

Assessing the use of remote underwater video (RUV) to identify fish and their feeding behaviour in New Zealand's Greenshell™ mussel (*Perna canaliculus*) farms

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ABSTRACT

Fish predation poses a significant and escalating challenge for the global mussel aquaculture industry. In New Zealand, Greenshell™ mussel farms experience crop losses of up to 100 % that are anecdotally attributed to fish predation, although the fish species responsible have not been confirmed. In this study, remote underwater video (RUV) was used to observe fish activity within four mussel farms at different stages of production in the Firth of Thames, New Zealand. The RUV enabled the identification of the fish species inhabiting mussel farms, including those responsible for predating cultured mussels. Four fish species were identified as frequent inhabitants of the mussel farms, with Australasian snapper (*Chrysophrys auratus*) and parore (*Girella tricuspidata*) the most abundant at three out of four mussel farm sites. Australasian snapper was the most common predator, taking as many as 2880 bites of the dropper lines holding mussels in a single 11 min 47 s video recording. Snapper formed feeding aggregations around dropper lines holding juvenile mussels (> 20 mm SL), indicating their potential to remove mussels from nursery farms in a short amount of time. Observations of the feeding behaviour of parore indicated their potential to contribute to the losses of mussels on recently seeded spat farms with these fish recorded tearing apart seeded lines, possibly targeting the macroalgae that is seeded out with the mussel spat. Besides confirming the identity and the predatory behaviour of fish species that are contributing to crop losses from mussel farms in New Zealand, this study also confirms the effectiveness of RUV methods for this purpose. This knowledge can be used to begin to develop mitigation strategies aimed at reducing crop losses in mussel aquaculture.

1. Introduction

Fish predation affects shellfish aquaculture in many parts of the world, often resulting in considerable (i.e., up to 100 %) crop losses (Hayden, 1995; Peteiro et al., 2010; Richard et al., 2020; Saito et al., 2008; Šegvić-Bubić et al., 2011; Strand, 2004). However, although the impacts of fish predation are widely identified as a problem, the stages of production most vulnerable to fish predation, and the species responsible, remain poorly understood (Anderson and Connell, 1999; Hayden, 1995; Peteiro et al., 2010; Richard et al., 2020; Šegvić-Bubić et al., 2011; Strand, 2004). Identifying the fish species responsible for crop losses on mussel farms is an important initial step toward developing targeted interventions. However, the fish species responsible for the predation are likely to vary both spatially and temporally, implying that

interventions will need to be location and species-specific.

Among the major groups of shellfish in aquaculture production globally, mussels appear to be the most widely affected by fish predation (Brehmer et al., 2003; Hayden, 1995; Peteiro et al., 2010; Richard et al., 2020; Šegvić-Bubić et al., 2011). The vertical extent in the water column of the infrastructure commonly used in mussel aquaculture, such as suspended and bouchot aquaculture systems, provides three-dimensional habitat for fish by offering both shelter and potential food sources in the form of cultured shellfish and associated biofouling (Costa-Pierce and Bridger, 2002; McKindsey et al., 2011; Morrisey et al., 2006). Many fish species are highly mobile and are capable of relocating among different habitats, often in response to differences in habitat quality (Rilov and Schiel, 2006b; Rilov and Schiel, 2006a; Robles and Robb, 1993) with wild fish species often attracted to the habitat offered

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by aquaculture operations (Barrett et al., 2019; Callier et al., 2018; Theuerkauf et al., 2021). Most studies on fish predation of cultured mussels have been undertaken in areas of Europe with extensive mussel aquaculture. For example, in Ría de Ares-Betanzos (Galicia, Spain) the predation of spat of the Mediterranean mussel (*Mytilus galloprovincialis*) by black seabream (*Spondyliosoma cantharus*) can cause losses of up to 60 % of mussels from coastal farms during early spring (Peteiro et al., 2010). Similarly, in the Adriatic Sea (Croatia) and the French Mediterranean, gilthead seabream (*Sparus aurata*) has been reported to cause losses of up to 54 % and 90 % of cultured Mediterranean mussels, respectively (Richard et al., 2020; Šegvić-Bubić et al., 2011). An increased abundance of gilthead seabream, a well-known shellfish predator, has also been implicated in a decline in aquaculture production of mussels and oysters along the Adriatic Coast (Croatia, Bosnia, Herzegovina and, Montenegro; Glamuzina et al., 2014). In some areas of the Mediterranean Sea, the predation on cultured mussels by these seabream has been so severe it has forced the closure of some farms (Avdelas et al., 2021).

In New Zealand, the cultivation of green-lipped mussels (*Perna canaliculus*), trademarked as Greenshell™, represents a significant component of the national aquaculture production, dominating the total export revenue from aquaculture and generating more than NZ\$400 million per annum (Ministry for Primary Industries, 2022). However, production from the Greenshell™ industry is currently constrained by the inefficiency of converting spat into market-ready adults, providing a significant opportunity for finding ways to improve production (Skelton et al., 2022). It has been estimated that, across the Greenshell™ industry, less than 1 % of the mussels that are first seeded out survive through to final harvest (Skelton et al., 2022). These losses of mussels occur at different stages of the Greenshell™ mussel production but are typically very high early in the production cycle, especially within six months of seeding coastal farms with spat (South et al., 2022).

Fish predation is believed to be a substantial contributing factor to crop losses on Greenshell™ farms during production (Skelton et al., 2021). However, the magnitude and timing of the losses from fish predation are yet to be quantified, and the fish species responsible are unknown. Mussel farmers in New Zealand's Firth of Thames region, which produces around one third of country's total annual mussel production, report that fish predation at times causes losses of up to 100 % of cultured mussels (M. Moy, North Island Mussels Ltd., pers. comm.). This aligns with findings from a study in the Marlborough Sounds mussel aquaculture region, where losses of mussels attributed to fish predation reached 100 % only 14 days after seeding out (Hayden, 1995). However, the fish species responsible for these losses were not confirmed. Anecdotal reports of fish predation on cultured mussels frequently rely on inferences drawn from field observations provided by mussel farmers of the presence of fish within farms and do not necessarily include confirmed observations of the predation of cultured mussels (Gibbs, 2004; Hayden, 1995; Stenton-Dozey and Broekhuizen, 2019). Large numbers of fish are frequently observed near the surface during mussel farming operations (Fig. 1), such as seeding, cleaning and harvesting, where substantial debris typically falls from the longlines, including some mussels, and hence the discharge of this material is thought to attract fish to feed (Gibbs, 2004; Stenton-Dozey et al., 2021). Additionally, the process of lifting and lowering lines in the water creates disturbances, and releases plumes of detached biofouling, that is thought to attract fish. Subsequently, these fish then feed on the mussels attached to the dropper lines on mussel farms. Therefore, it would appear that the presence of these fish can be associated with the loss of mussels from farms, but such an association is an inference and needs to be confirmed with direct evidence of predation from aquaculture structures.

While a wide variety of fish species are known to utilise mussel farm habitat in New Zealand (Morrisey et al., 2006) there is relatively little concrete evidence of the role of any species in preying on cultured mussels. Gut content analyses have identified that Australasian snapper



Fig. 1. Schooling snapper (*Chrysophrys auratus*) at the water's surface during mussel farm harvesting operations in the Firth of Thames region of northern New Zealand (Photo: Chris Dunn, North Island Mussels Ltd).

(*C. auratus*, hereafter snapper), and spotty (*Notolabrus celidotus*) captured from a mussel farm in the Marlborough Sounds had recently consumed green-lipped mussels (Hayden, 1995). Likewise, gut contents of snapper captured from farms in the Firth of Thames contained a high proportion of mussels that were presumed to have been predated from the farm, both green-lipped as well as an endemic blue mussel (*Mytilus edulis*), which settle and grow adventively on Greenshell™ farms (Underwood, 2023). However, the presence of mussels in the gut contents of a fish may not be due to predation from a farm but may have come from mussels which have dropped to the seafloor below the farm, from nearby wild populations, or from mussels incidentally discarded during normal farming operations. Indeed, a previous study that found high incidences of mussels in the guts of snapper caught in mussel farms in northern New Zealand also found that snapper made up a significant portion (46 %) of the fish observed inhabiting the seafloor beneath farms, where they would have immediate access to mussels that have dropped to the seafloor after detaching from farm lines or discarded from farming operations (Underwood, 2023).

First-hand underwater observations of fish predation of mussels from farms are lacking from New Zealand and elsewhere, largely due to the logistic difficulties in obtaining such evidence. Direct observations of fish predation by divers are constrained by the time available to divers underwater and usually confounded by fish behaviour being altered by the presence of divers (Bacher et al., 2015). Underwater, remotely operated vehicles (ROV) create less disturbance than divers and can operate at close distances from structures and are capable of covering a wider area than fixed camera systems (Cappo et al., 2003; Morrisey et al., 2006; Raoult et al., 2020). However, ROV systems can be difficult to operate and their movement and noise can interfere with fish behaviour (Cappo et al., 2003; Raoult et al., 2020). In situ observations using fixed remote underwater video (RUV) deployed within a habitat are increasingly being used to monitor fish abundance, diversity and behaviour, whilst avoiding confounding effects associated with other observation methods (Assis et al., 2013; Sheehan et al., 2019; Zarco-Perello and Enríquez, 2019). Fixed RUV offers the potential to undertake continuous and non-intrusive observations of fish behaviour over an extended period of time. Therefore, fixed RUV methods appear to be a potentially effective method for making direct observations of fish predation in mussel farms. The aim of this study, therefore, was to assess the potential for using fixed remote underwater video for identifying fish species and their behavioural interactions with Greenshell™ mussel farms, especially mussel predation events. This information can provide a valuable foundation on which to inform the development of mitigation strategies.

2. Materials and methods

2.1. Study sites

A total of six deployments (Table 1) of fixed RUV cameras were undertaken at different times using four Greenshell™ mussel farms in the Firth of Thames in northern New Zealand (Fig. 2). These deployments were conducted in collaboration with the mussel aquaculture industry which provided access and logistic support for sampling in the mussel farms. All coastal mussel farms in New Zealand utilise a modified Japanese long line system which consists of two parallel backbone lines (2 m apart) suspended near the sea surface from which a continuous dropper line is suspended in loops that descend to a depth of up to 15 m and provide an extensive growing substrate for cultured mussels (Jeffs et al., 1999).

Deployment 1 took place on a coastal mussel spat (<1 mm shell length - SL) farm (hereafter Hautapu Spat) in the northeast of Hautapu Channel (36° 44' 12" S, 175° 26' 40" E) on 17 October 2022. Deployment 2 was conducted in a farm culturing intermediate-sized mussel seed (>35 mm SL) (hereafter Hautapu Seed), also in Hautapu Channel (36° 44' 25" S, 175° 26' 56" E) on 27 September 2022. Deployments 3 and 4 were on a final adult mussel grow-out (>40 mm SL) farm in Wilson Bay (36° 58' 50" S, 175° 24' 7" E) on 7 November 2022 and 29 November 2022. Deployments 5 and 6 were located on a mussel farm culturing large spat (>20 mm SL) at Esk Point (36° 48' 28" S, 175° 26' 9" E) on 3 March 2023 and 24 March 2023. This selection of farms with mussels of different sizes was aimed at providing an initial assessment of the effectiveness of the fixed RUV for detecting the presence of fish predation behaviour at these various stages of mussel production, although it is recognised that the fish communities and behaviour may have differed among farm locations and times of deployment. However, controlling for these potentially confounding factors would have required much more extensive deployments which was beyond the scope of this preliminary study and the logistical support available for this study.

Table 1

Overview of the deployments of remote underwater video cameras into four mussel farm sites in the Firth of Thames, northern New Zealand, to capture observations of fish interactions with each mussel farm. Total recorded time indicates the length of video recording deemed suitable for analyses for each deployment.

Site (see Fig. 2 for locations)	Deployment	Date (Start time)	Depth (m)	No. Cameras	Total Recorded time (min)
Hautapu Spat	1	17/10/2022 (08:30)	<5	1	321
			>5	2	493
Hautapu Seed	2	27/09/2022 (09:00)	<5	2	803
			>5	1	424
Wilson Bay	3	7/11/2022 (10:30)	<5	3	847
			>5	3	419
Wilson Bay	4	29/11/2022 (11:00)	<5	3	721
			>5	2	688
Esk Point	5	3/03/2023 (08:30)	<5	3	721
			>5	4	871
Esk Point	6	24/03/2023 (08:30)	<5	1	229
			>5	3	688
Total			<5	13	3642 (60.7 h)
			>5	15	3583 (59.7 h)

2.2. Sampling design

The cameras used for this study were GoPro Hero 9 and GoPro Hero 10 (GoPro, Inc., USA) cameras, each housed in waterproof Suptig (Shenzhen Runshengxing Technology Co. Ltd., China) housings with external battery packs. Between 5 and 10 cameras were deployed at each site at two depth ranges (0–5 m and 5–10 m) and set to record continuous video until the battery was depleted (approximately 4–7 h). When recording continuously, GoPro cameras automatically save video files in sequential segments, each containing a recording of 11 min 47 s duration to manage file sizes and facilitate easier file handling.

The cameras were retrieved the following day. Due to initial issues with camera malfunctions, including cameras being destroyed after flooding with seawater, some of the camera deployments were unsuccessful and so the numbers of cameras capturing recordings from any deployment were not always consistent (Table 1).

To secure each of the cameras onto the mussel farms, camera mounts were made from 20 cm lengths of cylindrical PVC pipe (70 mm ϕ) which were split lengthwise, with a camera housing mounted on the outside of the pipe. Cameras could then be deployed onto mussel farm dropper lines by placing the PVC around the dropper line and securing it in place with cable ties so that the camera faced downward with a wide-angle view which captured fish activity across at least two adjacent dropper lines of the mussel farm (Fig. 3). The cameras were deployed by lifting dropper lines out of the water with a hydraulic lifting arm on a mussel farm service barge, attaching the cameras to the dropper lines, and then lowering them back into position in the water. Cameras were recovered in a similar manner. The deployment of cameras at a farm typically took up to 45 min, during which time the cameras that were initially deployed elsewhere within the same farm were recording fish behaviour which may have been affected by the presence of the vessel in the vicinity.

2.3. Processing of video recordings

2.3.1. Frame grabs

The range of observations down dropper lines was constrained by low water clarity in a small number of instances. Additionally, fogging and flooding of camera housings compromised the overall effectiveness of the RUV method. These challenges, coupled with difficulties in maintaining the desired angle down the mussel dropper lines at deployment, resulted in the exclusion of a total of 906 min out of a total of 8131 min (i.e., 11.1 %) of video from the analyses. Furthermore, the malfunction of four cameras due to flooding led to a complete loss of captured video recordings and the destruction of three cameras. On average, factoring in all deployments, cameras, and depths, this equates to a substantial loss of 602 min per affected camera, resulting in a cumulative loss of 2408 min (40.1 h) of video recordings.

After excluding video files where the recorded view from the camera was obstructed, a total of 120.4 h of video recordings were deemed suitable for further analysis. Of these, 60.7 h were recorded at 0–5 m depth and 59.7 h at 5–10 m depth (Table 1).

The video files were all processed with a bespoke MATLAB (MathWorks Inc., Natick, MA, USA) script which extracted individual frame grabs from the video files at regular 27.5 s intervals and saved them as individual JPEG image files. Each frame grab was then visually inspected and, where fish were present, they were; 1) identified to species level, and 2) the number of individuals of each species were counted. A standardised fish count was calculated for each camera deployment by dividing the total count of fish for all species that were observed in all frame grabs for the camera by the total number of frame grabs that were analysed.

The raw fish counts from frame grabs were aggregated to a maximum count for individual species of fish in every set of sequential 12 frame grabs (i.e., 6 min continuous video recording). By aggregating the count data, it made it possible for the data set to be processed with a Zero-

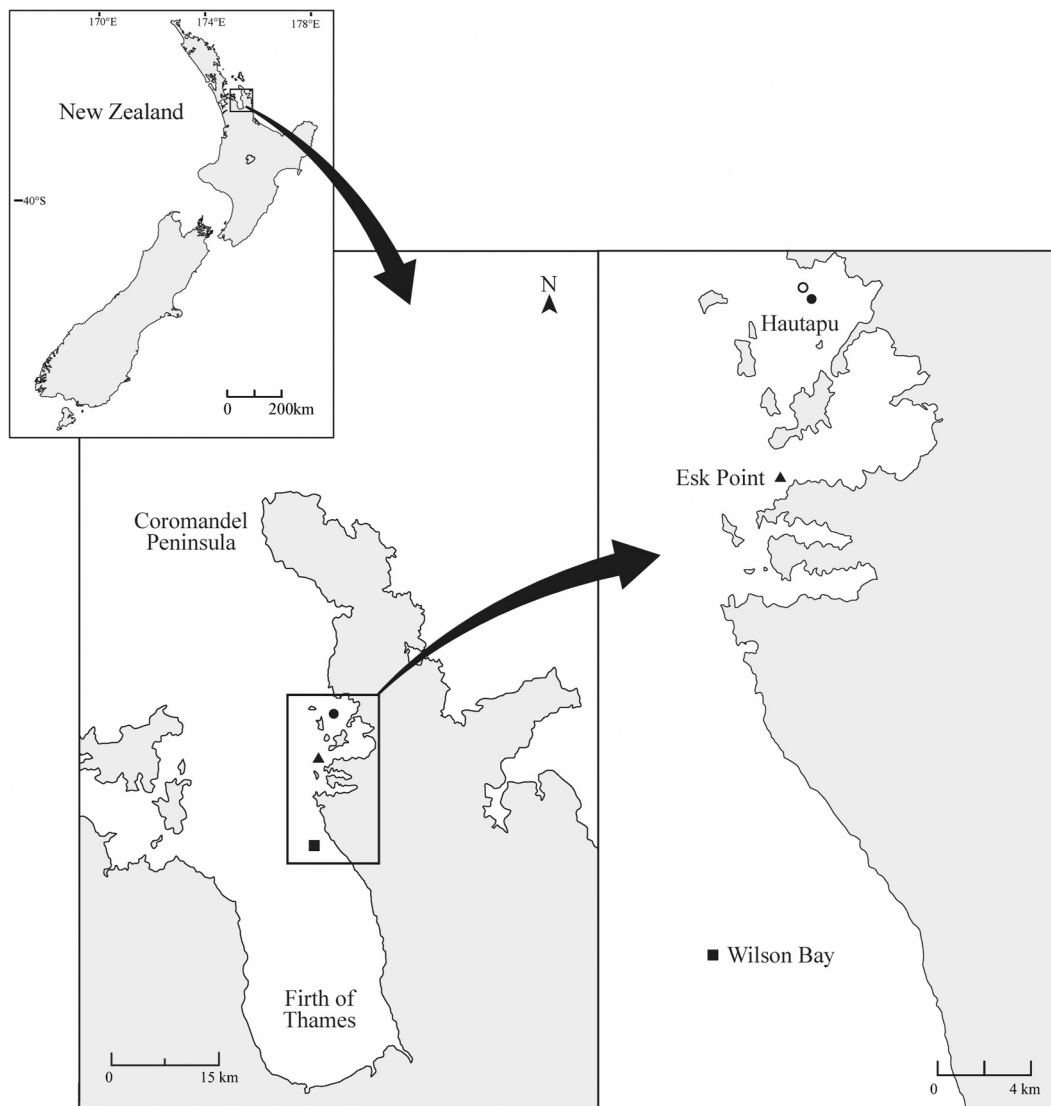


Fig. 2. Location of four mussel farms within the Firth of Thames that were used as study sites for deploying remote underwater video cameras. Circle (open) - Deployment 1) Hautapu Spat (<1 mm SL mussels), circle (filled) Deployment 2) Hautapu Seed (>35 mm SL mussels), triangle - Deployments 5 and 6, Esk Point (>30 mm SL mussels), square - Deployments 3 and 4, Wilson Bay (>40 mm SL mussels).

Inflated Negative Binomial (ZINB) model, as it was able to manage the zero inflation that could lead to numerical instability or undefined results.

2.3.2. Video recordings

Where fish were present in the frame grabs, the original video file was accessed and detailed visual analyses undertaken for the 30 s preceding and following the frame grab. The choice of a 30 s interval for frame grabs was made after observing the effects of different intervals ranging from 10 to 60 s. Observations indicated no significant differences in the frame grabs taken at both 10 and 30 s. Since both intervals provided similar results in terms of image clarity and content, the 30 s interval was selected. This duration allows for a good balance between capturing sufficient data while avoiding excessive image redundancy. When fish were present in all frame grabs from a recording, the entire video recording (i.e., 11 min 47 s) was analysed. The video recordings were reviewed to count the number of bites (i.e., a fish biting the mussel farm structure was counted as one bite), 2) the species responsible for each bite, and 3) the presence or absence of the mussel barge as determined by the recorded underwater sound of the vessel operating in the vicinity of the recording camera. A standardised bite count was

calculated for each camera deployment by dividing the total count of bites for each species by the total number of video recordings that were analysed. After observing fish picking off and masticating whole mussels with a single bite, bite count was used as a measure of predation effort for each species.

2.4. Statistical analyses

Zero-Inflated Negative Binomial mixed-effects models were run to determine the differences in the counts for each individual fish species among the four mussel farm sites, camera deployment depths, dates of deployment, and individual cameras based on data gathered from the frame grabs. The same type of statistical model was also used to determine whether there were differences in the standardised bite count for each fish species that were observed to be feeding (i.e., parore and snapper) using the same set of experimental factors. The ZINB model is well-suited for datasets with a high prevalence of zero values, accounting for excess zeros in count data. This model also accounts for overdispersion (negative binomial) and non-independence or grouping (mixed effects) in the dataset. The models were implemented using the glmmTMB package in R (version 4.3.2).

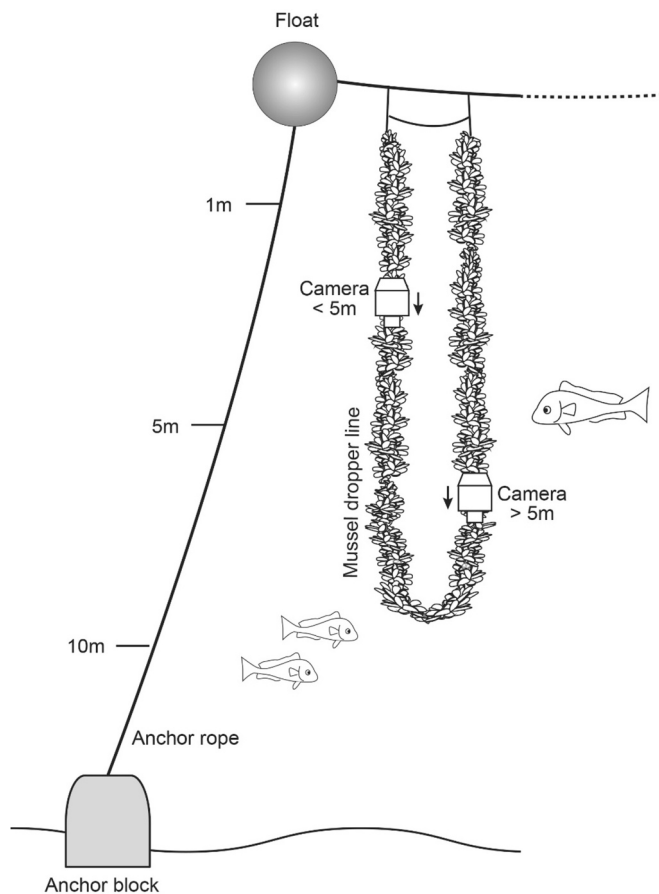


Fig. 3. Diagram of the arrangement for deploying underwater remote video cameras at two different depths (0–5 m, 5–10 m) on the dropper lines of mussel farms.

Separate ZINB models were employed to assess the relationships between individual species counts (parore, snapper, trevally and jack mackerel), total fish count (i.e., all fish species present), standardised bite count for each individual fish species (snapper or parore), and the variables of site, depth and the unique groupings of deployment dates and cameras (i.e., replicates). The individual fish species count (i.e., parore, snapper, trevally and jack mackerel), total fish count, or number of bites was designated as the response variable (for each model respectively), with site and depth, along with their interaction, included as fixed effects. The three corresponding models that were run were;

$$\text{Individual species count} \sim \text{site} * \text{depth} + (1|\text{deployment/camera})$$

$$\text{Total fish count} \sim \text{site} * \text{depth} + (1|\text{deployment/camera})$$

$$\text{Bite count (snapper or parore)} \sim \text{site} * \text{depth} + (1|\text{deployment/camera})$$

The effect of boat presence was modelled with the standardised bite count for each individual species as the response variable and boat presence as a fixed effect. The corresponding model was;

$$\text{Bite count (snapper or parore)} \sim \text{boat} + (1|\text{deployment/camera})$$

The combination of camera and deployment date was treated as random effects for all models. The ziformula was specified as 1 to model excess zeros in the count data without considering predictor variables. The family parameter was set to nbinom2 to account for overdispersion in the data.

Model assumptions were checked using the 'DHARMA' package through Q-Q and residual plots. While some deviations from the

assumptions of a well-fitted model were observed, no further refinements could be made. Therefore, the model is presented as is. Additionally, Tukey-corrected pairwise comparisons of estimated marginal means were performed using the 'emmeans' package.

To evaluate the occurrence of feeding events in relation to the presence of the commercial mussel barge, the recorded number of bites was transformed into a binary outcome variable, representing the presence or absence of feeding. Specifically, a binary code of 1 was assigned if at least one biting event was recorded, and 0 if no bites were observed. The same process was used to evaluate the occurrence of parore or snapper where, a binary code of 1 was assigned to each species if at least one fish of that specific species was recorded, while a code of 0 was assigned if the species was not observed.

Generalised linear mixed models (GLMM) were then used to investigate the relationship between the occurrence of feeding events for each individual species (i.e., parore and snapper) and the presence of the commercial mussel barge used for deploying the RUV to each study site. The same statistical model was used to determine the relationship between the occurrence of each individual species (i.e., parore or snapper) and the presence of the commercial mussel barge. Due to vast differences in fish presence among sampled sites, the analyses were only undertaken for the sites with the highest levels of feeding behaviour for each species (Hautapu Spat for parore and Esk Point for snapper) to mitigate potential confounding factors related to fish behaviour among different sites. Focusing on the individual sites with the highest levels of feeding behaviour for each of the two key predatory fish species provides for a targeted test of whether boat presence influences fish feeding activity.

Bites (presence/absence) and parore or snapper (presence/absence) was set as the response variable; boat (presence/absence) was set as a fixed effect and a random intercept for each unique combination of deployment and camera was included to account for the grouping structure in the data. The four corresponding models run were;

$$\text{Any bites by snapper} \sim \text{boat presence} + (1|\text{camera}), \text{ data} = \text{Esk Point}$$

$$\begin{aligned} \text{Any bites by parore} &\sim \text{boat presence} + (1|\text{camera}), \text{ data} \\ &= \text{Hautapu Spat} \end{aligned}$$

$$\text{Snapper presence} \sim \text{boat presence} + (1|\text{deployment/camera})$$

$$\text{Parore presence} \sim \text{boat presence} + (1|\text{deployment/camera})$$

The binomial family with a logit link function was used to model the binary nature of the response variable. Tukey-corrected pairwise comparisons of estimated marginal means were performed using the 'emmeans' package.

3. Results

3.1. Fish species present in Greenshell™ farms

Analyses of a total of 14,575 frame grabs (Fig. 4) sampled at 27.5 s intervals from all video recordings (i.e., total of 120.4 h) from all sampling sites and deployments contained a total of 30,701 observations of individual fish, regardless of species (Table 2). This total consisted of 11,503 fish in 6050 frame grabs at 0–5 m depth (i.e., 1.9 fish per frame grab) and 19,198 in 8525 frame grabs at 5–10 m depth (i.e., 2.3 fish per frame grab). That is, there were 18.4 % more fish observed at 5–10 m depth versus 0–5 m.

The dominant species present at 0–5 m depth, in all frame grabs, was snapper, consisting of 86.6 % of the total count of fish, followed by parore (*Girella tricuspidate*; 10.9 %), jack mackerel (*Trachurus novaezealandiae*; 1.7 %) and trevally (*Pseudocaranx georgianus*; 0.7 %). No other fish species were observed in frame grabs. At 5–10 m depth, in all frame grabs, the dominant species among all sites was snapper (94.4 %),

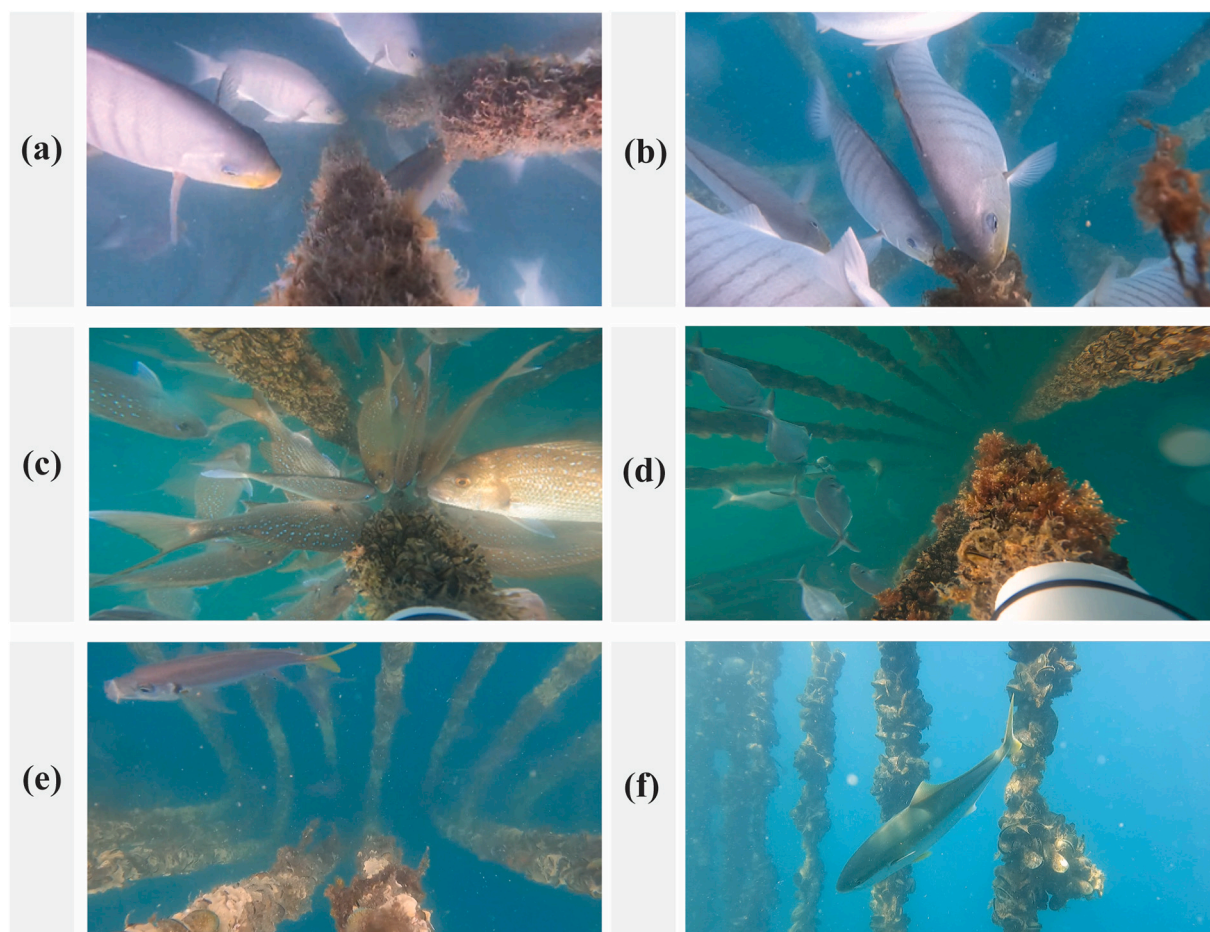


Fig. 4. Frame grabs of Hautapu Spat (a) and Hautapu Seed (b) show parore biting dropper lines, Esk Point (c) shows a snapper feeding aggregation on dropper lines and (d) shows a school of trevally swimming through the dropper lines and a jack mackerel feeding on particles in the water column at Hautapu Seed. A yellowtail kingfish swimming among dropper lines (f; Photograph by L. Underwood).

Table 2

Overview of the composition of observed species at each site and depth captured in frame grabs.

Site	Depth	Species (%)				N Fish	Frames
		Snapper	Parore	Trevally	Mackerel		
Hautapu Spat	0–5 m	0	100	0	0	458	650
	5–10 m	10.3	82	2.7	0	555	950
Hautapu Seed	0–5 m	0.5	78.3	0	21.2	576	446
	5–10 m	58.5	40.1	1.3	0	1575	900
Wilson Bay	0–5 m	20.2	0	2.4	77.3	83	1850
	5–10 m	48.3	0	0	51.7	153	4150
Esk Point	0–5 m	95.8	3.3	0.8	0.1	10,525	1975
	5–10 m	98.3	0.8	0.1	0.8	17,906	2525

followed by parore (4.2 %), jack mackerel (1.2 %) and trevally (0.2 %). No other fish species were observed in frame grabs. The greatest number of fish observed in a single frame grab was 49 snapper at the Esk Point site.

There were substantial differences in the composition of fish assemblages among different mussel farm sites (Fisher's Exact test, $P < 0.05$) (Fig. 5), particularly between inshore (i.e., Hautapu Spat, Hautapu Seed and Esk Point) and the offshore site (i.e., Wilson Bay). Notably, the Hautapu Spat and Hautapu Seed sites exhibited a dominance of parore, constituting up to 100 % (0–5 m depth) of the observed species. In contrast, no parore were recorded at Wilson Bay, and their presence at Esk Point ranged from 0.8 % of the fish counted in frame grabs (5–10 m depth) to 3.3 % (0–5 m depth). Conversely, snapper were observed at every site in this study. Snapper constituted up to 98 % of the observed

species at Esk Point (5–10 m depth) and were variable at both Hautapu sites where their presence ranged from 0 % (0–5 m depth) to 10.3 % (5–10 m depth) at the Hautapu Spat site and 0.5 % (0–5 m depth) to 58.5 % (5–10 m depth) at the Hautapu Seed site. Although observed in lower numbers, snapper appeared to be of larger size at Wilson Bay compared to Esk Point and both Hautapu sites.

The maximum total count of all fish species every 6 min was different among sites and between depths and their interaction. The maximum total count of fish every 6 min was significantly lower at Wilson Bay than Esk Point ($Z = -2.9$, $P < 0.01$, $n = 1220$). Post hoc tests indicate at the 0–5 m depth, the maximum count of all fish was higher at Esk Point than at Wilson Bay ($Z = 2.9$, $P < 0.05$). At the 5–10 m depth, there were more fish at the Hautapu Seed site ($Z = 3.1$, $P < 0.05$) and Esk Point ($Z = 3.7$, $P < 0.01$), than at Wilson Bay.

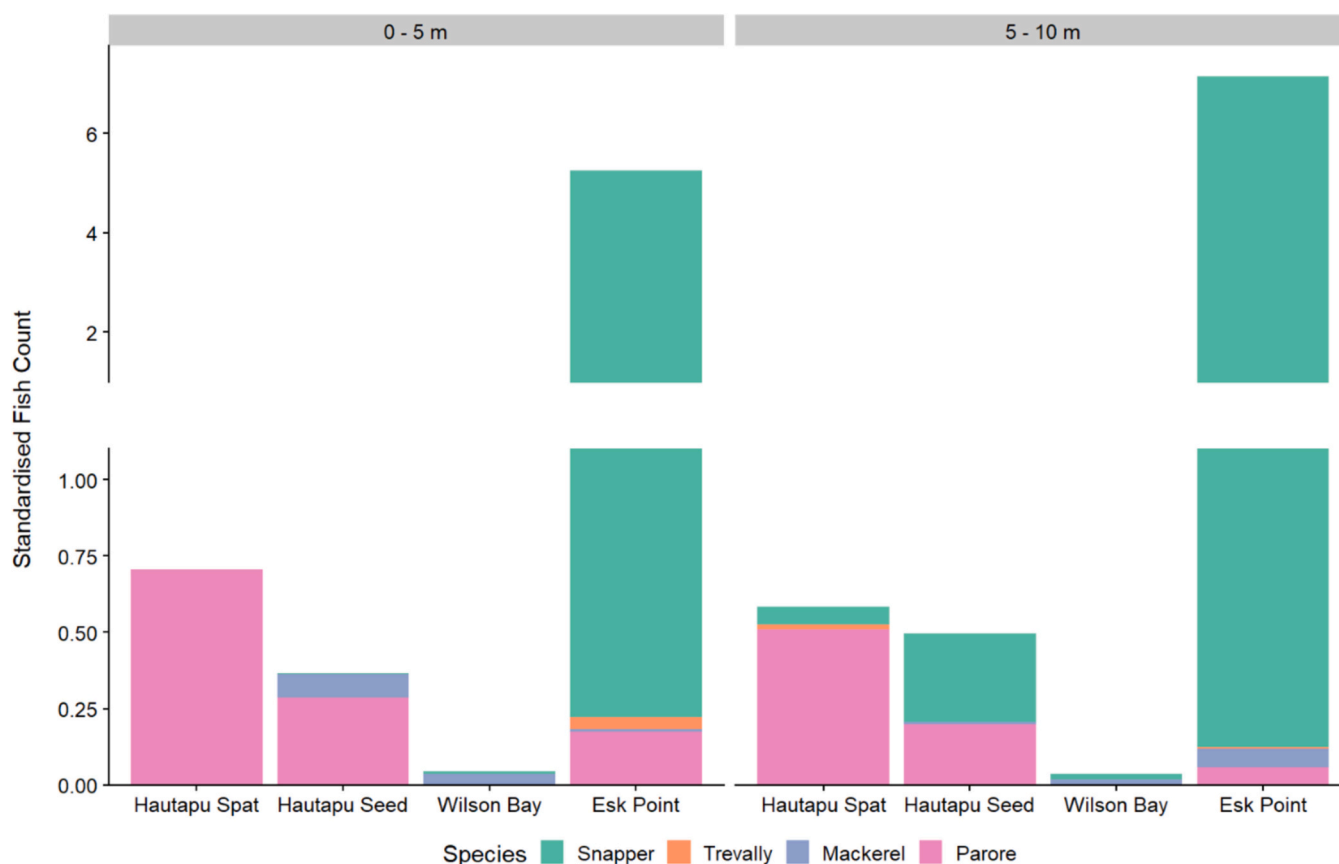


Fig. 5. Standardised fish count for four fish species observed at two depths (0–5 m and 5–10 m) at four mussel farm sites, in the Firth of Thames, northern New Zealand.

The maximum count of parore every 6 min (i.e., within every set of 12 contiguous frame grabs) was different among sites but not with respect to depth or the interaction between site and depth (Fig. 6). The mean maximum count of parore at Hautapu Seed was $3.2 \text{ individuals } 6 \text{ min}^{-1}$ ($Z = 12.4, P < 0.001, n = 1220$), which was 1.0 higher than for Hautapu Spat ($2.2 \text{ individuals } 6 \text{ min}^{-1}; Z = 9.1, P < 0.001, n = 1220$). Post hoc tests revealed the maximum count of parore at Hautapu Seed was higher than for Hautapu Spat by 1.1 more parore every 6 min ($Z = 5.5, P < 0.001$). Esk Point had $2.0 \text{ individuals } 6 \text{ min}^{-1}$, less than Hautapu Spat ($Z = -12.1, P < 0.001$) and 3.2 less than Hautapu Seed ($Z = -16.1, P < 0.001$).

The maximum count of snapper in frame grabs every 6 min was significantly influenced by site, depth, and their interaction. Specifically, lower maximum snapper counts were observed at Hautapu Seed ($Z = -3.9, P < 0.001, n = 1220$) and Wilson Bay ($Z = -4.4, P < 0.001, n = 1220$) compared to Esk Point and the 5–10 m depth was associated with a higher maximum snapper count than the 0–5 m depth ($Z = 2.1, P < 0.05, n = 1220$). At the Hautapu Seed site, there was a higher snapper count every 6 min at the 5–10 m depth compared to the 0–5 m depth ($Z = 3.1, P < 0.01, n = 1220$). Post-hoc tests revealed differences at 0–5 m depth, between Esk Point and Hautapu Seed ($Z = 3.9, P < 0.01$), and Esk Point and Wilson Bay ($Z = 4.4, P < 0.001$). Esk Point had 5.8 and 5.7 more snapper 6 min^{-1} than at Hautapu Seed and Wilson Bay (respectively). At 5–10 m depth, there was a 3.8 and 6.3 higher maximum count of snapper every 6 min between Esk Point and Hautapu Spat ($Z = 2.8, P < 0.05$) and Wilson Bay ($Z = 5.1, P < 0.0001$).

At the 0–5 m depth at Esk Point the maximum counts of snapper in frame grabs every 6 min was 5.5 more than at Wilson Bay, 5–10 m depth ($Z = 4.4, P < 0.005$), and at the 0–5 m depth at Wilson Bay there were 6.5 less snapper than at Esk Point 5–10 m ($Z = -5.0, P < 0.0001$). At Hautapu Seed, there was 6.6 less maximum snapper observed every 6

min than at Esk Point 5–10 m ($Z = -4.4, P < 0.001$). At Hautapu Seed there were 3.8 less maximum snapper observed at the 0–5 m depth than the 5–10 m depth ($Z = -4.2, P < 0.001$).

The maximum count of trevally every 6 min was not significantly different among sites or between depths. The maximum number of trevally observed in a single frame grab was 10, with a total of 111 observed in 43 out of 14,575 frames. There were no instances of direct predation by trevally on the mussel lines captured in the frame grabs.

The maximum count of jack mackerel was significantly higher at the 0–5 m depth than the 5–10 m depth ($Z = -2.6, P < 0.001, n = 1220$). Post-hoc tests confirm that at the 0–5 m depth, 1.7 more jack mackerel were observed every 6 min ($Z = 2.6, P < 0.001$). The maximum number of jack mackerel observed in a single frame grab was 6, with a total of 435 individuals observed in 289 out of 14,575 frames. There were no instances of jack mackerel observed directly biting the mussel lines.

The presence of the mussel barge had a significant effect on the presence of snapper ($Z = -3.2, P < 0.05, n = 538$) but not on parore ($Z = 1.8, P = 0.07, n = 538$). Post hoc tests show the probability of snapper presence is approximately 0.83 times lower when the boat is absent compared to when the boat is present ($Z = -2.5, P < 0.05$).

3.2. Fish species responsible for predation in Greenshell™ farms

Analysis of 2406.2 min (40.1 h) of video from all sampling sites and deployments returned a total of 17,979 bites on mussel lines for both species (i.e., parore and snapper). This total consisted of 11,342 bites in 1309.3 min (21.8 h) at 0–5 m depth (i.e., $8.7 \text{ bites min}^{-1}$) and 6637 bites in 849.3 min (14.2 h) at 5–10 m depth (i.e., $7.8 \text{ bites min}^{-1}$). Of the total bites, 4609 bites (25.6 %) were attributed to parore and 13,370 bites (74.4 %) were attributed to snapper. The greatest number of bites observed in a single 11 min and 47 s video was 2880 at the Esk Point

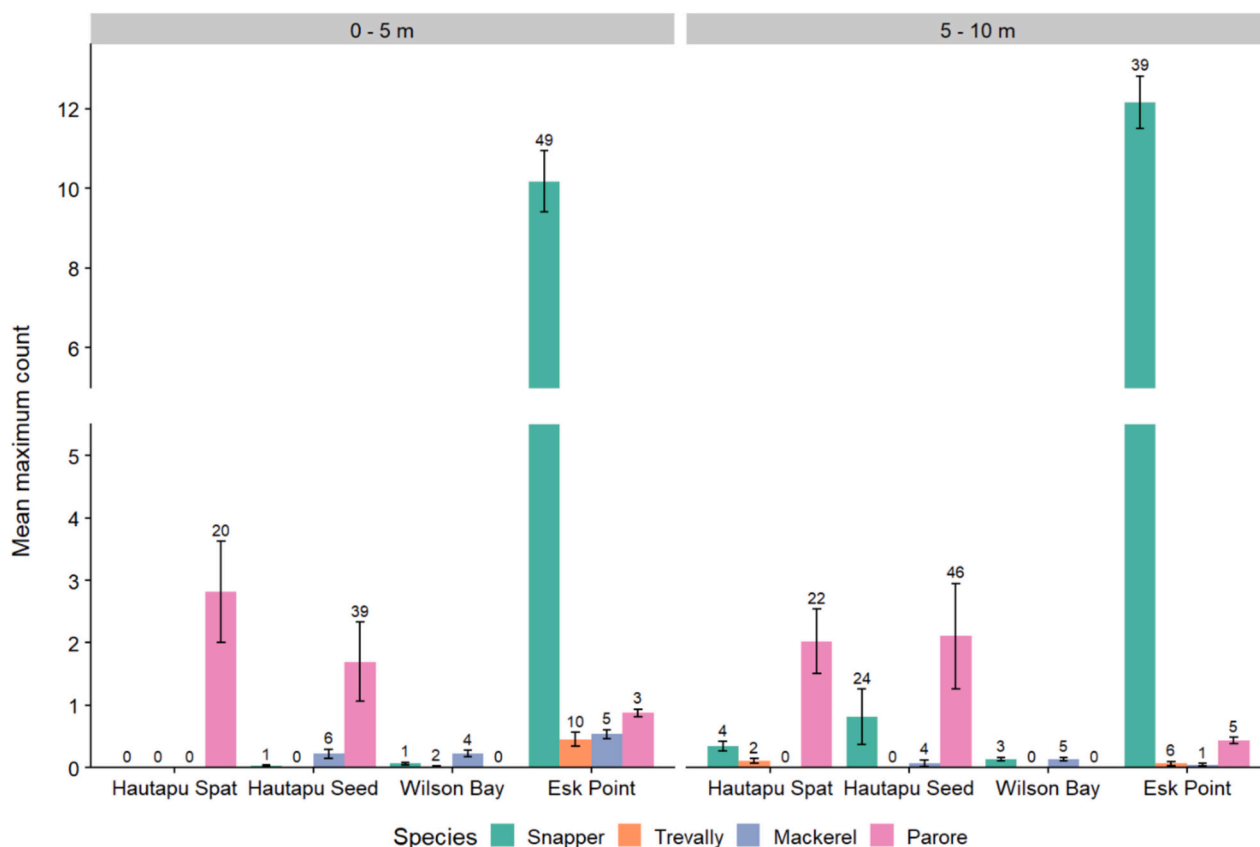


Fig. 6. Mean maximum count (\pm SE) of four fish species in a single frame grab for four fish species observed at two depths (0–5 m and 5–10 m) at four mussel farm sites, in the Firth of Thames, northern New Zealand. Maximum count for each fish species at each site and depth is presented above the error bars.

Site, with all of the bites by snapper.

Schooling trevally were observed very rapidly swimming through the dropper lines at Esk Point, engaging in feeding for a total of six occasions from all camera deployments at this site (24.7 h of observation in total). Each burst of feeding activity lasted a maximum of 6 s, contributing to a maximum of 36 s of feeding in the entire analysis. Additionally, the review of recordings for analyses of feeding revealed the presence of two yellowtail kingfish (*Seriola lalandi*) on two separate cameras at the Esk Point site. This species is a pelagic piscivorous predator that was not identified in any of the frame grabs and was not observed feeding on the mussel lines.

Fish species that were never or rarely observed feeding on mussel lines (i.e., trevally, jack mackerel, kingfish) were not included in further data analyses for fish feeding on mussel lines.

The number of bites by parore varied significantly among sites but not between depths (Fig. 7). At the Hautapu Spat site, there were 4.1 more bites min^{-1} by parore than at Esk Point ($Z = 3.3$, $P < 0.001$, $n = 175$), and at Hautapu Seed there were 3.9 more bites min^{-1} than at Esk Point ($Z = 3.1$, $P < 0.001$, $n = 175$). There were no differences in the mean number of bites by parore between Wilson Bay and Esk Point ($Z = -0.04$, $P = 1.00$, $n = 175$). Post-hoc tests confirmed that compared to Esk Point, Hautapu Spat and Hautapu Seed had 4.1 and 3.9 more bites min^{-1} by parore, respectively.

The feeding behaviour of parore varied markedly among the sampled mussel farm sites. At the Hautapu Spat and Hautapu Seed sites, parore were present as large schools and were often engaged in vigorous group feeding directed at mussel lines. For example, the maximum number of parore observed in a single frame grab for both Hautapu sites was 46 and the maximum number of bites in a single video file (i.e., 11 min 47 s) was 987 bites. In contrast, at Esk Point parore were primarily observed as individuals, hovering around the lines, and taking occasional bites,

however, no schools of parore were observed biting the dropper lines. Consequently, the maximum number of parore observed in a single frame grab at Esk Point was five, while the maximum number of bites in a single video file was 28 bites.

The occurrence of bites by parore was not significantly influenced by the presence of the boat at the Hautapu Spat site ($Z = 0.18$, $P = 0.86$, $n = 168$).

The number of bites by snapper was different among sites but not between depths. At the Hautapu Spat site, 4.5 less bites min^{-1} were observed than at Esk Point ($Z = -3.1$, $P < 0.001$, $n = 175$) and at Hautapu Seed, 4.6 min^{-1} less bites were observed than at Esk Point ($Z = -2.6$, $P < 0.05$, $n = 175$). Post-hoc tests confirm that compared to Hautapu Spat and Hautapu Seed, snapper at Esk Point took 4.5 and 4.6 more bites min^{-1} , respectively.

Snapper were observed in limited numbers at both the Hautapu Spat and Hautapu Seed sites, engaging in sporadic feeding behaviour with infrequent bites. For example, the maximum number of snapper observed in a single frame grab at the Hautapu sites was 24 and the maximum number of bites in a single video file was 9 bites. In contrast, at the Esk Point site, snapper exhibited feeding activity whilst schooling, aggregating around specific locations on the dropper lines to engage in rigorous feeding. For example, the maximum number of snapper observed in a single frame grab at Esk Point was 49 and the maximum number of bites in a single video file was 2880 bites. Apart from periods with group feeding activity, at least one or two snapper were consistently observed hovering around the dropper lines at Esk Point, occasionally taking bites. Snapper at Esk Point were frequently observed picking off and masticating whole mussels. At Wilson Bay a single snapper was observed pulling a large mussel off the dropper line and crushing the shell in its mouth. Additionally, snapper captured by mussel farmers at the Esk Point and Wilson Bay farm sites during camera

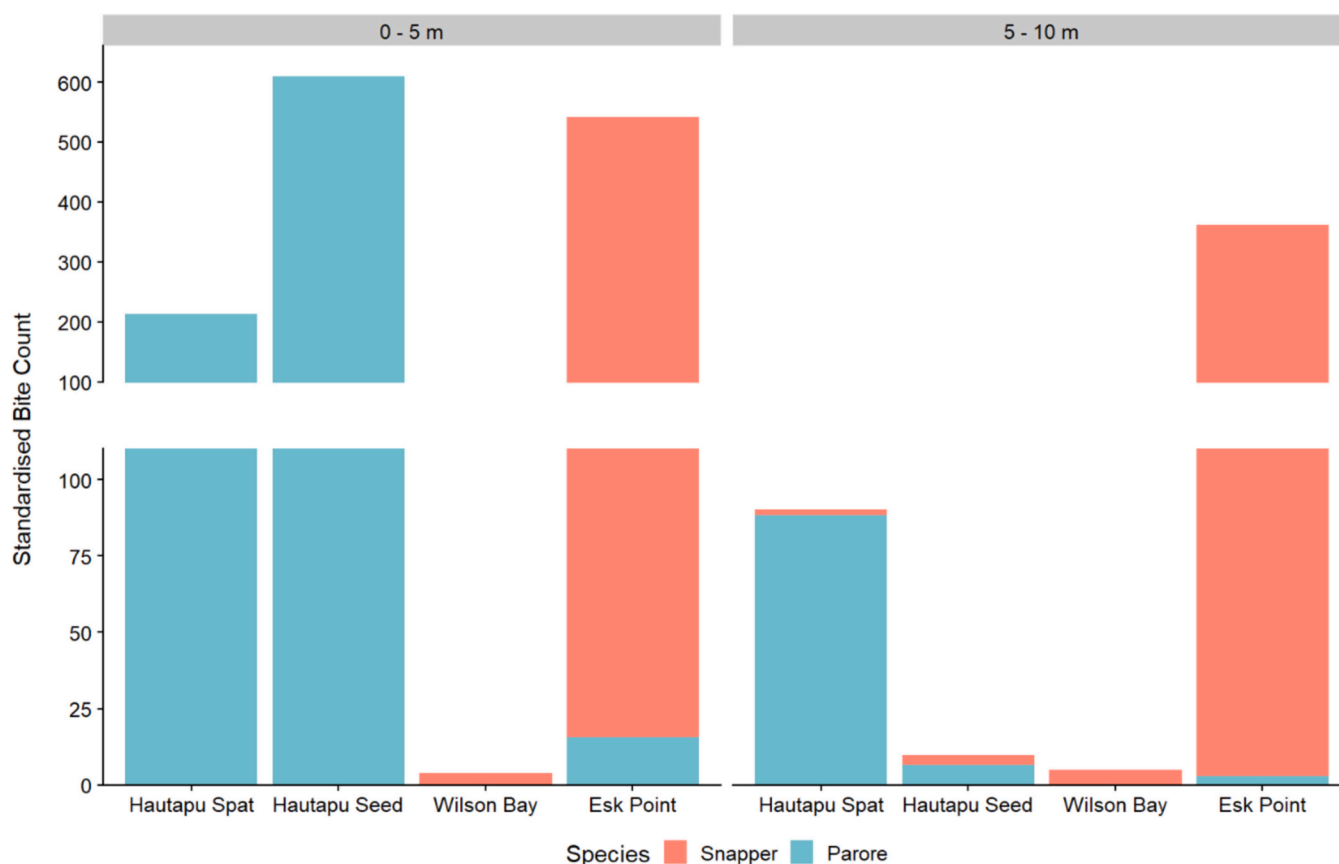


Fig. 7. Standardised count of observed bites by fish on mussel dropper lines for parore and snapper observed at two depths (0–5 m and 5–10 m) at four mussel farm sites, in the Firth of Thames, northern New Zealand.

deployments contained whole mussels and broken mussel shells in their guts.

The occurrence of bites by snapper was not significantly influenced by the presence of the boat at the Esk Point site ($Z = -1.8$, $P = 0.07$, $n = 127$).

4. Discussion

4.1. Fish species present in Greenshell™ farms

Non-fed coastal aquaculture activities, such as seaweed and shellfish aquaculture, are associated with increased abundance of wild fish that are utilising the aquaculture habitat for shelter, feeding and reproduction (Barrett et al., 2022; Callier et al., 2018; Theuerkauf et al., 2021). The median abundance of both recreationally and commercially targeted wild fish species is typically 1.6 times higher in non-fed aquaculture habitats compared to reference natural habitats (Barrett et al., 2022). In the case of mussel farms in the Firth of Thames region, the majority of wild fish species have been found at abundances more than 1.6 times higher compared to control sites, with mackerel and snapper five times higher than natural control sites (Underwood, 2023).

The presence of fish in non-feed aquaculture habitats, such as mussel farms, is facilitated by the provision of extensive areas of substrata, creating a more highly structured habitat than the surrounding natural environment that also provides food resources for fish through biofouling and the cultured species (Callier et al., 2018; Theuerkauf et al., 2021). In this current study, four fish species, snapper, parore, trevally and jack mackerel, were frequently observed within the mussel farms. In addition, two yellowtail kingfish (*Seriola lalandi*) were also observed swimming through the farm in video recordings at the Esk Point site. No other fish species were observed at any site.

Parore are known to inhabit coastal reefs in northern New Zealand, typically in shallow waters not exceeding 6 m depth, and they are rarely observed in depths exceeding 18 m (Brook, 2002; Kingsford, 2002; Meekan and Choat, 1997). The Wilson Bay site, as an offshore mussel farming site (i.e., 8.8 km offshore), was the deepest site in this study (i.e., depth of ~15 m) and RUV observations in the upper 10 m of water indicated that it was unlikely to be inhabited by parore. Additionally, parore have strong site fidelity to shallow rocky reef habitat which is found in abundance in the immediate vicinity of the other three study sites, i.e., Hautapu sites around 7 to 10 m depth and Esk Point 10 to 12 m (Ferguson et al., 2013; Waikato Regional Council, 2017). It is possible that parore are attracted into mussel farms which have been recently seeded with macroalgae covered in spat (Fig. 8), with these fish feeding on the available macroalgae. Furthermore, some macroalgae involved in seeding mussel farms can become established on the dropper lines, growing out from macroalgae fragments seeded onto the lines (Skelton and Jeffs, 2021). This material may continue to attract parore to feed in the farms. The depth differences, presence of macroalgae and proximity to rocky reef habitat may explain the marked differences in the abundance of parore observed among the mussel farm sites that were sampled.

Snapper, recognised as the most common coastal fish species in northern New Zealand, are known to inhabit coastal water depths of up to 200 m (Parsons et al., 2014), and their size generally increases with depth (Jones et al., 2010). Similar to parore, some snapper exhibit strong site fidelity on rocky reefs, a behaviour influenced by the perceived quality of their habitat in terms of shelter and food availability (Parsons et al., 2011; Parsons et al., 2014). Therefore, it is likely the snapper observed in this study are resident and taking advantage of the shelter and food availability provided by the mussel farms. Another sparid species, the blackhead seabream, *Acanthopagrus schlegelii*, has been



Fig. 8. Photograph of spat encrusted macroalgae or Kaitaia spat material (Photograph by B. Skelton).

shown to have similar residency among oyster aquaculture rafts in Japan, with their presence coinciding with the depth of oyster rafts that had been seeded out, suggesting their potential role in preying on oyster spat (Tsuyuki and Umino, 2018).

The abundance of fish and the composition of fish assemblages associated with aquaculture structures can vary seasonally and in accordance with reproduction and seasonal migrations (Fernandez-Jover et al., 2008). For example, some Australasian snapper are resident to rocky reefs year-round however, others are known to migrate between soft-sediment and rocky reef habitat especially moving inshore to spawn as water temperature increases (i.e., October–March; Parsons et al., 2014; Willis et al., 2003). Additionally, the Firth of Thames is a known snapper spawning location (Parsons et al., 2014). Therefore, in the present study, site and season are confounded, whereby, seasonal abundance and feeding activity of snapper were likely greater during the March deployments at Esk Point versus the September and October deployments at Hautapu. Conversely, the presence of parore may not be affected by season or alternatively, an interaction effect exists between snapper and parore. Snapper observed in the video recordings frequently exhibit aggressive behaviour toward parore and conspecifics which could influence the distribution and abundance of these species. Consequently, it is plausible that the elevated abundance of snapper at the Esk Point site deterred parore from this farm, however, more extensive camera deployments would be required to investigate this possibility.

Given the limitations of the sampling for this study, it is difficult to reliably assign the observed differences in species composition and abundance of fish to either site-specific characteristics, such as the size of farmed mussels, time of year, or the depth at which mussels are cultured. However, the results confirm marked differences that warrant further investigation as they may help with identifying farm locations that are subject to lower fish abundance and predation that could be usefully exploited as mussel nursery sites.

4.2. Fish feeding on Greenshell™ mussel lines

At the same time of this study taking place, substantial crop losses from mussel farms of up to 100 % were documented in the Firth of Thames (Stobart, unpublished data) and on occasion, the dropper lines, were observed to be entirely devoid of mussel crop (Fig. 9). This “clean and chewed” rope, combined with video recordings of fish feeding on the dropper lines in this study provide strong evidence that these losses of mussels can be attributed to fish predation.

Among the four fish species documented within the Greenshell™ farms, only snapper, parore and to a much lesser extent, trevally, were



Fig. 9. Photographs of mussel farm dropper lines from Esk Point on 3 March 2023 holding mussels of 20–25 mm shell length showing the effects of fish predation on mussel lines; A) intact dropper line, B) section of dropper line recently stripped of mussels by predation, and C) dropper line stripped completely bare (Stobart, unpublished data).

observed actively biting at the lines. In contrast, jack mackerel, while frequently present in the farms were only observed feeding on suspended particles in the water column. Frequently, jack mackerel appeared to follow snapper, opportunistically consuming particles dislodged by the snapper biting the lines.

It is unclear from the RUV recordings whether the biting of dropper lines by parore involved the predation of cultured mussels from the lines. However, it was clear from the recordings that parore were removing and consuming biofouling material, especially macroalgae, from the dropper lines. This feeding activity by parore may contribute to incidental losses of mussels, especially on spat farms, such as the Hautapu Spat site which was seeded with spat encrusted macroalgae (Fig. 8). At this site, parore were observed ripping out mouthfuls of macroalgae from holes they had created in the stocking material that is used to hold the spat encrusted seaweed against the dropper line during the seeding out operation. The mean number of spat attached to seaweed at the time of this study was $33,326 \text{ m}^{-1}$ of dropper rope therefore, it is likely that with one bite, hundreds of these spat would be dislodged from the rope (Stobart, unpublished data).

Parore in coastal New Zealand are considered omnivorous, with one study documenting animal material constituting 22.4 % of the diet in 85 % of sampled fish (Salewski, 2017). However, the specific diet of parore residing in mussel farms, particularly those in proximity to farms recently seeded with macroalgae encrusted with mussel spat has not been investigated. To ascertain the potential impact of parore on the losses of mussels at these sites, a thorough gut content analysis of parore within mussel farms, with a specific focus on spat farms recently seeded with spat encrusted seaweed would provide an indication of the contribution of parore to crop losses at mussel farms.

Snapper are well recognised for their adaptability and generalist feeding behaviour in the coastal ecosystem of New Zealand, particularly in the Hauraki Gulf region (Parsons et al., 2021). Large juvenile snapper (i.e., 20–23 cm) feed on benthic invertebrates, including brachyuran crabs, bivalves, and polychaetes, and as they grow larger their dietary focus shifts toward hard-shelled molluscs, particularly bivalves (Parsons et al., 2014; Usmar, 2012).

A recent study of the gut content analysis of snapper from mussel farms in the Firth of Thames found mussels as a dominant prey item, with caprellids and barnacles also important as prey items (Underwood et al., 2023). All of these organisms that were major items in the gut contents of snapper from a mussel farm are all abundant on mussel farm

dropper lines (South et al., 2019; Woods et al., 2012), and could be consumed by snapper biting at the lines. The recordings of snapper feeding on the dropper lines would strongly support linking the observed composition of gut contents of snapper (i.e., mussels, caprellids and barnacles) to their biting of dropper lines. Earlier research in the Marlborough region of New Zealand reported observations of snapper hovering around longlines, and gut content analyses confirmed the presence of Greenshell™ mussels (Hayden, 1995). Similar results were found in a large mussel farming region in Croatia, where gut content analysis confirmed *M. galloprovincialis* as the dominant prey for gilthead seabream (Šegvić-Bubić et al., 2011). Therefore, the collective evidence indicates that snapper are the dominant predator of farmed mussels in the Firth of Thames.

In RUV recordings trevally appeared intermittently in schools of four to 12 fish and on a small number of occasions were observed biting the dropper lines. Bivalves have been found to contribute between 5.8 % and 7.1 % to the diet of trevally on the lower west and south coasts of Australia (French et al., 2012). This contribution decreased as the size of the trevally increased (>299 mm TL) (French et al., 2012). It is therefore possible that trevally may contribute to losses of cultured mussels in a minor way, particularly smaller mussels in the ~20 mm size range, such as those farmed at Esk Point in this study.

4.3. Influence of mussel barge on fish abundance and feeding

The presence of the commercial mussel barge within a farm marginally increased the apparent abundance of snapper observed by RUV but not on parore. When the boat was present, the process of lifting and lowering mussel farm lines into the water released significant debris, primarily composed of biofouling, which descended into the water column. This disturbance, generated by the activity of handling the lines, appeared to attract snapper to the immediate vicinity. This is consistent with anecdotal reports from farmers who report large aggregations of specifically snapper feeding on debris released from the barge at the surface during farming operations (Fig. 1). From reviewing RUV observations the disturbance of dropper lines and release of biofouling from the lines as a result of snapper individuals actively feeding on the lines, also appeared to be involved in triggering aggregations of snapper when the boat was absent. The release of biofouling material suspended in the water column may be perceived by snapper as an indication of increased food availability and could be a learned response to the regular release of substantial quantities of mussels and other biofouling material into the water during seeding and harvesting operations. Likewise, the release of material during farming operations such as thinning and harvesting has been shown to attract fish and other scavengers such as birds and crustaceans (D'Amours et al., 2008).

While variations in fish species and their abundance among sites were observed, the nature of this preliminary study precluded the identification of a site, time or depth for deploying vulnerable stages of mussels to provide for reduced risk of losses due to fish predation. Research to determine this remains a complex task involving simultaneous underwater visual census at multiple sites, each with varying mussel sizes and repeated at different times of the year. Nonetheless, the findings of the current research suggest a potential association between mussel farm sites and fish assemblages, aligning with anecdotal reports from farmers who avoid certain farm sites for mussel spat deployment due to consistently high crop losses. However, the observed differences in fish assemblages among farm sites may not be indicative of predation pressure on mussels on the farm. For example, despite Esk Point hosting a significantly higher abundance of fish, the fish feeding activity (i.e., bites per minute) was not different to the Hautapu Seed site. Additionally, although snapper exhibited significant differences in abundance between depths, the number of bites did not vary significantly between depths. These findings suggest that, despite variations in species abundance, the feeding behaviour and predation rates may not be consistently influenced by the factors of mussel size or deployment depth.

To assess the potential for mitigation strategies to reduce the impact of fish predation on farmed mussels, extensive research is required. Three primary categories of mitigation strategies (i.e., physical exclusion, deterrence, and removal) have been tested across various fish species and industries globally. However, practical long-term solutions to fish predation in longline shellfish aquaculture have not yet been developed. In some European shellfish farming regions, such as Thau Lagoon in France, 85 % of surveyed farmers use physical exclusion methods (e.g., netting) to protect dropper lines from the gilthead seabream, a common predator (Gervasoni and Giffon, 2016). Despite this, farmers report losses of up to 26 %. Implementing physical exclusion also incurs additional maintenance costs for repairing holes or tears and cleaning biofouling (Richard et al., 2020). Physical exclusion might be a practical solution to protect the most vulnerable stages of mussels from predation but identifying the most vulnerable production stage is crucial. Deterrence strategies, which mainly exploit the sensory cues of fish, include visual and acoustic deterrents, often used in combination for the best results. Research on deterrence is ongoing, primarily at power plant intakes for freshwater fishes (Noatch and Suski, 2012), however, to the authors knowledge no effective fish deterrence strategies are currently implemented in longline shellfish aquaculture anywhere in the world. Removal strategies are considered undesirable for fish species like snapper, which have high recreational and commercial value. Therefore, preventative measures are preferable to eradication of fish species in farming regions.

4.4. Remote Underwater Video as a research tool

The aim of this study was to assess the potential for using fixed underwater remote video (RUV) for identifying fish species and their behavioural interactions with Greenshell™ mussel farms, particularly the predation of mussels. The application of the RUV provided valuable insights into the fish species present within Greenshell™ farms, particularly the identification of those species biting at the lines holding farmed mussels.

Despite the technical difficulties, resulting in the exclusion of 25 % of the video recordings, the RUV method demonstrated notable advantages, including providing prolonged observation of fish behaviour without the limitations of traditional techniques like diver surveys or ROVs. To enhance its reliability, external battery packs were introduced, which significantly extended the operational duration of the GoPro cameras. However, the integration of inexpensive battery units posed unforeseen vulnerabilities, leading to flooding issues and inconsistent recording times. While effective, technological and deployment enhancements are crucial for optimising the performance of RUV methods in future studies.

5. Conclusions

Remote underwater video observation is a valuable tool to assess the fish species composition and their feeding behaviour within mussel farms. The results from RUV in this study identified snapper as the dominant predator on Greenshell™ mussel farms in the Firth of Thames, northern New Zealand. There is potential for site and depth differences to exist in snapper abundance, however, predation while site-specific does not appear dependent on depth. The presence of snapper in mussel farms appears to be increased slightly by the presence of the commercial mussel barge, however, there is no evidence to suggest the barge influences feeding behaviour. Parore show potential to contribute to losses of mussel on recently seeded spat farms but their contribution to crop losses on farms with larger mussels (i.e., > 10 mm) appears somewhat unlikely from this preliminary study. To better understand the role of parore as a predator of cultured mussels would require gut content analyses of parore sampled from within mussel farms. While differences in abundance of parore among sites exists, depth was not a significant factor in this study. Future research should aim for

comparative underwater surveillance to eliminate confounding factors such as site variation, deployment date, and mussel size, as observed in this study. Additionally, the effect of disturbance of the mussel structure and associated release of biofouling from the lines on the feeding behaviour of snapper would be valuable for informing the development of potential effective mitigation strategies. Simultaneous underwater surveillance at similar or adjacent sites featuring different sizes of farmed mussels would enhance our understanding of fish predation characteristics in mussel farms. Comparative experiments are also essential to quantify the extent to which fish predation contributes to the losses experienced by farmed mussels.

CRedit authorship contribution statement

Rebecca L. Stobart: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrew G. Jeffs:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Jenny R. Hillman:** Writing – review & editing, Validation, Supervision. **Bradley M. Skelton:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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