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Experimental gill-netting of reef fish: Species-specific responses modify capture probability across mesh sizes

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Abstract

Gill-nets are highly selective in terms of the sizes of fish they catch, but often unselective in terms of the suite of fish species they capture. We investigated gill-net selectivity from the point of view of behavioural interactions between the fish and the gear. We observed interactions between fish and gill-nets of three mesh sizes (65 mm, 88 mm & 110 mm) set over rocky reefs in southern New Zealand. There were significant differences among eight species of mobile reef fish in their response to gill-nets and in their capture rates. Some species were more vulnerable because of their use of habitat, swimming motion or morphology. Species that occupied low visibility habitats (e.g., the herbivorous *Odax pullus*, which mostly swims beneath the algal canopy) were more susceptible to being caught because they had little time to detect and avoid the gill-nets. Species with carangiform or sub-carangiform swimming motion (e.g., *Latridopsis ciliaris* or *O. pullus*) were more susceptible to being caught because once in the gill-net, they could only attempt to force their way forwards becoming wedged further into the mesh. Species whose morphology makes tangling in the mesh more likely (e.g., large or protruding spines (*Aplodactylus arctidens*), fins (*L. ciliaris*) or opercula) are also more susceptible to being caught. Some species, particularly the common labrid *Notolabrus celidotus*, were less susceptible than other species to being caught. Fewer than 1% of 538 *N. celidotus* observed within one metre of the gill-nets were caught. Most *N. celidotus* altered their swimming direction near the gill-nets and did not hit the mesh. *N. celidotus* that swam through the nets were smaller than those that swam over the gill-nets or turned away. The fact that different size classes had different responses suggests that interactions with the gill-net are actively controlled. To divers, it appeared that this species could readily detect the gill-nets and treated them as part of the seascape. Furthermore, their labriform swimming motion allowed them to swim backwards out of gill-nets to avoid becoming caught. The species-specific responses of reef fish near the gill-nets and behavioural differences may explain the low numbers of some common reef fish that are caught in gill-nets and the disproportionately high numbers of others. The potentially great ancillary effects from by-catch of important species of untargeted reef fish, birds and marine mammals make gill-nets a somewhat blunderbuss method of catching fish on coastal reefs.

Keywords: Gill-nets; New Zealand; Reef fish; Responses; Selectivity

1. Introduction

Gill-nets are used worldwide to target and capture coastal reef fish. In terms of the size of fish captured, gill-nets are highly selective for most species (Hamley, 1975). However, they are unselective in terms of the suite of species they capture, and the by-catch of untargeted fish, birds and marine mammals is a worldwide problem (e.g. Bull, 2007; Burkhart and Slooten, 2003; Gray, 2002; Hodgson et al., 2007; e.g. Julian and Beeson, 1998). When gill-nets are used on highly structured coastal reefs the mosaic of habitats crossed by even small recreational nets (30 m) exposes a wide range of targeted and untargeted reef fish species to fishing mortality.

The primary measures to minimise capture of by-catch species and undersized fish are the use of suitable mesh sizes and fishing at selected locations (He, 2006). However, knowledge of the response of individual species to gill-nets could be used to minimise the catches of some species while still maintaining the fishery of others. For example, the use of different coloured gill-nets to select a particular species and reduce the by-catch of untargeted species would prevent

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Table 1
Categories used to classify the responses of fish to gill-nets

Swimming direction	Crosses line of gill-net	Interaction with gill-net
Towards gill-net (≤45 from perpendicular)	*Under* lead line	*Hits* gill-net firmly
Away from gill-net (≤45 from perpendicular)	*Over* float line	*Caught* and held
Parallel to gill-net (<45 from parallel)	*Through* mesh or hole	*Escapes* after being caught and swims away

wastage of fish, the handling of unwanted catch (Jester, 1973) and would also potentially reduce impacts on local fish communities. These would be significant developments in a gill-net fishery around multi-species assemblages.

The process of a fish becoming caught in a gill-net involves complex interactions between the physical properties of the gill-net itself, the morphological characteristics of the species and the behavioural traits of the fish. Most studies of gill-net selectivity have focussed on the first two of these factors (Gray et al., 2005; Mendes et al., 2006; Ozekinci, 2005; e.g. Reis and Pawson, 1999), with little reference to the behavioural responses of fish to gill-nets and how these may affect selectivity and efficiency.

Capture of fish by gill-nets results from them coming into direct physical contact with a gill-net and then being retained by becoming 'gilled' by the mesh or entangled in the netting (Hickford and Schiel, 1996). Gill-nets commonly used by commercial and amateur/recreational fishers are constructed from monofilament nylon that is relatively invisible to fish, particularly at low light intensities (Cui et al., 1991). When a gill-net is invisible, target species are unaware of its presence, swim into it, and become trapped. If a fish can sense the gill-net at a large enough distance, it may be possible for it to avoid becoming caught. The efficiency of gill-nets therefore depends on the mesh generating few stimuli that might provoke avoidance responses at a sufficient distance from the gill-net to prevent contact being made (Lunneryd et al., 2002), as well as on the morphology and sizes of fish in the area., Visual cues are the most obvious of the potential avoidance stimuli and the majority of experimental studies have been concerned with assessing their importance. Blaxter et al. (1964), for example, observed the reaction of herring to nets, showing that in daylight the extent of avoidance varied directly with how conspicuous nets were. The reaction distance of fish was greatest, and the number of fish making contact with the net was least, with the thickest filament, smallest mesh size and `brightest' colour. Visual stimuli are of primary importance in determining the avoidance responses of fish to gill-nets, and therefore in governing their `efficiency' (Cui et al., 1991; Olla et al., 2000; Ryer and Olla, 2000; e.g. Tweddle and Bodington, 1988).

There are, however, other cues that can influence the responses of fish to gill-nets. The movement of water through a gill-net generates low frequency sound (Wahlberg et al., 2000). Fish are able to detect such hydroacoustic stimuli with their lateral-line receptors (Kaljmin, 1989) and otoliths (Hawkins, 1986). However, the degree to which this ability is developed varies greatly among species, and only a few are able to locate stationary objects in their path (Kuiper, 1967). Furthermore, avoidance stimuli may be generated by the presence of other fish already caught by the gill-net. Sound and chemical stimuli from captured fish may elicit an avoidance response in other fish and produce a `saturation' effect (Dauk and Schwarz, 2001).

Here, we test whether the responses of fish to gill-nets can alter the probability of being caught. We test several hypotheses by observing the response of fish to gill-nets and quantifying species interactions with the mesh: Can species- and size-specific responses result in differences in capture probability among groups of temperate reef fish? Can variability in the response of fish to gill-nets with different mesh sizes confound size selectivity?

2. Materials and Methods

Gill-nets were set at 19 randomly selected sites around the Kaikoura Peninsula, New Zealand (42° 25.4'S 173° 41.8'E) and at five sites within the Marlborough Sounds, New Zealand (41° 7.9'S 173° 59.4'E). To maximise observation time by divers, sites were selected that were over rocky reef and shallower than 10 m where reef fish populations are greatest (Denny, 2005; Hickford and Schiel, 1995). At each site, three replicate gill-nets

Table 2
Responses of eight species of reef fish to gill-nets of three mesh sizes (65 mm, 88 mm and 110 mm)

Species	Family	Total	Altered	Hit	Caught	Crossed	Through
			%	%	%	%	%
Notolabrus celidotus	Labridae	538	56	2	1	68	72
Notolabrus fucicola	Labridae	163	60	17	6	52	76
Odax pullus	Labridae	23	39	26	26	52	67
Parapercis colias	Pinguipedidae	91	53	15	7	64	57
Aplodactylus arctidens	Aplodactylidae	4	50	75	50	25	100
Latridopsis ciliaris	Latrididae	29	45	17	10	62	89
Nemadactylus macropterus	Cheilodactylidae	21	48	5	0	71	93
Parika scaber	Monacanthidae	17	100	12	0	18	0
χ^2 test			19.67**	90.95***	85.04***	33.80***	21.27**

Altered: swimming direction changes from towards gill-net (Table 1) to parallel to or away from gill-net, Hit: made firm contact with the mesh filament, Caught: caught and held by the gill-net, Crossed: crossed the line of the gill-net, Through: the percentage of fish that crossed the line of the gill-net by swimming through the mesh. χ^2 tests of independence (done on raw frequencies, not the percentages that are shown) and significance are shown (*: $p<0.05$; **: $p<0.01$; ***: $p<0.001$).

(30 m) of each of three mesh sizes (65 mm, 88 mm, 110 mm) were set randomly in relation to each other and current direction. Each gill-net was at least 30 m from its nearest neighbour. Once set, each gill-net was left for ten minutes before being observed by SCUBA divers. Divers swam parallel to each gill-net, 2 m from the mesh and level with the midpoint of the gill-net. If a fish was seen to approach within one metre of either side of the gill-net, the diver hovered and observed the fish's response while it remained within one metre of the gill-net. Divers remained at least 5 m from fish to minimise the possibility of risk-aversive species, with high visual acuity, being more disturbed and thus influencing their response to the gill-net. The species and standard length (estimated to nearest 5 mm) of each observed fish was recorded. Subsequently, *Notolabrus celidotus* were arbitrarily divided into four size classes (standard length ≤ 110 mm, 115 − 130 mm, 135 − 150 mm, ≥ 155 mm). The response of the fish, while it remained within one metre of the gill-net, was classified during five-second blocks (Table 1). Observations were made of 886 fish (65 mm: 283; 88 mm: 315; 110 mm: 288). Any fish that was seen to become caught in a gill-net was observed for a further five minutes to determine if it subsequently escaped.

The data for each fish were summarised into a binary format (i.e. yes/no, did the fish alter its swimming direction within one metre of the gill-net? Did the fish hit the mesh? Was the fish caught? Did the fish cross the line of the gill-net? Did the fish swim through the mesh of the gill-net?). Response data were grouped by species, mesh size, and for the most abundant species, *Notolabrus celidotus*, by size class. Responses were tested with χ^2 analysis within and between groupings. ANOVA was used to compare the standard lengths of fish that did and did not swim through the gill-nets.

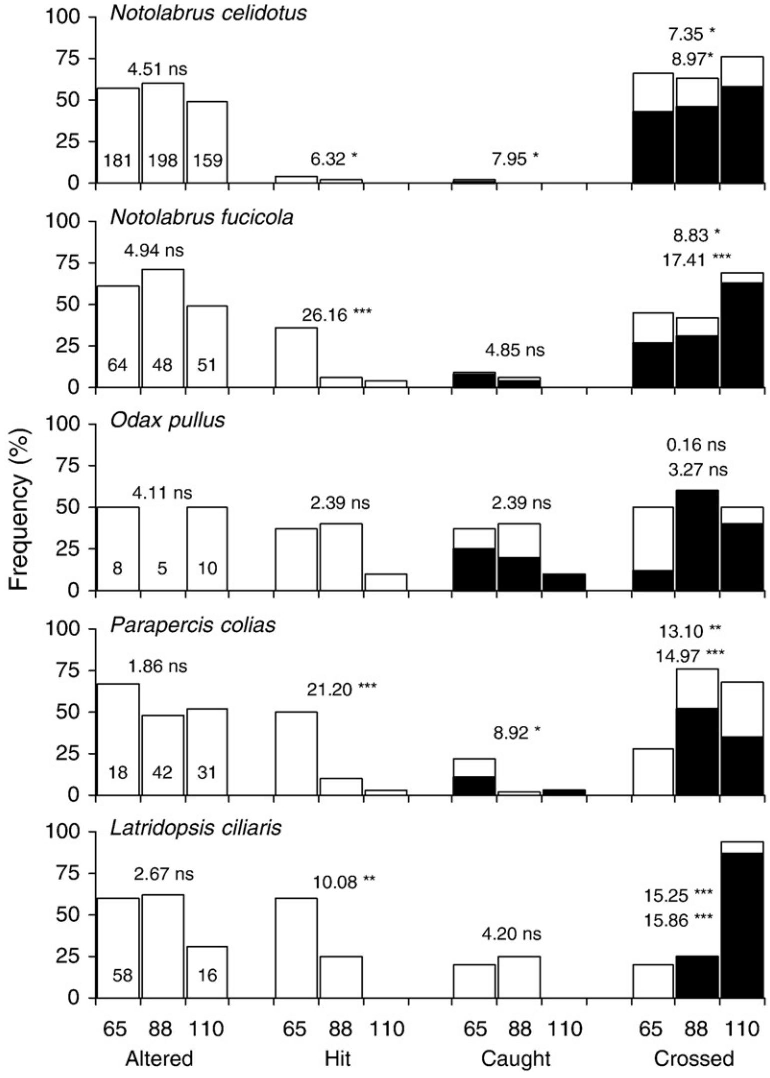

Fig. 1. The responses (categories from Table 2) of five species of reef fish to gill-nets of three mesh sizes (65 mm, 88 mm and 110 mm). Species (from those in Table 2) were included in further analyses only if ≥ 5 fish were observed near all mesh sizes. Sample sizes are shown at the base of the first cluster of bars. χ^2 tests of independence and significance (ns: not significant; *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$) are shown above each response. For Caught, the proportion that subsequently escaped is shown as solid. For Crossed, the proportion that swam through the net is shown as solid and the χ^2 result is listed below the Crossed result.

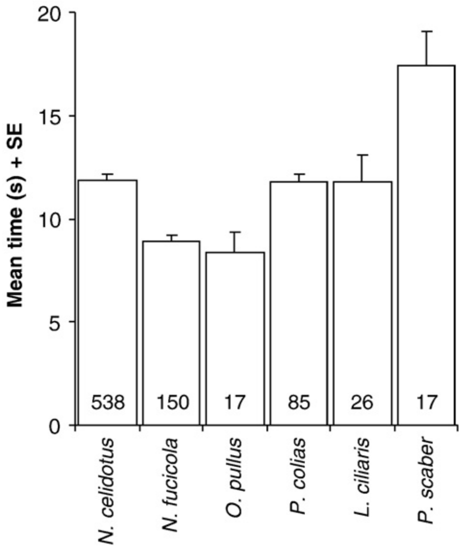

Fig. 2. The mean time spent within one metre of gill-nets by six species of reef fish. The data from the three mesh sizes have been pooled. Samples sizes are shown at the base of each bar.

3. Results

For all species except *Parika scaber*, ~40-60% of fish altered their swimming direction within one metre of the gill-nets (Table 2). For all species, this was independent of the mesh size of the net that they were approaching (Fig. 1). All *P. scaber* altered their swimming direction within one metre of the gill-net.

Greater proportions of *Notolabrus fucicola*, *Odax pullus*, *Parapercis colias Aplodactylus arctidens* and *Latridopsis ciliaris* hit the mesh filament than *Notolabrus celidotus* (Table 2). All of these species, except *O. pullus*, hit the 65 mm mesh more often than the larger two mesh sizes (Fig. 1). Only eleven (2%) of the 538 *N. celidotus* observed within one metre of the gill-nets hit the mesh and most of these hit the 65 mm mesh.

Species that hit the gill-nets frequently were caught more often ($r=0.962$, $p<0.01$, Table 2). Relatively high proportions of *Odax pullus* and *Aplodactylus arctidens* were caught, but capture frequency was independent of mesh size for these species, *Notolabrus fucicola* and *Latridopsis ciliaris* (Fig. 1). Only four (~1%) of the 538 *Notolabrus celidotus* observed within one metre of the gill-nets were caught and these were all in the 65 mm mesh (Table 2, Fig. 1). More *Parapercis colias*

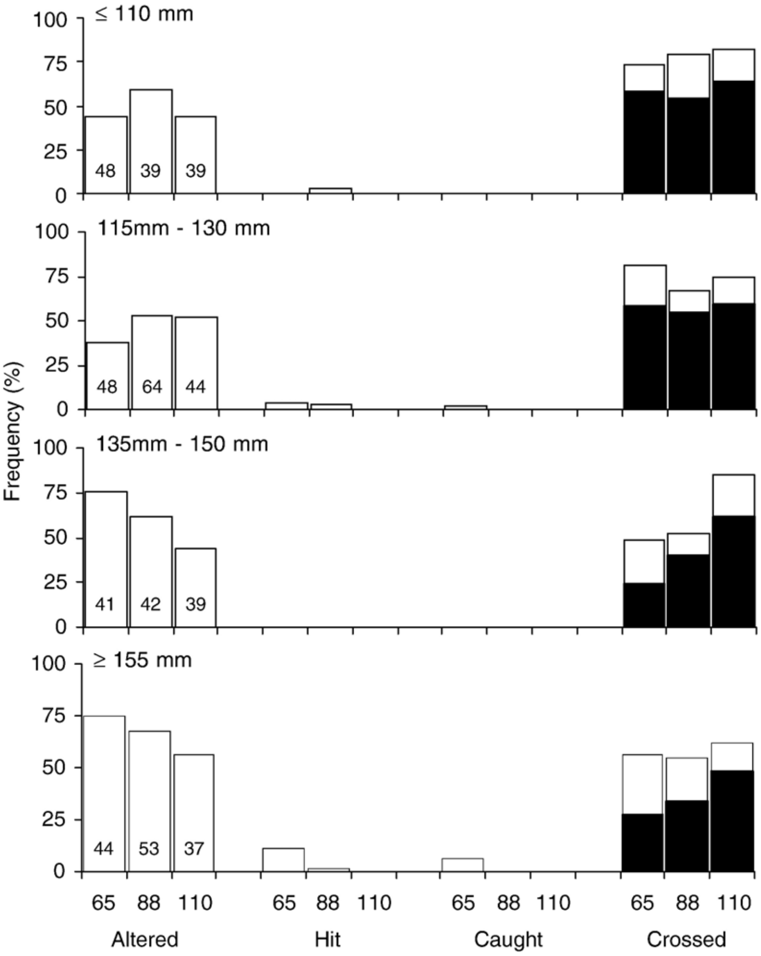

Fig. 3. The responses (categories from Table 2) of four size classes of *Notolabrus celidotus* to gill-nets of three mesh sizes (65 mm, 88 mm and 110 mm). Sample sizes are shown at the base of the first cluster of bars. For Crossed, the proportion that swam through the net is shown as solid.

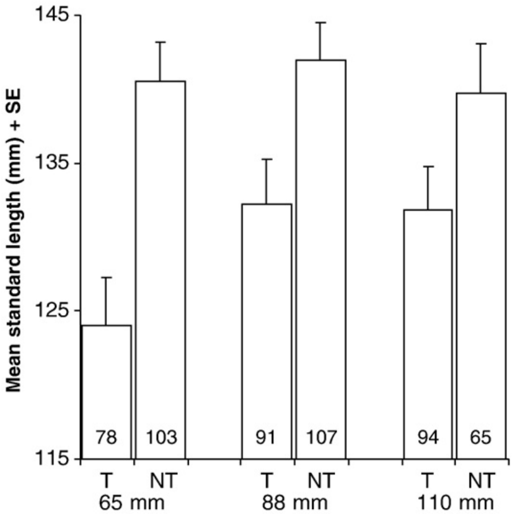

Fig. 4. The mean standard length of *Notolabrus celidotus* that swam through (T) and that swam over or turned away from (NT) gill-nets of three mesh sizes. Sample sizes are shown at the base of each bar.

were caught in the 65 mm mesh also. No *Nemadactylus macropterus* or *Parika scaber* were caught.

For all species except *Latridopsis ciliaris,* >50% of fish that were caught in a gill-net subsequently escaped (Fig. 1). The largest mesh size was poorest at retaining fish, with all of the *O. pullus* and *Parapercis colias* caught in the 110 mm mesh escaping (Fig. 1). Although all *Odax pullus* that hit a gill-net were caught, most subsequently escaped.

For all species except *Aplodactylus arctidens* and *Parika scaber*, ≥50% of fish crossed the line of the gill-net (Table 2). This was independent of mesh size for *Odax pullus* only (Fig. 1). In most cases, more fish crossed the line of the larger mesh sizes particularly the 110 mm gill-nets. Few *Parapercis colias* crossed the line of the 65 mm gill-net, and all that did went under the gill-net.

Parika scaber was the only species that did not have a high proportion of fish crossing the line of the gill-net by swimming through the mesh (Table 2). Again, this was independent of mesh size for *Odax pullus* only (Fig. 1). For all the other species, fewer fish swam through the mesh of the 65 mm gill-nets. All *P. scaber* that crossed the line of the gill-net did so by swimming over the mesh.

The amount of time fish spent within one metre of the gill-net differed between species ($F_{5,54}=2.83$, $p<0.05$) (Fig. 2). Only species with more than four fish observed near any one mesh size were included in this analysis. *Parika scaber* spent the longest time near the gill-nets, while *Odax pullus* spent the shortest. Mesh size had no significant influence on the length of time each species spent near the gill-net ($F_{2,54}=1.90$, $p=0.157$).

The two larger size classes of *Notolabrus celidotus* altered direction near the gill-nets (Partial $\chi^2=14.74$, $p<0.01$), particularly the 65 mm mesh ($\chi^2=31.53$, $p<0.001$), more often than the smaller size classes (Fig. 3). Low expected frequencies (<5) meant that the *N. celidotus* size class data could not be analysed with χ^2 for the proportions of fish hitting the gill-nets or being caught. Fewer large *N. celidotus* crossed the line of the gill-nets (Partial $\chi^2=17.05$, $p<0.001$), but this was not uniform across mesh sizes (Fig. 3). With the 65 mm and 88 mm gill-nets, approximately half the 135−150 mm size class crossed the line of the gill-net (Fig. 3). However, with the 110 mm mesh, most fish in this size class crossed the line of the gill-net. Most *N. celidotus* in the two larger size classes did not swim through the mesh, whereas most in the smaller size classes did (Partial $\chi^2=20.648$, $p<0.001$). Approximately half the ≥155 mm size class swam through the 110 mm mesh. However, most of the fish in this size class, and in the 135−150 mm size class, did not swim through the 65 mm and 88 mm meshes ($\chi^2=36.61$, $p<0.001$).

Notolabrus celidotus that swam through the gill-nets were smaller than those that swam over the gill-nets or turned away ($F_{1,532}=16.78$, $p<0.001$). This was consistent across all mesh sizes ($F_{2,532}=1.17$, $p=0.313$) (Fig. 4). Overall, the size of *N. celidotus* observed near the gill-nets did not differ with mesh size ($F_{2,532}=1.45$, $p=0.236$). However, fish that swam through the 65 mm mesh were smaller than those that swam through the other meshes (Tukey HSD, $p<0.05$).

4. Discussion

In our study there were significant differences among eight species of mobile reef fish in their responses to gill-nets. Some species, particularly the most abundant coastal labrid *Notolabrus celidotus*, are less susceptible than other species to becoming caught. The vulnerability of other species, particularly *Odax pullus*, and *Latridopsis ciliaris,* was a result of their use of habitat, swimming motion or morphology.

Notolabrus celidotus made up less than 15% of the fish caught during this study (and less than 4% of the 1749 fish caught in closely related studies (cf. Hickford and Schiel, 1995; Hickford and Schiel, 1996)) despite being the single most abundant mobile reef-dwelling fish species in New Zealand coastal waters (Ayling and Cox, 1987; Choat and Ayling, 1987). Fewer than 1% of the 538 *N. celidotus* observed within one metre of the gill-nets were caught. The fact that different size classes of *N. celidotus* had different responses to the gill-nets suggests that their interactions are actively controlled. *N. celidotus* that swam through the mesh of the 65 mm and 88 mm gill-nets were the smallest of those seen around the gill-nets. Very few *N. celidotus* hit the mesh of the gill-nets, clearly indicating avoidance by larger fish. Many *N. celidotus* swam through tears in the mesh and appeared to see individual mesh filaments. To divers, it appeared that this species could readily see the gill-nets and treated them as part of the seascape.

Visual acuity in *Notolabrus celidotus* probably relates to their feeding behaviour. Adults feed predominantly on small bivalves and crustaceans (Russell, 1983), picking them from kelp fronds and the substratum in highly heterogeneous environments. Daily foraging trips involve the negotiation of cracks, crevasses and holdfasts in the reef environment (Jones, 1984). This manoeuvring requires space awareness and fine-scale judging of distance, probably explaining the ease with which *N. celidotus* swam along, under and through gill-nets. The labriform swimming motion of *N. celidotus* also assists in avoiding capture because fish can reverse scull with their pectoral fins and swim backwards. Fish were seen doing this when contact was made with a gill-net.

Odax pullus is an herbivorous species that mostly swims beneath the algal canopy. This may be the primary cause of its vulnerability to being caught in gill-nets. The limited visibility among algal stipes probably prevents *O. pullus* from detecting a gill-net early and provides little time to avoid the mesh. Few fish of this species were observed to alter their swimming direction near the gill-nets and most fish appeared to hit the mesh at full cruising speed. Additionally, their fusiform body shape and sub-carangiform swimming motion also contribute to their vulnerability because they are unable to swim backwards out of a gill-net, and consequently drive forwards, often wedging themselves further into the mesh (Hickford and Schiel, 1996).

Latridopsis ciliaris are mostly caught in gill-nets, particularly smaller mesh sizes, by the mesh becoming tangled on their large fins and protruding fin rays (Hickford and Schiel, 1996). Like *Odax pullus*, they cannot swim backwards and try to push through the mesh, but because of their body shape can progress no further than their gills (Hickford and Schiel, 1996). Large *L. ciliaris*, with head girths too large to enter the mesh, were often seen trapped against a gill-net, held by nothing more than their own swimming motion propelling them into the mesh. Presumably many of these fish escape as a gill-net is pulled to the surface.

Notolabrus fucicola swim with a labriform motion, but this species hit the gill-nets more often than the other labriform species, *Notolabrus celidotus*. *N. fucicola* spend more time among kelp than *N. celidotus*, using the kelp and camouflage colouring as a defence against predators and foraging amongst holdfasts for food (Denny and Schiel, 2001; Russell, 1983). As for *Odax pullus*, this may reduce their ability to detect and avoid a gill-net. Furthermore, Jackson et al. (1983) noted that the facility with which a fish becomes wedged in a gill-net is generally a result of its momentum, which is in turn the product of the velocity and mass of the fish. These parameters are positively correlated with the size of fish (Marais, 1985). *N. fucicola* are generally larger than *N. celidotus* (Ayling and Cox, 1987), and are therefore likely to enter the mesh of a gill-net further than *N. celidotus*. The larger scales and more obtrusive gill covers of this species may also make it more vulnerable to gill-nets.

A high proportion of most species hit the 65 mm mesh gill-nets. This is surprising because although reaction distance is linearly related to the diameter of the mesh filament (Blaxter and Parrish, 1965) and the 65 mm mesh is constructed from the smallest diameter monofilament nylon (65 mm mesh: 0.36 mm, 88 mm mesh: 0.48 mm, 110 mm mesh: 0.59 mm), the 65 mm mesh also has more knots per unit area than the larger mesh sizes. Knots display a bright jewel-like glint, depending on the colour of the nylon, where parts of the knotted line are oriented parallel to the sea surface (Wardle et al., 1991). Therefore, although the thin nylon of the 65 mm mesh may be difficult for fish to see, the abundance of knots should be obvious. The fish that hit the 65 mm mesh may see the glint of the knots, but not recognise this as a gill-net and proceed to swim into it.

Data comparing the proportions of fish altering direction and swimming through the different mesh sizes suggests that the species that appear to be aware of the presence of a gill-net may also be able to determine whether they can fit through the mesh. Fewer fish altered their swimming direction within one metre of the 110 mm gill-net. This suggests that either they are unaware of the larger mesh size, or they are aware that they can swim through it. The fact that significantly fewer fish hit the 110 mm gill-net suggests the latter may be the case. The 110 mm mesh was constructed from larger filament with greater water resistance, possibly making it easier to see or sense.

There remains a possibility of learned avoidance behaviours to gill-nets. Ozbilgin and Glass (2004) suggested that conditioned responses could be developed following repeated exposure to fishing gear. Fish can be conditioned to respond to several different stimuli (Ferrari and Chivers, 2006; Larson and McCormick, 2005), including acoustic cues (Buwalda et al., 1983; Hawkins, 1986), so the possibility of some conditioned behaviour in species subject to intensive exploitation cannot be ruled out. Because so few *Notolabrus celidotus* are caught and most subsequently escape entanglement, avoidance behaviours could be reinforced in this species. Furthermore, that large and presumably more experienced individuals of *N. celidotus* more often altered direction near gill-nets indicates learning may play some role in reducing the susceptibility of this species to capture.

The species-specific responses of reef fish near the gill-nets and behavioural differences may explain the disproportionately low numbers of some common reef fish caught in gill-nets and the disproportionately high numbers of others. As fishing pressure increases, further knowledge of responses of fish to gill-nets and mesh sizes will aid in the management of communities of coastal fish and rocky reef ecosystems. Interestingly, fishers on coastal reefs in New Zealand generally use gill-nets to target *Odax pullus*, which do not take baited lines, and Cheilodactylids. Gill-nets are particularly good at catching these species, depending on mesh size. However, the potentially great ancillary effects from by-catch of important species of untargeted reef fish, birds and marine mammals make gill-nets a somewhat blunderbuss method of catching fish on coastal reefs, despite the behavioural acuity of many species.

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