatial overlap by both humans and NZFT was found within my study, and while individual occurrences of disturbance were low for the NZFT I observed, I did observe human disturbance of other sympatric species. However, my study did not include a valuation of prey availability, predator presence, or territoriality to control against disturbance (Yasué, 2006). My study also found NZFT use habitat outside of times of peak human densities, further implying the role humans may play within avoidance by this species. Low occurrence in resting locations and resting behaviours may support this evidence, however, caution should be taken to ensure other variables do not have a greater influence.

Current knowledge of NZFT territoriality is limited to field notes and observations. Territoriality within terns is a rarely performed behaviour, the role of foraging territories has however been seen in other allopatric species (McNicholl, 1980; Mcnicholl, 1990; Nisbet, 1983b), often only being expressed for short time periods when ecological conditions are favourable. My study has developed from previous knowledge on foraging territoriality within all terns through spatial mapping of territorial boundaries and dive locations within NZFT. Dive locations highlighted areas of avoidance around known territorial boundaries suggesting individuals actively avoid areas of greater foraging conflict and strongly express territorial behaviour.

Finally, my study has shown the potential for foraging trips to be of greater distance than previously thought, highlighting likely variation in foraging tactics depending on the role of a foraging trip (Ropert-Coudert et al., 2004) whilst still fitting the conditions for central-placed foraging (Huon et al., 2021). Overall, my findings highlight the importance of the marine environment for this species and the need to better understand the role of the marine environment in influencing NZFT breeding success and survival.

5.2. Approach taken

Due to the conservation status of NZFT my study was limited to observational approaches. NZFT are currently classified as Threatened – Nationally Critical with a population of less than 40 individuals (DOC, 2022). This restricts the research that can be undertaken on this species due to the management needs, and limitations of species recovery. Therefore, I focused on observations based away from vulnerable nest sites such as foraging territories that enabled me to address questions concentrating on foraging. This prevented me including detailed analysis of dietary composition using similar methods to Greenwell et al. (2021).

To support my observational data, stable isotope analyses of dietary composition using chick feathers were used. This approach uses mass spectrometry to determine variations in carbon and nitrogen isotope ratios between chick feathers and reference prey. This provided me with the opportunity to compare stable isotope profiles between years and look more broadly at habitat use and NZFT foraging ecology. Furthermore, this approach allowed me to build on knowledge, and compare my results with previous research that uses the same methodology (Ismar et al., 2014).

5.3. Limitations

The key limitation with my study was a low sample size; a result of working on a small, critically endangered species. Due to the size of the current NZFT population (<40; DOC, 2022), statistical analyses were limited to quantitative descriptions. However, in this study I collected detailed data on a large proportion of the current population (>20%), accounting for a large proportion of variance within the entire species in New Zealand.

Due to the management options required by species recovery plans for this species, the opportunity for research design was constrained within a research agreement. This meant nest observations were undertaken by staff working within the Department of Conservation program, and thus were limited to the availability of those staff. This caused a bias within data as observations by staff occurred primarily in the morning.

Finally, NZFT are small-bodied white terns and therefore the detection of this species through observational methods is difficult at between 300-400m, shorter during poor visibility conditions. The detection limits caused by this species should be considered in future research design and can potentially be mitigated using GPS tagging technology of individual birds.

Despite the small number of birds, the area needed to be covered to observe all foraging territories was large. Hence, limits on observer time prevented equal time being spent on marine versus estuarine habitats. As such bias was found for observations within the estuarine environment, a smaller more contained area.

Stable isotope analysis achieved the key aim of determining whether marine resources are used by NZFT. However, stable isotope analysis is expensive, and more funding would have allowed for a larger sample size. Furthermore, I was unable to collect marine specimens independent of industrially collected fish, and these fish were larger than those foraged by NZFT, hence the trophic role (nitrogen) was not easily interpreted. Finally, my stable isotope analysis was limited to chick feathers collected throughout routine banding operations by DOC staff. This prevented any comparison dietary between chicks and adults; thus, the role of the marine environment could only be implied for adult NZFT.

5.4. Final Recommendations

1) Use of GPS and protecting marine habitats

While marine foraging has been described and shown to occur within this species, the limitations of working on this species within this extensive environment prevented me from determining the true value of this habitat for foraging NZFT. Other studies have highlighted that different environments may play different roles for breeding within allopatric species (Greenwell et al., 2021). Based on my findings, I recommend that future analysis of foraging behaviour and diet covers multiple seasons to better understand annual variation and the significance of the marine environment. Specially, dietary composition, seasonal and annual changes in habitat use, and fine-scale spatial use. I recommend the use of methods such as GPS or digital photography be used to achieve these goals. The use of GPS trackers on wild populations has expanded in recent years and potentially provides novel discoveries and insights in species ecology (Fijn et al., 2017a; Seward et al., 2021; Wild et al., 2022). Furthermore, research into prey species will help conservation planners understand, and potentially mitigate, changes to prey bases associated with a warming climate allowing effective management actions to be implemented such as translocations.

The findings from my study that NZFT use the marine environment during breeding should be used to inform future resource management of that marine environment. The protection of areas outside of breeding locations is vital for species conservation and extinction prevention. I therefore suggest that lobbying occurs for protection of the coastlines surrounding all known NZFT breeding locations.

2) Supplementary feeding

This research has suggested that limitations to foraging lie within abiotic effects and less so on prey availability. Considering this pressure within the species, the role of supplementary feeding, if undertaken correctly, would not create a dependence or imbalance within the remaining NZFT populations. Non-invasive supplementary feeding methods have been shown to be effective in species recovery (Ewen et al., 2015). Supplementary feeding, if therefore undertaken correctly may have the potential to greatly improve breeding success, thus recruitment potential within NZFT.

3) Reducing human disturbances

The influence of human populations on resting shorebirds is well documented (Bowes et al., 2015; Cortés et al., 2021; Goss-Custard & Verboven, 1993; Stillman et al., 2002; Yasué, 2006). While my findings were limited, they were consistent with previous evidence of human impact. With the current human population of Mangawhai predicted to grow, the implementation of human management will become increasingly difficult (Brunsdon, 2020). Therefore, I recommend that Mangawhai estuary spatially and or temporally limits human activities with the aim of reducing potential impacts on not only NZFT, but on all other native species using this habitat. Furthermore, I recommend that Mangawhai estuary has dog access limited and ensures that a 'on lead' rule is applied to areas where dogs are allowed to reduce disturbance rates on all species.

6. Closing Statement

I do not have many words of wisdom regarding this process, but I would say one thing, do not rush into it and make sure the topic you are researching follows a passion of yours, for without passion I may never have completed this. Enjoy the process of the thesis itself and ignore the end objective for 90% of the time. The final thing I must mention is to embrace any opportunity to engage and discuss your chosen topic of passion, for it leads to many more interesting conversations, opportunities for help, and the potential to not only improve your results and others, but to do some incredible things. Reading other theses, I couldn’t comprehend the vast array of involvement from many individuals and stakeholders. Now I understand the process of writing a thesis is as dependant on them as yourself.

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