# Novel Drone Technology Improves Habitat Mapping for a Coastal Octopus Species

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# Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgments), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Samantha Michele Patterson

# Dedication

I am dedicating this to my magnificent parents, Michele and Brent Patterson,

whose love and support have allowed me to follow my dreams.

I love you both, you are my sunshine.

# Acknowledgements

I would first and foremost like to thank my primary supervisor, Dr. Kat Bolstad. Without her taking a chance on an American undergrad who showed up to CIAC 2018 I never would have experienced this once in a lifetime opportunity. Her academic guidance has helped me to grow in so many wonderful ways, and her support has helped me to overcome the difficulties of being a student in a foreign country. Kat is an innovative leader in every discipline she is involved in, and I am honoured to be one of her ALCES squidlings.

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# Abstract

This Master's project combines UAV footage and synchronous SCUBA footage with ArcGIS Pro, developing a robust method to map and record underwater environments using diver observations. Our focus organism is the 'peachy' octopus, *Octopus tetricus*, a coastal species commonly encountered in northern Te Ika-a-Māui (North Island, Aotearoa New Zealand), including the Hauraki Gulf. This species is known to occupy high-density den sites around Sydney, Australia, and has been anecdotally observed to do so in several local sites around Tāmaki Makaurau (Auckland). Two of these sites were examined across the summer season 2020–2021, aiming to observe octopus density and small-scale distribution across the breeding season using non-invasive methods and evaluate their ecological impact while trialling and refining our observation, recording, and mapping techniques. This project successfully demonstrated the proof of concept for our subtidal mapping technique using low-cost drones with synchronous diver footage. During the study, high-density *O. tetricus* sites were discovered and socially tolerant behaviour (two cases of adjacent occupied dens) was observed in the Tāmaki Makaurau region, though not all octopus found were exclusively in high-density areas. Mean observed den density at Kawau Island across all sampling occurrences was calculated as 3.2 dens per 500m$^2$, with boulder and sandpit den types most prevalent; Stanmore Bay's mean observed den density was calculated as 0.1 dens per 500m$^2$, with only rocky reef dens observed. The composition of shell middens between the two sites did vary, with Kawau Island having *Pecten novaezelandiae* (present in 92 middens) and *Tucetona laticostata* (present in 70 middens) constituting the majority of observed middens (94 observed middens across the sampling period), and Stanmore Bay having *Austrovenus stutchburyi* present in all observed middens (11 observed middens across the sampling period); this could suggest a difference in individuals' diet between sites. The observation methods used during this project were designed to have a low impact on the habitat and animals observed, as well as lower the task load for divers; this goal was met based on fish and octopus reoccurrence, as well as diver reports.

# General Introduction

Octopods are molluscs of the class Cephalopoda, characterised by their eight appendages. Octopods are split into two suborders, the suborder Cirrata, which have paddle-like fins and deeply webbed arms bearing cirri, and suborder Incirrata, with finless mantles and independent arms. The Incirrata are most familiar to humans, far better researched, and are the focus animal of this study. Incirrate octopus are mostly benthic, and while commonly thought of as shallow-water animals, they have been found as deep as 2,394m in the East Scotia Ridge (Rogers et al. 2012). These animals have long been observed as solitary hunters, using their elite camouflaging abilities to hunt and avoid predators. However, in the past few decades, reports of octopus communities have arisen (Aronson 1986, 1989; Hartwell et al. 2018; Scheel et al. 2014, 2017).

Octopus are soft-bodied animals which attract many predators, though they have developed various strategies to protect themselves, including the construction and use of shelters and dens. Octopus 'shelters' are often single-use, opportune protection to be used while resting or eating, and do not indicate a permanent residence (Ambrose 1982; Chase and Verde 2011). In contrast, 'dens' are often modified and include a midden (pile of discarded prey items), dens are often used for longer terms and can last to host multiple occupants (usually one octopus at a time) (Ambrose 1982; Katsanevakis and Verriopoulos 2004). Female octopus are known to lay festoons (egg chains) in their dens, then guard them continuously, this 'brooding' causes them to stay fixed to one location, tending to their eggs until their death (Anderson et al. 2002; Hartwell et al. 2018). Due to their camouflaging abilities, it can be difficult to keep track of individual identification (unless they have identifying permanent marking such as scars; e.g., Boyle 1980; Robison et al. 2014); and to determine whether they reside in the same den, change dens, or permanently leave a location is impossible without constant and long-term observation. Of course, this has been done with species that are able to be kept in captivity; however, the difference between *in vitro* and *in situ* behaviours can confound their true nature (Caldwell et al. 2015; Grearson et al. 2021; Hanlon and Messenger 1996).

Octopus have a long history in commercial fisheries, the first studies of octopus come from specimens caught within pot traps (e.g., review by Sauer et al. 2021). This technique has disadvantages, making the act of observing natural behaviour difficult, and keeping viable specimens when sourcing from a trawl, net, or pot trap makes the situation even more problematic. While pot fishing is still commonly used for sampling, SCUBA diving has also become common in underwater observation and sampling. However, with the cryptic nature of octopus it can be difficult for divers to find and assess individuals, as individuals are transient causing inconsistent populations (Ambrose 1982). In addition, divers may physically manipulate the specimen, if possible, to find species and sex indicators, as well as better document any prey items, den construction, and egg presence. When using this method, the octopus can be severely agitated, if not physically harmed, and will often flee the area when divers leave (Anderson and Leigh 1999).

Human awareness of octopus in Aotearoa New Zealand is as old as the island's discovery. According to some indigenous Māori traditions the legendary Polynesian navigator, Kupe, chased a giant octopus, Te Wheke-o-Muturangi, all the way to a new land (Aotearoa) (Biggs 1957). While octopus are not known to have been a staple food item early Polynesian settlers (or Māori as their culture evolved), this legend still suggests some familiarity with these animals and their habits (Te Wheke is said to have angered Kupe by plundering his favourite fishing grounds).

There are currently 42 known octopus species reported within New Zealand's Economic Exclusive Zone (EEZ) (O'Shea 1999), the majority of which are found in the open ocean (Wassilieff and O'Shea 2006). Of these, six coastal species are most commonly encountered by humans (e.g., Octopoda observations on the crowdsourced website iNaturalist): primarily the peachy octopus *Octopus tetricus* and the New Zealand octopus *Pinnoctopus cordiformis*, and less frequently the club pygmy octopus *Robsonella huttoni*, the common blanket octopus *Tremoctopus robsoni*, the Stareye octopus *Amphioctopus kagoshimensis*, and the knobbed argonaut *Argonauta nodosus* (including beach-cast egg cases or 'shells').

This study focuses on the 'peachy' octopus, *O. tetricus*, a shallow-water species (0-40m; O'Shea 1999) known for its common occurrence around the Sydney, Australia area, where it is known as the 'common Sydney' or 'gloomy' octopus. This species is known to inhabit the coastal areas of southeast Australia, southwest Australia, and New Zealand's North Island (Te Ika-A-Mui (Ramos et al. 2015)). It is often seen in reefs less than 30m deep. Being a small-egged species, the females will produce one large batch of eggs (100,000–700,000 eggs per female according to Anderson 1994; Joll 1976) shortly before dying. These eggs hatch as small planktonic paralarvae, continue to mature outside of the egg. This species was first discovered on an exploratory voyage to Australia in 1838 to 1842 and later described by Gould (1852) within his report of the molluscs found throughout the region. This report was expanded upon by Joll in the 1970's (Joll 1976, 1977, 1978) using personal observations from *O. tetricus* feeding, breeding, and egg hatching of specimens collected in Australia along with the original observations of Gould. Anderson (1994, 1997) provided the first official observations of this species in New Zealand waters in the 1990's, as the species had previously only been known within Australia and provided a study on habitat preference and general morphology. The study was done at the Goat Island (Te Hāwere-a-Maki) Marine Reserve, where solitary individuals were observed and denned in rocky reefs near sandflats, where the population was presumed to hunt (Anderson 1994, 1997). In 1999 O'Shea described *O. tetricus* within New Zealand's EEZ as a new species; however, genetics later showed the New Zealand populations to be conspecific with the southeast Australian population (Norman and Hochberg 2005; Ramos 2015). Instead, the southwest Australian population was experiencing allopatric speciation, were momentarily referred to as *O. cf. Tetricus*, and has recently been elevated to species status and called the 'star' octopus (*Octopus djinda)* (Amor and Hart 2021).

In 2012 Scheel et al. (2014) discovered a site in Jervis Bay Australia where *O. tetricus* individuals could be observed apparently coexisting at high densities. Many of the dens at this site were excavated from the sandy flat substrate and the layer of scallop shells that had accumulated throughout the area. Several individuals were within direct visual contact with another individual, with some dens close enough to allow physical contact between two denning individuals. Later, a second similar area was discovered within the same bay. While most dens observed were excavated sand pits surrounded by shell middens, both sites had artificial structures, some of which were used by octopus as housing or den structure. Both sites were recorded having social behaviours not previously seen for this species. While not as social as play behaviour, these individuals expressed non- agonistic social behaviours, and several varied mating behaviours without aggressive or cannibalistic actions following. Compared to the study by Anderson (1997), whose results have since been widely accepted throughout New Zealand, this same species' habits may vary widely among locations. In Anderson's study a population density calculation revealed a sparse distribution (2.2 individuals per $500m^2$) supporting solitary habits within the region. However, within the Hauraki Gulf, unusually high densities of *O. tetricus* had been recently observed by this project's supervisory team, providing an opportunity to investigate some potentially unreported behaviours for this species within New Zealand. Two locations of high-density *O. tetricus* dens have been anecdotally reported in the Tāmaki Mākaurau area. Observing the density, den type, and midden composition in these areas could provide valuable insight into this species' ecology.

Observing an intelligent species without affecting its behaviour can be difficult. If any accurate behavioural video is to be captured, the observation method should not affect the individuals or draw their attention (Godfrey-Smith 2013). Octopus have proven to be highly visual creatures, and tend to investigate, hide, or flee from unknown entities. To negate this, alternative options for underwater cameras and tripods need to be explored. For example, a camouflaged housing could be used to avoid unwanted attention by concealing the camera used to capture behaviour.

The possibility of observing local high-density sites is intriguing. Such sites provide an opportunity both to collect ecological information, and to develop and test methods for carrying out low-impact observations on these animals. This study therefore aimed to modify existing observation techniques to make use of recent technological and software advances, to gather and visualise data about the distribution and ecology of multiple octopus individuals at each site, ideally without disturbing them.

The open-current SCUBA diving system has existed for 80 years. Recently, modern dive computers have dramatically increased the sport's safety, allowing SCUBA to become a popular sport and profession (Cousteau and Dumas 1953; deepblu 2018). SCUBA diving has been used widely as a method of surveying marine habitats for the past half century. However, even in shallow, low-risk circumstances working on SCUBA can create a high-risk environment (Kur and Mioduchowska 2018; Sayer 2007). These dangers are only enhanced with the introduction of tools and task loading (Toyoshima and Nadaoka 2015). SCUBA surveying techniques, like any other human task, are imperfect; fish counts are often generalisations, and surveys are limited in time by air limits and no-decompression times. Mapping can also be subject to human error if no permanent markers are placed. Previously subtidal mapping methods have focused on creating an underwater benthic quadrat, involving giving physical markers for sites by erecting permanent structures in the environment to maintain consistency throughout the survey. These foreign structures can be left for months, years, or uncollected; and, unless the site in question is small, measurements are relative and can be unprecise (Heine 1999).

Unmanned Aerial Vehicles (UAV) and drones have also experienced technological advancements, allowing hobbyists and scientist alike to purchase more advanced craft on a smaller budget. The precision, stamina, and carry weight now available in over-the-counter UAVs has created a new discipline in ecological sciences (Duffy et al. 2018). These advancements are allowing scientists to purchase cheaper units and modify them to their project's needs. Commercial cameras and cheaper activity cameras have become a common addition, allowing for a higher resolution which provides greater precision in photogrammetry. Commercial-level drone imagery has been used before in ecological projects, but few have yet adapted it for use in a marine setting (Duffy et al. 2018, 2021; Cummings et al. 2017; Everaerts 2008; Fritz et al. 2018; Sankey et al. 2018; Stark et al. 2018). With the addition of geospatial software, drone Full Motion Video (FMV) combined with underwater footage could provide a unique insight into shallow (<30m) marine habitats.

In this study, I aim to apply FMV techniques recently developed at AUT (Hinchliffe 2021) to map the study site, assisted by aerial drones, using subtidal footage. Hinchliffe's research includes a variety of other projects utilising a variation of this method. Using the geocoded drone FMV, the underwater footage, and high-resolution pictures, this method could be used to map subtidal habitats with better relative accuracy and larger scale geographic precision.

This study paired low-cost drones with ArcGIS Pro to assist SCUBA divers in mapping subtidal environments, allowing researchers to trial and refine the observation, recording, and mapping process. The case study focuses on the species *O. tetricus*, a shallow-water coastal octopus. I focused on two sites in the Hauraki Gulf where *O. tetricus* can purportedly be found at high densities and investigate whether these methods can be used to gain insight into the ecology of *O. tetricus*. Using Hinchliffe's method with synchronous subtidal footage to observe octopus density and small-scale distribution across one breeding season I will attempt to gather ecological data for comparison with those reported by Anderson 25 years earlier, and to produce detailed maps of the sites. I will also attempt to improve on traditional SCUBA observation methods in two ways. First by reducing the impact on the environment using non-invasive methods, and second, reducing the impact on the divers by decreasing the task load of typical dive surveys. The questions and objectives are shown in Figure 1, which visualises the complimentary themes.

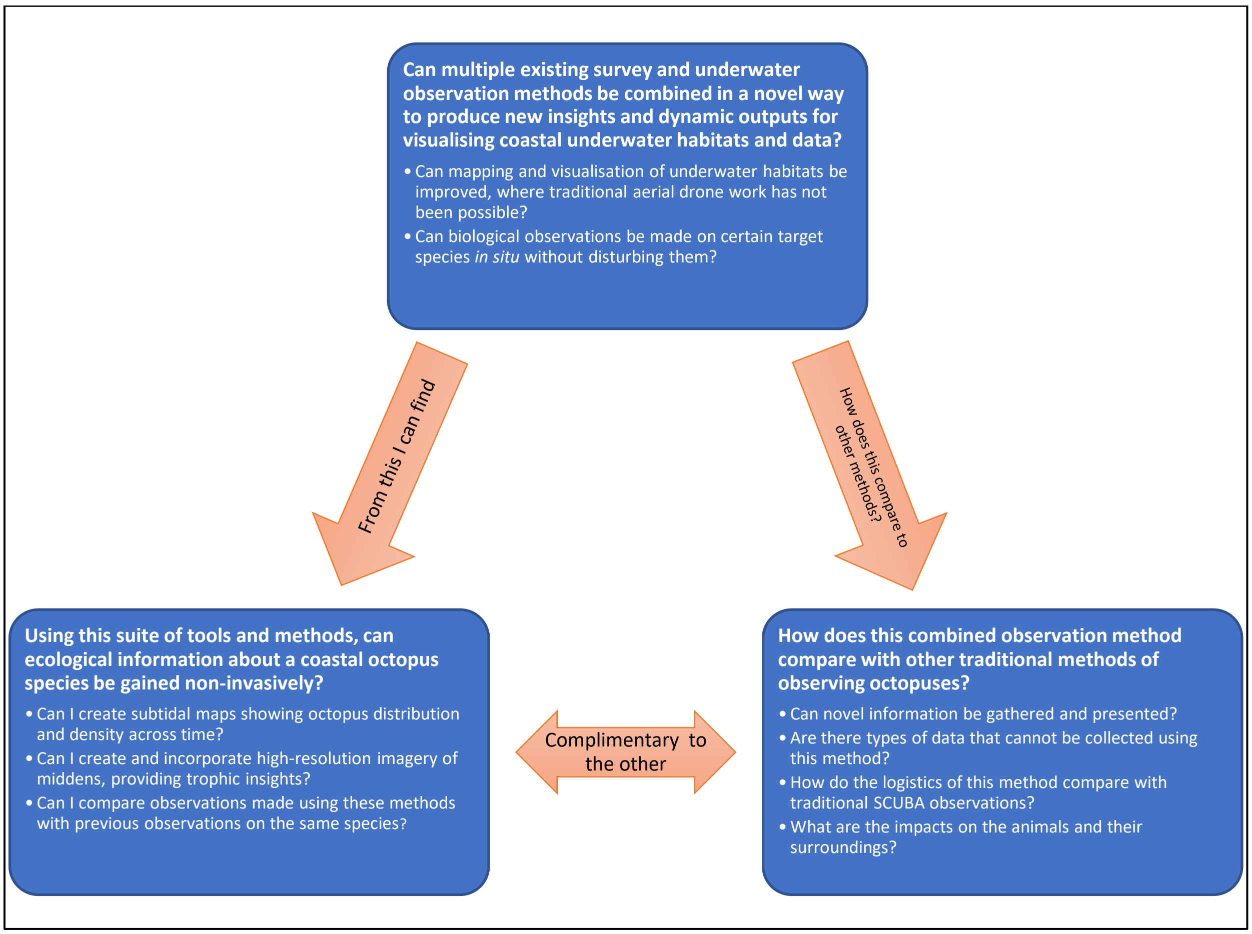



Figure 1: Thesis objectives and questions flow chart. Organised into three categories (represented as boxes) the objectives and questions are presented to visualise how each section relates to the other two. The top box focuses on the method creation and map making of this study, relating to Chapter 1. The bottom-left box focuses on the ecology and case study of *O. tetricus*, relating to Chapters 2 & 3. The bottom-right box focuses on the low impact design of this method and how our method compares to others, this theme is found throughout the thesis, and is in all Chapters.

# Background Information on *Octopus tetricus*

The octopus species *Octopus tetricus* or the 'peachy' octopus was first reported in the Linnaean system based on material collected in 1852 on an Australasian expedition describing the marine life of Australia (Gould 1852). Initially, *O. tetricus* was described as physiologically similar to the circumglobal common octopus *Octopus vulgaris* (Gould 1852) and is still considered part of the *O. vulgaris* complex (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2018). This species has only recently been comprehensively studied and, subsequently, is not as publicised as other octopus species. The works by Joll (1976), reviewing initial discovery and evaluation of the species, were the first published accounts of the life history of *O. tetricus* that later led to more in-depth studies. This species is found in temperate waters on shallow coastlines, rarely venturing deeper than 60m. Its main territory is the southeastern and southwestern coasts of Australia, extending into the Tasman Sea (Ramos 2015), and in northern Aotearoa New Zealand. The first description of *O. tetricus* in New Zealand was not until 1997, before this, all accounts of the species were only from Australian waters.

New Zealand's Exclusive Economic Zone (EEZ) is currently known to contain 42 octopus species (O'Shea 1999), however only six can be found in coastal waters, of which three are pelagic and three are merobenthic. The three merobenthic are all small-egged species with similar gross morphology who prey on similar species, although prey species differ based on location and life stage (Chiswell et al. 2003; O'Shea 1999).

The earliest recorded octopus species in New Zealand is the New Zealand octopus *Pinnoctopus cordiformis*, otherwise known as *Octopus maorum* or *Macroctopus maorum*. This species was originally identified as *O. maorum* in 1880 and was described as a large robust octopus (Hutton 1880). While there has been considerable debate about the correct nomenclature for this taxon, *M. maorum* was preferred until recently, when online resources shifted to favour *P. cordiformis* (iNaturalist). This species is the largest of the New Zealand coastal octopuses and reportedly the most aggressive of the three. Several studies have reported signs of aggression with other octopus of any species, including cannibalism (Anderson 1999). This species has a more southern distribution than *O. tetricus*, occupying temperate to subantarctic Australasia, yet the two have significant overlap in total distribution (Anderson 1999). While the two share preferred habitat types, sandy flats and rocky reefs, *P. cordiformis* are reported to prefer to live and den within long sandy flats and hunt in rocky reefs (Anderson 1997).

The smallest of the three, the club pygmy octopus, *Robsonella huttoni* (synonymised with species *Octopus adamsi* and *Octopus huttoni*) (MolluscaBase 2022), is also often identified by its accomplishments with camouflage. This species is hypothesised to be part of a monophyletic group that spans the southern Pacific, with New Zealand species Campbells octopus (*Octopus campbelli)* and Mernoo octopus (*Octopus mernoo*), along with South America's small octopus, *Robsonella fontaniana* (Ibáñez et al. 2020). While the species is genetically linked to a South American origin *R. huttoni* is believed to be another example of independent radiation, which is commonly found throughout New Zealand (Ibáñez et al. 2020). This species is more commonly found on the South Island, and while it can occasionally be found on the North Island it is unlikely to range as far north as the Hauraki Gulf.

A MSc thesis by Anderson from 1997 is the first account of *O. tetricus* in New Zealand and does include reports of some individuals co-occurring at close rages. Anderson reported behaviourally timid animals, who largely reside in rock crevasses during the day, but prefer to forage along soft sediment patches rather than within the rocky reef. The adult stage of this species was found to be most abundant in summer with diminishing numbers in autumn to nearly none in winter. While the density of this site was less than those reported for other octopodid species by Aronson (1986; 1989) and Mather (1982) these sites were not chosen for their density, but for their abiotic factors. Adult *O. tetricus'* appear to generally favour living on a reef edge, with soft sediment nearby for foraging, and in areas with high amounts of boulders. No juveniles or paralarvae were observed during Anderson's (1997) study.

Anderson (1997) found that sex differences between dens and shelters were apparent. Males were less likely to modify (accumulate debris adjacent to) shelters in broken reefs than in patch reefs. Throughout the sites 25% of males were seen at entrances of rudimentary shelters, as opposed to hiding within or creating some barrier. All females in patch reefs had modified their dens, and the majority (5 out of 7) of females in broken reefs had modified their den, while all brooding females found had modified their dens. Brooding females of all octopus species are typically seen with walled-off dens (Cosgrove 1993), den barricades (Scheel et al. 2018), or den defences (Aronson 1986) to protect their eggs. Brooding females were never seen at the entrances of dens or shelters, and only brooding females were observed to fully barricade their den.

Anderson (1997) also found that 69% of *O. tetricus* dens contained middens, with a wide variety of prey species (23 species). A mix of soft-sediment and reefal prey species were seen, with 63% of middens containing soft-sediment species (61% of species found were soft-sediment bivalves, while 3% were miscellaneous). The three most common midden species were the dog cockle (*Tucetona laticostata* then reported as *Glycymeris laticostata* was present at 29% of middens), the New Zealand scallop (*Pecten novaezelandiae* then reported as *Pecten zealandica* was present at 13% of middens), and *Dosinia* spp. (was present at 10% of middens); all of these being soft sediment species (Anderson 1997).

In 1999, the octopod fauna of New Zealand was revised by O'Shea, who included descriptions of many novel species. Specimens previously attributed to *O. tetricus* were redescribed as a new separate species, Gibbs octopus (*Octopus gibbsi)*, characterised as a shallow-water species, typically found in recesses, grottos, under ledges on rocky ground, and rarely seen in soft sediment areas. However, an extensive genetic study using two Australian populations of *O. tetricus* and New Zealand's *O. gibbsi* later showed the New Zealand animals to be conspecific with the eastern Australian *O. tetricus*, rendering *O. gibbsi* a junior synonym of *O. tetricus* (Amor et al. 2014; see also Norman and Hochberg 2005; Wassilieff and O'Shea 2006).

The paper by Amor et al. (2014) did suggest a difference between two of the populations studied, the *O. tetricus* populations in New Zealand and eastern Australian appear genetically distinct from *O. (cf) tetricus* populations of Western Australia, which has recently been granted species status as the star octopus, *Octopus djinda* (Amor and Hart 2021). This hypothesis was inspired by an observed morphological difference between the hectocotylus (male modified arm for spermatophore transfer), which is not apparent in females. Male octopus barcoding showed a distinct separation between southwestern and southeastern Australian (Tasmania and New Zealand included) populations. While there was some overlap with southeastern Australia and Tasmanian gene pools and with New Zealand and Tasmanian gene pools, these were relatively small and can be explained with the one-way range extension theory (Ramos 2015). However, females had a much more varied result within their western population – with 50 % resulting in southeastern Australia groups and 12% resulting in Tasmanian groups. The result of the barcoding found an interspecific variation of 3.4% between *O. tetricus* and the southwestern Australia population of *O. (cf) tetricus* (*O. djinda*). Genetic differences in species are highly relative, for example, the circumglobal *O. vulgaris* there is a level of differentiation of 1.3% expected to declare a different species, where in other species such as moths, butterflies, and birds there is a range of 5.8 – 9.1% expected between species (Hebert et al. 2003; Hebert et al. 2004; Moore 1995).

The morphological differences found seem to be exclusive to the hectocotylus, with *O. (cf) tetricus* (*O. djinda*) having significantly more suckers on their hectocotylus than the eastern or New Zealand populations. This species separation is expected to have occurred 3.2 – 6.9 m.y.a. when waters lowered with cooler temperatures and the Bassian Isthmus (a land mass connecting Tasmania and Australia) rose. The Bassian Isthmus was only inundated 14,000 years ago, which is relatively recent in evolutionary terms. Similar divergences have been observed within other south Australian marine taxa, such as decapods, echinoderms, and gastropods. The connection between the southeastern Australian population, the Tasmanian Sea population, and the New Zealand population is likely due to the trans-Tasman dispersal during the planktonic larval stage, a stage which lasts several months for *O. tetricus*

(Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017). The Tasman Front is the main mechanism of transportation from the Tasman Sea to the East Australian Current (Chiswell et al. 2015). The trans-Tasman front has acted as a genetic sink for other marine species in New Zealand, who also have a planktonic larval cycle. For example, two rock lobster species, southern rock lobster *Jasus edwardsii* and common crayfish *Sagmariasus verreauxi*, have genetic homogeneity between their eastern Australian and New Zealand populations, with consistent distribution of viable offspring through the Tasman Sea (Grearson et al. 2021). In 2014 Ramos et al. published a paper on the size, growth, and life span of *O. tetricus* and how climate change has and is predicted to affect the species. They identified this species as having great potential for adaption. The expansion of the species from Australia is thought to be driven by oceanic warming, which would indicate a rapid expansion into new ecosystems (Robinson et al. 2015).

In 2009 off the coast of Australia, a site was observed where many *O. tetricus* individuals appeared to be co-existing in densely distributed soft sediment (sand) burrows (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014). These organisms were studied for many years, producing evidence of site modification and social interaction. Soon after, a second site containing the same species and layout was discovered (Scheel et al. 2017). This site was also formally observed, producing similar data to that of the first site. In both sites, individuals appeared to cohabitate peacefully, with few reports of agonistic behaviour (relative to previously observed octopus' interaction) (Godfrey-Smith and Lawrence 2012; Scheel et al. 2016, 2018). While den inhabitation was still a point of contention for some individuals, most octopus would avoid confrontation (Godfrey-Smith 2013, 2019; Godfrey-Smith and Lawrence 2012). However, there is still much more to learn from this species. It is not yet known whether these two sites are isolated events or common for *O. tetricus*.

Within the first Australian site (Scheel et al. 2014), the shell bed mainly comprised of different species of scallops. The less weathered shells were primarily the scallop *Mimachlamys asperrimus* with some remains of the red swimmer crab *Nectocarcinus intergrifrons*. Older eroded shells were primarily *M. asperrimus* as well as commercially fished southern Australian scallop, *Pecten fumatus*. These scallops were found on disturbed surfaces of the bed (none were found fresh). Live scallops occurred sparsely on the bed and were never observed more than one at a time. Many live, small hermit crabs were also found walking on the scallop bed.

In a separately published observation (Godfrey-Smith and Lawrence 2012), the original Australian site had a dense bed of scallop shells throughout, so dense that the discoverers found it difficult to imagine octopus alone had amassed these shells without prior discovery. This spurred talk of a man-made shell dump, catalysing the octopus use of the site. While the shells of scallops are useful calcium carbonate many scallop farmers consider the shells of these animals to be a waste product. In fact, dumping the extra scallop shells isn't unheard of, and can be a common practice for commercial fishing vessels who choose to not bother selling the fishing by-product (Bull 1989).

The second Australian site (Scheel et al. 2017) was similar to the original site; however, this shell bed mainly consisted of *M. asperrima*, although the Sydney cockle *Anadara trapezia*, the pin shell *Pinna bicolor*, and the scallops *Notochlamys hexactes* and *P. fumatus* were also seen around the dens.

Several octopus diet papers have listed live crabs as the more favoured food of captive octopus (Boletzky and Hanlon 1983; Joll 1977), yet the majority of informal sightings report scallops to be the primary refuse within octopus identifying middens. While New Zealand has a different commercially fished scallop species than Australia, *P. novaezelandiae* instead of the Australian *M. asperrimus*, the fisheries are similar in abundance and specimen size. The New Zealand cockle species, *P. novaezelandiae,* is a serial spawner that can spawn over a period of several months, October through April, with a peak settlement in December and January. This species, unfortunately, does not form annual rings, which could be used as an indicator of age (Bull 1989).

Both sites found in Australia were unusual, compared to known (previously mentioned) *O. tetricus* habitat preferences. Within the Hauraki Gulf, individuals are often found within the rocky habitats reported as typical by Anderson (1997) and O'Shea (1999). Whereas at the Australian sites, apart from the shell bed, dens were found on a mostly sandy bottom, with a few scattered boulders. Amor has since stated that from his personal observation, *O. tetricus* can often be found within lairs on sandy bottomed estuaries (Amor et al. 2014).

Reports of high-density co-existence or 'socially tolerant' species of octopus have been the minority and were not even recorded as of 40 years ago. However, within the past decade there have been several reports of previously known species exhibiting high-density denning and socially tolerant behaviour (Godfrey-Smith and Lawrence 2012). O'Brien (2020, 2021) has repeatedly observed a closed marine lake with varying densities of denning Caribbean reef octopus *Octopus briareus* over a 30-year period. During the species peak season artificial dens were introduced, resulting in several cases of adjacent occupation and socially tolerant behaviours. Edsinger et al. (2020) has also published an *in vitro* study on socially tolerant behaviour, with the species *Octopus laqueus*, (or dako in Japanese), which had been previously reported in high-density den locations, suggesting an inherit ability for social tolerance. In the lab octopus were presented with limited dens, which resulted in several co-habitations of a single den. In the Jervis Bay sites there were many different reports of *O. tetricus* exhibiting adjacent occupation and non-agonistic mating behaviour, but no reports of co-habitation behaviour (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017).

Recently, evidence of a den preference hypothesis, that conspecifics have a hierarchy of preferred dens, and even compete for them, has arisen with the reports of high-density octopus sites. Den preference between conspecifics have been reported in several papers, with this hypothesis originating before the discovery of socially tolerant species and their resulting high-density sites. Boyle (1980) was one of the first to postulate the preference of a den (or several) within a central denning location with a local population of octopus, the case species being *O. vulgaris*. Cigliano (1993) provides comparisons of earlier reports of group living octopus, all occurring in artificial conditions. This study also conducted its own procedure, using the California two-spot octopus, *Octopus bimaculoides,* which concurs with other findings that, despite the lack of a known social species of octopus at the time, there is evidence of dominance determined den use which is based on individuals' size. Godfrey-Smith and Lawrence (2012) and Scheel et al. (2017) both observed octopus den preference within the high-density sites of Jervis Bay, Australia. Focusing on the *O. tetricus* residents researchers saw that either the larger individual or the current inhabitant (if conspecifics were of similar size) would win the den if there was an agonistic interaction at a den entrance.

Two high-density sites have been informally observed in the Hauraki Gulf, on New Zealand's northeastern coast, where the 'peachy' octopus, *O. tetricus*, was previously reported as solitary individuals (Anderson 1997). The first anecdotal observation by Bolstad of a high population of *O. tetricus* in a rocky reef off a public beach in Stanmore Bay (see General Methods for description). The second anecdotal observation by Brown was a sandy flat with unusually high abundance of octopus near Kawau Island (see General Methods for description). Studying these sites could provide a unique look into octopus ecology, as each site represents one of the habitats *O. tetricus* is known to inhabit: rocky reef and sandy flat. Observing this species will determine whether high-density sites can be found within New Zealand waters. This study aims to map potential high-density octopus sites using a novel drone FMV method, while collecting data to update the known ecology of *O. tetricus* in New Zealand. This will be done using drone FMV with synchronous dive footage to map the underwater environments using spatial analysis tool ArcGIS Pro. Other environmental factors of *O. tetricus*, such as den type and midden contents, will be recorded by divers while evaluating the site.

# General Methods

## Study Site

This study was carried out at two different sites, where previous anecdotal sighting identified high densities of the ‘peachy’ octopus, *Octopus tetricus*. The Kawau Island site sits on the western side of Challenger (or ‘Little Kawau’) Island (°36.45’ S, °174.87’ E), a small island off the southern coast of Kawau Island (Figure 2) in the Hauraki Gulf (eastern coast of Te-Ika- a-Māui/North Island of Aotearoa New Zealand). This site consists of a stretch of reef 150m long extending 10-15m out from Challenger Island. The coast is steep and rocky, extending from a cliff face to a depth of approximately 4m (at high tide) before meeting reef. On the seaward side of the reef the slope levels off and descends more gradually to sand flats around 9 m. The near-shore substrate consists of large boulders interspersed with pockets of sand and rubble (Figure 3). The rocky reef is 2-6m high with patches of the brown kelp *Ecklonia radiata* beginning around 3m depth. Octopus dens and middens were observed at 5-8m depth within the rocky reef and sand flats. There is often a south running current, which at times can be very strong. This site was accessed by giant-stride entry from the AUT Sciences boat, a 10.5m long Osprey 850 Hardtop with two 150hp Honda four-stroke outboards (Figure 7), on the dates stated in Table 1.

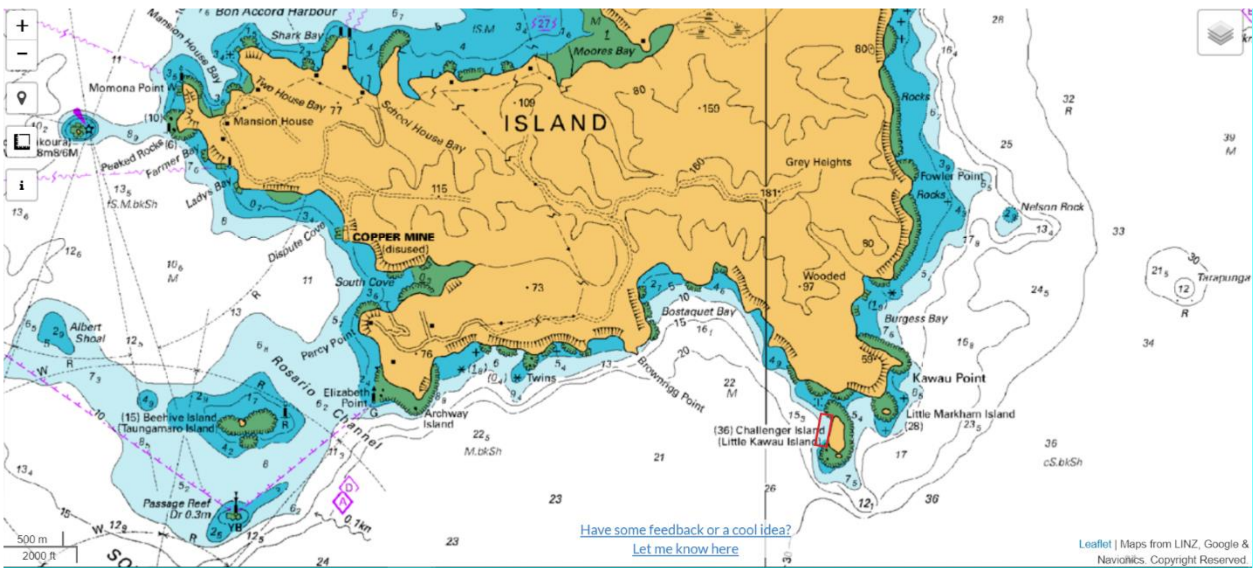



Figure 2: The Kawau Island site as seen on wetmaps, with a red box outlining the location, located on the west side of Challenger Island.


Figure 3: Kawau Island site underwater images. (A) An opening between rocky reef covered in *Ecklonia radiata* 5m deep, (B) a large midden and sandpit den on the sand flats 8m deep, (C) boulders with *E. radiata* over a den and midden in the sand flats, (D) a fallen tree 7m deep, marking the southern boundary of the Kawau Island site, (E) a repetitive boulder den 6m deep in the sand flat, (F) *E. radiata* on rock fall and rocky reef.

The Kawau Island site is close to (1km to the mouth of) Bostaquet Bay (formerly known as Bosanquet), which is well known to scallop fisheries as a staple Coromandel New Zealand Scallop fishery. This bay, however, is notorious for having a high number of scallops too small, or young, to harvest (Fiorito and Scotto 1992).

A historical copper mine on Kawau Island was active from 1844 to 1852. Efforts to revitalise the mine occurred in 1854 and 1855 and again from 1900 to 1902; however, there appears to be little to no ore left. The mine was initially abandoned due to most ore being located below sea level. With constant sea water inundation and dwindling findings, the mine was abandoned to process the ore at a new smelter also located on the island (New Zealand Department of Conservation History of Kawau Island).

According to Wilson and Pyatt (2007) copper can be found in sediment, water, and plants up to 3.4km away from a copper mine. The Kawau Island site is approximately 3.9km away from the Kawau island copper mine (all heavy metals are toxic to octopus, copper being the most volatile (Tang et al. 1996)). However, with the amount of time since the mine was initially dug the copper could have dispersed to a greater distance than that found in Wilson and Pyatt (2007), albeit the levels are likely much lower than those found as well.

The Stanmore Bay site is a rocky reef off a section of sandy beach north of Coopers Reserve (°36.61’ S, °174.73’ E), located within Stanmore Bay (Figure 4) on the Whangapāraoa Peninsula. This site is slightly larger, with a length of 300m located approximately 50m off the beach, depending on the tide. Several rocky reefs begin 15m out from the shore (at high tide) and extend to 100m offshore. The beach’s slope is extremely gradual throughout, the site depth ranging from 4-8m. The reef is patchworked greywacke rock covered with *E. radiata* and, at some points, is populated with dense patches of the invasive Mediterranean fanworm *Sabella spallanzanii* (Figure 5). This site is exposed to the Hauraki Gulf to the northeast, and susceptible to strong currents, choppy water, and high turbulence. This site was accessed by surf entry on the dates stated in Table 2.

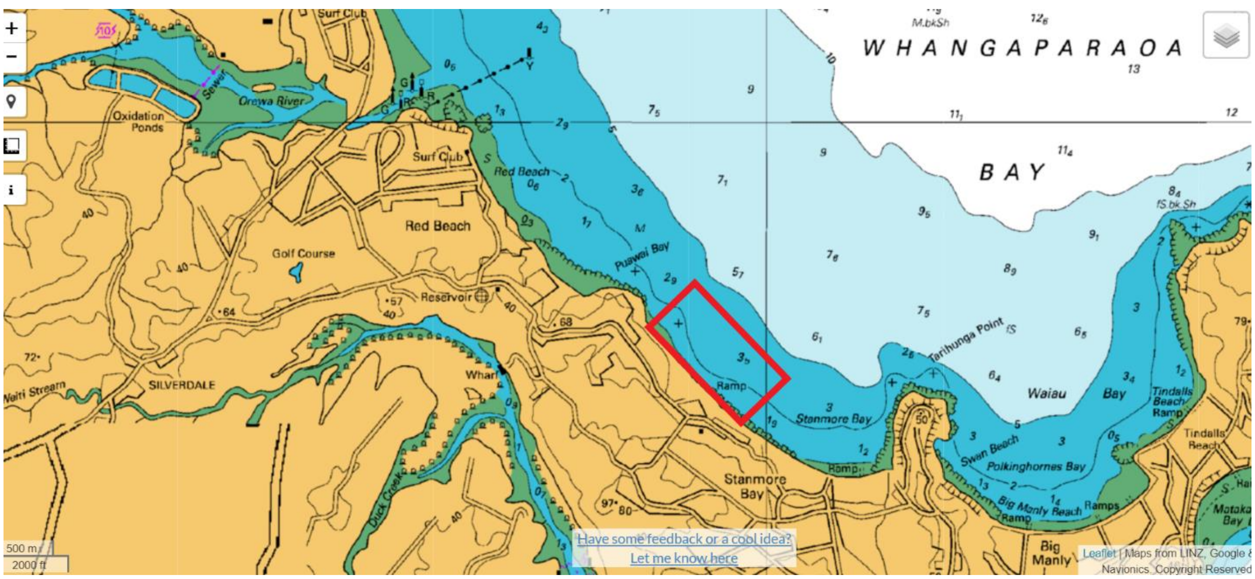



Figure 4: The Stanmore Bay site as seen on wetmaps, with a red box outlining the location, just north of the Cooper Reserve Boat Ramp


Figure 5: Stanmore Bay site underwater images. (A) A rocky reef covered with *E. radiata*, (B) a bare patch of rocky reef surrounded by *E. radiata*, (C) rivers between rocky reef ridges with aggregations of loose materials, such as *E. radiata*, (D) a rocky reef with *E. radiata* and *S. spallanzanii*, (E) the edge of a reef bordering sand flats with *S. spallanzanii* emerging from sand covered rock, (F) the deep end of two reef ridges, its river opening to the deeper sandflat.

These two sites, which represent the two habitat types *O. tetricus* is known to prefer, are situated over 22km apart. The Stanmore Bay site is south of a river mouth and adjacent to several densely populated urban areas, where the other is by a more uninhabited area of island. Different runoff and weather may affect these sites, possibly causing varying water parameters. To investigate whether any difference can be found between the two sites, the water parameters tested to compare the sites profiles.

## Sampling Design

In order to observe the local ecology of *O. tetricus*, including its potential occurrence at high densities, the sites were evaluated using a new subtidal mapping method. The two sites represent the two known habitat preferences of *O. tetricus*: sand flats with a strip of reef at one end (Kawau Island) and rocky reef bordering deeper sand flats (Stanmore Bay). These sites were surveyed by SCUBA divers using a non-specific search method and drone Full Motion Video (FMV) to map each site and test this new method. To capture the population across a summer season, two surveys a month (two dives per survey) for each site were planned from October 2020 to March 2021. However, with inclement weather, busy schedules, and additional challenges posed by Covid-19 Levels, the trip frequency was reduced. The Kawau Island site was visited four times and the Stanmore Bay site visited eight times, although only four of the Stanmore Bay surveys were successfully recorded by the drone. Originally surveys were intended to incorporate a single observation dive. However, as sites were visited, the sampling design evolved to incorporate two observation dives on each visit (see Figure 22). Two phases were undertaken: first, the original observation plan (Phase 1) ending with a gear exchange (on shore or boat) for a new round of observation to occur (Phase 2) (see Figure 23 for more information), with the drone present at both phases (see Figure 22 for more information). During boat trips water parameters were collected at both sites to compare abiotic factors. Divers used non-invasive methods and materials to 1) capture natural behaviour and presence of individual octopus; and 2) reduce the task load of divers.

## Sampling Procedure

The AUT Sciences boat (Figure 7) was used when going to the Kawau Island site, allowing for sampling of water parameters. Sampling the water parameters was done first before divers entered and disturbed the water column. After surveying the Kawau Island site, the Stanmore Bay site was sampled before returning to the marina.

To gather drone FMV a DJI Mavic 2 Pro (Figure 6A) was selected for this project, using the model's built-in camera and sensors for data collection. The PVC pipe stand (Figure 6B) was created to provide a standardised frame of reference for midden pictures. To make this structure a PVC pipe was cut to lengths that suspended the camera 0.6m from the base, while keeping the colour wheel at the bottom centre of the image. The PVC pipes were left unglued, to allow for collapsing during transport. A colour wheel with red, blue, and yellow was added using paint and a sealant to match size and colour between different pictures. The camouflaged stationary housing (Figure 6C) was created to minimise the visual disruption to the environment, while securing its position. The device was made from a short, wide PVC pipe connector with two threaded ends. A hole was drilled into one side for the camera lens. One cap was glued on, while the other was left detachable. The cap permanently attached was drilled and equipped with an eye screw, to attach a line with a weight and buoy. Once modified, the housing body and top cap were covered in a quick concrete and then covered with sand and native shells known from the area. The bottom cap interior was fitted with a slide and lock base for a GoPro Mount in a position that allows the GoPro to film straight out of the port hole when screwed on. Two cameras were used, a GoPro HERO8

Black (Figure 6D) in a HERO8 Black Protective Housing (rated to 60m) that was used in the stationary camouflaged housing (Phase 1) and the PVC pipe stand (Phase 2). And a SONY Cybershot DSC-W200 camera (Figure 6E) in a SONY Marinepack (rated to 40m) was used as the handheld video camera.


Figure 6: Sampling equipment. (A) DJI Mavic Pro 2 aerial drone, (B) PVC pipe camera stand with colour wheel for midden photographs, (C) Camouflaged stationary housing with GoPro sliding mount, (D) GoPro HERO8 Black, (E) SONY Cybershot DSC-W200 camera.

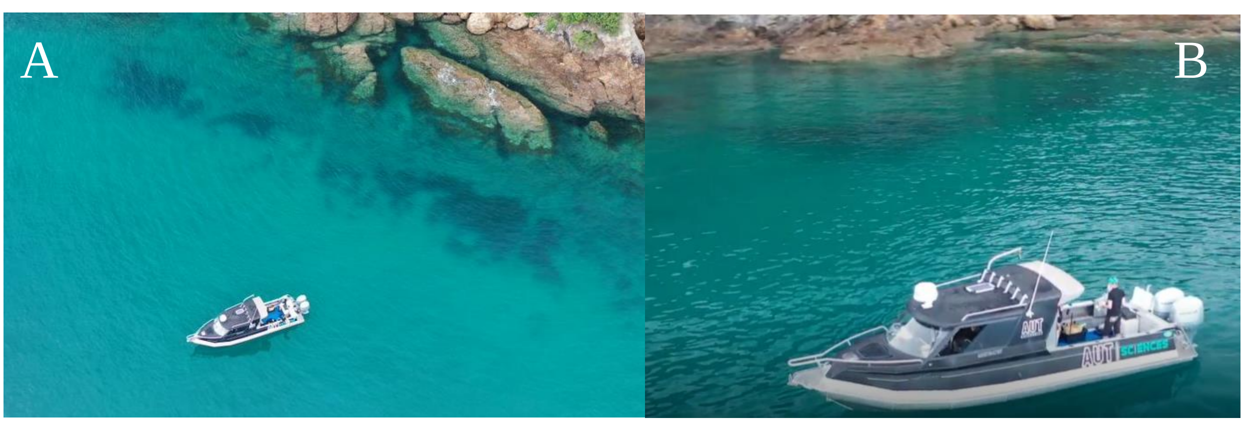



Figure 7: The AUT Sciences boat, a 10.5m long Osprey 850 Hardtop with two 150hp Honda four-stroke outboards. (A) Aerial view of boat with reef shown, (B) a lateral view with Dr. Bolstad on deck. Photos taken by G. Hinchliffe while at Kawau Island site using a DJI Mavic Pro2 drone.

The procedure for dives was the same for both sites (Figure 23), for more details on drone piloting methods, see Chapter 1 Methods or Appendix. The two sites were surveyed on separate days, and, for simplicity, will be referred to by code, rather than the date surveyed (see Tables 1 and 2).

Table 1: Kawau Island site sampling dates and code. At Kawau 63 individual dens were found across the sampling period, with a maximum of 28 dens on two occasions (9 occupied on K1, 3 on K3) and a minimum of 16 dens (2 occupied on K4). Of the 63, 17 dens were sighted on multiple sampling periods.

| Sampling code | Date | Dens sighted | Occupied dens |
|---|---|---|---|
| **K1** | 22 October, 2020 | 28 | 9 |
| **K2** | 16 December, 2020 | 22 | 8 |
| **K3** | 19 February, 2021 | 28 | 3 |
| **K4** | 16 March, 2021 | 16 | 2 |

Table 2: Stanmore Bay site sampling dates and code. At Stanmore 11 individual dens were found across the sampling period, with a maximum of 5 dens on two occasions (2 occupied on both S2 and S4) and a minimum of 0 dens found on S1, S3, S6, and S7. Of the 11, only 1 den was sighted on multiple sampling periods. Survey S3 was called due to poor visibility and no data were collected. Surveys S5 and S8 were completed but did not have successful drone surveillance, dens were found on both surveys but only S5's were mapped due to its identifiable location.

| Sampling code | Date | Dens sighted | Occupied dens |
|---|---|---|---|
| **S1** | 8 October, 2020 | 0 | 0 |
| **S2** | 23 October, 2020 | 5 | 2 |
| **S3** | 9 November, 2020 | 0 | 0 |
| **S4** | 19 November, 2020 | 5 | 2 |
| **S5** | 3 December, 2020 | 1 | 1 |
| **S6** | 22 January, 2021 | 0 | 0 |
| **S7** | 5 February, 2021 | 0 | 0 |
| **S8** | 23 March, 2021 | 1 | 1 |

After observing the site, all subtidal recordings were reviewed back in the lab to annotate observations of fish, dens, middens, and octopus. For more details on the subtidal footage methods and analysis see Chapter 2 Methods or Appendix. For more details on the fish count methods and analysis, see Appendix. Data from the multiparameter YSI Sonde were downloaded after the sampling day. For more details on the water parameter methods and analysis, see Appendix.

The processing of drone footage to a MISB compliant file was done by Graham Hinchliffe (AUT); for more detail, see Chapter 1 Methods.

Once the drone FMV was created, it could be embedded into ArcGIS Pro and used to identify points in the site. After a base map was created the paths of the divers were tracked with FMV alone. With the dive path on the map the FMV was synchronised with the subtidal footage and played simultaneously to locate each den and midden found, using the diver path as a guide. Once plotted the information collected from the subtidal footage was added to the dive path, den, and middens for analysis. For more details on ArcGIS Pro methods, see Chapter 1 Methods and Appendix.

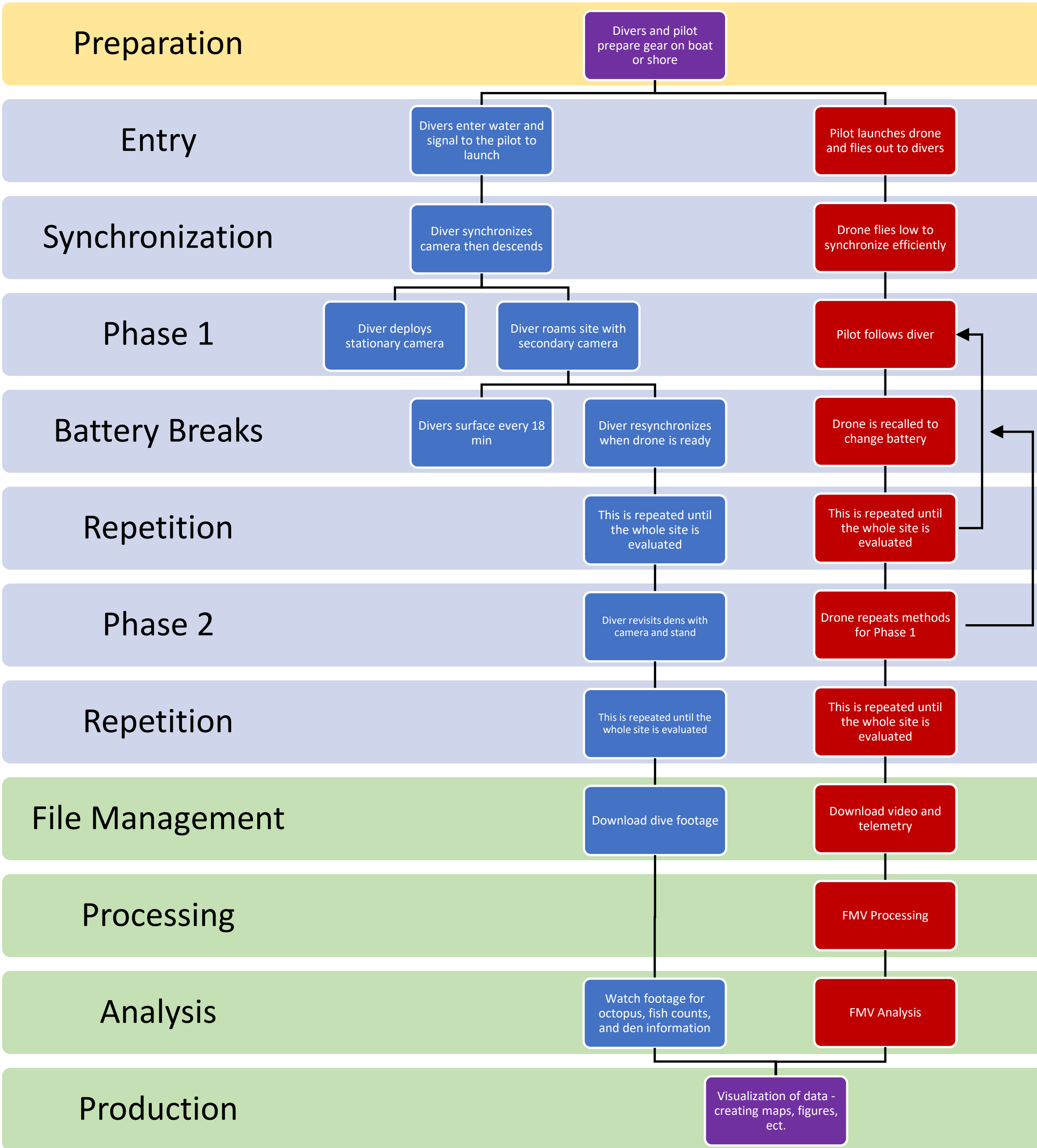



Figure 8: Parallel timelines showing simultaneous diving (blue boxes) and drone (red boxes) methods. The individual steps occur within one of the three main phases describe the steps: Preparation (yellow), data collection (light blue), and data analysis (green).

In the dual timelines pictured above (Figure 8), three sections of the data collecting process are signified by different colours. The first is shown with a yellow section, this is the preparation phase, where plans were made, and equipment was prepared. The blue section, the data collection phase, is where divers collected underwater footage and the drone collected FMV. The third green section was data analysis, this is where the data were downloaded, processed, and analysed.

## Ethics

Octopuses are highly advanced and intelligent invertebrates (Browning 2019). Historically, in laboratory ethics considerations, octopods have been treated like any other invertebrate, with no special exceptions. However, considerable work by Mather and others (Mather 1980, 1992, 1985, 2004; Mather and Alupay 2016; Mather and O'Dor 1991) has demonstrated their advanced capabilities and made a strong case for treatment more aligned with the ethics and considerations for vertebrate scientific subjects. This body of work, alongside public attention from media such as the recent Netflix film *My Octopus Teacher* (2020), has elevated political interest in octopus handling and treatment. Numerous countries and institutions worldwide have begun reviewing policies on cephalopods as captive/experimental subjects. For example, the United Kingdom's House of Lords has recently submitted a bill designed to change its ethics policy, which would consider octopods and other invertebrates to be sentient (*the Animal Welfare (Sentience) Bill [HL]),* and as a result would be afforded more ethical rights.

In advance of this project, both AUT and University of Auckland ethics personnel were consulted, confirming that additional animal ethics approval would not be required for this project as proposed. All parties agreed that maintaining a set physical distance of at least 2m from individuals (octopus) being observed while withholding any physical contact or other intentional interaction or manipulation would maintain the integrity of the organism's personal environment. Indigenous landscapes, marine habitats, organisms, and resources were also left undisturbed.

# Chapter 1: Mapping Subtidal Habitats

## Introduction

Humans have always been interested in mapping their surroundings, for millennia, civilisations have been using maps to share and learn information about their surroundings. Ancient maps were centred around cities or civilisations and their placement in the known world (Thrower 2008). Due to ease of accessibility, the mapping of landforms was more advanced than the mapping of large bodies of water. However, with the advance of seafaring occurring around the 1400's the eastern worlds records of seas and coasts became far more accurate (Edson 2007). Yet marine mapping was still limited until the 1900's, which advanced greatly with the Third Industrial Revolution or Digital Revolution of the second half of the 20th Century (Shannon and Weaver 1949; Veneris 1990). Since then, seabed mapping and exploration have exploded, and new disciplines have radiated within this field leaving many unexplored.

The Unmanned Aerial Vehicle (UAV) or drone are aircraft controlled by a remote pilot (Everaerts 2008). The rise of the UAV has given scholars, enthusiasts, and citizen scientists accessibility to aerial data sampling. Allowing for a new medium, between in person surveys and satellite imagery, often utilising photogrammetry or aerial scanning with various sensors. The American Society for Photogrammetry and Remote Sensing (2018) defines photogrammetry as the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of record of electromagnetic radiant energy and other phenomena (i.e., Full Motion Video (FMV) or aerial photography) (The American Society for Photogrammetry and Remote Sensing 2018). With affordable drones and Geographic Information System mapping software, photogrammetry is now an option for researchers and enthusiasts alike. Geographic Information Systems or GIS is a conceptualised framework that allows one to create, manage, analyse, and map spatial and geographic data. Utilising the raw telemetry of drones, such as integrated GPS, allows for geotagging (adding geospatial metadata to digital media such as photographs or videos) within FMV.

Metadata is "data that provides information about other data", but not the content of the data, such as the text of a message or the image itself. Raw telemetry is the untouched data collected by the drone during the flight. The telemetry is recorded within UAVs as an encrypted .txt for data integrity, this can be edited on a computer as a Text file and edited to the needs of the operator. The .txt can be encrypted and saved out as a .csv, which can then be processed further for the MISB (Motion Imagery Standards

Board) ( Esri. FAQ: What are the Full Motion Video Add-in's Motion Imagery Standards Board (MISB) metadata requirements? nd).

The term FMV refers to a very narrow subset of Motion Imagery; one that assumes geo-spatial metadata, commercial image formats, and playback rates. The FMV package in ArcGIS Pro allows for the playing of a geospatial analysis of any FMV-compliant video (Esri. ArcGIS Pro: FMV Package nd). An FMV-compliant file refers to a file containing a video stream with associated metadata, making the video geospatially aware. Very specific metadata is required to make FMV spatially aware, both the position and orientation are needed. For aerial vehicles this requires the heading, pitch, and roll of the machine. While not as detailed as other sensory techniques, the ease of access and wide range of secondary applications makes FMV a useful asset. Using the metadata collected, along with the FMV, many parameters can be measured post-survey using various software. This requires only a camera to record in a resolution high enough (typically 4K) to aerially survey a site to MISB standards (Phillips 2005).

Motion Imagery is a sequence of images, that when viewed (e.g., with a media player) must have the potential for providing informational or intelligence value. MISB is any imaging system that provides the functionality of collecting, encoding, processing, controlling, exploiting, viewing, and/or storing Motion Imagery as defined in MISP-2015.1 or later (Motion Imagery Standards Board, 2014).

## Drones

When conducting an ecological UAV project, the scale, habitat, and parameters should all be considered when finding the appropriate UAV. For ecology projects there are generally three types of scale, based on the size of land covered. The local or plot scale, which focuses on land cover and vegetation structures; the patch scale, which observes species richness and abundance; and the landscape scale, which uses remotely sensed data to show geographic characteristics (Sankey et al. 2018).

There are several different classifications for UAVs, the most common, and one of the easiest to operate, are low altitude systems (flying under 200m), within this classification there is a variety of UAV types. A tethered or free flying balloon (or blimp) is the simplest of vehicles, they can be sized to the weight of any sensor but are slow and bulky. Micro-UAVs have become more common, but must fly at quick speeds to generate enough lift, which is a problem for fixed-wing models as well. Larger fixed-wing low altitude aircrafts are widely used for multipurpose monitoring and can fly autonomously. Unmanned helicopters can vary in size and can be used commercially as well. Power paragliders need little ground support and can carry heavy payloads. Multirotor drones can take off and fly in more restricting conditions but don’t have the battery or weight capacity of fixed-wing paragliders (Everaerts 2008).

In *Location, Location, Location* (Duffy et al. 2018) various projects and their suggested drone specifications are described, based on the environment and goal of the study. The article focuses on lightweight (<7 kg take-off-weight), fixed-wing, and multirotor drones equipped with photographic equipment for ortho-mosaic (e.g., Husson et al. 2014) and structure-from-motion photogrammetry (e.g., Smith and Vericat 2015) type applications, which encompasses the practices used in this project. Before flight can be considered, the location of interest should be examined to determine the equipment needed. Take-off location can limit options if the take-off space is limited, requiring the use of a multirotor drone, as fixed-wing types require a runway. The salt and sand particulate carried by wind in coastal environments can clog or corrode exposed drone equipment, such as cables, motors, and ports; however post-flight cleaning maintenance can mitigate these effects. Supplemental landing pads, anti-corrosion spray, and using sealed cases or ruggedised waterproof cameras are also effective but require additional purchases.

In Fritz et al. (2018), data collection with UAVs was proven to provide fine-scale and continuous information of vegetation and landscape structure. In the paper they defined three advantages to using UAVs that stand out to the ecological community. The ability to collect data is straightforward and possible even in difficult to access areas. The continuous data collection can recover lost information with any geolocation or pixel errors. And if the UAV data perception is like satellite imagery, then the data allows for image segmentation.

Commercial drones that are used for professional marine mapping, and other ecological projects, are outfitted with any number of additional sensors for data collection; the result of which, is the need for a larger, more powerful drone. With every additional task and item that is added on to a drone its size, complexity, and price range needs to increase to accommodate the increasing task load. Multirotor models can fly with more dexterity, yet they typically lack the lift capacity for heavier and more complex sensors, where the fixed-wing models are able to carry several, depending on the size. These models need large batteries to compensate for the heavy frame and require consistent flight speeds to maintain lift. This requires consistent forward flying, as opposed to multirotor drones whose multi-directional and hovering capabilities allow them to operate in confined spaces. The larger fix-wings also require certain ground conditions to take off, specifically a runway of varying length depending on the size and model (Everaerts 2008).

A paper by Duffy et al. (2021) shows how drone mounted sensors can produce viable data, provide micro-meteorological measurements, and be incorporated to 3D radiative transfer models. Along with FMV this project used LiDAR, a light detection and ranging sensor that emits pulsed light waves into the surrounding environment to create a 3D representation of the study site. While cameras can perform similar tasks using Structure-from-Motion Multiview Stereo photogrammetry, the result is far less detailed and lacks substructural information. Structure-from-Motion photogrammetry, which is now a mature data processing technique, produces a 2.5-dimensional representation of an environment in the form of a spatially explicit point cloud or gridded raster product (typically a digital surface model unless the ground is unvegetated). A high-quality recreational camera can be used to create these models, making them a cheap and useful tool able to capture detailed aerial surveys.

Recreational drones have improved in power and capability to such an extent that, in some instances, they are able to take the place of commercial drones. More serious hobbyists have taken to commercially producing modified drones to fit niche markets, closing the gap between the commercial and low-cost recreational market. However, some low-cost recreational drones have the tools themselves to conduct accurate ecological surveys.

The DJI Mavic 2 Pro (Figure 6A) is a recent model (released in 2018) costing approximately $3,500 NZD in 2021, depending on location and condition purchased. A high-performance Hasselblad camera built into the framework provides the high-resolution imagery required for ecological surveys and marine mapping. The official and practical capabilities of the DJI Mavic 2 Pro can be viewed in Table 3.

Table 3: DJI Mavic 2 Pro drone specifications and practical uses.

| | **Drone Capabilities** | **Practical Limitations Used** |
|---|---|---|
| **Drone max flight time** | 31 min | 20 min, less with higher winds |
| **Footage resolution** | 4k | 2.7k |
| **Max flight speed** | 20m/s | Never went over 10m/s |
| **Max wind speed** | 9.4m/s without draining battery | Under 10m/s with some gusts going over |
| **Max distance from pilot** | 8km | 400m, but usually within 200m |

## Rules and Regulations

Air rights are the legal dominion over all air directly above a property. The purchase or renting of land or a building includes the rights to use and develop the air space above it unless specified otherwise (Paris Convention of 1919 and the Pan American Convention on Commercial Aviation 1928). Initially, air rights once extended indefinitely upward, however with the popularisation of air travel in the early 1900s, public easements were created at high altitudes for air transit, regardless of real estate. However, with the rise of UAVs, and subsequently the hobbyist drone, which fly far lower than transit aircraft, new standards were set by distinguishing airspace. Airspace is the section of the atmosphere controlled by a country above its territory, including its territorial waters (AIM Airspace nd).

Airspace can fall under several classifications in Aotearoa New Zealand: controlled, special use, and no-fly zone. Controlled airspace needs an air traffic control service, where special use airspace includes restricted areas, military operating areas, mandatory broadcast zones, volcanic hazard zones, danger areas, and low flying zones. The zones that can be found within the Auckland area can be found on the AirShare (nd) website (Table 4), which provides official New Zealand Airspace zone locations and information.

Table 4: Auckland airspace zones and their descriptions as seen on AirShare (nd).

| | |
|---|---|
| Control Zones | Control Zones are managed by Air Traffic Control and extend down to ground level. |
| Low Flying Zones | UAVs are not permitted to fly in any Low Flying Zones, as these are reserved for larger commercial and military aircraft. |
| Military Operating Areas | Permission from the administering authority is required to fly in these zones. |
| Aerodromes | UAVs are not allowed within a 4km radius around aerodromes (the locations where aircraft flight operations take place). |
| Other Authorities Areas | These areas require pilots to gain approval before flight from the administering authority or landowner. |
| Danger Areas | These areas are where an activity within is a potential danger to aircraft flying over the area. |
| No Fly Zones | These areas are where pilots are unlikely to receive approval to fly from the administering authority or landowner. |

There is no universal drone frequency on radios, leading to different countries having different rules (Duffy et al. 2021). Learning the international and local rules and laws, along with the local low flight frequencies, are important prefight measures for any drone pilot.

New Zealand laws covering the use of drones have determined that all operators must follow both the National air traffic rules as well as following the policies of whichever local government authority is responsible for the area intended for flight. New Zealand Air traffic rules and regulations are determined by the Aviation Security Service (ASS)– Kaiwhakamaru Rererangi, and the Civil Aviation Authority of New Zealand (CAA) – te Mana Rererangi Tūmatanui o Aotearoa. An unlicensed pilot can fly a drone legally if they follow the CAA Part 101 regulations (Table 5) (Aviation Security Service 2021).

Table 5: CAA Part 101 rules and regulations for noncertified drone users in New Zealand (Aviation Security Service 2021).

| |
|---|
| Aircraft must NOT exceed 25kg and must always be safe to operate and well maintained. |
| Pilots must take steps to minimise hazards to people, property, and other aircraft. |
| Only fly during daylight unless pilots are doing a shielded operation. |
| Pilots must give way to all crewed aircraft (e.g., planes, helicopters, hang gliders, and paragliders), and land the aircraft immediately if another aircraft approaches. |
| Pilots must be able to always see the unmanned aircraft, with no unnatural visual aids. |
| Fly below 120 metres (400 feet) above ground level. |
| Get consent before flying over people and property, it is always safer to not fly over people. This goes for both private and public property, like parks and reserves, for the latter check with the local council or Department of Conservation before flying. |
| There are several no-fly zones – check for any airspace restrictions in the area before flight. |
| Stay 4km away from all aerodromes (including the helipads at hospitals, and those used by helicopters conducting scenic flights) unless the pilot has got clearance from the aerodrome operator. |
| Do not fly in special use airspace without the permission of the administering authority. |

Depending on the project the CAA Part 101 rules can be too restrictive, and more leniency is needed. If so, a shielded operation is a favourable alternative to obtaining a CAA Part 102 certification. Shielded operations are flights in which the aircraft remains within 100m of, and below the top of, a natural or man-made object. No authorisation is needed from air traffic control if the flight can be conducted as a shielded operation. When flying as a shielded operation, flights are allowed to occur at night and within controlled airspace without Air Traffic Control clearance, as other aircraft are unlikely to be flying so low and close to structures. When relying on a shielded operation to fly within 4km of an aerodrome, with the need to remain within 100m of, and below the height of the object providing the shield, there must also be a physical barrier like a building or stand of trees between the unmanned aircraft and the aerodrome. This barrier must be capable of stopping the UAV in use, in the event of a fly-away (Aviation Security Service 2021).

## Ethical Considerations and Permissions

The use of drones is remote and less invasive than many other survey techniques, however there are still concerns to the impacts drones can have on the area around them, namely in the disturbance of local wildlife. To minimise the magnitude of a drone’s presence the Department of Conservation (DOC) - Te Papa Atawhai has rules and recommendations for drone etiquette around wildlife.

Since the popularisation of hobbyist drones concern has risen for their effect on birds in the immediate area. In response several studies have focused on drones and their impacts to a variety of bird types. Two of these papers concluded that giving birds a 100m wide birth was the only way to assure no birds were affected (Vas et al. 2015; Weston et al. 2020). New Zealand's DOC has public suggested drone protocol when flying near birds (Table 6).

Table 6: Guidelines for drone flights near birds in New Zealand according to the DOC (New Zealand Department of Conservation Flying Drones Near Birds nd).

| Pilots should: |
|---|
| take off at least 100m from any bird. |
| fly no closer than 50m in any direction to shorebirds or seabirds. |
| abandon contact at the first sign of any bird being disturbed. |
| land the drone at a safe distance away if a bird circles or otherwise interacts with a drone in flight. |
| not fly within 300m of any shorebird or seabird if there are already three drones present. |

There is a recent rise of concern that drone activity over marine mammals causes undue stress that should be avoided. An AUT study by Fettermann et al. (2019) found that drones can agitate marine mammals, based on their study using bottlenose dolphins. When flying their drone under 10m the marine mammals were clearly agitated, as shown by a tell-tale tail splash. In-between 25m and 10m there were mixed results, and when flown above 25m the dolphins appeared unbothered (Fettermann et al. 2019). The DOC has both mandatory and suggested regulations for marine mammals, both of which are required in AUT's drone flight standards. These rules are far more conservative than those found in the study, reassuring our presence will not seriously affect the wildlife in the area.

Table 7: Rules and guidelines for drone flights near marine mammals within New Zealand's EEZ according to the DOC (New Zealand Department of Conservation Interacting with Marine Mammals nd).

| Pilots must: |
|---|
| fly no closer than 150m horizontally from a point directly above any marine mammal. |
| not disturb or harass any marine mammal with the drone, e.g., don't chase, herd, or scatter them. |
| not make any sudden or repeated change in speed or direction. |
| not make any loud or disturbing noises near marine mammals. |
| abandon contact at the first sign of any marine mammal being disturbed. |
| **Pilots should:** |
| take off at least 100m from any marine mammal on the shore or the land. |
| not fly within 300m of any marine mammal if there are already three drones, other aircraft, or boats within 300m of that marine mammal. |
| keep at least 50m from any other drone. |

In accordance with Te Tiriti o Waitangi, all have a responsibility to ‘give effect to the principles’ in the work done within Aotearoa New Zealand. This means including the interests of iwi/hapū/whānau regarding local sites and native species and supporting them to contribute to decisions about activities occurring within their tribal boundary. The locations surveyed in this project were all under the land of the Ngāti Whātua iwi. The stewardship of this iwi extends to activities that affect natural and physical resources (such as air and fresh or coastal waters), heritage, and archaeology. Recognition also requires the consultation of the iwi when traveling to or through ‘areas of significance to Māori’. Since no natural or physical resource was affected and all land was public, and under no special consideration by the Ngāti Whātua iwi, no special consideration was sought (New Zealand Department of Conservation Iwi/hapū/whānau Consultation nd).

## Methods

### Preparation

The drone used for this project was the DJI Mavic 2 Pro (Figure 6A), which was purchased in a bundle with additional batteries and a travel case. For the Stanmore Bay site, the drone operator brought a high-vis vest, launch pad, and warning sign. At the Kawau Island site, instead of a launch-pad the drone took off and landed with the aid of a small handle specially attached to the drone. While the sign was not used on the boat the high-vis vest was.

### Sampling Procedure

Acting drone pilot was Senior Research Officer Graham Hinchliffe, who holds a CASA RePL (Remote Pilot License). During the surveys, Hinchliffe was actively piloting from either the beach at Stanmore Bay or aboard the AUT Sciences boat at the Kawau Island site. All flights were flown according to the CAA Part 101 regulations. Both sites were in open air space and no special permission or measures were needed.

To ensure the data collected could be used together the drone FMV and the subtidal footage was synchronised at the start of each video capture. At the start of each dive the divers would get in position and signal to the drone operator to launch – thus starting the drone footage. The signal was given by divers, by extending one arm with a fist, and moving their hand in a large circular motion overhead. Once the drone flight had initiated the divers’ footage was initiated. When the drone arrived at its initial viewing location it would stop moving and hover in the air. At this point the diver would focus their camera on the drone and move it in a large circular motion several times. This allowed both cameras to view each other and observe the same motion, allowing for a precise synchronisation that could be used for the remainder of each recording.

The drone's angle of view and flight path was chosen by the pilot, depending on the light refraction and surface interference, to give the best view of the divers under the water. Both close ups and wider (high elevation) views were given to best discern underwater locations.

When the drone's battery was low it was recalled to the boat and battery packs were exchanged, ending the recording. Several backup batteries were brought to each site; charging was not done in the field. The divers attempted to surface every 18 minutes to refrain from observing key factors without drone surveillance. The battery length depended on external forces, typically the wind was the limiting factor; the windier the environment the harder the drone had to work to counteract the force. This caused the pilot and divers to adjust the battery change frequency depending on the daily circumstances. If any rain was seen the drone was immediately recalled as it is not waterproof.

## Post-Sampling Procedure

The FMV processing was done by supervisor Graham Hinchliffe. A broad explanation of this method, the telemetry recorded during the flight, at approximately 0.1 second or 10 Hertz, is converted to a MISB compliant file (Esri. FAQ: What are the Full Motion Video Add-in's Motion Imagery Standards Board (MISB) metadata requirements? nd). The footage was then downloaded at 2.7k then downsampled to 1080p (for efficient FMV playback) and is then multiplexed with the MISB telemetry, creating the geocoded FMV. This FMV is the file that can be used within ArcGIS Pro.

The mapping of these sites was done by Samantha Patterson using ArcGIS Pro. To give the FMV a reference elevation a constant raster DEM was created on the current field of view, which was given an elevation value of zero. That DEM was then turned into the elevation source to provide the drone video with a base elevation. Next, a .tif extension of multiple overview photos of the site was created, these images were screen captures taken from drone FMV. The separate surveys were confined to separate maps within the project, each containing the FMV from that day. First the diver paths were plotted using only the drone FMV (using the annotate points tool), then den locations were plotted using both the drone FMV and the dive footage. The diver path points were selected and used to create a new line feature class, which was given a buffer (buffer values differed depending on the dives visibility). The dive footage was synchronised with the drone FMV when using ArcGIS Pro. Den locations were sometimes adjusted manually to fit to the base map. The den points were used to create a new point feature class, where each point was given various descriptors for later analysis. A visualisation of the procedures ArcGIS Pro is shown in Figure 9, for a more detailed list of pictures and procedures see the Appendix.


Figure 9: ArcGIS Pro methods flow chart. General explanations and pictures of the five steps taken to produce the maps within this paper. For a more detailed procedure see the Appendix.

## Results

The footage taken by the DJI Mavic 2 Pro drone provided FMV was capable of mapping both subtidal sites. A base image of each site was produced (Figures 11 and 12) from drone FMV of flights over each site without divers present. This created a more detailed image than the satellite imagery within Esri’s base maps.

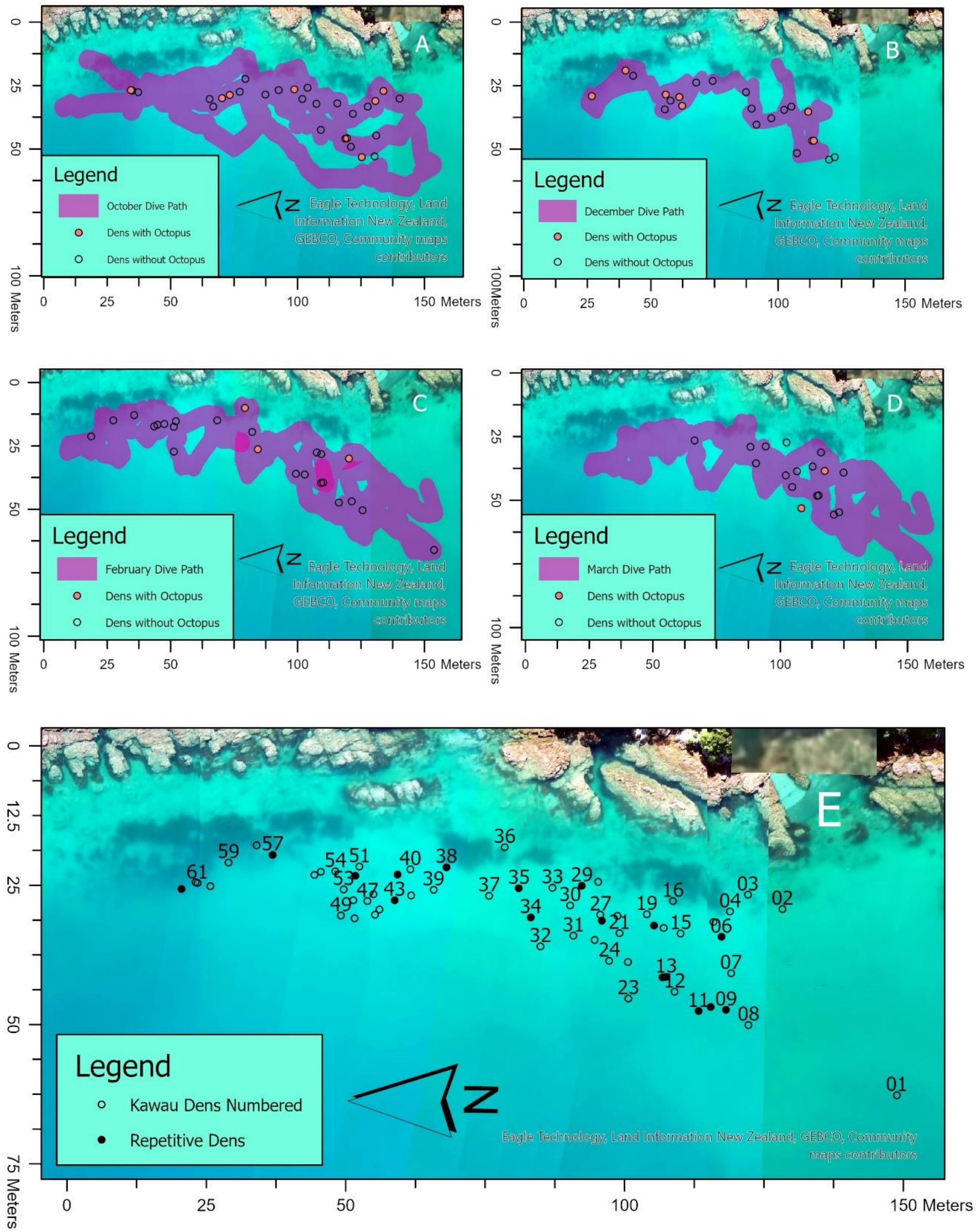



Figure 10: Kawau Island site diver path with field of view and dens across the sampling period. (A) K1 diver path and dens found on October 22, 2020 (B) K2 diver path and dens found on December 16, 2020 (C) K3 diver path and dens found on February 19, 2021 (D) K4 diver path and dens found on March 16, 2021. (A-D) Individual surveys had den locations coloured peach to indicate the presence of an octopus. (E) The complete den count, 63, with locations coloured black to represent repetitive dens, those that were seen multiple times across the sampling period.

The Kawau Island site was observed 4 times over the sampling period of October of 2020 to March of 2021. At the Kawau Island site 63 dens were found in total (Figure 10E); 28 of these were found in K1 (Figure 10A), 22 were found in K2 (Figure 10B), 28 were found in K3 (Figure 10C), and 16 were found in K4 (Figure 10D). Of these dens 17 were found more than once and were considered repetitive. The purple paths shown (Figure 10A-D) represent the course divers took and what area they observed, the buffer differed based on the visibility of the day. Survey K1 had exceptional visibility and was given a 4m buffer, K3 and K4 had good visibility and a path buffer of 3m, K2 was a rough day, with lower visibility, and was given a buffer of 2m.

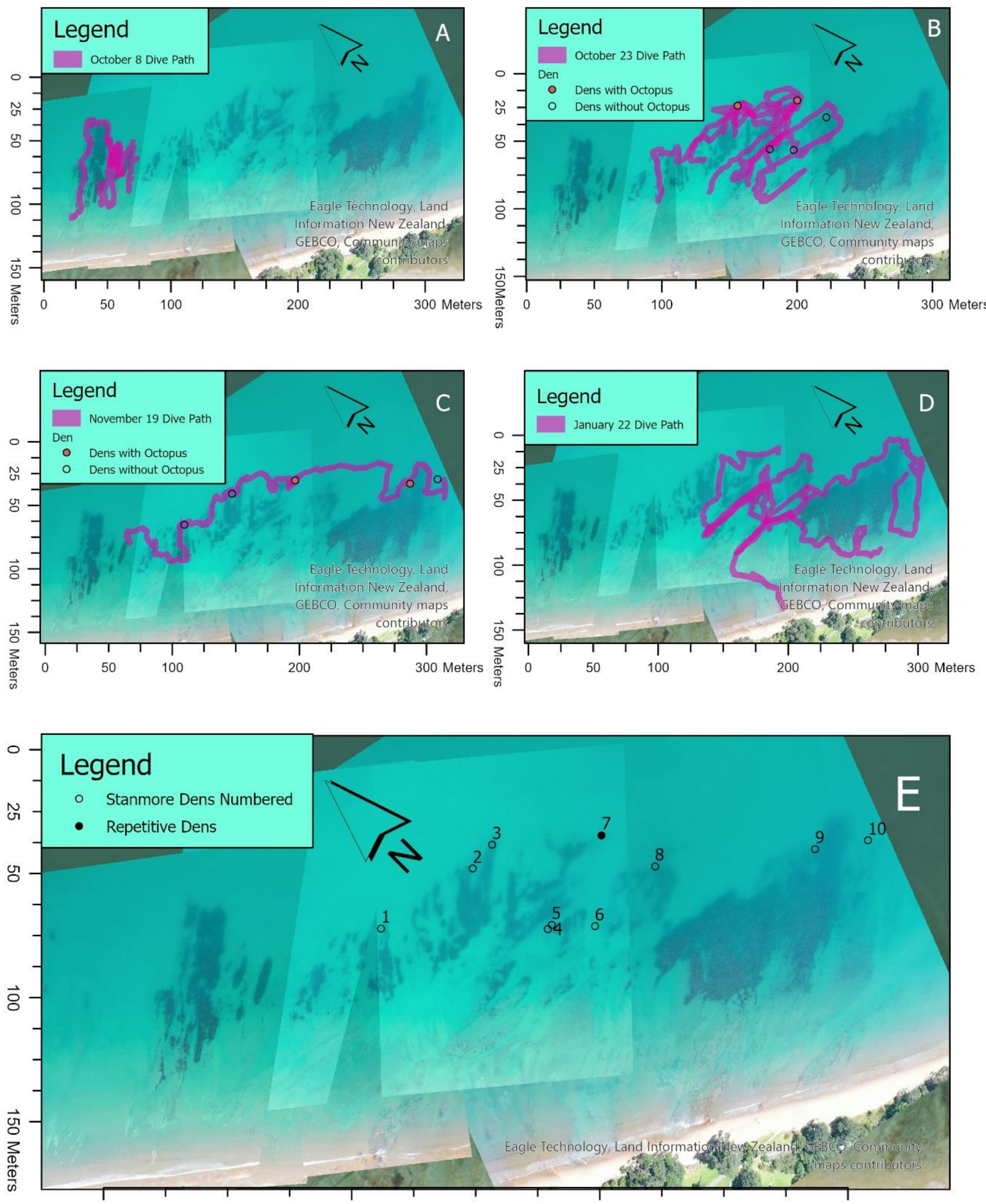



Figure 11: Stanmore Bay site diver path with field of view and dens across the sampling period. (A) S1 diver path from October 8, 2020 (B) S2 diver path and dens found on October 23, 2020 (C) S4 diver path and dens found on November 19, 2020 (D) S6 diver path from January 22, 2021 (A-D) Individual surveys had den locations coloured peach to indicate the presence of an octopus. (E) The mapped den count, 10, with locations coloured black to represent repetitive dens, those that were seen multiple

times across the sampling period. An additional den found on S5 is displayed, this den was found on December 5, 2020 and was mapped without original drone footage.

The Stanmore Bay site was observed 8 times over the sampling period of October of 2020 to March of 2021, however only 4 of these were successfully recorded by the drone. At Stanmore Bay 11 dens were found in total, however only 10 were mapped (Figure 11E); none were found in S1 (Figure 11A), 5 dens were found in S2 (Figure 11B), 5 dens were found in S4 (Figure 11C), and no dens were found in S6 (Figure 11D). Only 1 den was observed on more than one survey and was considered repetitive (Figure 11E). The purple paths shown (Figure 11A-D) represent the course divers took and what area they observed, the buffer differed based on the visibility of the day. All surveys (S1, S2, S4, and S6) had poor visibility and a path buffer of 2m.

## Discussion

### Developing this Method

This method was a collaboration with Hinchliffe G. and his working PhD project, including several case studies. To our knowledge, this study is currently the only one utilising the Hinchliffe method with synchronous SCUBA footage used to create subtidal maps.

In the past decade alone, the rise of the hobbyist drone has led to a dramatic increase in UAV DIY modifications. In the USA more than one million civilian UAV were expected to be sold for the Christmas of 2015, marking a major turning point in the accessibility of non-commercial UAV's. The emergence of self-modified UAVs for environmentally related studies has utilised sensors modified from commonly arisen label cameras (i.e., Cannon with a Cannon hack kit) (Cummings et al. 2017). While the drone used in this project was entirely created by the manufacturer (DJI) small modifications were made as needed throughout the project (i.e., a handgrip was added for certain flights). The ability, flexibility, and adjustability of small multirotor drones have made them a preferable option to many environmental researchers, as opposed to commercial applications or satellite imagery (Cummings et al. 2017).

### Drone Preparation

When planning for this project many environmental parameters were taken into consideration before any flight was attempted. While the drone had already been purchased for previous projects the DJI Mavic 2 Pro was chosen for its relatively low price compared to prebuilt hobbyist drones, its above-average Hasselbad camera, and its flight ability. The multi-rotor models are able to complete far more flexible and agile flight plans allowing it to follow a target more easily than a more robust fix-wing model (Duffy et al. 2018). A launch-pad was used at the shore sites, reducing the amount of particulate agitated into the air, which could enter the motors. The boat take-off and landings were more difficult, a handgrip was added to the body of the drone, allowing the pilot to retrieve or release the drone mid-flight (hovering), by hand. While this allowed for a much more stable take-off and landing from a boat, this was still difficult for the drone pilot, requiring very calm weather. The drone used was not waterproof and had to be recalled if any rain (light or heavy) was present. Duffy et al. (2018) description of pre-flight preparation assisted in the planning for this project and the majority of their advice was followed, which was helpful to a drone novice planning dive surveys around the use of a drone.

ArcGIS Pro

The dive footage was synchronised with the drone FMV by hand, no program was used to synchronise videos or stitch them together. Using a specialised software might have been more accurate; however, the scale of this project did not require such fine precision. Den locations were determined based on diver orientation in accordance with the subtidal footage so a few seconds difference between the two videos would not confound the resulting placement. Den locations were also sometimes adjusted manually to assure the location on the base map of each site best represented the location on the footage.

Creating the base map (the .tif file) for each site took considerable time to find the right shots to incorporate and their respective levels within the resulting mosaic. Each frame varied in view colour, detail, and glint. Finding the frames that worked best together while giving an accurate and detailed view of the site (the rocky reef under the water) was a lengthy and subjective process. The process was worth the effort exerted; the detailed image had a clear view of seafloor structure which assisted divers in mapping den locations more accurately.

To represent the areas that were viewed by divers the diver paths were given a buffer to represent the search area of the divers. The buffer depended on the site's dive visibility, this was not the vertical visibility usually used to describe a water column, but instead the distance divers were able to confidently spot the presence of a den or lack thereof. Often the Kawau site had good visibility, 3m, although the October Survey was exceptionally clear and had a 4m visibility. The December survey was done in rougher conditions, which is what caused the trip to get cut short to 2 dives, yet the area still had 3m visibility. The Stanmore site was far more turbid and had lower visibility, all surveys accompanied by a drone were considered to have 2m of diver visibility.

The mapping of the different sites were done on separate GIS project files to keep the two sets of FMV, and data organised. The separate surveys were confined to separate maps within the project, each containing the FMV from that day. At the end of the individual survey mapping the final products from each survey were added to an additional map within that file to produce a uniform layout of each site.

While there were several annotation types available by the end of the map creation this project only used point annotations, rather than polyline or polygon annotations. This is due to the Kawau Island site mapping being completed before the ArcGIS Pro 2.8 update, where point annotation was the only choice available. Since the diver paths were already created with points and converted to separate class features, the same method was continuously used for continuity. However, the addition of these features would make future projects more streamlined, requiring lest steps (i.e., using polyline feature for diver paths).

Two dens were found at the Stanmore Bay site without supporting drone FMV to assist in their mapping. One of these dens was mapped using previous dive footage of the location and its synchronous drone FMV. This den was found in S5 on December 5, 2020 with an *O. tetricus* inhabitant and was added into the total den map (Figure 11E) as den 5. While not mapped, an 11$^{th}$ den was found in a location new to divers, and without previous underwater footage with paired drone FMV the location could not be confirmed. This den was found in S8 on March 23, 2021, within the Stanmore Bay site, in a rocky reef section that was either not fully explored or had major landscape changes (due to storm surges) since its last observation. This den was covered in many different shells being actively barricaded by its *O. tetricus* inhabitant (Figure 12H).

## Further Analysis

ArcGIS Pro has numerous applications that could be used to further a project such as this. The addition with the greatest outreach impact would be a digital map website where those interested in the research could look at the map in detail. The addition of interactive media would allow for others to conduct a virtual investigation. This could be done with high-quality images and perhaps a few 3D models of certain dens or middens. However, if in the future a 360° camera could be used the whole area could be mapped in a digital space, allowing for others to fully experience the area without having to enter the water (like in VR headset).

The inclusion of a larger population model would also have been useful; however, due to time restraints, these were not completed. The presence only model, Maxent, is useful in underwater environments where species exclusion is not always certain. The water parameter data collected could have been used with the observations from all surveys to map out other predicted *O. tetricus* locations (Hermosilla et al. 2011). Edsinger et al. (2020) used maxent to predict, not location, but co-habitations of *Octopus laqueus* (or dako in Japanese), an asocial octopus species given anthropogenic den locations in a lab setting. Using Maxent scientist were able to predict the occurrences of co- and solitary habitation of individuals. Since *O. tetricus* is thought to have only recently extended its range, the extent of this range within New Zealand waters is unknown. Another program ENFA: Environmental-Niche Factor Analysis, is usually used for studies with more complete information, but can also be used with presence only data, and could be another program to explore this species range (Bennice 2019; Phillips et al. 2006).

<u>Complications</u>

Since this method was being developed and trialled there were several complications throughout the study that were corrected within the sampling period. At some points of the FMV the geolocation would be skewed, this occurred mostly at the start of the project as the drones geodata were adjusting with the flight. However, a few times this problem occurred later in the sampling period, the best mitigating action was to orient the drone at the start of each flight. The drone would sometimes need to be oriented a few degrees past its intended direction to correct this mistake. The mistake would often cause the geolocation to be 2m south or more, but the difference could be adjusted manually after creating the point.

The site's overview flights were done spontaneously, and the Kawau Island sites base map had a boat in several of the screen shots that had to be removed after the map layouts were exported. The Stanmore Bay site overview was taken in varying cloud coverage and resulted in different brightness between some of the frames. Additionally, both layout areas are not completely covered by a base map. While the resulting base covers the areas of interest, in the future a more thorough site overview flight would be done to ensure a more coherent base map result.

After the divers exited the boat or left the shore there was no verbal communication with the drone operator. At some point, either due to unexpected rain or low battery, the drone had to be recalled before the divers surfaced, causing divers to continue the survey without the drone for spatial reference later. The use of a mobile communicator, even a nonverbal one, could have been useful to alert divers to the drone being recalled.

During some surveys, various animals did approach researchers during above ground operations. During some Stanmore Bay surveys small groups of red-billed gulls would approach and circle the drone, despite active avoidance by the drone's pilot. Often the seagulls would not be within eyesight upon the drones' initial launch, but they would seek out the drone during its flights. The pilot did attempt to evade them according to DOCs regulations; however, they followed the drone for the remainder of the day. This only happened for one full survey day and the latter half of two others. During boat surveys at Kawau Island wasps would occasionally pass by the boat and those on the vessel, appearing to be originating from Challenger Island. The longer the boat stayed the more wasps would visit the boat, often landing on divers making gear donning and removal difficult. While the amount of wasps increased post drone flight this could be due to the longer exposure of the boat and its various scents, rather than the attraction of the drone.

Camera issues arose after the data collection when the images were analysed, the GoPro HERO8 Black (Figure 6D) that was used was able to take SuperPhotos, but the resulting images had a distorted edge and extremely wide frame of view, preventing us from creating more detailed midden mosaics. The diver footage on the GoPro HERO8 Black (Figure 6D) was clear and useful in species analysis; however, the Handheld SONY Cybershot DSC-W200 (Figure 6E) camera quality was poor and difficult to discern details of octopus presence within a den. More research into camera image quality prior to use would have been useful; however, the cameras used were the only ones available when beginning this project, so the outcome would not have been affected.

## Conclusion

This study was able to provide a realistic application of using a low-cost DJI Mavic 2 Pro drone to map subtidal environments. By utilizing synchronous SCUBA footage paired with geocoded FMV two underwater octopus denning sites were mapped using ArcGIS Pro software. The use of higher resolution dive cameras would enable the creation of digital models of each site, creating the possibility of virtual underwater exploration. This process was of relatively low cost and required minimal training compared to many other drone and coastal mapping processes. This project successfully facilitated the creation of subtidal maps of an octopus denning site.

# Chapter 2: Octopus Den Density and Ecology

## Introduction

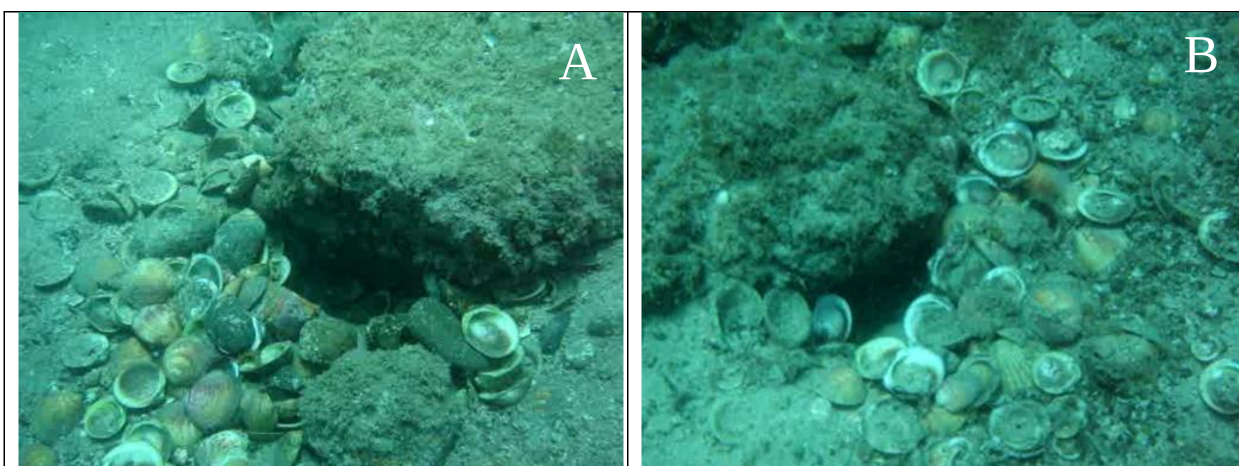
In most octopus species studied to date, individuals are solitary creatures (Godfrey-Smith 2019), with aggression and even cannibalism occurring during conspecific encounters. However, peaceful, prolonged coexistence, or a 'social tolerance' among individuals has also been reported. This has been reported both in labs (Caldwell et al. 2015) and the wild (Aronson 1986, 1989; Hartwell et al. 2018) in several species; these reports started with discoveries of high-density sites of octopus, where many individuals would den in a small area. These revelations have caused researchers to evaluate the intraspecific relations between certain octopus species (Godfrey-Smith and Lawrence 2012; Grearson et al. 2021; Mather and Alupay 2016). The coastal benthic octopus species *Octopus tetricus*, also known as the 'peachy' octopus, has been found inhabiting two high-density denning sites in Jervis Bay, Australia; each site contained a bed of used shells, or midden, that completely covered an area containing several dens. Similar high-density den sites have been anecdotally observed in the Tāmaki Makaurau region of the Hauraki Gulf (K. Bolstad & E. Brown, pers. comms).

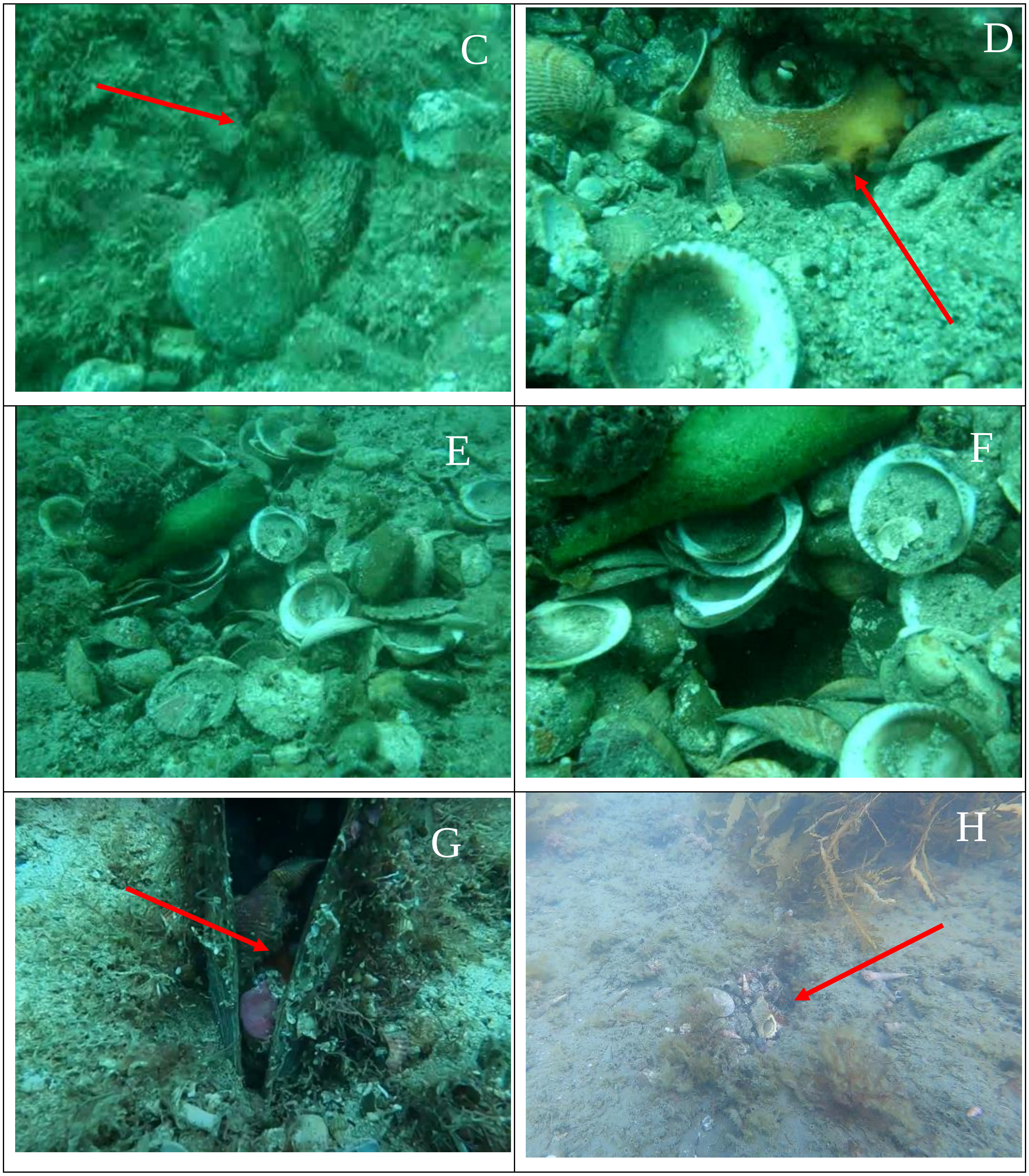
This species is found on the southwestern and southeastern coasts of Australia, the Tasman Sea, and northern Aotearoa New Zealand (Ramos 2015). Published studies of *O. tetricus* in New Zealand have described them as a solitary species, who reside in rocky holes and crevices (Anderson 1997; O'Shea 1999). The original study in New Zealand waters (Anderson 1997) primarily observed the octopus and their relation to the abiotic factors of their habitat; however, the density, sex, and den type were analysed as well.

Octopus dens are enclosed body-sized spaces that provide protection to the individual and are often associated with an accumulated bed of shells, or midden, discarded from their prey. Dens can be found within a variety of terrain, some are modified with shells and stones, some by excavating pits in sand, and some are opportunistically found in a rocky reef crevasse. In Anderson's (1997) paper dens were described as being in varying degrees of rocky reef, and were sometimes surrounded by boulders.

Although the terms 'den' and 'shelter' are sometimes used interchangeably between octopus studies, defining a distinction between them is useful. Shelters are short-term, opportunistic retreats that an octopus uses relatively briefly for protection. They are usually not modified and do not accumulate octopus-related debris. Dens, which are the focus of this study, are structures used longer-term by an octopus, often modified and with an associated midden (a bed of shells discarded from their prey). They are generally large enough for an octopus to fully hide within. Some dens are excavated from sand and others are opportunistically selected caves or crevices in rocky reefs or under boulders, but all dens have an overhead barrier. In sandpits dens the cavity is either dug at an angle or is barricaded on top with rocks and shells. Dens can be found with varying degrees of barricades; there are fully (den entrance is completely obstructed with stacked items), partially (den entrance is partially obstructed with stacked items), or actively (den entrance is obstructed with items held in place by the octopus occupant) barricaded dens, which often using shells and rocks to produce said barricades. Anderson's (1997) paper reported *O. tetricus* dens within rocky reef structures, some were surrounded by boulders, and some were not. By observing and mapping or otherwise quantifying the distance between individual dens, I can conservatively estimate population density (bearing in mind that additional undetected octopuses may be present) and compare 'high-density' octopus sites with those showing the more typical (sparse) distribution of individuals.

In Anderson's (1997) thesis the population density of *O. tetricus* at four Hauraki Gulf sites was calculated, revealing their presence to be rather sparse (2.2 individuals per 500m$^2$) (Anderson 1997). At the first Jervis Bay (Australian) site there was a range of octopus found at the 12x8m (96m$^2$) site. The count was never greater than 10 individuals in one day (two instances both in December) in Scheel's accounts (Scheel et al. 2014), and in Godfrey-Smith's paper there were 11 (Godfrey-Smith and Lawrence 2012). At the second site, there were 13 occupied dens within an 18x5m (90m$^2$) stretch of reef (Scheel et al. 2017). At both sites, dens were found in dense groups, and not spread throughout the full 18m length of reef, though not all were occupied. However, in one case in the second site 7 out of 11 dens were occupied at once in a 4.6x4.3m (less than 20m$^2$) shell bed. Across these high-density sites, octopus individuals were therefore coexisting at a much higher density of 35 individuals per 100m$^2$, 80 times higher than the density observed at Anderson's study sites.

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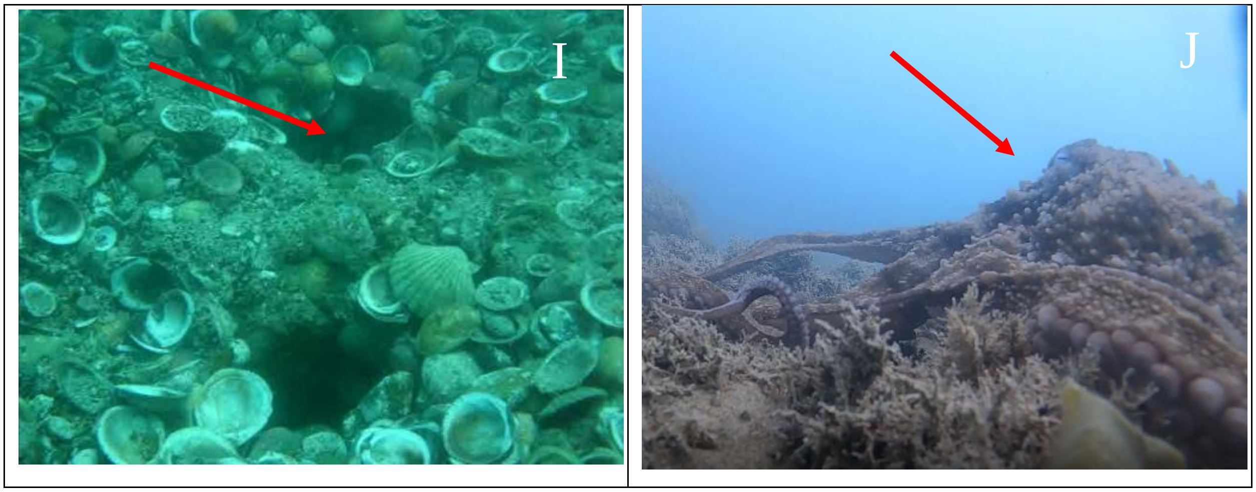


Figure 12: Octopus dens from varying surveys at both Kawau Island and Stanmore Bay. (A) Boulder den Kawau Den (KD) 35 found unoccupied with two entrances was repetitively found at Kawau Island (6m, K4). (B) Boulder den KD34 is unoccupied and repetitively found at Kawau Island (6m, K3). (C) Rocky reef den KD62 is occupied by visible *O. tetricus* individuals on Kawau Island (4m, K1). (D) Rocky reef den KD61 occupied by a visible *O. tetricus*, adjacent to the individual in the previous picture (13C), Kawau Island (4m, K1). (E) Sandpit den KD11 is distinguished by a green bottle, shown with the whole midden, Kawau Island (8m, K2). (F) Sandpit den KD11 is distinguished by a green bottle, shown with an unbarricaded entrance, Kawau Island (8m, K2). (G) Alternative den KD1 with an *O. tetricus* visibly inside an articulated mussel shell, the one alternate den found at Kawau Island (8m, K4). (H) A rocky reed den, the only den not mapped, with a visible *O. tetricus* under an active barricade at Stanmore Bay (5m, S8). (I) Sandpit dens KD13 and KD14, the further is occupied by one *O. tetricus* which is not visible, both dens were found repetitively on all four surveys at Kawau Island (8m, K1). (J) The one non-*O. tetricus* octopus seen, a *Pinnoctopus cordiformis* moving across the Stanmore Bay reef (3m, S1).

## Octopus Behaviour

Reports of high-density sites exhibiting octopus co-existence or 'socially tolerant' behaviour have traditionally been in the minority, naturally occurring adjacent occupation of octopus dens do not appear in the literature until 40 years ago (Aronson 1986; Mather 1982) and such reports remain relatively few. However, within the past two decades, several species previously described as solitary have been observed exhibiting high-density denning and socially tolerant behaviour (Scheel et al. 2018). O'Brien (2020, 2021) has reported on a naturally isolated marine lake hosting a stable population of the Caribbean reef octopus *Octopus briareus* over a 30-year observation period. During the austral summer artificial dens were introduced, producing evidence of adjacent occupation (individuals in separate adjacent dens, within close proximity, often within eyesight) and socially tolerant behaviours. Another species, *Octopus laqueus* (also called dako), previously reported in high-density den locations (suggesting an inherit social tolerance) was observed in a lab setting by Edsinger et al. (2020). Here, octopus were presented with limited dens, which resulted in several instances of co-habitation (several octopus in one den at a time, without exhibiting agonistic behaviour). In the Jervis Bay sites, looking at high-density *O. tetricus* sites, there were many reports of adjacent occupation and non-agonistic mating behaviour, but no reports of co-habitation behaviour (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017). Additional field observations will likely reveal such tolerance in other species, although at present most species still appear to be solitary.

Den preference between conspecifics within high-density sites has been reported in several papers, with the hypothesis originating before the discovery of naturally occurring high-density sites. Boyle (1980) was one of the first to postulate the preference of a den (or two dens) within a contained population of octopus, this case study species was the common octopus, *Octopus vulgaris*. This study was done within a lab and the results were the first to suggest socially tolerance within an octopus population, which were yet to be formally described. Cigliano (1993) provides comparisons of earlier reports of group living octopus, all occurring in artificial conditions. This study also conducts its own procedure, using the California two-spot octopus, *Octopus bimaculoides*, which concurs with other findings that, despite the lack of a known social species of octopus at the time, there is evidence of dominance determined den use which is based on an individual's size. Godfrey-Smith and Lawrence (2012) and Scheel et al. (2017) both observed octopus den preference within the high-densities sites of Jervis Bay, Australia. Den preference was observed with the *O. tetricus* present, they saw that when conspecifics engage in agonistic behaviour at a den entrance either the larger individual or, if conspecifics were of similar size, the current inhabitant would win the den while the other would retreat.

## Methods

### Preparation

Depending on which site was being observed different preparation occurred. On Stanmore Bay days divers would evaluate and collect gear from the AUT North Campus storage shed before continuing to the site. From there the gear would be donned and carried to the entry point on the shore. When going to Kawau Island far more preparation was needed. Dive gear would have to be evaluated and retrieved before the day of sampling. The water sampling devices would have to be picked up and evaluated before the day of sampling, and the multiparameter YSI Sonde would have to be programmed (using EcoWatch Lite) to start and stop sampling during the correct times.

### Sampling Procedure

Sampling days were selected based on weather, wind, and tide predictions, aiming for calm weather with no swell and observation periods during daylight hours within 2 hours of high tide. Weather conditions across the preceding week were also noted; in several cases (e.g., S3, S4), the effects of recent storm activity were clear during underwater observations.

The first phase of data collection (see Figures 8, 9, and 10 for further details) started with the GoPro (Figure 6D) secured in the stationary housing (Figure 6C) and synchronised with the drone (Figure 6A) before descending. The stationary acted as the initial roaming camera, to document dens and middens until an octopus was sighted. The divers would begin with a non-specific search method, zig-zagging from drop off to reef. Octopus were identified within dens by first observing from the initially allocated 2m distance, and if no individual could be seen a closer inspection with a camera and flashlight would be used to confirm the absence of any octopus or festoons (egg chain). Once the first octopus was found the stationary housing was placed (2m away) in an area that had a full view of the specimen. A surface marker buoy would then be deployed and attached to a weight tied to the housing (1m away from the camera, 3m away from the den). Then the SONY roaming camera (Figure 6E) would be synchronised with the stationary before continuing the survey. In the first phase divers attempted to find and record all octopus, dens, and middens in the site area, which often took two (18min) drone flights. When Phase 1 was completed the stationary (if deployed) would be retrieved.

Divers would surface every 18 minutes to allow the drone to be recalled and given a new battery, and then the diver and drone would synchronise before divers descended to continue the survey.

In the second phase, the GoPro was used to closely document each midden that had been found in Phase 1, to better identify prey remains in the middens. The GoPro was removed from the camouflaged housing and placed on a standardized PVC pipe stand (Figure 6B). For dens and middens without an octopus, the stand was placed facing north with the base on the sea floor. For dens with octopus present, the camera was removed from the stand and photos were taken from 2m above the den, still facing north. Dens without octopus would also be photographed this way after using a stand for comparison. After pictures, the second diver would hold a measuring tape across the middens as a close-up video was taken.

## Water Parameters

The water parameters were collected before any diving began, to prevent diver disturbance of the natural conditions. The parameters were collected to compare the two sites, barring any exceptionally unusual results this analysis was done simply to ensure similar conditions between sites. Three devises were used during this process, a multiparameter YSI Sonde, a LI-193 Spherical Quantum Sensor (LI-COR), and a Secchi Disk. For water parameter methods, including data collection and analysis, see the Appendix.

## Post-Sampling Procedure

The footage was analysed back in the lab for detailed site evaluation and analysis. First, the diver footage was viewed to streamline the mapping using drone FMV. The footage was reviewed for fish counts, dens, middens, and octopus presence. All fish seen in the course of the handled roaming video were counted, where the stationary camera fish counts would begin once it was placed the handheld camera was synched, after this all fish that passed through the field of view were counted (maximum of 250 individuals per species, after which it was simply noted as ‘abundant’).

Two separate rounds of viewing the Phase 1 footage were done to ensure accuracy. The first round identified any middens, dens, or octopus within the dens; throughout this round of viewings, the drone synchronisation times were recorded for ArcGIS Pro mapping later. The second viewing focused on the fish count and species identity. Midden species were identified later using Phase 2 images and footage. These pictures were taken from 0.67m above the midden if no octopus was present, or 2m if an octopus was present. If an octopus wasn't present a close-up video was taken of the midden with a tape measurer to determine the size and get different angles on shells for identification. To evaluate these the different middens were separated via time stamp and the visual differences between middens.

Analysis of midden species, fish, Secchi Disk, and YSI Sonde was done in Microsoft Excel, which was used to turn the raw data into graphs. Analysis of the LI-COR water column data were done in Microsoft Excel using the vertical propagation of PAR (Equation 4).

To analyse the density of surveys found the Average Nearest Neighbour tool was used, returning five values: Observed Mean Distance, Expected Mean Distance, Nearest Neighbour Index, z-score, and p-value. These combined values are meant to discern whether the points are random or form in clusters. This tool can be found within the ArcGIS Pro Spatial Statistics toolbox. The Nearest Neighbour Index calculates the ratio of the Observed Mean Distance to the Expected Mean Distance (the average distance between points in a hypothetical random distribution). The z-score and p-value results are measures of statistical significance, suggesting whether to reject the null hypothesis (features are randomly distributed) or not (features are clustered).

## Results

### Octopus Sightings

From October 2020 through March 2021 octopus individuals were observed 28 times (Tables 1 and 2; Figure 13). Twenty-two octopus were observed at the Kawau Island site and six were observed at the Stanmore Bay site. All but one individual was identified as *O. tetricus*. The first octopus caught on camera, but not seen by divers, was identified as the New Zealand octopus, *Pinnoctopus cordiformis*; it passed by the stationary camera during the first survey at Stanmore Bay. This was the only individual observed outside of a den structure. Octopus seasonality of those found within this study is compared to the original site found within Jervis Bay, Australia in Figure 13.

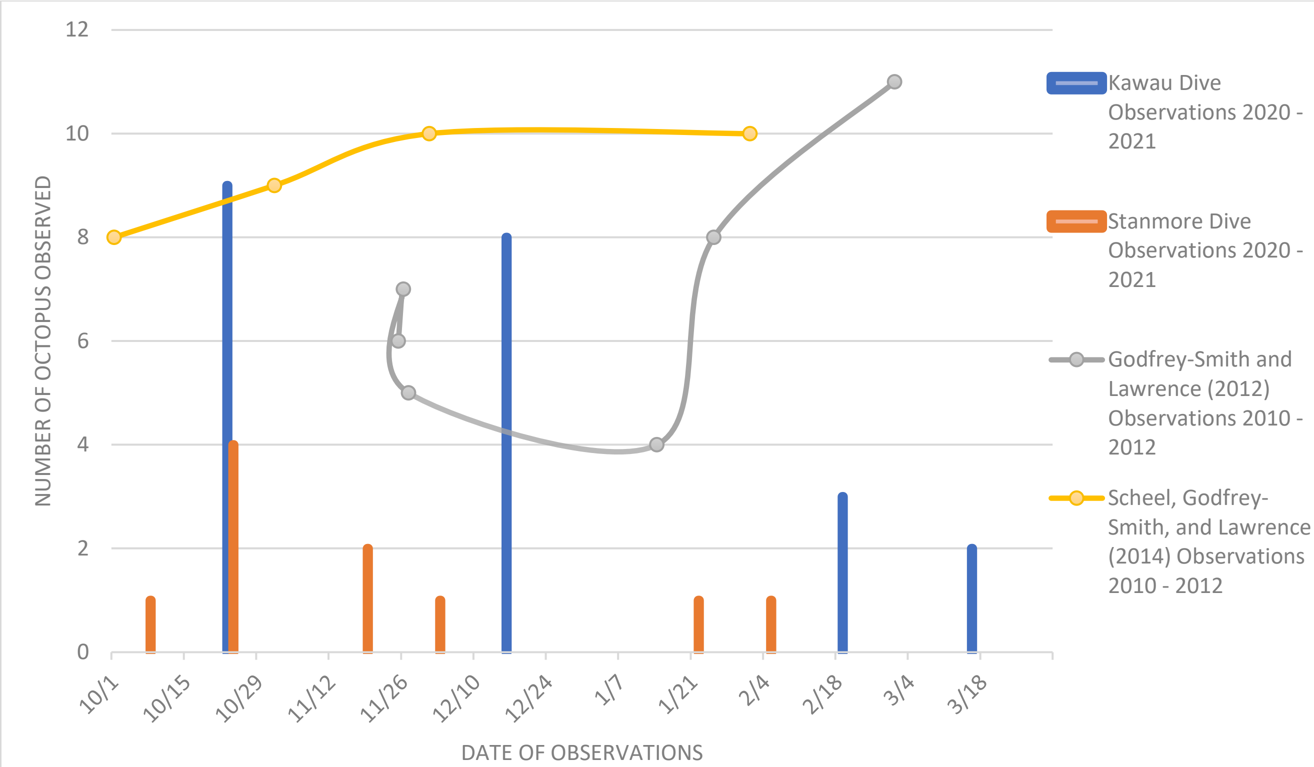


Figure 13: Seasonality of *O. tetricus* populations across varying years and locations. The findings of this site are displayed as bar graphs with the amount of *O. tetricus* observed at both Kawau Island surveys (orange) and Stanmore Bay surveys (blue) between October 2020 and March 2021. The points with smoothed lines show two different observations of the same site in Jervis Bay, Australia, data from ref (Godfrey-Smith and Lawrence 2012) in grey and (Scheel et al. 2014) in yellow, over the course of the site's evaluations through their peak seasons of 2010 – 2012.

## Den Type Comparison

There were three main types of dens that were identified: rocky reef, boulder, and sandpit. Both rocky reef and boulder dens were observed with and without a midden, but the sandpits consistently had a midden present, often with shells lining the entrance. Sandpit and boulder dens both require a level of structural modification by the original occupant, often excavation and sometimes a reinforcing of walls with rocks and shells; however most rocky reef dens did not have any structural modifications.

Rocky reef dens (Figures 12C, 12D, and 12H) are described as any den within a rock crevasse or hole. If the den had its structure without the octopus' help, then it was a rocky den. Some rocky reef dens contained sand or were near the sea floor, like boulder dens, but the surrounding walls were still contained within the reef structure. Boulder dens (Figures 12A and 12B) were excavated dens with one or more side openings, and most of the excavated space being underneath a boulder. Sandpit dens (Figures 12E, 12F, and 12I) were excavated dens without the presence of a boulder, containing a bottle neck entrance often opening at an angle. Sandpits always had a midden to line the sand around the pit entrance and to reinforce the walls within the pit. A fourth less common type of den are the alternative dens, described as any area inhabited by an octopus that did not fit, sandpit, boulder, or rocky reef; this could include both artificial items (i.e., concrete block or glass bottle) or a naturally occurring items (i.e., coconut or mollusc shell). One alternative den was observed, comprising a horse mussel shell (Figure 12G). Alternatively, all dens found at the Stanmore Bay site were rocky reefs. No boulder (patch reef), sand pit, or alternative dens were found, hence why they do not appear in the den representations in Figure 14.

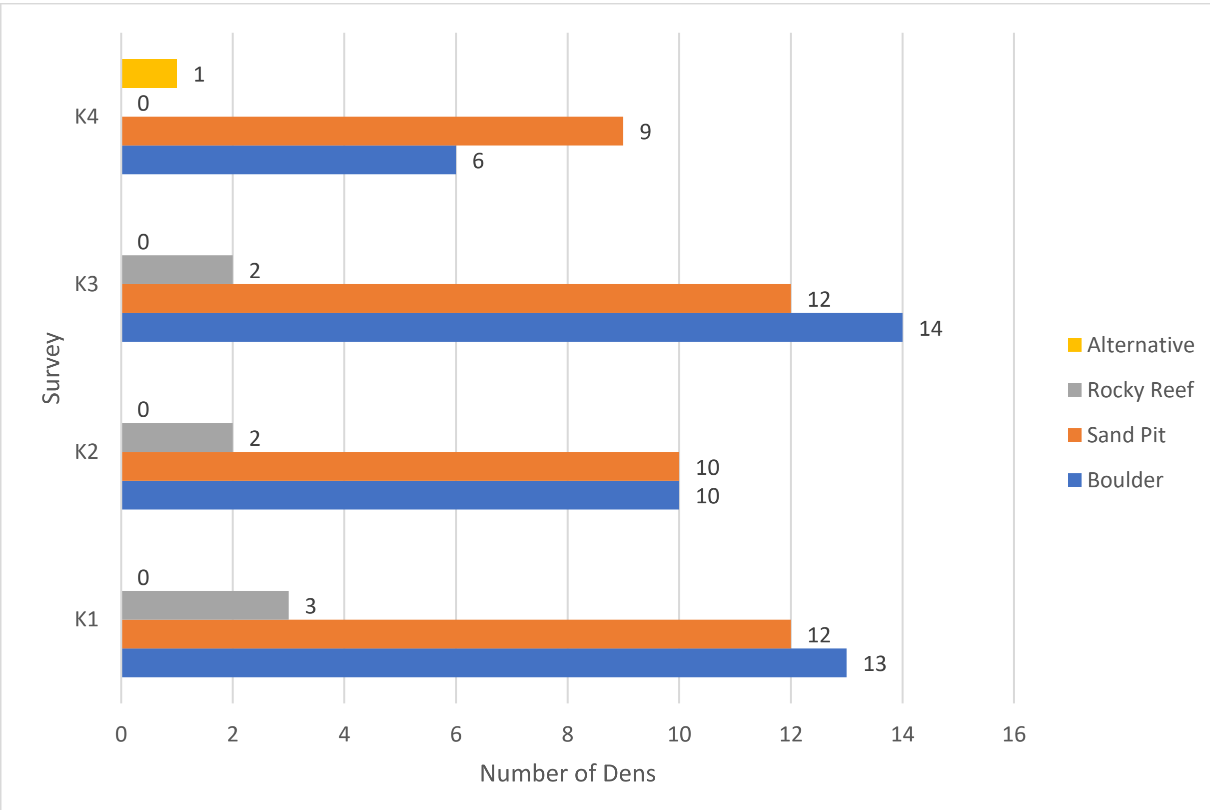


Figure 14: Comparison of octopus den types at Kawau Island site throughout the sampling period, consisting of four observations. Boulder and sandpit dens were the most common at Kawau Island, with few rocky reef dens and only one alternative den (a horse mussel) throughout the whole sampling period.

At Kawau Island, sandpit and boulder dens were prevalent (Figure 14). Boulder dens were more abundant in the Kawau site. While some areas could be described as patch reefs (as seen in Anderson 1997) the den use was not that of a reef den. Despite some octopus denning underneath patch reefs, they were residing in an excavation (boulder den), not the reef itself. At Kawau Island there were some reef dens, all on the northern side of the reef and often close to the sandy bottom. The boulder dens typically existed within 3m of the rocky reef, and never extended past 5m, seemingly lining the seaward side of the reef. The sand pit dens were found 2-10m beyond the reef but typically fell within 3-7m beyond the reef. The one alternative den was found 9m out among the sand pits.

Despite seeing several octopus as this site in proximity no interaction or socially tolerant behaviour was recorded. All octopus observed (apart from the *P. cordiformis*) were within their den or at the entrance but did not exhibit any display features or interactive behaviours. Festoons or egg chains were also found, the spent (hatched) festoons were seen in only one den throughout the summer season, during the K4 survey.

## Density

At Kawau Island 63 dens were found in total across the sampling period (Figure 15E), with a maximum of 28 dens on two occasions (9 occupied on K1, 3 on K3) and a minimum of 16 dens (2 occupied on K4) (Table 1).

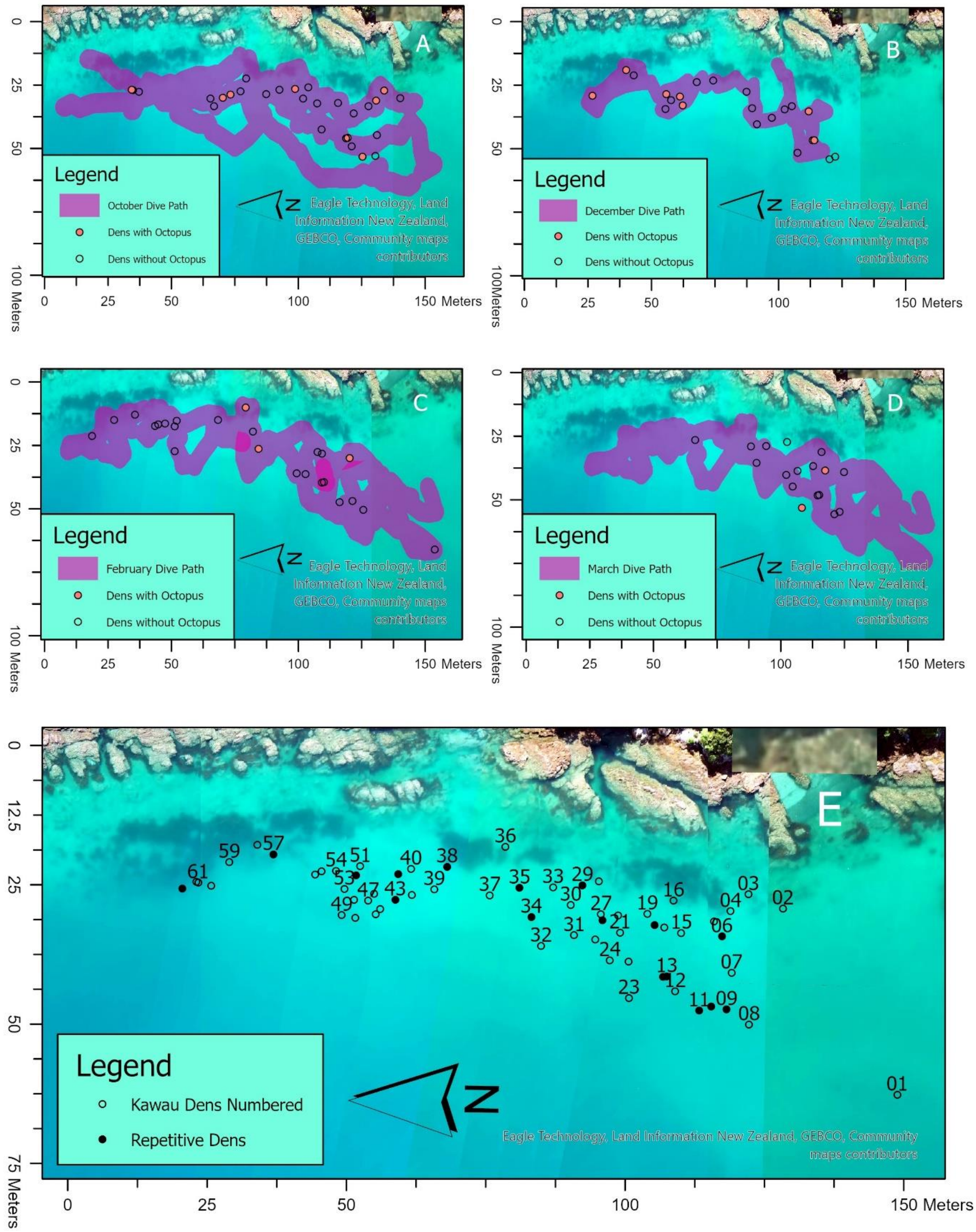


Figure 15: The Kawau Island site, with individual surveys and the resulting map of all dens found across the sampling period. In total, four surveys were completed at the Kawau Island site from October 2020 to March 2021, 63 dens were found across the

sampling period. (A-D) Individual surveys had den locations coloured peach to indicate the presence of an octopus, and a purple line to represent the diver's field of view on each observation. (E) The complete den map with dens numbered, the solid black dots represent repetitive dens, those that were seen multiple times across the sampling period. (A) Survey K1 revealed 28 dens, of these 9 contained an octopus inhabitant. (B) Survey K2 revealed 22 dens, 8 of these contained an octopus inhabitant. (C) Survey K3 revealed 28 dens, 3 of these contained an octopus inhabitant. (D) Survey K4 revealed 16 dens, 2 of these contained an octopus inhabitant. (E) All dens found at Kawau Island, across the sampling period of October 2020 through March 2021, totalled 63 dens, of which 17 were seen on more than one survey and were considered repetitive dives. These numbers serves as IDs for each den, following KD (Kawau Den) for future den reference.

In total, four surveys were completed at the Kawau Island site (3,696m$^2$) from October 2020 to March 2021, 63 dens were found across the sampling period. Individual surveys had den locations coloured peach to indicate the presence of a 'peachy' octopus, and a purple line to represent the field of view on each observation (Figure 15A-D). The complete den map with all dens observed numbered had repetitive dens shaded in, and those that were seen multiple times across the sampling period (Figure 15E). Survey K1 revealed 28 dens, of these 9 contained an octopus inhabitant (Figure 15A). Survey K2 revealed 22 dens, 8 of these contained an octopus inhabitant (Figure 15B). Survey K3 revealed 28 dens, 3 of these contained an octopus inhabitant (Figure 15C). Survey K4 revealed 16 dens, 2 of these contained an octopus inhabitant (Figure 15D). All dens found at Kawau Island, across the sampling period of October 2020 through March 2021, totalled 63 dens, of which 17 were seen on more than one survey and were considered repetitive dives (Figure 15E). These numbers in Figure 15E serve as IDs for each den, following KD (Kawau Den) for future den reference.

Table 8: Kawau Island site Average Nearest Neighbour calculations. The z-score and p-value that are of a significant value appear in bold text. Only K4 has significant values for both, this suggests the dens found are randomly scattered and not grouped.

| | Observed Mean Distance: | Expected Mean Distance: | Nearest Neighbour Ratio: | z-score: | p-value: |
|---|---|---|---|---|---|
| K1 | 4.060918 m | 4.487626 m | 0.904914 | -0.962553 | 0.335772 |
| K2 | 4.455448 m | 4.081337 m | 1.091664 | 0.822507 | 0.410788 |
| K3 | 4.330313 m | 5.365382 m | 0.807084 | -1.917702 | 0.055149 |
| K4 | 5.711881 m | 4.099540 m | 1.393298 | **3.102253** | **0.001921** |
| All Kawau Dens | 3.553403 m | 3.793285 m | 0.936762 | -0.960246 | 0.336931 |

The Average Nearest Neighbour calculations (Table 8) show a mean distance of 4m in all but one survey, and 3.8m across all dens. Nearest Neighbour Index is expressed as the ratio of the Observed Mean Distance to the Expected Mean Distance, with an index of more than 1 the site tends to be random points, which occurred in K2 and K4. With an index of less than one the points tend to be clustered, which is the case with K1, J3, and the total den distribution. In all surveys except K4 the p-value favours the clustering of dens (>0.05), where the K4 p-value and z-score were both significant, indicating random distribution (<0.05 p-value; > 2.58 z-score). With these results highly indicative of clustering in the site a density map was produced.

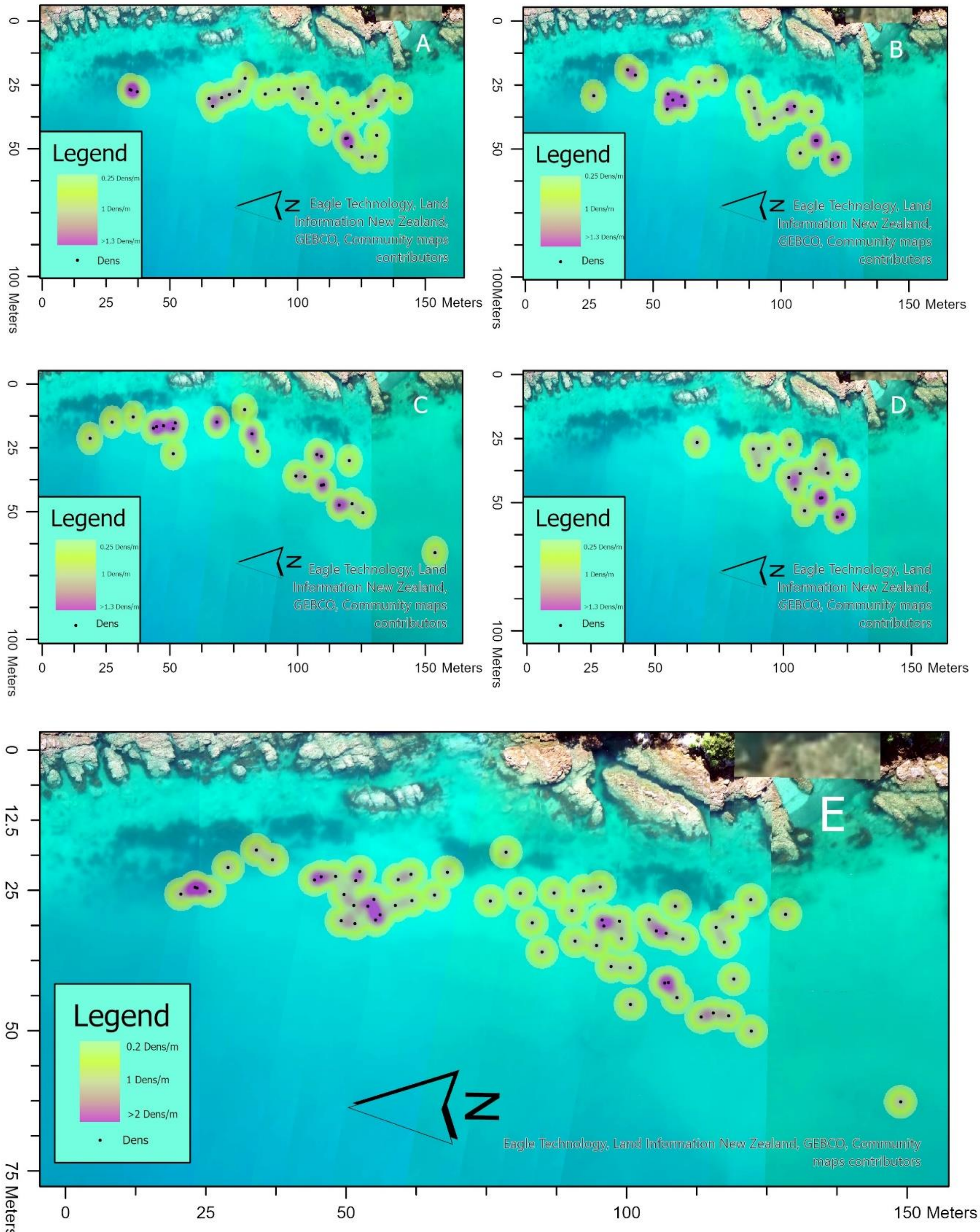


Figure 16: Kawau Island site den density heat map. The density of the Kawau Island site is visualised in all four surveys and the total den location using a heat map symbology. In the individual survey maps (A- D) the densest symbology bar represented 1.3 dens per meter, whereas the total den count map (E) densest symbology represents 2 dens per meter. (A) The K1 survey revealed

28 dens creating two den clusters, (B) the K2 survey revealed 22 dens creating five den clusters, (C) The K3 survey revealed 28 dens creating six den clusters, (D) the K4 survey revealed 16 dens, with 3 den clusters. (E) In total 63 dens were found across the sampling period, showing several areas of den groupings with seven den clusters containing two or more dens per meter.

The density of the Kawau Island site (Figure 16) was visualised in all four surveys and the total den location using a heat map symbology. At Kawau 63 dens were found (Figure 16E) across the sampling period, showing several areas of den groupings with seven den clusters containing two or more dens per meter. K1 revealed 28 dens, with two den clusters (Figure 16A), K2 revealed 22 dens, with five den clusters (Figure 16B), K3 revealed 28 dens, with six den clusters (Figure 16C), and K4 revealed 16 dens, with 3 den clusters (Figure 16D).

Two instances of adjacent occupation were observed, once at KD61 and KD62, and across the sampling season with KD13 and KD14. These den entrances were within 50cm of each other and in both cases the occupying individuals had a clear line of sight between each other. No instances of co-habitation were observed at this site.

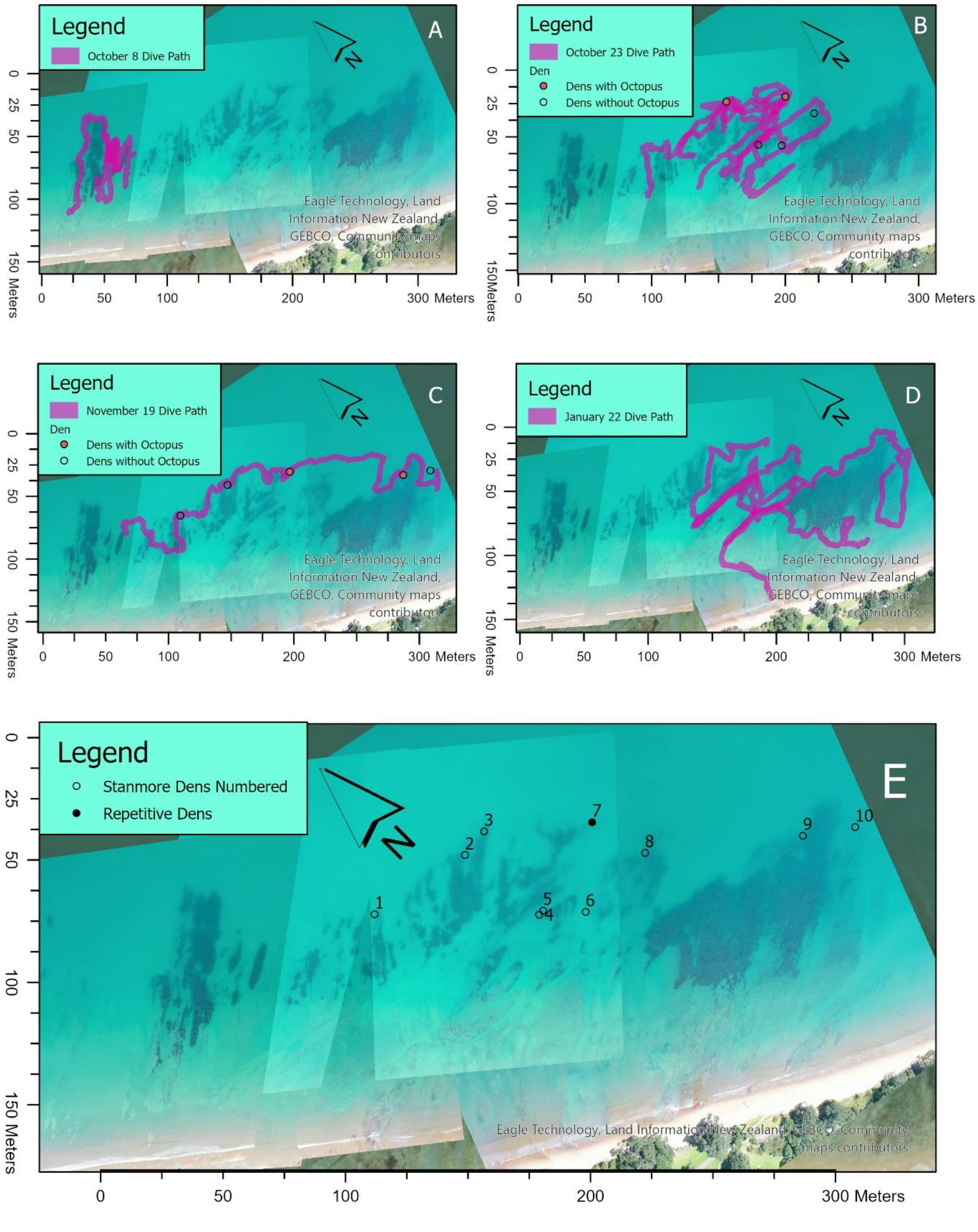


Figure 17: The Stanmore Bay site, with individual surveys and the resulting map of all dens found across the sampling period. In total, eight surveys were completed at the Stanmore Bay site from October of 2020 to March of 2021, four of which were recorded by the drone, 11 dens were found across the sampling period with 10 mapped. (A-D) Individual surveys had den

locations coloured red to indicate the presence of an octopus, and a purple line to represent the diver's field of view on each observation. (E) The complete den map with dens numbered, the solid black dots represent repetitive dens, those that were seen multiple times across the sampling period. (A) Survey S1 revealed 0 dens. (B) Survey S2 revealed 5 dens, 2 of these contained an octopus inhabitant. (C) Survey S4 revealed 5 dens, 2 of these contained an octopus inhabitant. (D) Survey S6 revealed 0 dens. (E) 10 of the 11 dens found at Stanmore Bay, across the sampling period of October 2020 through March 2021, of which only 1 was seen on more than one survey and were considered repetitive dives. These numbers serves as IDs for each den, following SD (Stanmore Den) for future den reference.

The S2 and S4 surveys were the two sources of den location at Stanmore bay, with one den reported in S5 the location was determined based on previous synchronous dive footage (Table 2). In total, 8 surveys were completed at the Stanmore Bay site (18,214m$^2$) from October of 2020 to March of 2021. At Stanmore 11 dens were found across the sampling season, of which only 10 were mapped (Figure 17E). Survey S1 revealed 0 dens, one *P. cordiformis* was seen roaming; however, no fixed location was found (Figure 17A). Survey S2 revealed 5 dens, 2 of these contained an octopus inhabitant (Figure 17B). Survey S4 revealed 5 dens, 2 of these contained an octopus inhabitant (Figure 17C). Survey S6 revealed 0 dens, with no octopus observed (Figure 17D). Only 10 of 11 dens found at the Stanmore Bay site across the sampling period of October 2020 through March 2021were mapped, with the one den seen repetitively filled in black (Figure 17E). These numbers serve as IDs for each den, following SD (Stanmore Den) for future den reference.

Table 9: Stanmore Bay site Average Nearest Neighbour calculations. The z-score and p-value that are of a significant value appear in bold text. Both S2 and S4 have significant values for both, this suggests the dens found are randomly scattered and not grouped.

| | Observed Mean Distance: | Expected Mean Distance: | Nearest Neighbour Ratio: | z-score: | p-value: |
|---|---|---|---|---|---|
| S2 | 24.067977 m | 9.697685 m | 2.481827 | **6.338893** | **0.000000** |
| S4 | 30.495966 m | 12.258098 m | 2.487822 | **6.364538** | **0.000000** |
| All Dens | 16.237420 m | 12.017264 m | 1.351175 | 2.124486 | **0.033630** |

The Average Nearest Neighbour tool was applied to two surveys at the Stanmore Bay site (Table 9) reporting in a significantly random scattered distribution. The S4 observations had a greater observed and expected distance than S2, yet both had a Nearest Neighbour Ratio of above 1, indicative of random distribution. Combined with the p-value less than 0.05 and a z-score of more than 2.58 these results suggest the dens chosen at this site have a randomly scattered distribution. With these results indicating a lack of clustering a density map was not done for this site.

## Fish Counts

The number of fish species and individuals seen on camera were counted to provide a secondary reference for the impact diver presence had on the wildlife in the sites. Being highly mobile macroorganisms the presence or lack of fish was considered another indicator of how diver presence could affect results. For more details see the Appendix (Figures 24, 25, 26, and 27).

Weather and Water Parameters

To compare the two site's physiochemical profiles the PAR was taken to compare the two site's water column's light attenuation coefficient. This was taken with a multiparameter YSI Sonde on two external sensors (PAR1 and PAR2) and with a LI-COR Spherical Quantum Sensor. The Sonde's depth sensor malfunctioned during the two trips were used it as did both PAR sensors, so the only light information used was the LI-COR data.

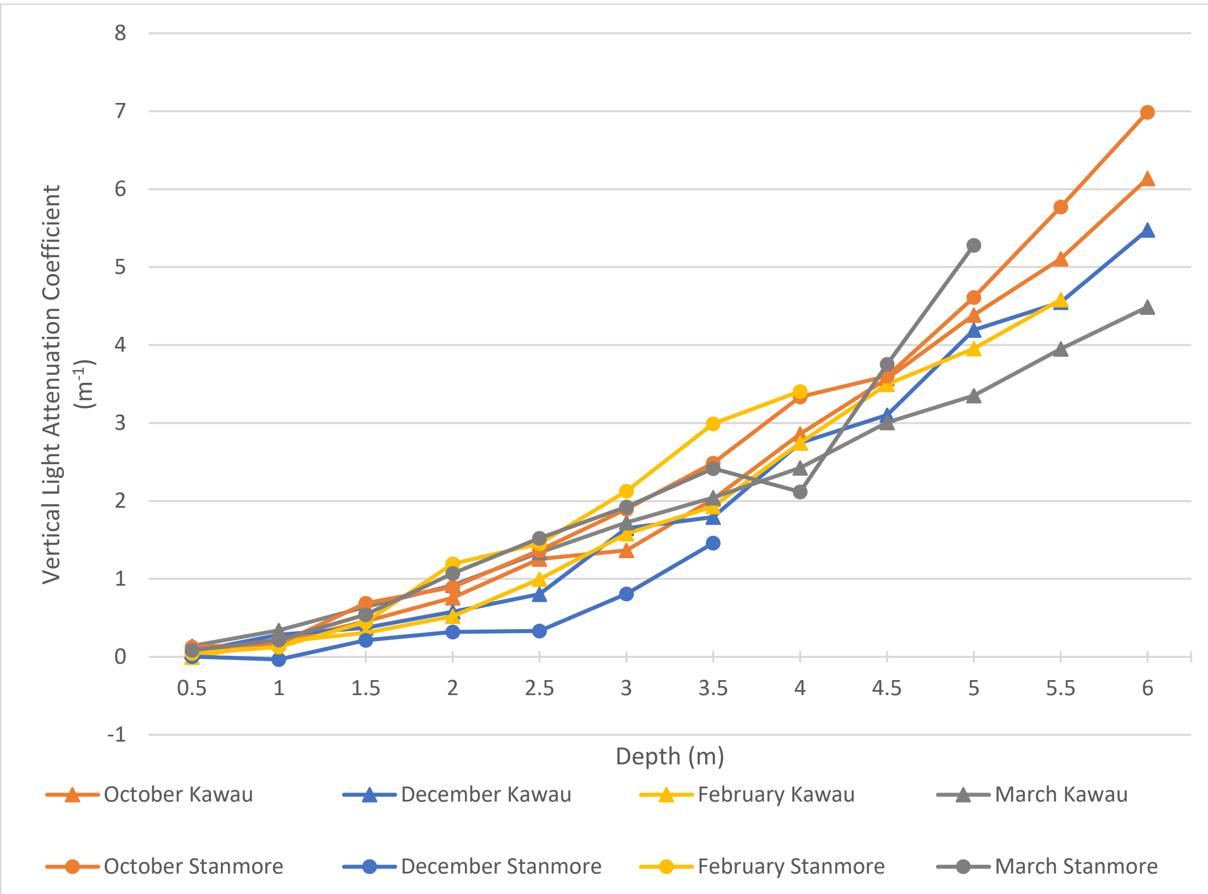


Figure 18: Light attenuation coefficient profile of both sites across four survey periods. Each site was evaluated the same days as the Kawau Island surveys (Table1); the October Kawau and October Stanmore parameters were measured on K1 (orange), the December Kawau and December Stanmore parameters were measured on K2 (blue), the February Kawau and February Stanmore parameters were measured on K3 (yellow), the March Kawau and March Stanmore parameters were measured on K4 (grey). With Kawau data points represented as triangles, and Stanmore data points as circles. All light profiles follow a similar curve, until their end point. Three Stanmore profiles and one Kawau profile were stopped short due to site depth at the time of data collection.

Light attenuated reliably with depth across both sites (with some irregularity at Stanmore on occurrence K2). Observations of octopuses at both sites and across all sampling events therefore occurred under reasonably constant and predictable light conditions. The light attenuation coefficient profiles for

Stanmore and Kawau sites (Figure 18) shows throughout the study. The different sites are shown with different symbols and the different surveys are shown with different colours. Each coinciding profiles were taken on the same day between 1000 and 1700 hours. All Kawau evaluations followed an upward curve in light attenuation whereas the Stanmore profile is more erratic. One Stanmore and three Kawau profiles went down to 6m, the others stopped short and varying depths.

The third survey's visibility was so low that divers decided to call the day short, no octopus or fish were found on this day. And in the sixth, seventh, and eight surveys the stationary was not deployed so no stationary fish could have been observed.

## Discussion

### Octopus Sightings

Several dens were seen being repetitively used throughout the survey season. While it cannot be confirmed that the same individuals were seen in the same dens throughout the sampling period, some dens appeared to have gone through the last stages of an octopus' life. These stages would be the reproduction and senescence phases of life, these stages cause females to stay in a fixed location creating a den for and brooding over her eggs until death (Anderson et al. 2002). Two such dens were KD13 and KD14, these two dens were first observed at the beginning of the end of an octopus' life, the preparation for brooding. These two adjacent dens were first observed in K1 with KD13 empty and KD14 occupied by an adult *O. tetricus*. In K2 the dens were found partially barricaded dens both occupied by adult *O. tetricus'* with a larger midden than observed prior in K1. In K3 divers observed their dens fully barricaded, with tightly packed shells and sediment over the previous den entrances, with a less dense, smaller midden around the two dens. The last observation, K4, recorded two empty dens, with no sign of octopus or festoons, but with 'restored' midden, with a diameter and fullness resembling what was seen in K2. Several other dens at the Kawau Island site were also seen across the sampling period with varying degrees of change. The Stanmore Bay site only had one den seen on more than one survey, but was only seen during two consecutive surveys, S2 and S4 (S3 was called early on for poor visibility). After S4 the den was not seen again, the den was low and was likely filled in with sediment, as the Stanmore Bay site had drastic landscape changes with each storm rearranging the silt and sediment.

Similar to O'Brien et al. (2021) reports on *O. briareus*, our findings also had two examples of adjacent den use, with no reported occurrence of cohabitation. Adjacent denning has been reported in this species, *O. tetricus*, at the two sites in Australia (Godfrey-Smith and Lawrence 2012; Scheel et al. 2017). However, *O. briareus*, studied by O'Brien et al. (2021) was also reviewed by Aronson (1986) thirty years earlier and reported no instances of cohabitation or adjacent denning. A more likely explanation would be that the O'Brien et al. (2021) study was done during a population dearth, and the Aronson (1986) during a population high, which has previously been theorised to decrease the limit of accepted social interaction between individual octopus.

Mather (1980, 1892) stated that octopus aggregation does not necessarily reflect interaction, an observation supported by several ensuing papers (Edsinger et al. 2020; O'Brien et al. 2021; Scheel et al. 2014, 2016). Expanded the theorem describes how the higher the population density of an octopus species the more aggressive and/or antisocial individuals become. This theory is included in the 'Octopolis' hypothesis, describing the positive and negative feedback loops defining the two *O. tetricus* sites in Jervis Bay, Australia. Scheel et al. (2014) postulates that with an excess of food available (scallop beds), but limited shelter (dens) combined with an abundance of predators (wobbegong sharks) individuals aggregate to the one location with cover. In this case, the cover is created by the remains of prey foraged, causing animals to den in the one available shelter (the metal wheel) then forage and bring back more shelter materials for more individuals, creating a positive feedback loop. The negative feedback loop is the previously stated theory, that an indirect relationship of individuals' social tolerance with the population density creates a population ceiling, preventing the sites from continual expansion.

It could be that this inverse relationship of social tolerance and population density could be an evolutionarily trait, preventing depletion of resources. As reported by Godfrey-Smith and Lawrence (2012) and Scheel et al. (2014, 2016) the three years spent surveying the original Jervis Bay, Australia site saw the shell bed grow and change in shape. These sites also saw the source of live scallop beds shrink in size and reduce in density. For more on the shell midden and prey species see Chapter 3.

The number of individuals observed at Kawau Island were comparable to previous reports during earlier summer but lower during late summer, and lower at Stanmore across the sampling season (Figure 16; Anderson 1997; Godfrey-Smith 2012; Scheel et al. 2014 included). Since Anderson (1997) did not provide specific dates, those observations were not included. The numbers of octopus seen at the Kawau Island site (22 individuals) were similar to observations at two high-density sites in Australia's austral summer of October through December (as described in Godfrey-Smith and Lawrence 2012). While the Stanmore Bay site observed far fewer individuals (6 individuals), this site was observed to have 2 species of octopuses, the first octopus was not our target species, but a *P. cordiformis*, every other octopus (5 individuals) viewed after this was identified as an *O. tetricus.*

Festoons were found at only one den throughout the summer season. During their brooding period female octopus stay within their dens and massage and aerate their eggs for the last 1-2 months of their life. During this time, they stay within their dens with barricaded entrances (Anderson 2002). The mother octopus can sometimes open these entrances shortly before her death, leaving open dens only containing spent festoons (Joll 1976). I suspect there were dozens of dens with festoons within our sites. However, viable eggs are usually hidden behind walls of shells and their brooding female as described in (Anderson 1999; Anderson 2002).

Effects of Diver Presence

The project plan included remaining a minimum of 2m from all known octopus individuals. However, on several occasions octopuses were undetected until divers were within this range, but once aware of the animal, they retreated to an appropriate distance.

An inking occurred when a diver unknowingly swam over an occupied den. The octopus within the den recoiled slightly but when divers returned to the same den weeks later in the next survey the den was barricaded. While this den could have been empty, a completely intact barricade usually indicates an inhabitant, likely a brooding female and her eggs. However, even if this was the case there is no way to know whether there was an octopus or if it was the same one that inked. In a previous study of *P. cordiformis* observers both physically manipulated and tagged (using garment tags) individuals through their web, individuals never inked, but retracted their arms upon needle piercing (Anderson 1999). However, the following survey the den was open, indicating that at least once after our visit the den was inhabited again, leading us to believe that our most invasive sampling did not effect the octopus community choice of area or certain dens. Several of the same dens were observed to repetitively contain octopus of similar size and species. While I cannot confirm these are the same individuals the den inhabitants did not seem to be affected as far as I was concerned.

While divers maintained a 2m distance from known *O. tetricus* individuals some individuals were approached unintentionally due to divers not noticing them initially. While sometimes this was due to their cryptic nature sometimes the dens octopus were residing in were so hidden that divers were near the entrance before the presence of an octopus was apparent. This is demonstrated in Figures 13E & 13F, while no octopus is residing in this den (KD11) at the moment the hidden entrance is apparent. Other times the den was so dark it took divers shining lights within the cavity to determine whether it was empty or occupied.

This species is known to brood and die throughout the summer in large numbers so the decline would fit that profile (Anderson 1997). However, Ramos et al. (2015) found that while the majority of females died off after the austral summer, there was still a low level of female individuals found throughout the year. Where adult males number were consistently caught regardless of season. However, the denning and die-off of this cohort was earlier than expected, and the off-season cohort had even begun to inhabit the shallow coastal dens by the last two Kawau Trips (KD06 and KD23).

In S5 as divers approached an octopus it reacted once divers were 3m away, but did not appear seriously affected, and had a negligible reaction to the stationary camera. Upon the diver's initial approach, the first signs of the octopus were a siphon blast of detritus, sand, and its own discarded skin. This was seen being done later as a routine cleaning, so this was unlikely spurred by the presence of divers. When the stationary camera was placed and divers left the octopus both emerged from and retreated into its den, apparently in response to the amount and size of fish that were in the vicinity. The octopus also cleaned itself repeatedly within and slightly outside of its den. The octopus' reaction to the divers was much more distinct in its colouration, posture, and skin texture than with the fish it was avoiding. However, while the individual's camouflage response was more drastic for the diver's approach than for the fish, its position in its den did not change. While the diver's approach did cause the *O. tetricus* to react, the individual only temporarily disrupted its original action (cleaning), which it recommenced upon their departure. The response was a primary defence behaviour, crypsis, and not a secondary defensive behaviour, flight, as was seen when large snapper aggressively approached the specimen (Hanlon and Messenger 1996). The demonstrated behaviour leads us to believe the octopus was aware of our presence but was not negatively impacted and was either not at all impacted by the presence of the stationary camera or was impacted negligible amount.

In S1 a *P. cordiformis* did pass by the stationary camera. Initially, a single arm entered the field of view, the tip curving around the housing's viewport; the arm then exited the field of view, and the individual swam past. The initial investigation of the housing might not be an indication of the octopus identifying it as a foreign object, but merely moving across the landscape. The *P. cordiformis* was then seen moving forward on its path, several arms are positioned in front with constantly moving and curling tips feeling out its foreground. This behaviour appears to be the octopus treating the housing as a natural obstacle in its path. Later in the video the octopus reacted to divers moving in both its path and through the view of the camera. The octopus went from a slow forward movement to a halt. It then flattened its mantle lower to the ground, tucked its arms in a circular motion, more so tucking the distal portions under the mantle and proximal arms. It then darkened and erected its papillae to resemble rocks and algae. At this point the two divers swam within a meter of the animal, without noticing it. The divers passed and 30 seconds later the octopus loosened its formation and continued swimming on its initial path. While the presence of the divers did alter the subject's behaviour, their presence appeared to only have postponed its original intentions.

## Den Type Comparison

Smooth ‘boulders’ were almost always found at sandpits and boulder dens at Kawau Island. The ‘boulders’ were similar to the size of bricks, made of a dark grey rock with smoothed corners and edges; these rocks were commonly found defining and lining entrances and used structurally to keep walls in place. Their occurrence was odd in that the ‘boulders’ looked very uniform to one another and were consistently used throughout the site for den modification.

Rocky reef dens had very few modifications if they were on a lower area of the reef, or in the rivers. Although at Stanmore Bay, a considerable amount of effort must have been needed to continually excavate the dens, due to the high particulate and sediment settling around the area.

Anthropogenic items have been known to play host to denning octopus, often pots which are used to capture octopus by commercial fishermen. Glass bottles have previously been reported to be dens for octopus. In the Kawau Island site they were observed being used in middens and barricades. Although no octopus was seen inhabiting the bottles found. A spark plug was found within a midden at the Stanmore Bay site. The metal spark plug was severely corroded and rusted; however, when discovered the resident octopus was using the spark plug in an active barricade, along with several other shells. Since removing the spark plug would have directly interfered with an octopus it was left alone. Freitas et al. (2021) recently compiled a base of 261 citizen science underwater images, each depicting benthic octopuses interacting with litter. This study characterized the interaction of varying types of litter, 24 species were identified interacting with one of 8 types of materials. This paper found individuals often interacted with glass products making it the most common litter occurrence being present in 41.6% of the interactions. Godfrey-Smith and Lawrence (2012) and Scheel et al. (2014, 2017) also found several occurrences of litter interaction in the Australian sites. The original Jervis Bay site was formed around a now corroding metal wheel, and several glass bottles were found throughout the two sites within the middens. Freitas et al. (2021) suggest a use of litter when shells and natural products are low, while this could be the case for our Kawau Island site, this seems unlikely for the glass bottle use at Jervis Bay. While the centre metal wheel is theorized to be the original catalyst of the first site it still appears to be the most coveted den out of the original site.

## Den Occurrence

Repetitive dens were present at each site, although they were more common at Kawau Island (Figure 15E and 17E). While the Stanmore Bay site had one repetitive den it was only seen twice, whereas the Kawau Island site had several dens that appeared to be in used throughout the entire sampling period (e.g., KD13, KD14, KD35, and KD38). This aligns with diver observations of the two sites, Stanmore Bay often had landscape changes after each storm creating a shift in the sedimentation, opening new areas in the rocky reef, and covering others. Where the Kawau Island site was calm and often clear of sedimentation, the Stanmore Bay site often had low visibility and strong currents.

The Average Nearest Neighbour results showed a significant difference between the two sites. At the Kawau Island Site had several indicators of clustering throughout K1, K2, K3, and the total Kawau Island den map ($p>0.05$ signified a rejection of the hypothesis that items were randomly scattered) (Table 8), with several locations of more than one midden within one square meter, which is to be expected (since there are four times as many dens). Whereas the Stanmore Bay site dens were very spread out, with significantly random scattered distribution ($p<0.05$) (Table 9). The distances between dens at all Kawau surveys were far lower than Stanmore's, where all Kawau results had a range of 4-6m Observed Mean Distance the S2 and S4 dens had a 24m and 30.5m Observed Mean Distance, respectively. While the statistical significance for this method can be affected by study area size, it would have caused the Stanmore Bay site to look more clustered, and the Kawau site to appear less clustered. Since this was not the case it appears the difference in study size did not confound the Average Nearest Neighbour tools results.

The occurrence of individual *O. tetricus* diverged the sites, while there were more dens at each site than previous New Zealand sites, Anderson (1997) reported inhabited dens. The Kawau Island site covered a 50m by 100m area and the larger, sparser Stanmore Bay site covered a 100m by 200m area. Anderson's (1997) study reported 2.2 individuals per $500m^2$, where our Stanmore Bay site contained 1 individual per $1000m^2$, and the Kawau Island site contained 1.8 individuals per $1000m^2$. However, both of our sites had a more clustered individual occurrence, and a denser den occurrence. Our clustered areas of dens at Kawau Island were similar to the Jervis Bay sites, where they reported 13 occupied dens in a 12x8m ($96m^2$) site, where in K1 and K2 several small areas 10x20m ($200m^2$) containing 7 dens, with 2 or 3 being occupied at a time.

## Weather and Water Parameters

Both the PAR 1 and PAR 2 sensors on the multiparameter YSI Sonde produced results that did not represent three consecutive water profiles for each site. Since the LI-COR Spherical Quantum Sensor also measured PAR and produced appropriate these measurements were used, rather than those from the sonde. Only the PAR 1 & 2 and the depth meter produced incorrect results. Yet, as known from the sampling process, the depth of each drop site the depth did not affect the data to a noticeable degree, and still produced three consecutive drop trials, so the rest of the data were not hindered.

The light proliferation data (PAR) of the water column is pertinent to the study due to octopuses' heavy reliance on visual cues. Since our study took place at two different sites there was cause to assess the difference, if any, between the two sites, and if there were any inconsistencies between the known habitat preferences and what was observed.

The LI-COR can create a vertical model of the light through the water column. However, if a base line is incorrect or the variables change during the data collection then the results would not represent a singular water column but selective depths in varying situations. As such when a cloud or shadow came across the sampling area sampling would cease, or sampling would restart for the interrupted instruments measurements for that site. The same would occur if there the sunlight broke through heavy cloud cover. For one of the sites visited the cloud coverage completely changed and with inclement weather sampling was immediately stopped rather than restarting.

In some of the Stanmore light attenuation coefficient the Sonde, and resulting data, did not go as deep as the rest. Since the boat was needed to sample water parameters, sampling would only occur when the boat was used, which was only done for the Kawau surveys. Because of this the Kawau water parameters were taken within a few hours of high tide, but the Stanmore measurements were taken hours after the Kawau diving and water parameters had been completed. Often making these occur several hours after high tide. Because of this the sites depth was shallower than when divers would typically survey. Since the area past the reef had different sediment and consistently had a lower visibility water parameters were taken from the deepest part of the Stanmore reef.

While the Sonde did collect the data it was programmed for the values it collected, when plotted and compared with the methods used, did not line up. The depth was either half or a third of the true value. And in one instance did not report three consecutive deployments, but one long deployment. The PAR 1 and 2 were both too scattered and had little evidence of three drops. This could be said of most other parameters collected, except for temperature and salinity. In all but one of the surveys they both showed three tiers of collection. Even though the results were often compounded and exasperated by the third deployment there is still evidence of semi-accurate result table.

The maximum depth at both sites was 6m due to the early arrival at Kawau (before high tide) and the late arrival at Stanmore (after high tide); however, at Stanmore the tide and reefs were more variable and would often be shallower. When lowering the Sonde deeper into a drop off that was repeatedly viewed to be lower in visibility and not joined with the rocky reef environment. Often the Secchi disk would be visible when it touched the sea floor, but taking the boat out further would have moved into a deeper sand flat with current and would have given information not accurate to the study site. Surveys were only able occur on to the boat during fair weather. Light measurements were taken when the sun was least covered (varied depending on the days weather), at peak visibility. At Stanmore during surveys the visibility would often be quite poor and could change on a dime so this visibility data it really its peak visibility.

Complications

Our non-invasive technique does limit us to leaving barricades intact in the instance of a brooding octopus being behind the wall of shells. Because of this any shells under the first layer were not recorded and the presence of an octopus could not be confirmed.

Scheduling each survey was difficult to manage with the staff involved. The weather during the time frame of October 2020 to March of 2021 was very limiting. To use the boat, optimal open wind conditions were needed to go out, and while divers can dive during rain the drone is inoperable with any precipitation. Along with this the Stanmore site sediment would become agitated with an on-shore wind and as a result was very turbid for our less than optimal dives.

## Conclusion

The two sites anecdotally containing high-density *O. tetricus* sites were surveyed repeatedly, both contained *O. tetricus* with dens and middens. While both sites were found to contain multiple *O. tetricus* within a stretch of reef, only the Kawau Island site had multiple dens used repetitively, adjacent occupation, and examples of social tolerance. The non-invasive method supplied enough information to observe den type and midden contents. At the Stanmore Bay site individuals were seen only in rocky reef dens, despite the availability of boulders and sandy flats. The Kawau Island site was observed to have predominantly boulder and sandpit dens, with very few rocky reef dens, and one alternative den. There were two cases of adjacent occupation at the Kawau Island site, one case was ongoing throughout the sampling period, but no observed occurrences of cohabitation at either site. These two New Zealand sites were not as densely covered in dens or middens as Jervis Bay; however, the population density and den frequency found at Kawau Island were far denser than previously reported in New Zealand waters. The similarities suggest that while the Jervis Bay, Australia sites are far more established, high-density sites containing *O. tetricus* exhibiting socially tolerant behaviours could be considered not uncommon, but infrequent, across their known species range.

# Chapter 3: Inferring Prey from *Octopus tetricus* Middens

## Introduction

The shallow water benthic octopus species *Octopus tetricus* or the ‘peachy’ octopus has previously been found inhabiting two high-density denning sites in Jervis Bay, Australia (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017, 2018). The main substrate of these sites is a bed of used shells, or midden, that completely covers an area with several dens. These shells are, likely, refuse from their previous prey, which is often brought live to their dens and discarded once the animal inside is eaten. These middens are often used to identify octopus dens, since octopus themselves are often hidden or camouflaged. However, the extent of middens found at the two Jervis Bay sites are more extensive than previously reported octopus middens (Huffard and Godfrey-Smith 2010), with the midden covering several patches (approximately 15$m^2$) of seafloor (Scheel et al. 2017). The *O. tetricus* sites from Anderson’s (1997) Aotearoa New Zealand study did not find such extensive midden coverage; however, the sites studied were not high-density sites, containing a less dense octopus population (2.2 individuals per 500$m^2$) than the Australian sites (35 individuals per 100$m^2$). While midden species differed between the Australian and New Zealand sites both comprised mainly mollusc species native to Australia and New Zealand, respectively. The Australian site’s middens almost entirely consisted of Doughboy Scallop *Mimachlamys asperrimus*, and the New Zealand site’s middens consisting of a variety of mollusc shells, predominantly the Large Dog Cockle *Tucetona laticostata* and the New Zealand Scallop *Pecten novaezelandiae* (Anderson 1997; Scheel et al. 2014, 2017).

Due to their superb camouflaging abilities spotting an octopus in the wild can be quite difficult, causing an octopus midden to be the primary visual indicator of an octopus or den. Due to their lack of physical protection, octopus can often be seen foraging for prey and returning to a den before consuming their quarry (Godfrey-Smith and Lawrence 2012; Mather 1991; Mather and O’Dor 1991). Octopus are specialised predators, using chemotactile exploration to find prey, mostly molluscs and crustaceans. In one study the common Octopus, *Octopus vulgaris*, was found to only eat 30% of its caught prey when outside of its den. While the rest of the prey were saved for later consumption inside a den, with the resulting shells added to the adjacent midden (Mather 1991). The same study also found that waves and currents can remove shells from middens, suggesting a midden is not necessarily an intact or complete record of the resident's diet. With both the presence of currents and individuals eating while foraging, middens are assumed to be an underestimation of the octopus’ diet; however, with intrusive species, such as hermit crabs, it cannot be assumed that all shells present within a midden comes from an octopus’ diet.

Due to these confounding factors, feeding rates cannot be assessed on an individual scale, but instead should be evaluated on a population level (O'Brien et al. 2021).

Due to the area and density of shells at the Jervis Bay sites some speculate the beds to be artificially initiated, which would also explain the numerous anthropogenic items present at the site (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014). At the first site, as reported by Godfrey-Smith and Lawrence (2012) and Scheel et al. (2014), divers postulated a large amount of scallop shells being dumped by a commercial fishing vehicle, explaining the large tire wheel made of metal also found in the middle of the bay. However, with the discovery and examination of the second site, containing similarly large and dense middens, the instigation of these sites by human action is less likely. It is still unclear whether these midden accumulations were two isolated events, initiated by outside factors, or completely engineered by the octopus inhabitants (Scheel et al. 2014, 2017).

Stacking midden shells is a behaviour familiar to many human observers of subtidal habitats within New Zealand. It is a common indicator of octopus in general to those who gather kaimoana[3] or local SCUBA divers (A. McNie & M. Costar, pers. comms; Huffard and Godfrey-Smith 2010). Stacking is said to be indicative of an octopus currently inhabiting the den and is more common among individuals when a bed of scallops or cockles is somewhere nearby (A. McNie & M. Costar, pers. comms). Midden stacking was seen repeatedly throughout the survey, though was far more common at the Kawau Island site. Most non-barricaded dens did not have extensive stacking, and instead had many shells lining the wall of the dens and their entrances.

No speculation on connections concerning midden size or prey species and an *O. tetricus* individual's size or age have been made. In Anderson (1997) divers found 69% of octopus 'shelters' contained middens, with mostly soft sediment species (64% of middens) and some reefal species (36% of middens), dominated by *T. laticostata* and *P. novaezelandiae*. While the dominant species made up the majority of shells observed there was a wide variety of other mollusc species found within the middens; Anderson (1997) found 24 prey species within middens at 4 different sites. At the two Jervis Bay, Australia sites midden prey species were almost completely *M. asperrimus* with a few southern Australian scallops, *Pecten fumatus,* found throughout the shell bed (Scheel at al 2014, 2017).

Despite recent reports of other socially tolerant octopus species, no other reports have yet been made of middens as large and dense as those found within the two Jervis Bay, Australia sites. In this study, species composition of the prey shells in *O. tetricus* middens was recorded as part of the dive

[3] Kaimoana refers to the scallops producing these shells, octopus (wheke) are not commonly considered to be kaimoana.

survey processes outlined in Chapter 2. Imagery was analysed back on land to provide insight into the ecology of these animals and sites, and for comparison with previous accounts of *O. tetricus* middens in New Zealand and Australia.

## Methods

### Sampling Procedure

As outlined in General Methods and Chapter 2 two phases of exploration occurred (Figure 22; Figure 9), the first phase explored the sites (see General Methods, Chapter 1, and Chapter 2) then the previously located dens and middens were revisited and photographed in Phase 2.

In Phase 2 a GoPro Hero Black 8 (Figure 6D) was used to record each midden that was previously found, to better identify midden species. The GoPro was used previously in the camouflaged housing (Figure 6C) for Phase 1 and was transferred in between dives to a standardised PVC pipe stand (Figure 6B). For dens and middens without an octopus present the stand was placed facing north with the base on the sea floor. For dens with octopus present, the camera was removed from the stand and photos from 2m above the den (to comply with this projects ethics), with the camera facing north. Dens without octopus would also be photographed in this manner after using the stand, for later comparison. After taking pictures, the second diver would hold a measuring tape across the middens as a close-up video was taken. Middens were not disturbed, so only the visible upper layer of shells was observed and analysed.

### Analysis

The analysis of middens consisted of examining videos and pictures of each midden (Figures 12E, 12F, 12I, and 12J). After prey species and size were determined their attributes were entered into a Microsoft Excel document for analysis. Prey species shells were identified primarily using the Collins Field Guide to the New Zealand Seashore (Carson and Morris 2017), and if a species could not be found within the book the website iNaturalist was consulted. If the species was found on iNaturalist a published work was sought to reinforce the identification (Wei and Lee 2013), although this was not possible for every species. Only species presence was counted, not the number of individuals. Since the middens were left undisturbed, only those visible to divers would be counted and a total count would not be possible.

Within the middens a shell was counted if it had 75% of the shell and all identifying parts, including the full-length width, and 90% of hinge and clear ridges. For gastropods the shell often needed to be 90% intact to make an ID, otherwise the shells would be counted as debris. Debris was the term for pieces of shells that were not recognizable, often very small pieces of shell were scattered around both sites, likely deposited by the current. A small amount of shell debris was always present near dens, as there were often pieces of shells within the substrate. A midden was not counted as having significant levels of debris unless the shell debris covered 50% of the natural substrate, including larger pieces of shell (approximately 40% of a specimen).

## Results

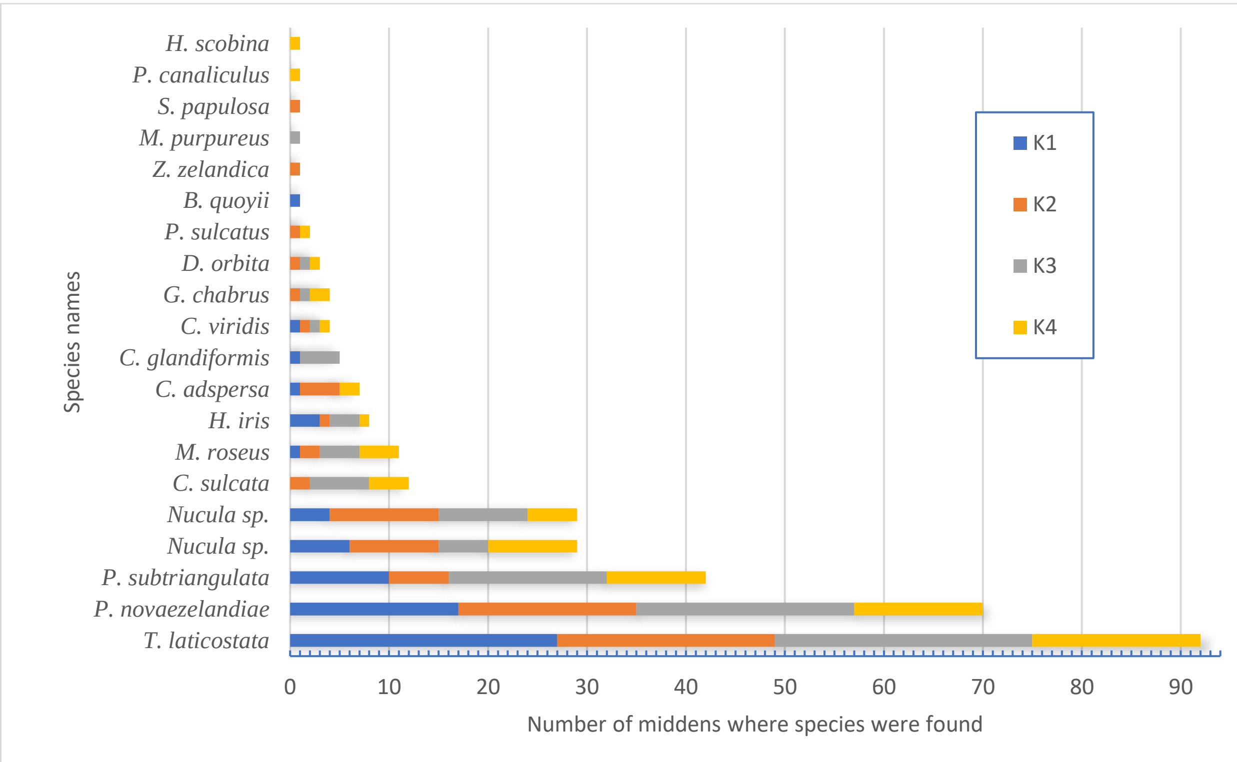


Figure 19: Midden species composition at Kawau Island site across all surveys. Data is grouped by species occurrence, with K1 (blue), K2 (orange), K3 (grey), and K4 (yellow) surveys represented by separate bar colour. With *T. laticostata* being present at 92 out of the 94 middens found at Kawau Island across the sampling period, making it the dominant and most frequently occurring species within Kawau Island middens.

Within the 94 middens at the Kawau Island site the shells of 20 different mollusc and crustacean prey species were found throughout the summer of 2020-2021 (Figure 19). The most frequent and most numerous species in every survey and across the site was *T. laticostata*, this species was only absent from two middens, but present in and often forming the majority of visible shells in other middens. The second most common shell, *P. novaezelandiae*, was also prevalent throughout this survey, present at most dens during each survey. Combined, these two species made up 42% of visual species presence in midden composition in this survey.

The first survey done at Kawau Island, K1, was at the beginning of the summer season (Table 1). Out of the 28 middens observed 11 out of the eventual 20 different species found at this site were observed in the middens. The cockle *T. laticostata* was the dominating species and was present within all but one (96%) of the middens. The second most common shell, *P. novaezelandiae*, was also prevalent throughout this survey, with an occurrence rate of 60%. Combined, these two species made up 62% species presence in midden composition in the October survey.

Of the 22 middens observed in K2 (Table 1) 15 out of the eventual 20 different species found at this site were observed in the middens. The cockle *T. laticostata* was the dominating species, being present at every midden evaluated. The second most common shell, *P. novaezelandiae*, was also prevalent throughout this survey, with an occurrence rate of 81%. Combined, these two species made up 49% species presence in midden composition in this survey.

Of the 27 middens observed in K3 (Table 1) 13 out of the eventual 20 different species found at this site were observed in the middens. The cockle *T. laticostata* was the dominating species, being present at all but one midden (96%). The second most common shell, *P. novaezelandiae*, was also prevalent throughout this survey, with an occurrence rate of 81%. Combined, these two species made up 48% species presence in midden composition of this survey.

Of the 17 middens observed in K4 (Table 1) 15 different species were found at this site were observed in the middens. *T. laticostata* was the dominating species, being present at every midden evaluated. The second most common shell, *P. novaezelandiae*, was also prevalent throughout this survey, with an occurrence rate of 81%. Combined, these two species made up 42% species presence in midden composition in this survey. This survey had the highest number of auxiliary species (not *T. laticostata* or *P. novaezelandiae*), although the number species found are the same as the second survey, this survey had more middens with ulterior species.

The Stanmore Bay site had a smaller more solitary *O. tetricus* population, which was reflected in that fewer middens were observed. Due to the easily accessible nature of this site, it was visited more, a total of 8 times. Within the 11 middens at the Stanmore Bay site 14 different species were found throughout the summer of 2020-2021 (Figure 20). The surveys S1, S3, S6, and S7 of this site yielded no den or midden observations, and as such have no species information.

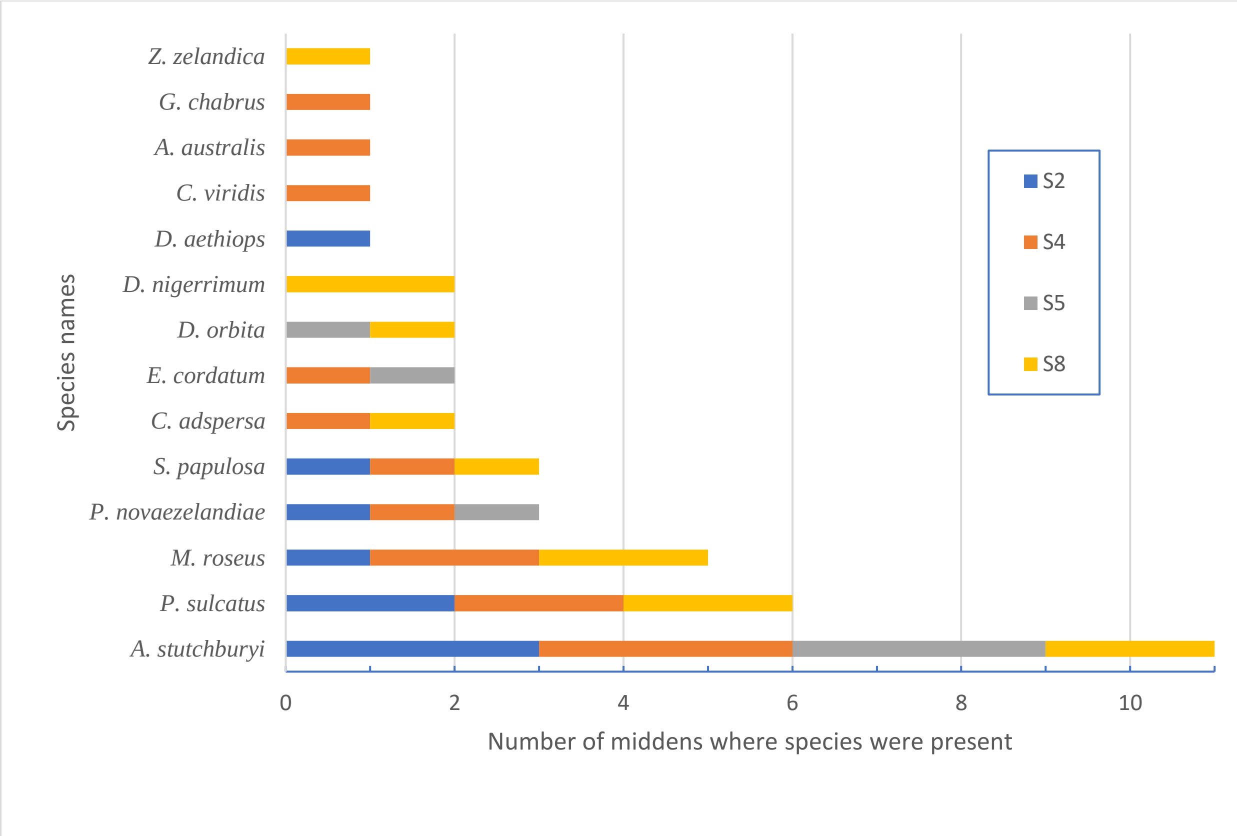


Figure 20: Midden species composition at Stanmore Bay site across all surveys. Data is grouped by species occurrence, with S2 (blue), S4 (orange), S5 (grey), and S8 (yellow) surveys represented by separate bar colour. With *Austrovenus stutchburyi* being present at all 11 middens found at Stanmore Bay across the sampling period, making it the dominant and most frequently occurring species within Stanmore Bay middens.

Of the 3 middens discovered in S2 (Table 2) 6 different species were observed. The dominating species of both the second survey and the ensuing surveys was the New Zealand cockle, *Austrovenus stutchburyi*, being present at all three middens. The second most common shell, *P. sulcatus*, was also prevalent throughout this survey, occurring at two of the three sites this survey. Combined, these two species made up 56% of the species presence in midden composition of this survey.

Of the 3 middens discovered in S4 (Table 2) 10 different midden species were observed. The most common was again *A. stutchburyi*, with the second most common being a tie between *P. sulcatus*, and *M. roseus*. Combined, these three species made up 50% of the species presence in midden composition of this survey.

Of the 3 middens discovered in S5 (Table 2) only 4 different species were observed. Only one of the three middens were contained multiple species, the two first middens were only observed to contain *A. stutchburyi*. The dominating species of both the second survey and the ensuing surveys was *A.*

*stutchburyi*, being present at all three middens. Combined, this species made up 50% of the species presence in midden composition of this survey.

Of the 2 middens discovered in S8 (Table 2) 8 different midden species were observed. While *A. stutchburyi*, was found at both sites there was a four-way tie between species frequency, along with *A. stutchburyi* the species *P. sulcatus*, Turret shell *Maoricolpus roseus*, and the bluish top shell *Diloma nigerrimum* were all present at both middens observed. Combined, these four species made up 66% of the species presence in midden composition of this survey.

Midden stacking was seen repeatedly throughout the survey, occurring more frequently at the Kawau Island site. Most non-barricaded dens did not have extensive stacking, other than lining the wall of the den with shells. Some dens at the Kawau Island site occurred with defined entrances, with rocks lined up and shells stacked on top of each other as a partial barrier. A few octopus had varying defined entrances, both rocks and shells stacked in a non-pattern manner. However, several partially barricaded dens (especially in the first two Kawau Island surveys) showed their left (our right) side of their dens lined uniformly with big, blocky, brick-like boulders, and their right (our left) side was "neatly" stacked shells (*T. laticostata*), the shell stack occupying approximately 33% of entrance barrier. "Neatly" stacked describes a stacking of similarly oriented shells, with bottom shell exterior to top shell interior, auricle on auricles, and valve on valve. The interior of each shell was typically always facing down. For more detail on den barricades see Chapter 2.

## Discussion

The Kawau Island site was far more populated than the Stanmore Bay site, with more den types, fish species, and number of *O. tetricus* seen (see Chapter 2). This abundance was also apparent in the middens observed. Due to the difficulty involved with taking a boat out to this area the site was only surveyed 4 times.

The findings of this study can be compared to previous studies of *O. tetricus* middens at both high-density sites (similar to Jervis Bay, Australia) and their more solitary habitats, common within New Zealand (similar to Andersons sites in New Zealand). At Kawau Island 20 prey species were observed within middens, whereas at Stanmore Bay 14 prey species were observed within middens. The highest diversity of prey species was observed within K2 and K4 at Kawau Island with 15 different prey species observed within middens on one survey and S4 at Stanmore Bay with 9 different prey species observed within middens. While both sites had a greater number of gastropod species (Kawau having 13 gastropods out of 19 mollusc species and Stanmore having 10 gastropods out of 12 mollusc species), there was a difference between species frequency. With Kawau having far more bivalve species occurring in middens (making up 263 out of 324 species occurrences) while Stanmore maintained gastropod majority, with more gastropod species present at middens (making up 24 out of 41 species occurrences). Middens were far more numerous at the Kawau Island site than at the Stanmore Bay site, with 94 middens found at the former, and 11 the latter. At the isolated Sweetings Pond, as described by O'Brien et al. (2021) only 47% of dens were observed contained middens. The authors attribute this to a lack of variety of shelled prey species (only 5 different species shells found within middens), suggesting more soft-bodied species make up their octopus species diet.

Across the sampling period, the majority of middens were found at the Kawau Island site, with the exception of a few smaller den middens (less than 1m diameter), the Kawau middens were substantial, with some middens more than 2m in radius. While not as big as those found within Jervis Bay ($18m^2$) (Scheel et al. 2014, 2017) where middens were the culmination of several dens, they are notably larger than previous reports (Huffard and Godfrey-Smith 2010) and personal observations. Although shell size was not statistically analysed, the shells found in Kawau middens tended to be larger than those at Stanmore. Divers noticed that, typically, the larger the midden the larger the average width and length of the shells present.

Groupings of shells at Stanmore could be seen stacked tightly under the rocky reef overhang. These could be remnants of older den middens, but the shells did not appear aged (not sun bleached), this could in part be due to their constant covering by changing sand lay outs. Or they could be from roaming transient octopus, such as New Zealand octopus *Pinnoctopus cordiformis*, which roams these areas (rocky reefs) to hunt while not actually denning within the sites (Anderson 1997, 1999). One *P. cordiformis* was observed in this study at Stanmore on the deployed stationary camera. Since there is evidence that this species is present this is a likely alternative however with the widely dispersed and sporadic nature of these stacking deposits, their origin cannot be confirmed nor denied without further research.

Many additional possible middens were passed in both Stanmore Bay and Kawau Island. However, these large areas of discarded shells were not stacked or dense enough to prove the area was a midden as opposed to a natural accumulation of items, by currents or animals. Remnants of a high-density rocky reef site were found both at the Kawau Island site near a patch of reef dubbed 'The Steps' and near a recorded den at the Stanmore Bay site.

## Species Diversity

The species found within these middens could give insight into the diet of *O. tetricus*. However, it cannot be certain all shells within these sites are resulting from *O. tetricus* predation, or that all shells found were the result of an octopus consumption. The presence of hermit crabs at both sites also confounded the certainty of species within the middens. At both sites, New Zealand hermit crabs, *Pagurus novizealandiae*, were seen in the area and on middens. These creatures can confound the midden species list if they exchange or remove shells. The middens at these two sites are indicative of both an octopus' presence and a history of the resident's diet. Yet, whether the diet belongs to an individual or multiple octopus of one or more species is uncertain.

At Kawau the most frequent and numerically dominant species found within the midden composition was *T. laticostata* (present at 98% of all Kawau middens), whereas at Stanmore it was *A. stutchburyi* (present at 100% of all Stanmore middens). At both sites the most frequently occurring shells within middens were medium to large cockle shells (*T. laticostata* and *A. stutchburyi*), with each site having a second most frequent species present in most middens. These secondary species were not as prolific as the main species, often having half to a third as many shells at each midden as the primary species. At Kawau the secondary species was the scallop *P. novaezelandiae* (present at 74% of all Kawau middens). At Stanmore the secondary species was the whelk *P. sulcatus* (present at 55% of all Stanmore middens). In Anderson's (1997) study the 3 most commonly found prey species within *O. tetricus'* middens were *T. laticostata* (present within 29% of all middens); *P. novaezelandiae* (present within 13 % of all middens); and varying *Dosinia* spp. (present within 10% of all middens). These species and percentages are similar to the Kawau middens than the Stanmore middens. No *Dosinia* spp. were observed however, the *Nucula* species observed within this study were similar in appearance, suggesting a possibility of misidentification in previous papers. The first Scheel et al. (2014) paper focusing on the original Jervis Bay site found mostly doughboy scallop shells, *Mimachlamys asperrimus*, with occasionally some fresh rough rock crab remains (*Nectocarcinus integrifrons*). While neither of these were found at the Kawau Island or Stanmore Bay sites these species are native to Australia and are not found in the Hauraki Gulf. However, a scallop species, *P. novaezelandiae* and a marine crab species were found at both sites.

Table 10: Midden species found within the Hauraki Gulf present within *O. tetricus* middens from Australian and New Zealand studies. Alternative data from reference Anderson 1997; Godfrey-Smith and Lawrence 2012.

| **Latin Name** | **Common Name** | **Present at Stanmore Bay Middens** | **Present at Kawau Island Middens** | **Identifying Source** |
|---|---|---|---|---|
| *Tucetona laticostata* | Large Dog Cockle | No | Yes | Anderson 1997 |
| *Pecten novaezelandiae* | New Zealand Scallop | Yes | Yes | Anderson 1997 |

| | | | | |
|---|---|---|---|---|
| *Dosinia* spp. | Saltwater clams | No | Yes | Anderson 1997 |
| *Plagusia* spp. | Crabs | Yes | Yes | Anderson 1997 |
| *Cookia* spp. | Large Turban Snails | No | Yes | Anderson 1997 |
| *Crepidula* spp. | Slipper Limpets | No | No | Anderson 1997 |
| *Notomithras* spp. | Crabs | No | No | Anderson 1997 |
| Pectinidae spp. | Scallops | Yes | Yes | Godfrey-Smith and Lawrence 2012 |
| *Paphies subtriangulata* | Northern Tuatua | No | Yes | Carson and Morris 2017 |
| *Nucula* sp. | White Nut Clam | No | Yes | Carson and Morris 2017 |
| *Nucula* sp. | Small Cockle | No | Yes | Wei and Lee 2013 |
| *Maoricolpus roseus* | Turret Shell | Yes | Yes | Wei and Lee 2013 |
| *Bulla quoyii* | Olive Bubble Shell | No | Yes | Carson and Morris 2017 |
| *Cominella adspersa* | Speckled Whelk | Yes | Yes | Wei and Lee 2013 |
| *Haliotis iris* | Black-foot Pāua | No | Yes | Carson and Morris 2017 |
| *Cookia sulcata* | Cooks Turban | No | Yes | Wei and Lee 2013 |
| *Coelotrochus viridis* | Green Top Shell | Yes | Yes | Carson and Morris 2017 |
| *Dicathais orbita* | Ridged Whelk | Yes | Yes | Carson and Morris 2017 |
| *Zethalia zelandica* | Wheel Shell | Yes | Yes | Wei and Lee 2013 |
| *Penion sulcatus* | Northern Siphon Whelk | Yes | Yes | iNaturalist |
| *Guinusia chabrus* | Red Rock Crab | Yes | Yes | Wei and Lee 2013 |
| *Cominella glandiformis* | Mud Whelk | No | Yes | Carson and Morris 2017 |
| *Micrelenchus purpureus* | Red Top Shell | No | Yes | Wei and Lee 2013 |
| *Struthiolaria papulosa* | Large Ostrich Foot | Yes | Yes | Carson and Morris 2017 |

| | | | | |
|---|---|---|---|---|
| *Perna canaliculus* | New Zealand Green-lipped Muscle | No | Yes | Carson and Morris 2017 |
| *Haustrum scobina* | Oyster Borer | No | Yes | Wei and Lee 2013 |
| *Austrovenus stutchburyi* | New Zealand Cockle | Yes | No | Wei and Lee 2013 |
| *Diloma aethiops* | Spotted Black Top Shell | Yes | No | Wei and Lee 2013 |
| *Amalda australis* | Southern Olive Snail | Yes | No | Carson and Morris 2017 |
| *Echinocardium cordatum* | Uncommon Sea Urchin | Yes | No | iNaturalist |
| *Diloma nigerrimum* | Bluish Top Shell | Yes | No | Carson and Morris 2017 |

Several of the same midden species were found across separate *O. tetricus* den sites (Table 10). In Australia, the two Jervis Bay sites contained many of the same midden species. The northeastern Hauraki Gulf and the Cape Rodney-Okakari Point Marine Reserve also share prey species found in this study (Table 10). Like the Kawau Island site, Anderson's (1997) study found the majority of midden species to be *T. laticostata* (reported as *Glycymeris laticostata*) and *P. novaezelandiae* (reported as *Pecten novaezealandica*). While there were several other prey species found within the Jervis Bay middens, their species were not specified beyond the two. These were the two species most prevalent across the 94 middens found at Kawau Island; and, while not as prevalent, *P. novaezelandiae* was also commonly found in Stanmore Bay middens. The two Jervis Bay sites had far fewer similarities, as those sites consisted of mostly one species, native to Australia, while those found within our sites were native to New Zealand (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017). However, both Australian and New Zealand sites consist of bivalves, typically scallops (*M. asperrimus*, *P. fumatus*, and *P. novaezelandiae*) and occasionally cockles (*T. laticostata*). These species are all 'soft-sediment species' following the general classification set forth by Anderson (1997) generalising *O. tetricus* prey species, distinguishing soft-sediment species (residing in sandy sediments) and reefal prey species (species attaching or living within hard, rigid structures). While Anderson (1997) only characterised *P. novaezelandiae* and *T. laticostata* the other two found within the Jervis Bay sites, *M. asperrimus and P. fumatus*, are also bivalves that live in varying degrees of 'soft-sediment' habitats (Mendo et al. 2014).

Larger octopus typically had less variety within their midden, suggesting that the wider variety came from a higher diversity in smaller mollusc, yet there were never many of the same gastropod. Eliciting that *T. laticostata* and *P. novaezelandiae* were widely available whereas the smaller bivalves and gastropods were less so, suggesting once individuals grow to have enough strength to open and eat scallops and cockles, they choose those prey items instead. This is supported by Joll (1977) and Greenwell et al. (2019), which show the species preference for larger bivalves when available. With only minor differences in the amount of prey consumed between young (smaller) adults and more mature (larger) adults, once the individual is large and strong enough to open a live bivalve.

Remains of the crustacean *G. chabrus* were seen at both sites, however their presence was far more common at Stanmore, the one den containing it in its midden had two full crab sets (two claws and a carapace) and several more were found post consumption within the rivers of the Stanmore site. While they were observed a few times at Kawau the claws were smaller and not with the pairing claw and carapace.

Within the middens a shell was counted if it had 75% of the shell and all identifying parts, including the full-length width, and 90% of hinge and clear ridges. For gastropods the shell often needed to be 90% intact to make an ID, otherwise the shells would be counted as debris. Debris was the term for pieces of shells that were not recognizable, often very small pieces of shell were scattered around both sites, likely deposited by the current. A small amount of shell debris was always present near dens, as there were often pieces of shells within the substrate. A midden was not counted as heaving significant levels of debris unless the shell debris covered 50% of the natural substrate, including larger pieces of shell (approximately 40% of a specimen).

At Kawau Island the majority of shells present both in species and shell count were bivalves, where at Stanmore the majority of species were gastropods. With other octopus species known to live near both sites (and one *P. cordiformis* sighted at Stanmore Bay) the shells found within the middens cannot be confirmed to be the prey of only *O. tetricus* octopus', nor were they an exclusive representation of an *O. tetricus* diet. Shells can be transported via current or animal (e.g., *P. novaezelandiae*), both removal and addition of shells to middens are possible and therefore confound the validity of middens as a representation of diet.

## Complications

While there were initially plans to measure the size of each shell to approximate its age, this turned out to be an exhaustive and arduous task. The retractable tape measurer was not brought to every survey (accidentally) and as a result the measurement of each visible shell was not done. Although using the measuring tape during a few surveys a trend was noticed by divers, but with sparce data later statistical analysis to confirm the trend could not be done.

Due to the non-invasive nature of this project, it was not possible to evaluate all shells within a midden. The only midden shells evaluated were those viewable to the naked eye. It was expected that when dens were fully barricaded with shells there were many other shells under the top layer. This was supported by some middens drastically reducing in size when the barricade appeared, and returned to original size when the barricade was gone. However, this cannot be confirmed due to the lack of invasive investigation done.

In the future, a better camera would be used for the roaming diver footage, the midden species identification had poor quality and some species were difficult to determine. The GoPro's photographs, even on the 4K SuperPhoto, was unable to produce non-distorted photographs to create 3D models for a digital environment. While there were shortcomings with the cameras both cameras were chosen simply because they were readily available and were the most economical high quality underwater options.

## Conclusion

Prey species found within *O. tetricus* middens differed between two New Zealand sites. Although both contained the scallop *P. novaezelandiae* and a cockle species (*T. laticostata* at Kawau Island and the *A. stutchburyi* at Stanmore Bay) as two of their most abundant species, the sites differed drastically in species, species frequency, and midden frequency. With the Stanmore Bay site containing fewer middens, fewer species, and generally consisted of gastropods. Whereas the Kawau Island site had more middens, more species, and predominantly displayed bivalves. Both sites consisted of predominantly soft-sediment species, similar to both previous New Zealand (Anderson 1997) and Australian (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2016, 2017) sites, enforcing the hypothesis that *O. tetricus* forage predominantly on soft-sediment areas. A trend of larger prey found at Kawau Island with smaller prey shells found at Stanmore Bay was noticed by divers but could not be supported with data. While these results can be used to speculate the diet of *O. tetricus*, the shells found within the middens were in no way exclusive to the species *O. tetricus*, nor were they an exclusive representation of an *O. tetricus* diet.

# General Discussion

The aim of this study was to map potential high-density octopus sites using a novel drone FMV method, while collecting data to update the known ecology of the 'peachy' octopus, *Octopus tetricus*, in Aotearoa New Zealand. These two, previously anecdotally reported, sites somewhat resemble two *O. tetricus* denning sites found in Jervis Bay, Australia, which have challenged what was previously known of *O. tetricus* ecology (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017). With no reports of high-density or group living of *O. tetricus* in New Zealand this study aimed to observe and report on what can be found of *O. tetricus* in New Zealand waters. To map out these sites more accurately drone FMV was used, this reduced diver task load and environmental impact while enabling a high geospatial accuracy. Divers observed dens, middens, and octopus inhabitants using cameras to record for later observation.

The combination of synchronous dive footage and drone FMV, using the versatile Hinchliffe (2021) mapping method, allowed for the ArcGIS Pro mapping of a subtidal *O. tetricus* denning site. This novel method is one of few utilising consumer level drone imagery for marine purposes (Duffy 2018). While restricted to shallow (<30m) and coastal environments, this method provides a data collection technique to researchers with low budgets. Using synchronous dive footage, the geocoded drone FMV was able to map the underwater sites in ArcGIS Pro, producing two subtidal maps, with a detailed base map and geocoded points. The expected output of this project was successful, with accurate amps created of the subtidal site (see Figures 10/15, 11/16, and 17). Further works creating additional online supplemental material for public use and geospatial analysis using Maxent were workshopped and could be created in the future. While Duffy et al. (2018) did describe several low-cost drone marine ecology projects few exist within the scope of the field, the use of hobbyist level drones in marine ecological surveys is vastly expanding (Cummings et al. 2017; Duffy et al. 2021). This novel technique should expose new opportunities to marine ecology researchers without the means for professional drone use.

To evaluate the *O. tetricus* sites I specifically sought to use minimally invasive methods during the evaluation of the octopus sites. Rather than anchor permanent buoys (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014) or remove specimens from their den for inspection (Anderson 1997, 1999) divers used a camouflaged stationary and a second hand-held camera to record the sites and the inhabitants. This alternate survey method did provide less detailed information for the octopus, dens, and middens (as only what could be seen from 2m away was recorded); however, the impact on the environment was negligible, octopuses appeared (through stationary footage and continued presence) to not be seriously impacted by diver's presence, and task load was reduced (causing dives to be shorted and more efficient). A trade-off in effort required on-site vs back on land resulted, however, with less work by divers in the field causing the data processing and analysis to take much longer.

Considerable differences were observed between the two sites, notably den types and frequency. The Kawau Island site was observed to have far more dens (total count 63 individual dens, some observed multiple times), with primarily boulder and sandpit dens; where at Stanmore Bay only 11 dens were found, all of which were rocky reef dens. The Kawau Island site closely resembled the two Jervis Bay sites, with boulder and sandpit dens, adjacent den occupations, and large middens completely coving the sediment (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2016, 2017); although our site was less dense and spread out over a larger area. Where the Stanmore Bay site resembled the sites described by Anderson (1997) with rocky reef dens, smaller middens, and spread out across a reef area; however, the Stanmore Bay site was denser than the four Anderson (1997) sites. The dens were found to form several dense clusters at Kawau Island; in fact, surveys K1, K2, K3 and the total Kawau den count had significant clustering (Table 8). At Stanmore Bay the dens were found to be randomly scattered according to the Average Nearest Neighbour tool in ArcGIS Pro (Table 9).

The camouflaged housing created for the stationary camera had many purposes, while designed to reduce the impact of the presence of a camera the housing also removes the need for a permanent structure. The weight of the materials used, i.e., the concrete, allowed the structure to be heavy enough to not drift with the current, and the addition of an eye screw on top allowed a buoy line to be attached. This marker provided visual placement to the drone and allowed divers to recall the housing from the surface without descending again, which was useful in a quick evacuation. The camouflaged housing appears to have successfully hidden the camera contained within and only a few organisms actively investigated the structure. The sole *P. cordiformis* inspected the structure as it passed but did not appear to linger, and upon passing had no further investigation. During several deployments small triple fin blennies would consistently position themselves in front of the lens while investigating the structure. Blennies are known to be territorial and can confront their own reflection (Gallup Jr 1968; Neat 2001), it appeared that the animals saw their own reflection in the lens and were performing territorial displays. Other than these instances no interaction with the structure or the camera within it was observed. The fish species and individual counts further support the effectiveness of the stationary camera and its lack of impact on the organisms there. More fish species and individuals were consistently observed on camouflaged stationary camera as opposed to handheld roaming footage when the stationary was placed (Figures 24, 25, 26, and 27). The camouflaged stationary recorded several 'rare' species not commonly seen in such shallow areas (Adult Red Moki (*Cheilodactylus spectabilis*) and Giant Boar fish (*Paristiopterus labiosus*)) which were not seen by divers.

Throughout this sampling period (October 2020 – March 2021) octopus numbers increased to the peak of summer before decreasing, as expected. With a repetitive presence of divers this could be taken as indication that diver presence and observations did not deter inhabitants from residing. Although, there can be no certainty whether those octopuses encountered were the same throughout the observation period or if numbers were retained by an influx of new residents. Compared to other octopus observation methods, including those used on *O. tetricus*, this observation process was far less intrusive to the organism's personal environment; since I did not physically manipulate the individual or its personal environment.

While this study focused on *O. tetricus*, the New Zealand octopus, *Pinnoctopus cordiformis*, is known to have range overlap, as well as the club pygmy octopus, *Robsonella huttoni*; however the latter is less commonly observed in the Hauraki Gulf (Anderson 1997; Braid and Bolstad 2019; Ibáñez et al. 2020). A single *P. cordiformis* was seen early in the study in S1, crossing the camouflages stationary camera and hiding from divers, this appeared to be the only non-*O. tetricus* observed. Two of these octopus species had previously been described with habitat preferences. With *O. tetricus* inhabiting rocky reefs and foraging on sandflats, where *P. cordiformis* supposedly inhabits sandflats and forages on rocky reefs (Anderson 1997).

While this description matches what was observed at the Stanmore Bay site, this is not the case at the Kawau Island site, with *O. tetricus* inhabiting the sandflat near the reef and boulders, and no *P. cordiformis* observed at the Kawau Island site. At the Kawau Island site octopus dens were found to be clustered in a high-density area (clusters of 7 dens within $200m^2$, with 2 or 3 dens occupied at a time), while not as dense as the Jervis Bay site (13 occupied dens in $96m^2$) (Godfrey-Smith and Lawrence 2012), it was more densely populated than what had been previously reported in New Zealand waters (2.2 individuals per $500m^2$) (Anderson 1997). The similarities suggest that while the Jervis Bay, Australia sites are far more established, high-density sites containing *O. tetricus* exhibiting socially tolerant behaviours could be considered not uncommon, but infrequent, across their known species range.

The middens found in the two *O. tetricus* sites had consistent differences between them. The Kawau Island site middens numbered far higher, with 94 in total (of which 17 were repeatedly observed), despite being half the size of Stanmore Bay, in which 11 middens were observed (including 1 repeat observations). Middens were smaller and less species diverse at the Stanmore Bay site; however, this could be skewed due to the small sampling pool. At Kawau Island several extensive middens (or shell beds) were found throughout the site and sampling period, resembling those reported at the two Jervis Bay sites (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017), enforcing the similarities found between the Kawau Island Site and Australian *O. tetricus* reports. Kawau Island middens contained more species variety, with large bivalve remnants dominating the midden contents, where at Stanmore Bay smaller gastropods were the majority. Several anthropogenic items were found in middens at both sites. Two middens at Kawau Island contained glass bottles, which appeared to be integral to the octopus den barricade (Figures 12E and 12F). At Stanmore Bay the repetitive den contained a rusted spark plug (during S2), which was being used in an active barricade by an octopus. The two bottles were both found in the middens barricade consistently, whereas the spark plug, while seen multiple times, was only used in a barricade (in S2) and after was left within the rest of the discarded midden. Several anthropogenic items were also found in the two Jervis Bay sites, not including artificial dens placed by the authors, at the first site a large, corroded metal wheel was at the centre of the midden, and many glass bottles were found near dens (Godfrey-Smith and Lawrence 2012; Scheel et al. 2014, 2017). Recently, many reports of benthic octopuses interacting with rubbish, glass, and other anthropogenic items have arisen, Freitas et al. (2022) compiled 261 citizen science reports highlighting octopus interaction with litter items, revealing a far greater reach of rubbish and microplastics (i.e., the deep-sea *Octopus salutii* interacting with litter at 400m) and using citizen science the level of litter use by cephalopods is far greater than previously thought.

Unfortunately, the camera setting I used to photograph the middens had distorted edges and could not be used to make a detailed mosaic or 3D model for digital embedding; however, the resolution was high enough to distinguish between species. If possible, an online map would have been made for digital exploration; however, with the distorted photographs the quality would have been poor, so the model was not made. While shell stacking is informally reported by divers, no formal reports could be found on the subject. Middens at Kawau Island created several large shell beds throughout the site and sampling period, while not as extensive as those found in Jervis Bay, they were more like the high-density Australians sites than what has previously been reported in New Zealand.

# Conclusion

Drone FMV combined with synchronous SCUBA footage facilitated the creation of detailed subtidal maps, using the geographic software ArcGIS Pro. The drone and dive cameras were relatively low-cost models that produced a high-resolution map containing ecological information and density analysis. This process was continually developed throughout the project and has potential to grow. Yet, as demonstrated in this thesis, this method can be used presently to map shallow underwater environments, with a relatively low cost, providing a new resource to many other researchers without greater means.

A relatively high-density *O. tetricus* site with evidence of social tolerance was found in the Hauraki Gulf, Aotearoa New Zealand. Compared to previously known *O. tetricus* sites within New Zealand and Australia similarities were found, with both sites surveyed in this study representing a different known habitat type of *O. tetricus*. The Stanmore Bay site represented the solitary rocky reef habitats traditionally known within New Zealand (as described in Anderson 1997), while the Kawau Island site was more like the high-density sand flats of Australia (as described in Godfrey-Smith and Lawrence 2012 and Scheel et al. 2014, 2017). At the Stanmore Bay site only one den was inhabited consecutively, this den was also the only den observed repetitively. At the Kawau Island site seventeen dens were observed in consecutive surveys inhabited with octopus, and even more dens were observed being maintained over the summer season. Octopus population grew and diminished according to the known seasonality of the species (Anderson 1997), rising in spring, reaching a peak in austral summer, and diminishing to nearly none before fall. Two instances of adjacent occupation were seen at the Kawau Island site, supporting the species ability of social tolerance.

Both sites had a prominent cockle species found within the majority of middens, Kawau Island had the Large Dog cockle, *Tucetona laticostata*, and Stanmore Bay had the New Zealand cockle, *Austrovenus stutchburyi*. Both sites had a consistent use of the New Zealand scallop, *Pecten novaezelandiae*, present in many of the middens. Both sites had predominantly soft-sediment prey species, similar to both Australian and New Zealand reports, concurring that *O. tetricus* forages in soft-sediment areas. Due to image distortion image mosaics and models of dens and middens were not made although image equality was enough to positively identify midden species.

Traditional SCUBA observation methods were improved upon using non-invasive techniques with a lower task load, leading to increased safety and better spatial awareness. This transition to digital recording rather than divers' written records drastically increased the safety and ease of this project. Though less detailed information about the octopus residents, dens, and middens was gathered, due to a lack of physical interaction, divers were able to evaluate more of the site with greater awareness, and what divers recorded could be repeatedly reviewed and referenced (although this did add considerable amount of analysis time). No permanent structure or mark was made on the sites, and, referencing octopus presence and fish abundance, I conclude that the environment was not negatively impacted by our study.

Within this project the use of drone FMV combined with synchronous underwater footage was used to map subtidal environments. This study used low-cost drones to create accurate and detailed subtidal maps. The case study showed that yes, *O. tetricus* can be found in high-density sites exhibiting social tolerance within New Zealand, as well as living solitarily in rocky reefs. Octopus density and distribution across the breeding season in two sites was observed and concluded that den preferences and speculative diets based on midden composition varied between sites but consisted primarily of soft-sediment species (although middens are not a definitive example of *O. tetricus* diet). Non-invasive methods appeared to leave no impact on environments and animals studied, but did impact quality of data, collection safety, and post-collection analysis. A concentrated visualisation of these findings can be seen in Figure 21.

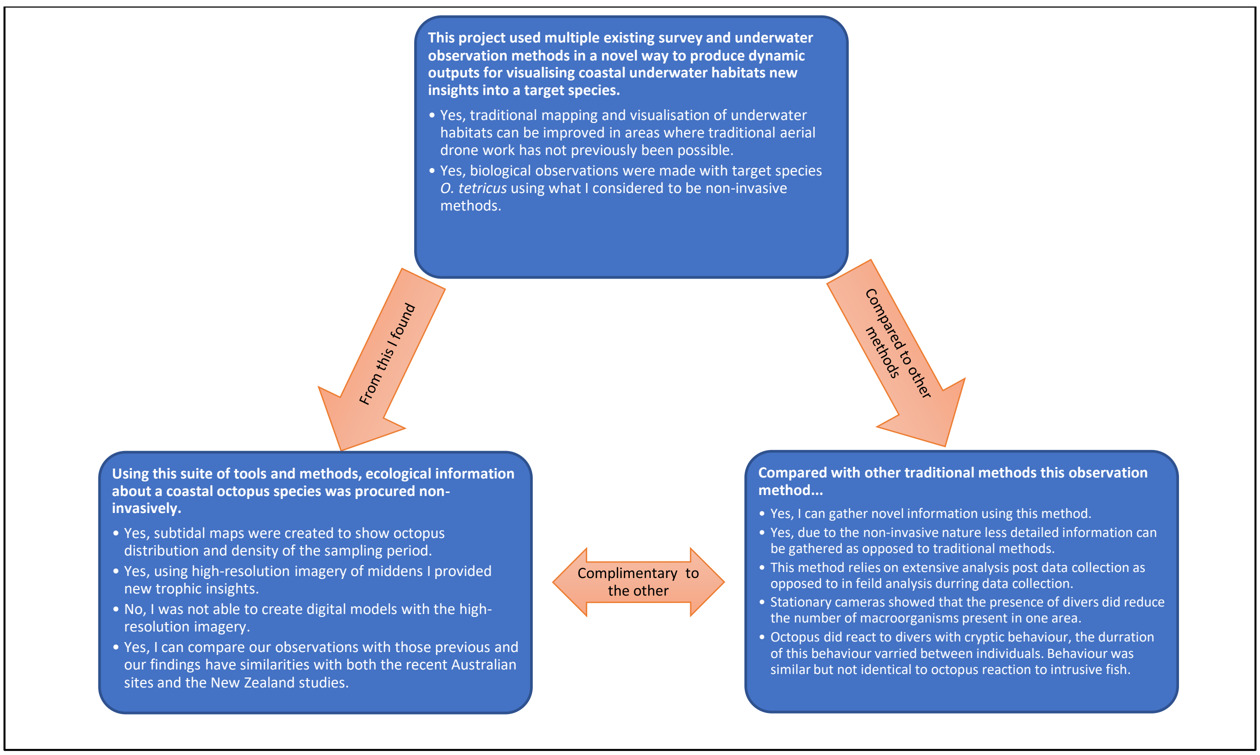


Figure 21: Thesis results and answers flow chart. Organised into three categories (represented as boxes) the results and answers are presented to visualize how each section relates to the other two. The top box focuses on the methods of this study. The bottom-left box focuses on the ecology and case study of *O. tetricus*, relating to Chapters 2 & 3. The bottom-right box focuses on the low impact design of this method and how our method compares to others, this theme is found throughout the thesis, and is in all Chapters.

# Citations

*AIM Chapter 3*. Airspace. Archived 7 June 2014 at the Wayback Machine. <https://web.archive.org/web/20140607005739/http://www.faraim.org/aim/aim-4-03-14-129.html>

AirShare. *Maps*. AirShare. Viewed 12/1/21 <https://pilot.airshare-utm.io/maps>

Ambrose, R.F., 1982. Octopus bimaculatus. *Marine Ecology-Progress Series,* 7, pp.67-73.

*The American Society for Photogrammetry and Remote Sensing (ASPRS).* 2018. About ASPRS. Viewed on 21/10/21. <http://www.asprs.org/a/society/about.html>

Amor, M.D. and Hart, A.M., 2021. *Octopus djinda* (Cephalopoda: Octopodidae): a new member of the Octopus vulgaris group from southwest Australia. *Zootaxa*, 5061(1), pp.145-156.

Amor, M.D., Norman, M.D., Cameron, H.E. and Strugnell, J.M., 2014. Allopatric speciation within a cryptic species complex of Australasian octopuses. *PLoS One,* 9(6), p.e98982.

Anderson, T.J., 1994. Taxonomy and ecology of shallow-benthic octopus in north-eastern New Zealand (*Doctoral dissertation, University of Auckland*).

Anderson, T.J., 1997. Habitat selection and shelter use by *Octopus tetricus*. *Marine Ecology Progress Series*, 150, pp.137-148.

Anderson, T.J., 1999. Morphology and biology of *Octopus maorum* Hutton 1880 in northern New Zealand. *Bulletin of Marine Science*, 65(3), pp.657-676.

Anderson, T.J. and Leigh, R.B., 1999. Subcutaneous electromagnetic tagging of benthic octopus: a preliminary evaluation. *Marine and Freshwater Research*, 50(3), pp.225-227.

Anderson, R.C., Wood, J.B. and Byrne, R.A., 2002. Octopus senescence: the beginning of the end. *Journal of Applied Animal Welfare Science*, 5(4), pp.275-283.

*Animal Welfare (Sentience) Bill [HL]*. 2022. Originated in the House of Lords, Session 2021-22

Aronson, R.B., 1986. Life history and den ecology of *Octopus briareus* Robson in a marine lake. *Journal of Experimental Marine Biology and Ecology*, 95(1), pp.37-56.

Aronson, R.B., 1989. The ecology of *Octopus briareus* Robson in a Bahamian saltwater lake. *American Malacological Bulletin*, 7(1), pp.47-56.

Aviation Security Service. 2021. *Part 101 Rules for Drones*. Civil Aviation Authority. https://www.aviation.govt.nz/drones/rules-and-regulations-for-drones-in-new-zealand/part-101-rules-for-drones/

Bennice, C., 2019. Mechanisms of Coexistence between Two Octopus Species in a South Florida Lagoon (*Doctoral dissertation, Florida Atlantic University*).

Biggs, B., 1957. The Story of Kupe. As Written Down by Himiona Kaamira. *The Journal of the Polynesian Society*, 66(3), pp.232-248.

Boletzky, S.V. and Hanlon, R.T., 1983. A review of the laboratory maintenance, rearing and culture of cephalopod molluscs. *Memoirs of the Natural Museum Victoria*, 44, pp.147-187.

Boyle, P.R., 1980. Home occupancy by male *Octopus vulgaris* in a large seawater tank. *Animal Behaviour*, 28(4), pp.1123-1126.

Braid, H.E. and Bolstad, K.S., 2019. Cephalopod biodiversity of the Kermadec Islands: implications for conservation and some future taxonomic priorities. *Invertebrate Systematics*, 33(2), pp.402-425.

Browning, H., 2019. What is good for an octopus?. *Animal Sentience*, 4(26), p.7.

Bull, M.F., 1989. The New Zealand scallop fishery: a brief review of the fishery and its management. *Edited by: MLC Dredge, WF Zacharin and LM Joli*, p.42. <50-58>

Caldwell, R.L., Ross, R., Rodaniche, A. and Huffard, C.L., 2015. Behavior and body patterns of the larger pacific striped octopus. *PLoS One*, 10(8), p.e0134152.

Carruthers, T.J., Longstaff, B.J., Dennison, W.C., Abal, E.G. and Aioi, K., 2001. Measurement of light penetration in relation to seagrass. *Global Seagrass Research Methods*, pp.370-392.

Carson, S.F. and Morris, R., 2017. *Collins Field Guide to the New Zealand Seashore*. Collins.

Chase, E.R. and Verde, E.A., 2011, October. Population Density and Choice of Den and Food Made by *Octopus rubescens* Collected from Admiralty Bay, Washington, in July 2011. *In American Academy of Underwater Sciences 30th Scientific Symposium* (p. 110).

Chiswell, S.M., Bostock, H.C., Sutton, P.J. and Williams, M.J., 2015. Physical oceanography of the deep seas around New Zealand: a review. *New Zealand Journal of Marine and Freshwater Research*, 49(2), pp.286-317.

Chiswell, S.M., Wilkin, J., Booth, J.D. and Stanton, B., 2003. Trans-Tasman Sea larval transport: Is Australia a source for New Zealand rock lobsters?. *Marine Ecology Progress Series*, 247, pp.173-182.

Cigliano, J.A., 1993. Dominance and den use in *Octopus bimaculoides*. *Animal Behaviour*, 46(4), pp.677-684.

Cosgrove, J.A., 1993. In situ observations of nesting female *Octopus dofleini* (Wülker, 1910). *Journal of Cephalopod Biology*, 2(2), pp.33-45.

Cummings, A.R., McKee, A., Kulkarni, K. and Markandey, N., 2017. The rise of UAVs. *Photogrammetric Engineering & Remote Sensing*, 83(4), pp.317-325.

Cousteau, J.Y. and Dumas, F., 1953. *The Silent World* (p. 80pp). London.

deepblu. *Equipment: How the Dive Computer Revolutionized Diving.* January 4, 2018. DEEPBLU MAG. Accessed 3/12/2021. <https://www.deepblu.com/mag/index.php/2018/01/04/how-the-dive-computer-revolutionized-

diving/#:~:text=Many%20inventors%20and%20deep%2Dsea,a%20wider%20range%20of%20people.>

Duffy, J.P., Anderson, K., Fawcett, D., Curtis, R.J. and Maclean, I.M., 2021. Drones provide spatial and volumetric data to deliver new insights into microclimate modelling. *Landscape Ecology*, pp.1-18.

Duffy, J.P., Cunliffe, A.M., DeBell, L., Sandbrook, C., Wich, S.A., Shutler, J.D., Myers-Smith, I.H., Varela, M.R. and Anderson, K., 2018. Location, location, location: considerations when using lightweight drones in challenging environments. *Remote Sensing in Ecology and Conservation,* 4(1), pp.7-19.

Edsinger, E., Pnini, R., Ono, N., Yanagisawa, R., Dever, K. and Miller, J., 2020. Social tolerance in *Octopus laqueus*—A maximum entropy model. *PLoS One,* 15(6), p.e0233834.

Edson, E., 2007. The World Map, 1300-1492: The Persistence of Tradition and Transformation. *JHU Press.*

Esri. *ArcGIS Pro: FMV Package.* 22/7/2021. <https://pro.arcgis.com/fr/pro-app/latest/help/analysis/image-analyst/introduction-to-full-motion-video-in-arcgis-pro.htm>

Esri. *FAQ: What are the Full Motion Video Add-in's Motion Imagery Standards Board (MISB) metadata requirements*? 22/7/2021. <https://support.esri.com/en/technical-article/000015970. 8/9/2021>

Everaerts, J., 2008. The use of unmanned aerial vehicles (UAVs) for remote sensing and mapping. The International Archives of the Photogrammetry, *Remote Sensing and Spatial Information Sciences,* 37(2008), pp.1187-1192.

Fettermann, T., Fiori, L., Bader, M., Doshi, A., Breen, D., Stockin, K.A, and Bollard, B., 2019. Behaviour reactions of bottlenose dolphins (*Tursiops truncatus*) to multirotor Unmanned Aerial Vehicles (UAVs). *Scientific Reports,* 9(1), pp.1-9.

Fiorito, G. and Scotto, P., 1992. Observational learning in *Octopus vulgaris*. *Science*, 256(5056), pp.545-547.

Freitas, T.B., Leite, T.S., de Ramos, B., di Cosmo, A. and Proietti, M.C., 2022. In an octopus's garden in the shade: Underwater image analysis of litter use by benthic octopuses. *Marine Pollution Bulletin*, 175, p.113339.

Fritz, A., Li, L., Storch, I. and Koch, B., 2018. UAV-derived habitat predictors contribute strongly to understanding avian species–habitat relationships on the Eastern Qinghai-Tibetan Plateau. *Remote Sensing in Ecology and Conservation,* 4(1), pp.53-65.

Gallup Jr, G.G., 1968. Mirror-image stimulation. *Psychological Bulletin,* 70(6p1), p.782.

Godfrey-Smith, P., 2013. Cephalopods and the evolution of the mind. *Pacific Conservation Biology,* 19(1), pp.4-9.

Godfrey-Smith, P., 2019. Octopus experience. *Animal Sentience,* 4(26), p.18.

Godfrey-Smith, P., and Lawrence, M., 2012. Long-term high-density occupation of a site by *Octopus tetricus* and possible site modification due to foraging behavior. *Marine and Freshwater Behaviour and Physiology*, pp.1-8.

Gould, A. A., 1852. Mollusca and shells. *In: United States Exploring Expedition during the years 1838, 1839, 1840, 1841, 1842 under the command of Charles Wilkes*. Boston. 12: 1-510; atlas 1856: 1-16., pp. 474.

Grearson, A.G., Dugan, A., Sakmar, T., Dolen, G., Gire, D.H., Sivitilli, D.M., Niell, C., Caldwell, R.L., Wang, Z.Y. and Grasse, B., 2021. The lesser Pacific striped octopus, *Octopus chierchiae*: an emerging laboratory model for the study of octopuses. *BioRxiv*.

Greenwell, C.N., Loneragan, N.R., Tweedley, J.R. and Wall, M., 2019. Diet and trophic role of octopus on an abalone sea ranch. *Fisheries Management and Ecology,* 26(6), pp.638-649.

Hanlon, R.T. and Messenger, J.B., 1996. *Cephalopod Behaviour*, Cambridge (MA): Cambridge University Press.

Hartwell, A.M., Voight, J.R. and Wheat, C.G., 2018. Clusters of deep-sea egg-brooding octopods associated with warm fluid discharge: An ill-fated fragment of a larger, discrete population?. *Deep Sea Research Part I: Oceanographic Research Papers*, 135, pp.1-8.

Hastings, A., Byers, J.E., Crooks, J.A., Cuddington, K., Jones, C.G., Lambrinos, J.G., Talley, T.S. and Wilson, W.G., 2007. Ecosystem engineering in space and time. *Ecology Letters*, 10(2), pp.153-164.

Hebert, P.D., Cywinska, A., Ball, S.L. and DeWaard, J.R., 2003. Biological identifications through DNA barcodes. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 270(1512), pp.313-321.

Hebert, P.D.N., Stoeckle, M.Y., Zemlak, T.S., Francis, C.M. and Godfray, C., 2004. Identification of birds through DNA barcodes. *PLoS Biology*, 2(10), p.e312.

Heine, J.N., 1999. *Scientific Diving Techniques: A Practical Guide for the Research Diver* (p. 225). Flagstaff, Arizona: Best Publishing Company.

Hermosilla, C., Rocha, F. and Valavanis, V.D., 2011. Assessing *Octopus vulgaris* distribution using presence-only model methods. *Hydrobiologia*, 670(1), pp.35-47.

Hinchliffe, G., 2021. *Low-cost Unmanned Aerial Vehicle Full Motion Video for Marine and Ecological Survey*. Manuscript in preparation.

Huffard, C.L. and Godfrey-Smith, P., 2010. Field observations of mating in *Octopus tetricus* Gould, 1852 and Amphioctopus marginatus (Taki, 1964)(Cephalopoda: Octopodidae). *Molluscan Research*, 30(2), p.81.

Husson, E., Hagner, O. and Ecke, F., 2014. Unmanned aircraft systems help to map aquatic vegetation. *Applied Vegetation Science*, 17(3), pp.567-577.

Hutton, F.W., 1880. Manual of the New Zealand mollusca. *Colonial Museum and Geological Survey Departmen*t, Wellington, New Zealand, pp. 224.

Ibáñez, C.M., Fenwick, M., Ritchie, P.A., Carrasco, S.A. and Pardo-Gandarillas, M.C., 2020. Systematics and Phylogenetic Relationships of New Zealand Benthic Octopuses (Cephalopoda: Octopodoidea). *Frontiers in Marine Science*, 7, p.182.

iNaturalist. <https://www.inaturalist.org/ >

iNaturalist. *Observations: Octopoda within New Zealand's Exclusive Economic Zone*. <https://www.inaturalist.org/observations?locale=en-US&place_id=80358&subview=map&taxon_id=47458&view=species>

Joll, L.M., 1976. Mating, egg-laying and hatching of *Octopus tetricus* (Mollusca: Cephalopoda) in the laboratory. *Marine Biology*, 36(4), pp.327-333.w2

Joll, L.M., 1977. Growth and food intake of *Octopus tetricus* (Mollusca: Cephalopoda) in aquaria. *Marine and Freshwater Research*, 28(1), pp.45-56.

Joll, L.M., 1978. Observations on the embryonic development of *Octopus tetricus* (Mollusca: Cephalopoda). *Marine and Freshwater Research*, 29(1), pp.19-30.

Katsanevakis, S. and Verriopoulos, G., 2004. Den ecology of Octopus vulgaris Cuvier, 1797, on soft sediment: availability and types of shelter. *Scientia Marina*, 68(1), pp.147-157.

Kur, J. and Mioduchowska, M., 2018. Scientific diving in natural sciences. *Polish Hyperbaric Research*, 65(4).

Mather, J., 1980. Social organization and use of space by *Octopus joubini* in a semi-natural situation. *Bulletin of Marine Science*, 30(4), pp.848-857.

Mather, J.A., 1982. Factors affecting the spatial distribution of natural populations of *Octopus joubini* Robson. *Animal Behaviour*, 30(4), pp.1166-1170.

Mather, J.A., 1985. Behavioural interactions and activity of captive *Eledone moschata*: laboratory investigations of a 'social'octopus. *Animal Behaviour*, 33(4), pp.1138-1144.

Mather, J.A., 1991. Foraging, feeding and prey remains in middens of juvenile *Octopus vulgaris* (Mollusca: Cephalopoda). *Journal of Zoology*, 224(1), pp.27-39.

Mather, J.A., 2004. Cephalopod skin displays: from concealment to communication. *Evolution of Communication Systems*, pp.193-214.

Mather, J.A. and Alupay, J.S., 2016. An ethogram for Benthic Octopods (Cephalopoda: Octopodidae). *Journal of Comparative Psychology*, 130(2), p.109.

Mather, J.A. and O'Dor, R.K., 1991. Foraging strategies and predation risk shape the natural history of juvenile *Octopus vulgaris*. *Bulletin of Marine Science,* 49(1-2), pp.256-269.

McNaught, A.D., 1997. *Compendium of Chemical Terminology* (Vol. 1669). Oxford: Blackwell Science.

Mendo, T., Lyle, J.M., Moltschaniwskyj, N.A., Tracey, S.R. and Semmens, J.M., 2014. Habitat characteristics predicting distribution and abundance patterns of scallops in D'Entrecasteaux Channel, Tasmania. *PLoS One*, 9(1), p.e85895.

MolluscaBase eds., 2022. *Robsonella huttoni Benham, 1943*. MolluscaBase. Accessed through: World Register of Marine Species. 17/03/21. <https://www.marinespecies.org/aphia.php?p=taxdetails&id=342385>

Moore, W.S., 1995. Inferring phylogenies from mtDNA variation: mitochondrial-gene trees versus nuclear-gene trees. *Evolution*, 49(4), pp.718-726.

*Motion Imagery Standards Board.* 2014. <https://gwg.nga.mil/misb/faq.html. 8/9/2021>

*My Octopus Teacher* 2020, motion picture, Netflix, South Africa.

Neat, F.C., 2001. Male parasitic spawning in two species of triplefin blenny *(Tripterigiidae)*: contrasts in demography, behaviour and gonadal characteristics. *Environmental Biology of Fishes*, 61(1), pp.57-64.

New Zealand Department of Conservation. *Flying drones near birds*. New Zealand Government. 14/12/2021 <https://www.doc.govt.nz/get-involved/apply-for-permits/drone-use-on-conservation-land/flying-drones-near-birds/>

New Zealand Department of Conservation. *History of Kawau Island.* New Zealand Government. 17/4/21. https://www.doc.govt.nz/parks-and-recreation/places-to-go/auckland/places/kawau-island-historic-reserve/historic-kawau-island/

New Zealand Department of Conservation. *Interacting with marine mammals*. New Zealand Government. 14/12/2021 https://www.doc.govt.nz/get-involved/apply-for-permits/interacting-with-marine-mammals/

New Zealand Department of Conservation. *Iwi/hapū/whānau consultation.* New Zealand Government. 14/12/2021 https://www.doc.govt.nz/get-involved/apply-for-permits/iwi-consultation/

Norman, M.D. and Hochberg, F.G., 2005. The current state of octopus taxonomy. *Phuket Marine Biological Center Research Bulletin*, 66, pp.127-154.

O'Shea, S., 1999. The marine fauna of New Zealand: Octopoda (Mollusca: Cephalopoda). *NIWA Biodiversity Memoir.* 112 : 1-280. pp. 120

*Paris Convention of 1919 (Convention for the Regulation of Aerial Navigation, Oct. 13, 1919, 11 L.N.T.S. 173) and the Pan American Convention on Commercial Aviation*, U.S.-Cuba, Feb. 20, 1928, see 47 Stat. 1901)

Phillips, S.J., 2005. A brief tutorial on Maxent. *AT&T Research*, 190(4), pp.231-259.

Phillips, S.J., Anderson, R.P. and Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190(3-4), pp.231-259.

Ramos, J.E., 2015. Life-history and population dynamics of the range extending *Octopus tetricus* (Gould, 1852) in South-Eastern Australia (*Doctoral dissertation, University of Tasmania)*.

Ramos, J.E., Pecl, G.T., Moltschaniwskyj, N.A., Strugnell, J.M., León, R.I. and Semmens, J.M., 2014. Body size, growth and life span: implications for the polewards range shift of *Octopus tetricus* in south-eastern Australia. *PLoS On*e, 9(8).

Robinson, L.M., Gledhill, D.C., Moltschaniwskyj, N.A., Hobday, A.J., Frusher, S., Barrett, N., Stuart-Smith, J. and Pecl, G.T., 2015. Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions. *Global Environmental Change*, 31, pp.28-37.

Robison, B., Seibel, B. and Drazen, J., 2014. Deep-sea octopus (G*raneledone boreopacifica*) conducts the longest-known egg-brooding period of any animal. *PLoS One*, 9(7), p.e103437.

Rogers, A.D., Tyler, P.A., Connelly, D.P., Copley, J.T., James, R., Larter, R.D., Linse, K., Mills, R.A., Garabato, A.N., Pancost, R.D. and Pearce, D.A., 2012. The discovery of new deep-sea hydrothermal vent communities in the Southern Ocean and implications for biogeography. *PLoS Biology*, 10(1), p.e1001234.

Sankey, T.T., McVay, J., Swetnam, T.L., McClaran, M.P., Heilman, P. and Nichols, M., 2018. UAV hyperspectral and lidar data and their fusion for arid and semi-arid land vegetation monitoring. *Remote Sensing in Ecology and Conservation*, 4(1), pp.20-33.

Sauer, W.H., Gleadall, I.G., Downey-Breedt, N., Doubleday, Z., Gillespie, G., Haimovici, M., Ibanez, C.M., Katugin, O.N., Leporati, S., Lipinski, M.R., and Markaida, U., 2021. World octopus fisheries. *Reviews in Fisheries Science & Aquaculture*, 29(3), pp.279-429.

Sayer, M.D.J., 2007. Scientific diving: a bibliographic analysis of underwater research supported by SCUBA diving, 1995-2006. *Underwater Technology*, 27(3), pp.75-94.

Scheel, D., Chancellor, S., Hing, M., Lawrence, M., Linquist, S. and Godfrey-Smith, P., 2017. A second site occupied by *Octopus tetricus* at high densities, with notes on their ecology and behavior. *Marine and Freshwater Behaviour and Physiology*, 50(4), pp.285-291.

Scheel, D., Godfrey-Smith, P. and Lawrence, M., 2014. *Octopus tetricus* (Mollusca: Cephalopoda) as an ecosystem engineer. *Scientia Marina*, 78(4), pp.521-528.

Scheel, D., Godfrey-Smith, P., Linquist, S., Chancellor, S., Hing, M. and Lawrence, M., 2018. Octopus engineering, intentional and inadvertent. *Communicative & Integrative Biology*, 11(1), p.e1395994.

Shannon, C.E. and Weaver, W., 1949. The mathematical theory of information. *Urbana: University of Illinois Press*, 97.

Smith, M.W. and Vericat, D., 2015. From experimental plots to experimental landscapes: topography, erosion and deposition in sub-humid badlands from structure-from-motion photogrammetry. *Earth Surface Processes and Landforms*, 40(12), pp.1656-1671.

Stark, D.J., Vaughan, I.P., Evans, L.J., Kler, H. and Goossens, B., 2018. Combining drones and satellite tracking as an effective tool for informing policy change in riparian habitats: a proboscis monkey case study. *Remote Sensing in Ecology and Conservation,* 4(1), pp.44-52.

Tang, S.S., Lin, C.C., and Chang, G.G., 1996. Metal-catalyzed oxidation and cleavage of octopus glutathione transferase by the Cu (II)-ascorbate system. *Free Radical Biology and Medicine*, 21(7), pp.955-964.

Thrower, N.J., 2008. Maps and civilization: cartography in culture and society. *University of Chicago Press.*

Toyoshima, J. and Nadaoka, K., 2015. Importance of environmental briefing and buoyancy control on reducing negative impacts of SCUBA diving on coral reefs. *Ocean & Coastal Management*, 116, pp.20-26.

Vas, E., Lescroël, A., Duriez, O., Boguszewski, G. and Grémillet, D., Approaching birds with drones: first experiments and ethical guidelines. *Biology Letters.* 2015 Feb 28;11(2):20140754.

Veneris, Y., 1990. Modelling the transition from the industrial to the informational revolution. *Environment and Planning.* A, 22(3), pp.399-416.

Wassilieff, M. and O'Shea, S., 12 Jun 2006. *Octopus and Squid - Octopus in New Zealand.* Te Ara - the Encyclopedia of New Zealand. 1/9/21. <http://www.TeAra.govt.nz/en/octopus-and-squid/page-4>

Wei, J. and Lee, Z., 2013. Model of the attenuation coefficient of daily photosynthetically available radiation in the upper ocean. *Methods in Oceanography*, 8, pp.56-74.

Weston, M.A., O'Brien, C., Kostoglou, K.N. and Symonds, M.R., 2020. Escape responses of terrestrial and aquatic birds to drones: Towards a code of practice to minimize disturbance. *Journal of Applied Ecology*. 57(4), pp.777-785.

Wilson, B. and Pyatt, F.B., 2007. Heavy metal dispersion, persistance, and bioccumulation around an ancient copper mine situated in Anglesey, UK. *Ecotoxicology and Environmental Safety*. 66(2), pp.224-231.

# Appendix

## Diving Methods

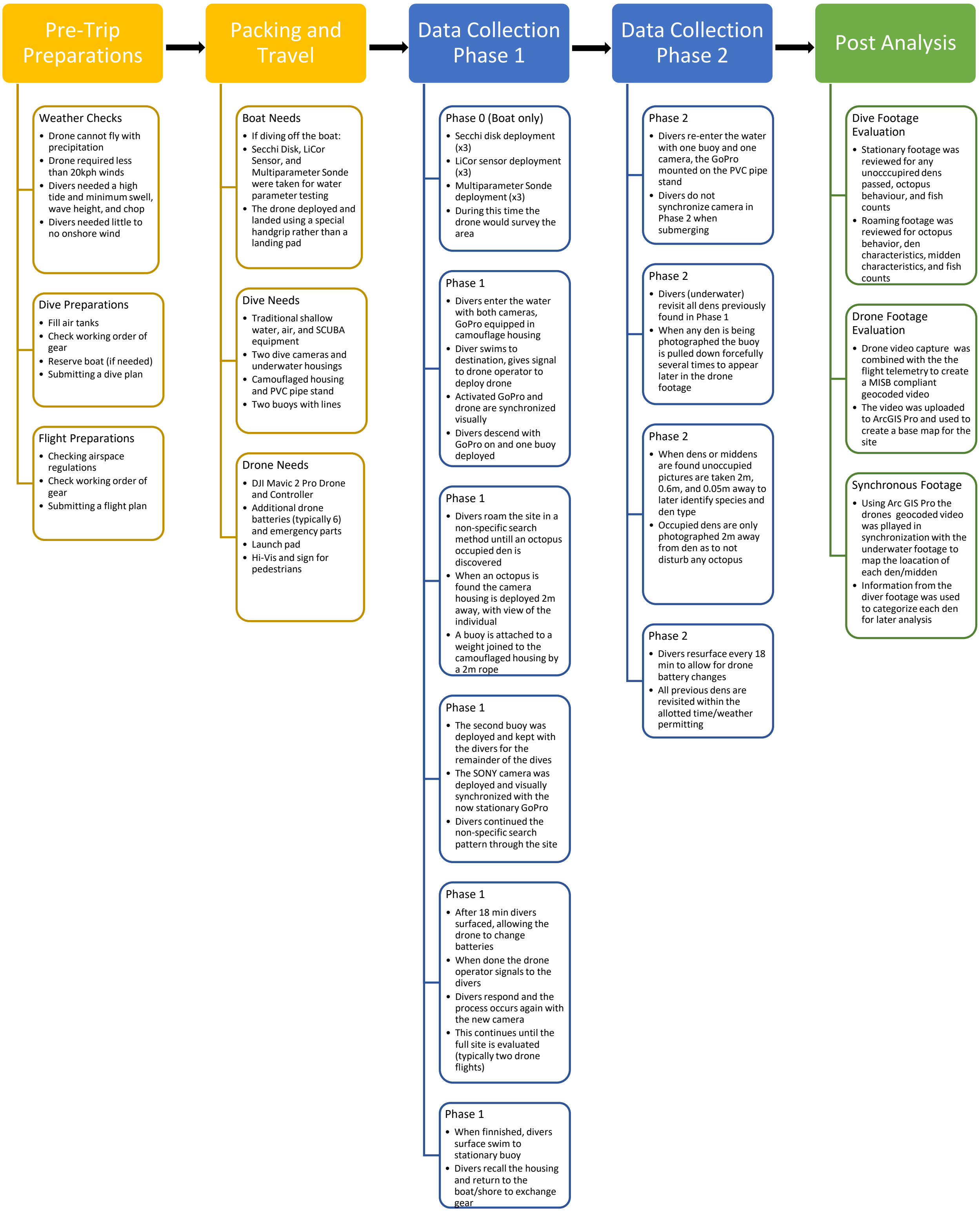

Figure 22: Description of general methods for data collection. Preparation steps (yellow) included Pre-trip Preparation and Packing and Travel for both divers and drone pilot, data collection (blue) occurred in two phases, and data analysis (green) for both diving and drone imagery.


Figure 23: Methods for observational Phases (0-2). Phase 0 consisted of water parameter sampling, which only occurred during boat trips. Phase 1 was broken into two parts and consisted of the initial observation of the site while accompanied by drone surveillance. Phase 2 consisted of revisiting the dens and middens observed in Phase 1 for more detailed photography.

## Water Parameters

The multiparameter YSI Sonde was fitted with two light sensors PAR1 and PAR2. The other sensors that were fitted to the typical Sonde attachments collected a variety of parameters. The Sonde was programmed the day before to continuously measure data across the day of sampling.

The Sonde data were collected by slowly lowering (1m per 10 seconds) down the Sonde on a rope to the sea floor or to 6m, whichever came first. The Sonde was then quickly pulled up and lowered again for three separate profiles to average later. The data were later downloaded from the sonde to a computer using the program EcoWatch Lite. The data were received in a .TXT file and transferred to an excel file for further analysis.

The LI-193 Spherical Quantum Sensor was used to measure radiation in PAR, it measures from all directions (360°) both in air and underwater. The measurement is referred to as Photosynthetic Photon Flux Fluence Rate (PPFFR) or Quantum Scalar Irradiance. These measurements can be used to measure photosynthesis or another side the clarity of the water column.

Radiometry is the measurement of radiant energy properties, specifically joules (J). Photometry refers to the measurement of visible radiation (light) with a sensor having a spectral responsivity curve equal to the average human eye. Photosynthetically Active Radiation (PAR) is defined as radiation in the 400 to 700 nm waveband. PAR is the general radiation term that covers both photon terms and energy terms. The attenuation coefficient, or linear attenuation coefficient, characterises how easily a volume of material can be penetrated by a beam of light, sound, particles, or other energy or matter (Carruthers et al. 2001). The larger the attenuation coefficient, the quicker a beam is "attenuated" (or weakened) as it passes through the medium, and the smaller the attenuation coefficient the more transparent the medium is, relative to the beam.

The combination of light absorption and scattering by water and its contents results in the reduction of light with depth. The reduction of attenuation of light with depth is defined by the Beer-Lambert exponential decay function:

Equation 1: Beer-Lambert exponential decay function

$$I_z = I_0 e^{-Kd\, z}$$

Where light $I_z$ is light measured at depth *z*, $I_0$ is light measured just under the surface, and $K_d$ is the light attenuation coefficient, with units $m^{-1}$. (Carruthers et al. 2001)

PAR (represented here by downwelling plane irradiance, $E_d$, in energy units of W $m^{-2}$) at depth z can be expressed as

Equation 2: PAR of a depth using downwelling plane irradiance

$$PAR_z = \int_{400}^{700} E_d(z, \lambda)\, \mathrm{d}\lambda$$

and the vertical propagation of $E_d$ is

Equation 3: Vertical propagation of downwelling plane irradiance

$$E_d(z, \lambda) = E_d(0\text{-}, \lambda) e^{-K_d(\lambda) z}$$

with $K_d(\lambda)$ the diffuse attenuation coefficient of Ed at wavelength λ. Based on the radiative transfer theory, it has been found that $K_d$ is a function of water's inherent optical properties (IOPs) and the solar zenith angle. For vertically homogeneous waters, $K_d$ varies with depth but is generally within 10% for low solar zenith angle and low scattering waters. The vertical propagation of PAR is commonly expressed as:

Equation 4: Vertical propagation of PAR

$$PAR_z = PAR_{0^-} e^{-K_{PAR} z}$$

With $K_{PAR}$ representing the vertical attenuation coefficient for PAR, it is technically the diffuse attenuation coefficient of instantaneous PAR. Due to the strong selective absorption by water constituents, $K_{PAR}$ varies strongly with depth and can change by a factor of 3–4 between the surface and deeper depths (McNaught 1997). This equation (Equation 4) was used to convert the PAR data collected by the LI-COR into a light attenuation profile for each site.

The air (control) light measurements were taken before the LI-COR was submerged. Measurements were taken every half meter starting just below the surface to 6m. To ensure vertical sinking, a lead weight was zip-tied to the tether directly above the sensor, just far enough away to where the weight didn't touch the sensor. The profile was measured three times for a more accurate average of all three. Light conditions needed to be constant across the sampling occurrence (e.g., all cloud-covered or all full sunlight), so if light conditions changed after sampling had begun, the sampling was paused or restarted. The measurements were read from a display connected by a tether connecting it to the sensor. The data were recorded manually by an observer, no digital recording was done within the LI-COR

The Secchi disk was lowered three times to assess water clarity. Typically, the Secchi disk was visible at the sea floor, so the visibility was recorded as the site's depth but was likely greater. A lead weight was connected to the bottom of the Secchi to make sure there was no horizontal movement due to current, which could skew the reading.

## Fish Counts

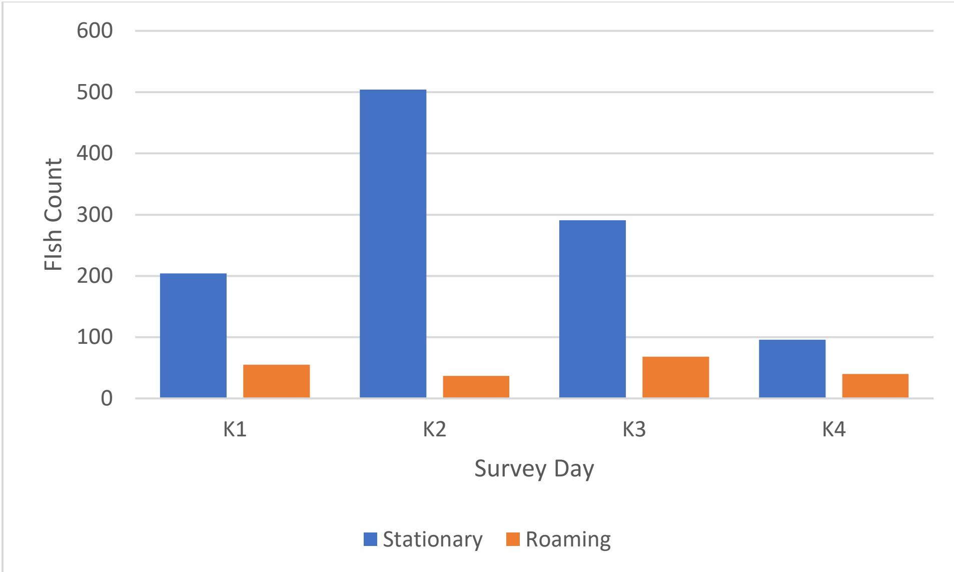


Figure 24: Number of fish individuals sighted at Kawau Island site using stationary (blue) vs roaming (orange) cameras. Stationary fish counts were always higher than roaming fish counts.

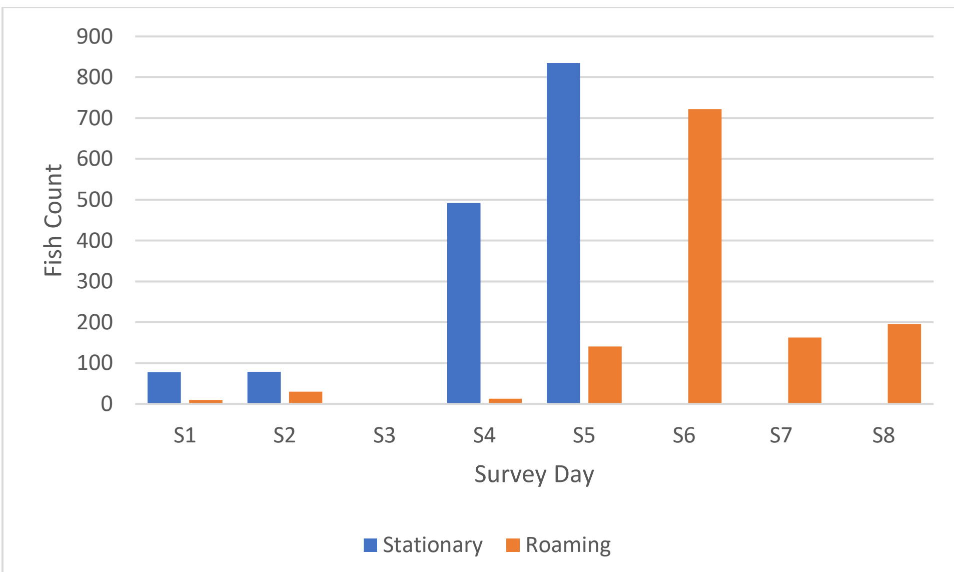


Figure 25: Number of fish individuals sighted at Stanmore Bay site using stationary (blue) vs roaming (orange) cameras. When the stationary was placed (S1, S2, S4, and S5) the stationary fish count was always higher than the roaming fish count.

Kawau Island's fish counts (Figure 24) show far more fish being seen by the camouflaged stationary camera as opposed to the diver's handheld camera. Stanmore Bay fish counts (Figure 25) were confounded on several occasions (see 'Weather and Water Parameters'). As a result, only the S1, S2, S4, and S5 surveys produced data that can be reliably compared with Kawau observations, within these surveys the camouflaged stationary camera observed equal or greater fish than the roaming camera.

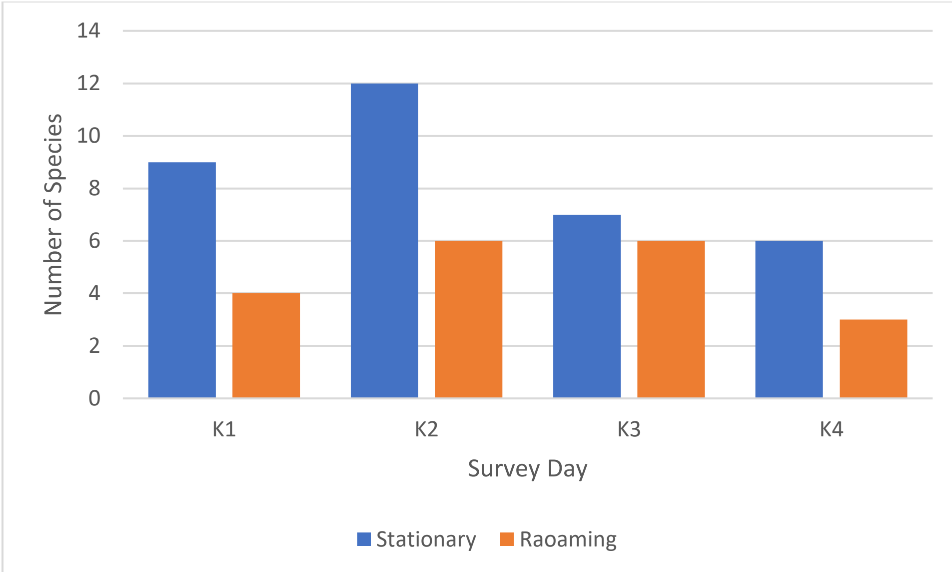


Figure 26: Kawau Island fish species count comparing stationary and roaming numbers. Stationary footage consistently recorded a greater number of fish species than the roaming footage.

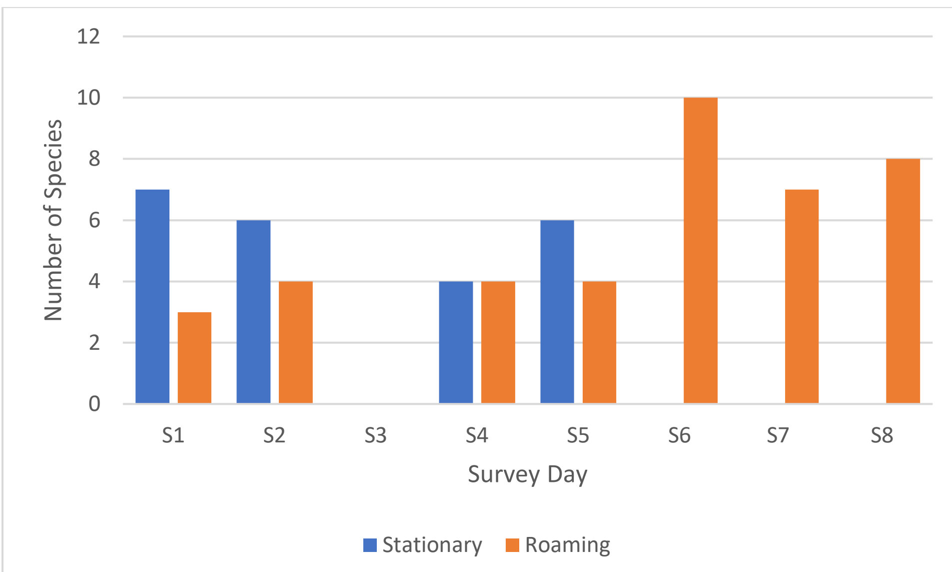


Figure 27: Stanmore Bay fish species count comparing stationary and roaming numbers. When placed (S1, S2, S4, and S5) the stationary footage recorded an equal or greater number of fish species than that of roaming.

The number of species seen on each type of footage, the stationary camera and the roaming camera (during Phase 1) was also evaluated. Kawau Island's fish species counts (Figure 26) show consistently more species being seen by the camouflaged stationary camera as opposed to the diver's handheld camera. Stanmore Bay fish species counts (Figure 27) were confounded on several occasions (see Chapter 2 'Weather and Water Parameters'). As a result, only the S1, S2, S4, and S5 surveys produced data that can be reliably compared with Kawau observations, within these surveys the camouflaged stationary camera observed equal or greater fish species than the roaming camera.

## ArcGIS Pro

The processes was completed within ArcGIS Pro (using versions 2.7 and 2.8). Once the drone Full Motion Video (FMV) is geocoded it can be visualised and processed within a GIS file. To prepare the map for the FMV a base elevation was added first for the drone's field of view, the elevation was established by first creating a new constant raster over all possible drone view area and set the elevation to "0". The same coordinate system is used throughout the project, the Geographic Coordinate System NZGD2000 was a predownloaded coordinate system and was used for all maps. The elevation raster should be saved within a Geodatabase, along with any other geocoded data. After the raster is created, the drone FMV was added.

To create a more detailed map of the study site a short overview flight of each site was conducted and incorporated into the respective GIS Projects. Geocoded screenshots were taken within the program's FMV view window, using the export frame button on the FMV plane banner (Figure 28). The individual images were then combined into a single image using the Mosaic functionality (Figure 31). Due to the image overlap, the file processing order was specified to prioritize the glint-free southern portion of each frame (Figure 29, Figure 30) Using consistent geocoded images derived from the same device use to collect the other FMV allows for higher accuracy when pinpointing subtidal locations later.

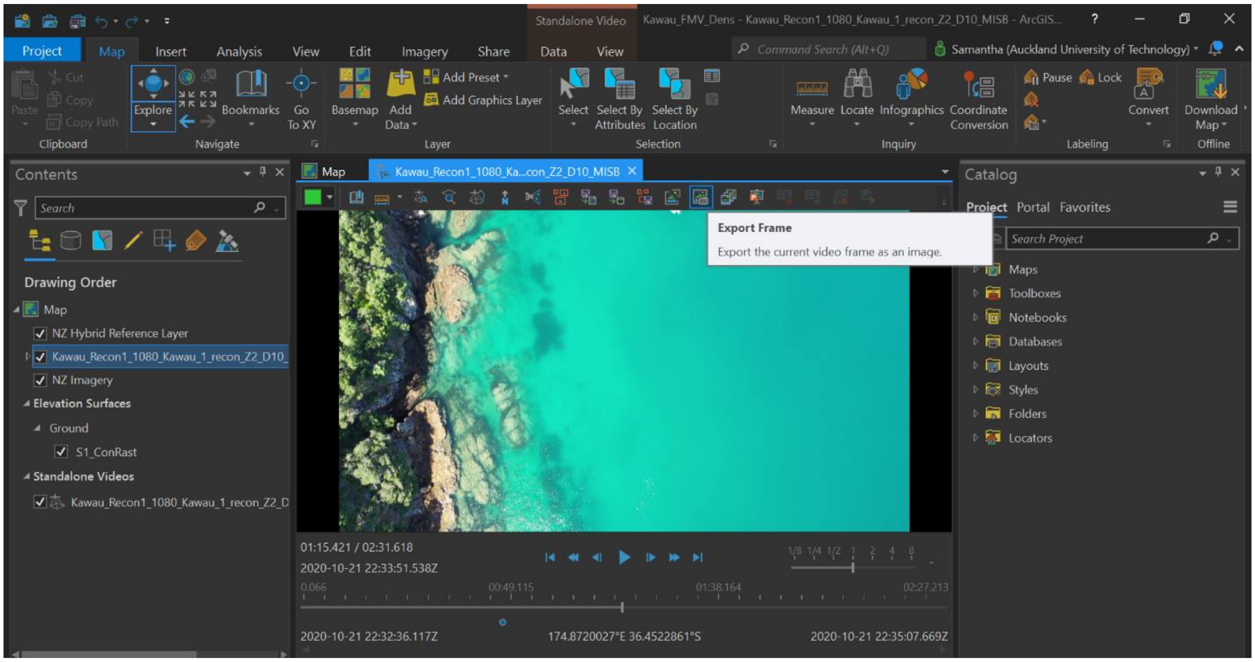


Figure 28: ArcGIS Pro with a FMV tab open using the export frames feature to take geocoded images of the Kawau Island site. These images were taken from a site overview flight of the Kawau Island site taken on K1.

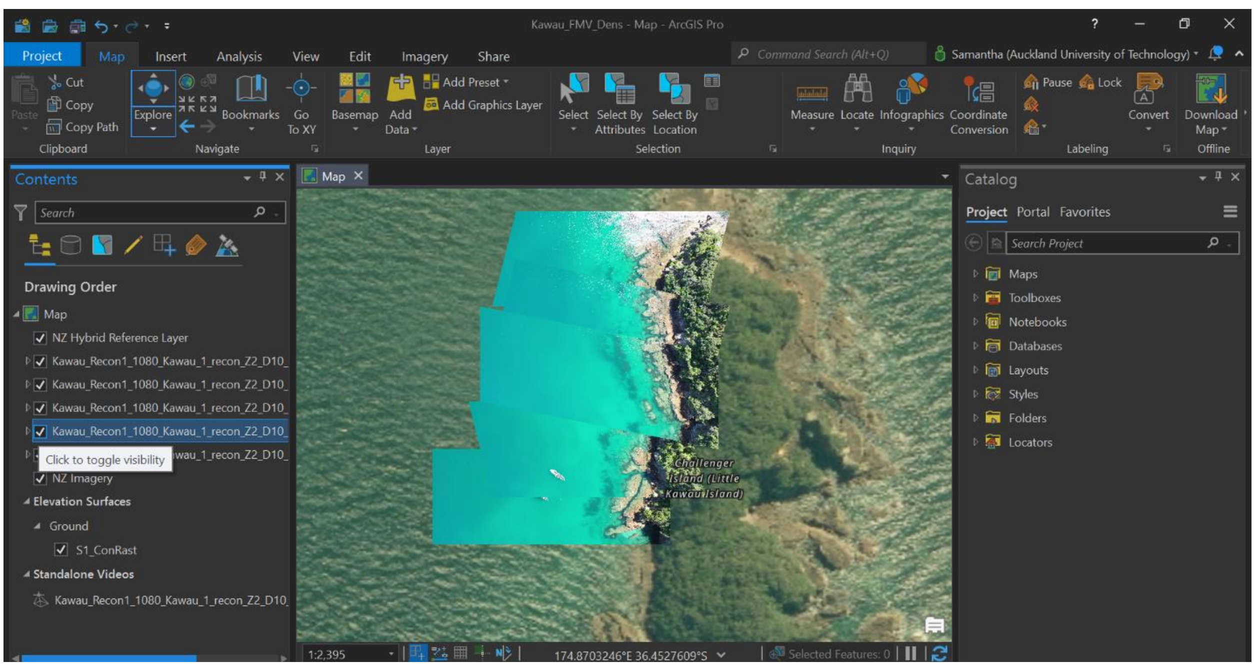


Figure 29: ArcGIS Pro with contents panel (left) displaying layers of previously captured images. Images layers were arranged and eliminated to present the most cohesive view of the site and better display its subtidal features.

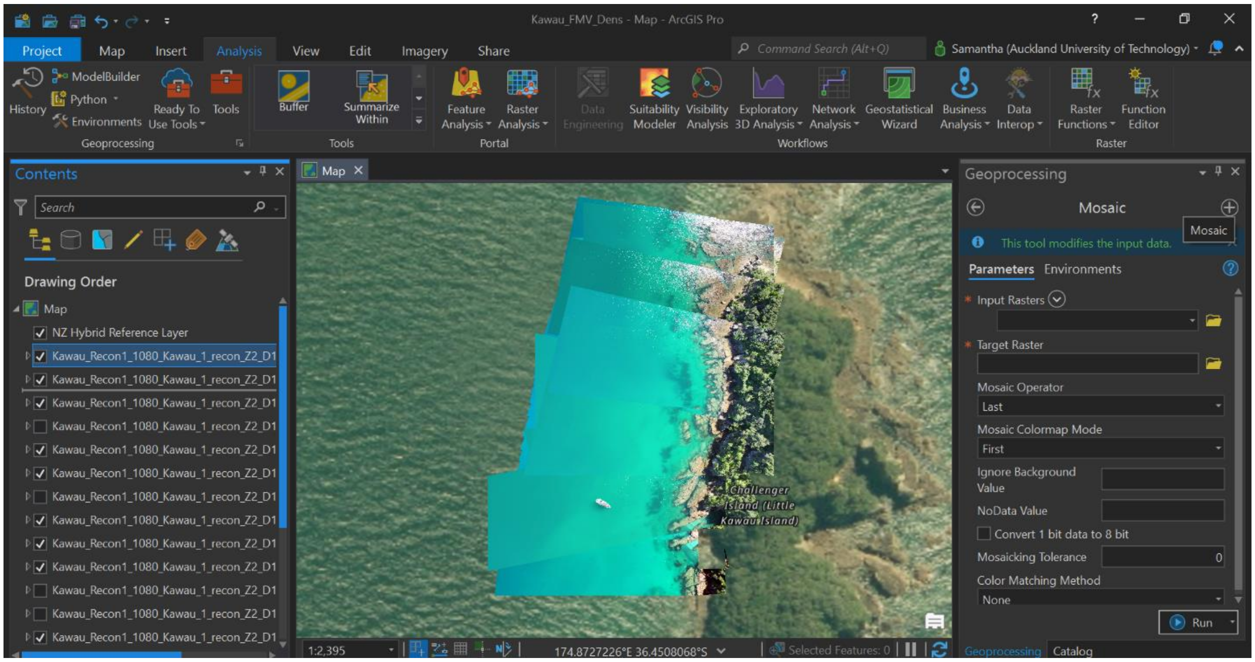


Figure 30: ArcGIS Pro image mosaic creation of Kawau Island site base map. Using the geoprocessing tool Mosaic the images chosen previously (Figure 29) are used as input rasters to create a single .tif file.

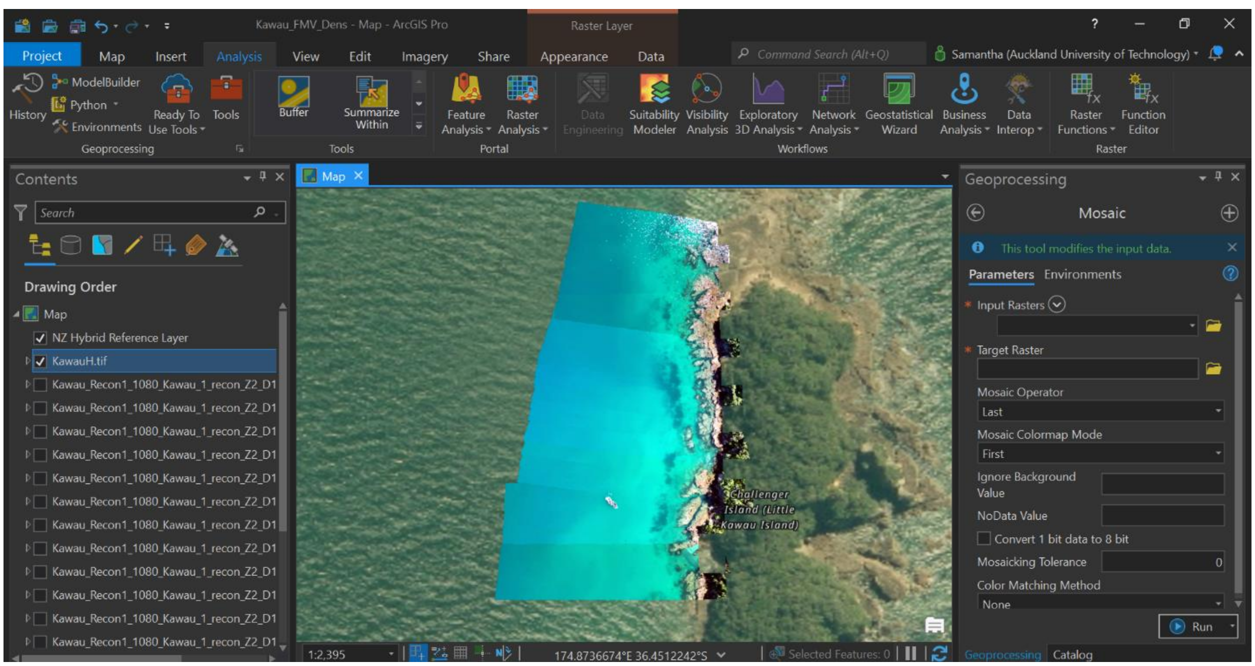


Figure 31: ArcGIS Pro site mosaic base map. The result of the mosaic of FMV exported images used to create a .tif file. This is the image that will be used as base map, as it is more detailed than that provided by Esri's general New Zealand Imagery.

Once the FMV files are prepared and the map has an appropriate background the diver paths and den locations can be plotted. This is done by running the intended FMV video within ArcGIS Pro, preferably on separate screens, or at least where both panes can be visible. When viewing first, the divers' path was plotted out, with numerous points focused on the diver with the cameras. The point annotation tool was used to point out the location of the divers on the FMV plane (Figure 32), which would then appear on the main map in the correct location (Figure 33). This tool can be found under the standalone video tab View, the annotations can be done in several ways, for this experiment the only annotations taken were points. Then a track was created by converting the point annotations representing the diver into a new line feature class (using the create feature class tool).

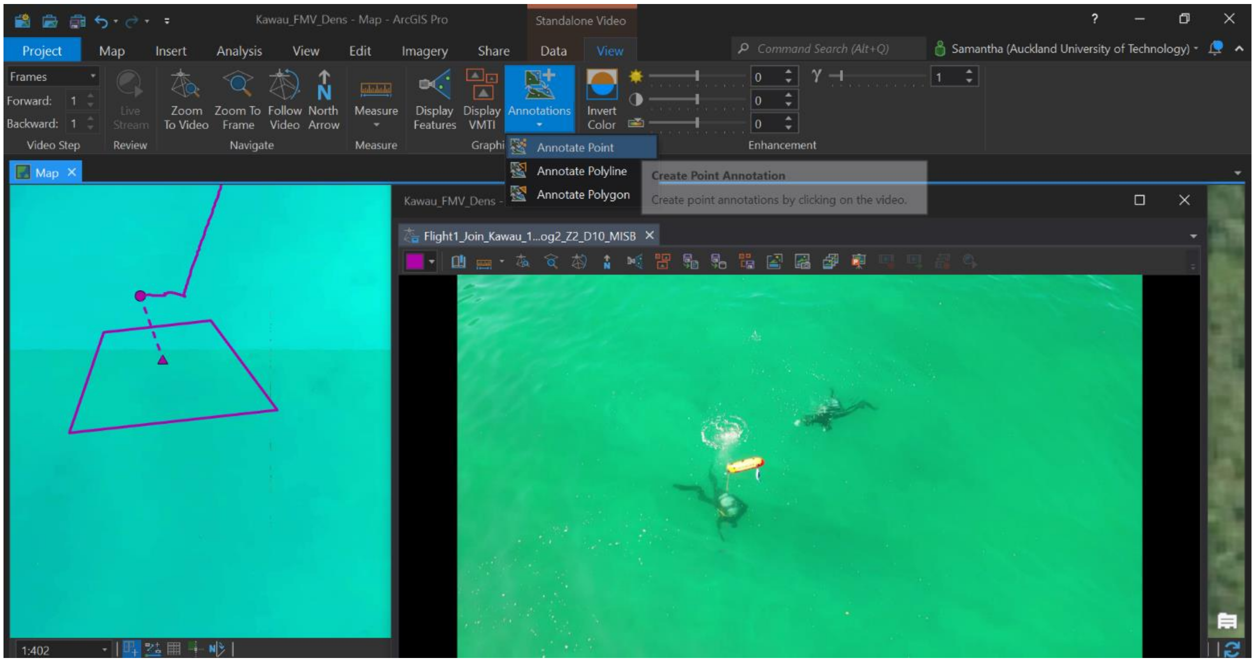


Figure 32: ArcGIS Pro map (left) with drone FMV (right) opened, ready to create point annotations. Esri's FMV package is used within ArcGIS Pro to run the drone FMV. Point annotations can be selected, once FMV is open, on the View banner, under the annotations button. This figure is a screen capture of a single screen during the mapping of K3.

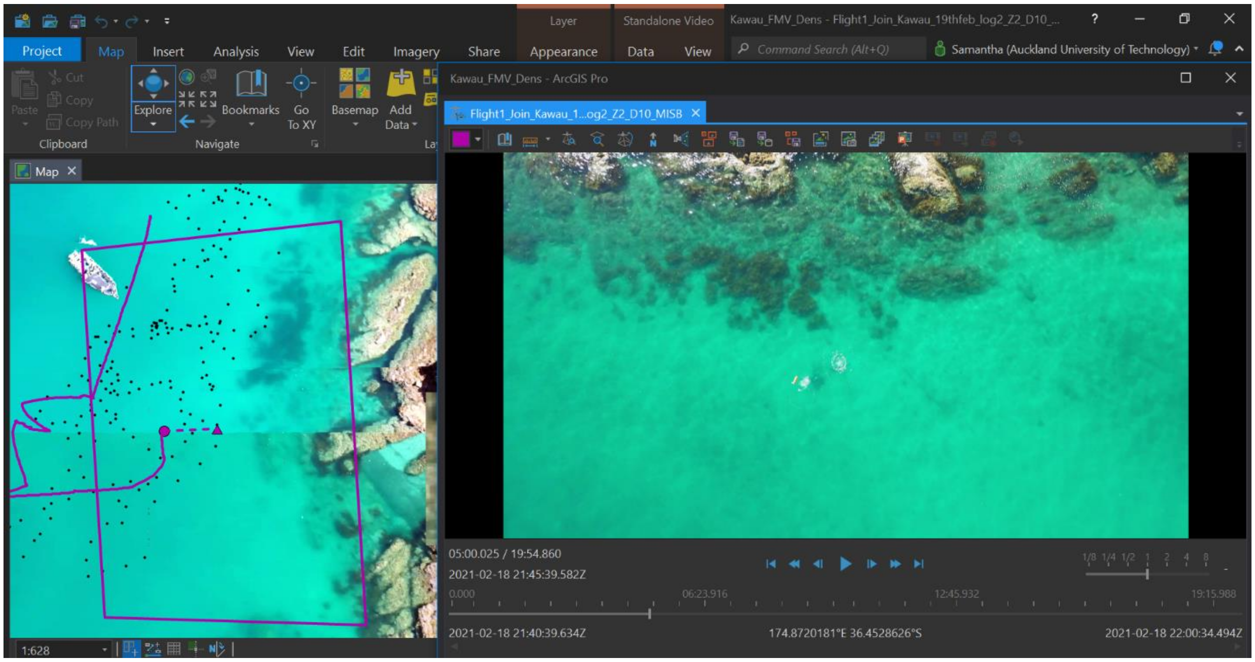


Figure 33: ArcGIS Pro map (left) using point annotations with the drone FMV (right) to map the diver's path during survey K3. Esri's FMV package is used within ArcGIS Pro to run the drone FMV, when points are made on the footage those points are displayed on the Map tab (left). This figure is a screen capture of a single screen during the mapping of K3.

To plot dens, the diver path methods are repeated, while adding the separate underwater footage. The diver video and drone video must then be played in synchronisation, this was determined by the initial drone and camera synchronisation at the start of each dive (Figure 34). When the diver approaches a den both their orientation on the underwater video and the drone FMV can be used to pinpoint the location of the den while plotting (Figure 35). Once all dens were identified they were added to their own feature class, similar to the diver path, except as a point feature class.

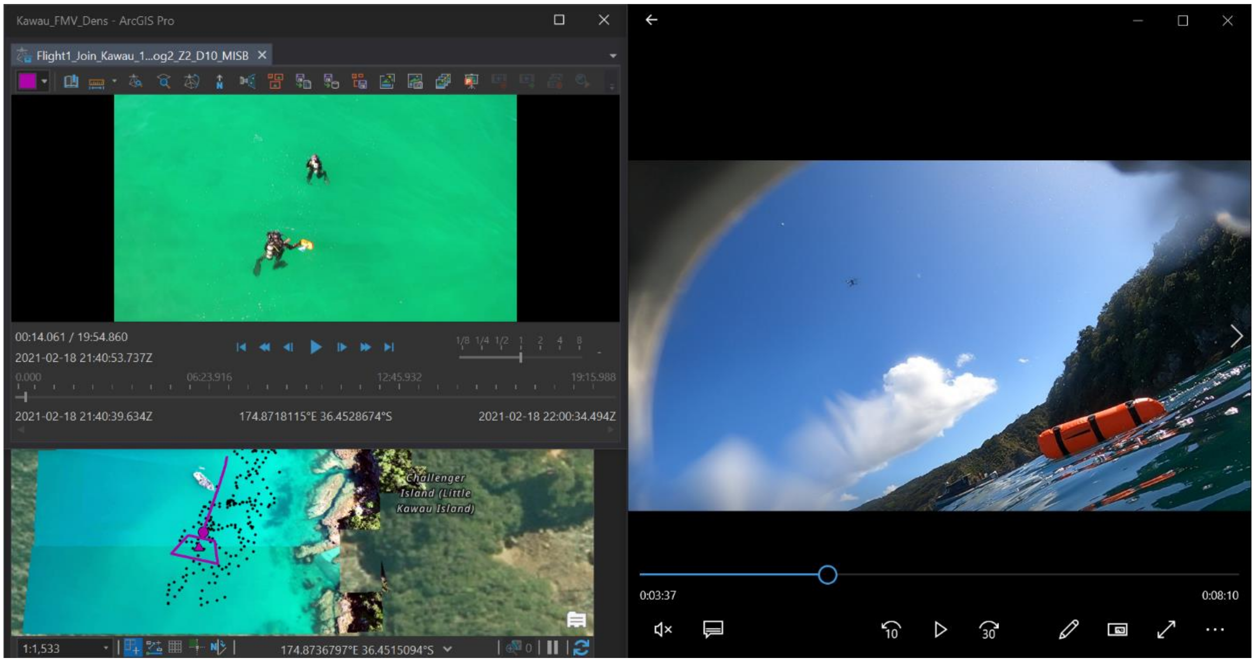


Figure 34: ArcGIS Pro (bottom left) during the synchronisation of drone FMV (upper left) with dive footage (right). These applications are used simultaneously for the process of mapping dens, before mapping the sites the FMV and diver footage must be synchronised to get the correct den locations. This figure is a screen capture of a single screen during the synchronisation of K3.

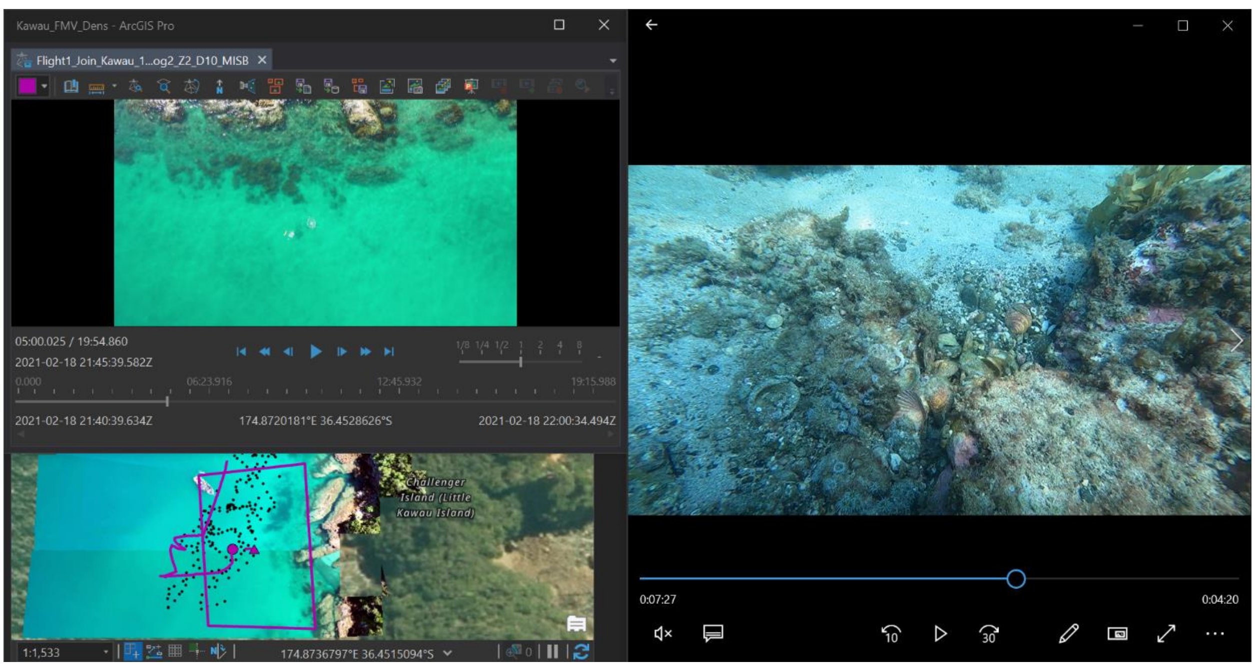


Figure 35: ArcGIS Pro (bottom left) with drone FMV (upper left) running next to dive footage (right). These applications are used simultaneously for the process of mapping dens using synchronous dive footage. This figure is a screen capture of a single screen during the mapping of K3.