Gillnetting in southern New Zealand: duration effects of sets and entanglement modes of fish

Michael J. H. Hickford
David R. Schiel
Department of Zoology, University of Canterbury
Private Bag 4800, Christchurch, New Zealand
e-mail address:Mike@zool.canterbury.ac.nz

Abstract.–This study examined the catch from gill nets set on nearshore rocky reefs around the Kaikoura Peninsula on the east coast of the South Island of New Zealand. The combined catch of 114 net sets of three net mesh sizes (2.5", 3.5", and 4.5") was analyzed for the mode of entanglement of captured fish and for duration effects on fish. Fusiform species were commonly gilled and wedged, whereas laterally compressed species usually became tangled by fins or spines; these patterns appeared to be a consequence of the behavioral and morphological characteristics unique to each species. The average fork length of caught fish increased with mesh size for gilled and wedged fish but not for those that were tangled. Within each mesh size, entangled fish tended to have the largest mean fork length, gilled fish were intermediate in mean fork length, and wedged fish had the smallest mean fork length. Nets of 2.5" mesh size caught the most fish over all set durations. There was no significant difference between a 6-hour set and a 15-hour set in the number of fish or number of species caught. The proportion of damaged fish in the landed catch was small for nets of all three mesh sizes set for six hours but increased markedly for set times that were longer. Clearly both mesh size, as well as morphological and behavioral differences between species affect the susceptibility of individual fish to gill nets.

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Different species of fish are not equally vulnerable to a given method of fishing. Gill nets, in particular, are highly selective in terms of the sizes and species of fish they catch (Hamley, 1975; Boy and Crivelli, 1988). There are many factors, however, other than the species or size of a fish that can influence the susceptibility of a fish to being caught in a gill net. Hamley (1975) listed these factors as the reaction of fish to nets, the different behavior of fish around nets, the type of net construction, the hanging coefficient, net saturation and characteristics of nets, such as their visibility, elasticity of meshes, and filament size. Dimensional characteristics of fishes, such as length-weight relationships (Kipling, 1957), length-condition relationships (Regier, 1969), and length-girth relationships (Kawamura, 1972), can also influence selectivity.

It is generally agreed that a given mesh size provides a size selection for a particular species that is characterized by a lower size limit, below which fish are small enough to pass through the mesh without hindrance, and by an upper size limit, above which fish are too large to enter the mesh and become entangled (Hamley, 1975). Between these limits the length-frequency distribution of the catch is approximately normal, with a mode at the length where the corresponding girth measure is slightly greater than the mesh perimeter (McCombie and Fry, 1960; Berst, 1961; Garrod, 1961; McCombie and Berst, 1969).

The number of fish caught in gill nets does not necessarily increase in direct proportion to the time that nets are in the water (Kennedy, 1951). Van Oosten (1935) showed that gill nets left for eight nights caught only 47 percent more fish than the same nets left for four nights, whereas if the catch increased in direct proportion to the time fished, the increase would have been 100 percent. The presence of captured, struggling fish and of dead fish may result in the efficiency of gill nets decreasing with time (Kennedy, 1951).

The analysis of catches of fish taken in gill nets is complicated by the passive nature of this type of fishing gear (Berst and McCombie, 1963). Several factors affect gill-net catches, such as the movement of fish, the shape and structure of the fish, and the associative pattern or grouping of the individuals of any species or assemblage of species (Moyle, 1950).

The aim of the present study was to analyse the size range and abundance of the most common fish species in gill-net catches from nearshore reefs in southern New Zealand. The data for this analysis were derived from the catch of nets used for comparison of reef fish populations previously assessed by visual survey (Hickford and Schiel, 1995) and from gill nets that were used for behavioral observations. By recording the morphological features of the catch, along with the form of entanglement, the primary factors that determine the vulnerability of individual species to particular mesh sizes could be identified. Analysis of the quantity and quality of the catch landed from gill nets set for various periods should yield an optimum set time that will maximize landings and reduce wastage.

Materials and methods

The gillnet catch analyzed in this study was pooled from several experiments. Consequently, the resulting sampling design is not orthogonal. The netting was done on rocky reefs around the Kaikoura Peninsula on the east coast of New Zealand's South Island (42°25'S, 173°42'E) from 8 January 1993 to 26 February 1993. The nets (Table 1) were set from a 6-meter runabout and hauled in by hand. Each net was set in a random direction and the ends were anchored with weights and marked with surface buoys. At least 10 meters separated any two nets. The nets were set on the bottom at depths ranging from 3 to 15 meters and for periods of 11–17 hours. At all sites the benthic habitat type had been described (Hickford and Schiel, 1995) and the fish populations had been surveyed with visual transects by divers immediately before the nets were set. At the end of all sets, the nets were placed in bins and brought back to the laboratory with fish still entangled in the mesh for analysis of the catch. The combined catch of 114 net sets of three mesh sizes over a single known habitat type (rocky pinnacles, mixed algae [Hickford and Schiel, 1995]) was analyzed.

As each fish was removed from the net, its species and fork length (mm) were recorded as was the method by which each fish had become trapped in the mesh. If a fish was held by the mesh encircling its body between the posterior edge of its operculum and the base of its pectoral fin, it was determined to have been "gilled." If the mesh encircling the body was posterior to the base of the pectoral fin, the fish was determined to have been "wedged." If a fish was held because mesh had snagged an appendage, such as the fins, spines, teeth, or maxilla, or if the fish's struggling had simply enveloped it in the mesh, it was described as "tangled." Careful handling of the nets resulted in very few "drop-outs" from the net. However, any fish that were loose in the net were excluded from subsequent entanglement analysis.

Entanglement data were collated for each species in each mesh size. Because the species composition of individual net sets was so variable and because many species were caught only in a small proportion of sets, the analyses of entanglement data were restricted to the five most commonly caught species. This produced a 5×3×3 contingency table, in which the number of fish caught were categorized according to species, mesh size, and entanglement mode. This table was analyzed by using a log-linear model that required thirteen iterations for the G-value to be minimized ($|\Delta G| < 0.001$; Sokal and Rohlf, 1981). The odacid *Odax pullus* was the only species caught in large enough numbers across most net sets for individual statistical analysis of entanglement to be done.

The duration of each net set was recorded. Two set times were chosen for analysis: a 6-h daytime set from late morning to late afternoon and a 15-h night set from late afternoon to early morning. The number of fish and number of species caught during each set were compared. A comparison of the capture rates of common species was also made between day and night sets and between mesh sizes. Each fish caught was given a condition index according to the degree of damage it had sustained while in the net (Table 2).

Results

The 114 net sets caught 1,165 fish from 14 families (Table 3). The odacid *Odax pullus* (46% of the total

Table 1

The dimensions of the gill nets used in fishing during this study. Mesh size is given in inches by the manufacturers and is measured as the diagonal length of a stretched mesh. Filament size is the diameter of the monofilament.

Net and mesh dimension	Measurement		
Net length (m)	30	30	30
Net height (m)	1.80	1.75	1.72
Mesh size (inches)	2.5	3.5	4.5
Filament size (mm)	0.36	0.48	0.58

Table 2

Descriptions of the indices used to categorize the condition of fish landed in gill nets.

Condition index	Damage
No damage	Chafing or scale loss from contact with gill net
Minor damage	Minor lesions; fin or eye damage
Major damage	Major lesions; flesh loss or sea lice damage
Severe damage	Loss of skeletal material

Table 3

The species, common name, fisheries code, and number of fish caught in each of the three mesh sizes and in total. The number of individual net sets are shown in parentheses under the mesh size.

Family and species	Common name	Fisheries code	No. of fish, Mesh size 2.5" (29)	3.5" (30)	4.5" (55)	Total no. (114)
Myliobatidae						
Myliobatis tenuicaudatus (Hector, 1987)	Eagle ray	EGR	0	1	0	1
Moridae						
Lotella rhacinus (Bloch and Schneider, 1801)	Rock cod	ROC	2	1	0	3
Pseudophycis bachus (Bloch and Schneider, 1801)	Red cod	RCO	2	4	1	7
Carangidae						
Pseudocaranx dentex (Bloch and Schneider, 1801)	Trevally	TRE	0	0	1	1
Trachurus declivis (Jenyns, 1841)	Jack mackerel	JMA	1	1	2	4
Arripidae						
Arripis trutta (Bloch and Schneider, 1801)	Kahawai	KAH	88	6	13	107
Aplodactylidae						
Aplodactylus arctidens Richardson, 1839	Marblefish	GTR	56	45	19	120
Cheilodactylidae						
Cheilodactylus spectabilis (Hutton, 1872)	Red moki	RMO	0	0	5	5
Nemadactylus macropterus (Bloch and Schneider, 1801)	Tarakihi	TAR	0	1	0	1
Latrididae						
Latridopsis ciliaris (Bloch and Schneider, 1801)	Blue moki	MOK	115	40	29	184
Latridopsis forsteri (Castelnau, 1872)	Copper moki	CMO	0	4	2	6
Latris lineata (Bloch and Schneider, 1801)	Trumpeter	TRU	2	0	0	2
Mendosoma lineatum Guichenot, 1849	Telescope fish	TEL	1	0	0	1
Mugilidae						
Aldrichetta forsteri (Cuvier and Valenciennes, 1846)	Yellow-eyed mullet	YEM	22	1	0	23
Labridae						
Notolabrus celidotus (Bloch and Schneider, 1801)	Spotty	STY	7	0	0	7
Notolabrus fucicola (Richardson, 1840)	Banded wrasse	BPF	46	7	5	58
Pseudolabrus miles (Bloch and Schneider, 1801)	Scarlet wrasse	SPF	2	2	0	4
Odacidae						
Odax pullus (Bloch and Schneider, 1801)	Butterfish	BUT	462	72	7	541
Pinguipedidae						
Parapercis colias (Bloch and Schneider, 1801)	Blue cod	BCO	6	3	1	10
Gempylidae						
Thyrsites atun (Euphrasen, 1791)	Barracouta	BAR	0	1	0	1
Istiophoridae						
Seriolella brama (Günther, 1860)	Blue warehou	WAR	45	31	1	77
Monacanthidae						
Parika scaber (Bloch and Schneider, 1801)	Leatherjacket	LEA	0	0	2	2
		Total	857	220	88	1,165

catch), the latrid *Latridopsis ciliaris* (16%), and the aplodactylid *Aplodactylus arctidens* (10%) represented most of the total catch. For the five most commonly caught species, the degree of association between mesh size and method of capture differed for different species (G=81.395, $\chi^2_{0.05[16]}$=26.296, P<0.001). For example, the coastal labrid *Notolabrus fucicola* was mostly gilled in the 2.5" mesh; few of these fish were caught in the larger mesh sizes, and few were caught by wedging and tangling (Table 4). In contrast, the large, slow-moving latrid *L. ciliaris* was mostly tangled in the 2.5" mesh, gilled and tangled in approximately equal numbers in the 3.5" mesh, and mostly gilled in the 4.5" mesh. *Odax pullus* was mostly gilled in the 2.5" and 3.5" meshes and few were caught in the 4.5" mesh. The bottom-dwell-

Table 4
Observed catch frequencies by mode of entanglement for five commonly caught species.

Species	Mesh (inches)		Observed catch			
			Gilled	Wedged	Tangled	Total
Notolabrus fucicola	2.5		39	4	1	44
	3.5		4	1	1	6
	4.5		2	1	1	4
		Total	45	6	3	54
Odax pullus	2.5		317	74	41	432
	3.5		35	25	3	63
	4.5		2	1	1	4
		Total	354	100	45	499
Aplodactylus arctidens	2.5		18	5	28	51
	3.5		24	14	4	42
	4.5		5	10	2	17
		Total	47	29	34	110
Arripis trutta	2.5		61	13	9	83
	3.5		1	1	3	5
	4.5		4	1	3	8
		Total	66	15	15	96
Latridopsis ciliaris	2.5		18	11	60	89
	3.5		15	1	19	35
	4.5		16	5	3	24
		Total	49	17	82	148

ing *A. arctidens* was mostly tangled in the 2.5" mesh, but most fish were gilled and wedged in the 3.5" and 4.5" mesh sizes. The pelagic *Arripis trutta* was mostly gilled in the 2.5" nets, but the number of fish gilled and tangled was approximately equal in the 3.5" and 4.5" nets.

Overall, the mean fork length of each species increased with mesh size for gilled, wedged, and tangled fish (Fig. 1). For example, the mean fork length of gilled *Arripis trutta* was 240 mm in the 2.5" mesh, 310 mm in the 3.5" mesh, and 505 mm in the 4.5" mesh. There was a similar pattern for this species for tangled fish that averaged 460 mm, 560 mm, and 580 mm for the three mesh sizes respectively. There was considerable variation among species in their size interaction among mesh sizes and form of entanglement. However, for most species within each mesh size, the general pattern was that tangled fish had the largest mean fork length, gilled fish had an intermediate mean fork length, and wedged fish had the smallest mean fork length.

There was a clear transition in the proportion of *Odax pullus* captured by each mode as fork length increased in both the 2.5" and 3.5" mesh sizes (Fig. 2). Too few *O. pullus* were caught in the 4.5" mesh for analysis. Gilled fish were significantly larger than wedged fish ($F_{1,104}$=35.77, P<0.001) in both the 2.5" and 3.5" nets. In the 2.5" mesh, tangled fish were significantly larger than gilled fish ($F_{2,453}$=78.41, P<0.001). Overall, the 3.5" mesh caught significantly larger fish than did the 2.5" mesh ($F_{1,104}$=453.36, P<0.001).

With respect to set duration, the 2.5" mesh caught significantly more fish (all species) than the other mesh sizes over both 6 and 15 hours ($F_{2,12}$=36.96, P<0.001) but there was no significant difference between the two set durations in the number of fish caught (Fig. 3A). The 2.5" mesh size also caught a significantly greater number of species over both set durations ($F_{2,12}$=7.60, P=0.007). Again, there was no significant difference between the two set durations in the number of species caught (Fig. 3B).

There was variation among species in the number of fish caught at different set durations (Fig. 4, A–D). The 2.5" mesh caught significantly more *Odax pullus* per hour over both set durations ($F_{2,12}$=5.40, P<0.05). However, there was no significant difference between the two set times in the number of *O. pullus* caught per hour ($F_{2,12}$=3.57, P=0.08). There was also no significant difference between the three mesh sizes

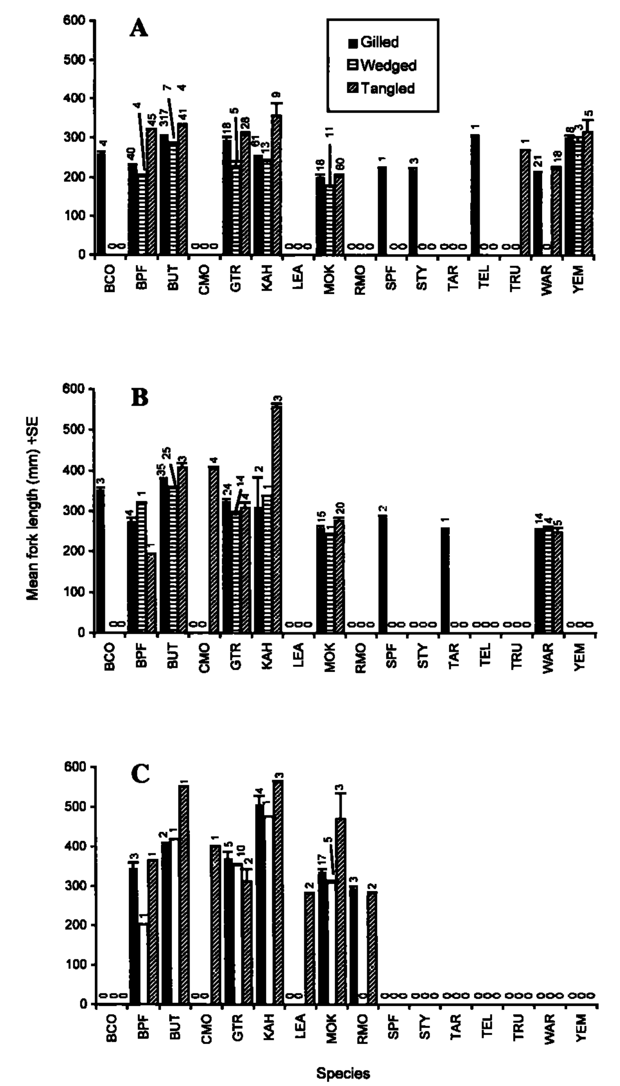

Figure 1

The mean fork length (+1 SE) of fish captured by each entanglement mode in the (A) 2.5" mesh, (B) 3.5" mesh, and (C) 4.5" mesh. n = the number of fish from each species caught in each method. See Table 3 for species codes.

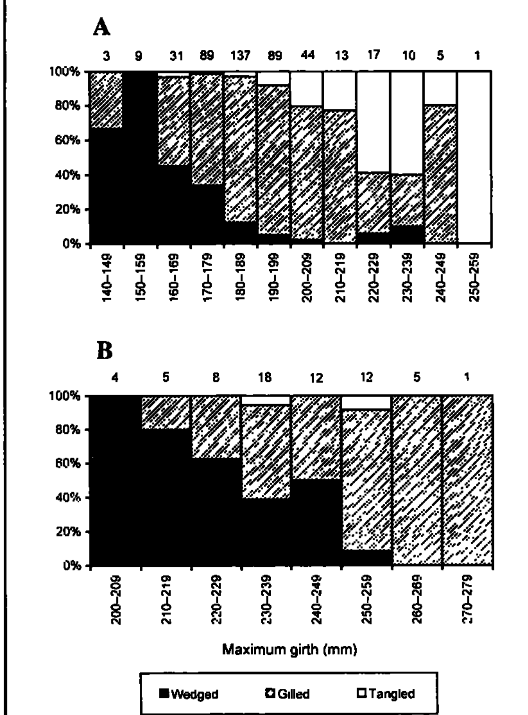

Figure 2

Proportion of butterfish, *Odax pullus*, caught by each entanglement mode in the (A) 2.5" mesh and (B) 3.5" mesh. n = the number of fish in each size class.

or the two set durations in the number of *Aplodactylus arctidens*, *Latridopsis ciliaris*, or *Arripis trutta* caught per hour (all F values were not significant).

The proportion of damaged fish in the landed catch was small for nets of all three mesh sizes set for six hours but increased markedly for the longer set times (Fig. 5). ANOVA of the condition index of 16 fish selected randomly from each mesh size and each set time showed that fish were significantly more damaged in the longer sets ($F_{1,90}$=19.23, P<0.001), but there was no significant difference among the three mesh sizes in the degree of damage suffered by landed fish ($F_{2,90}$=2.76, P=0.069).

Discussion

Each species showed a distinctive pattern in its form of entanglement in the three mesh sizes. These patterns appear to be a consequence of the behavioral and morphological characteristics unique to each species. For example, *Arripis trutta* were caught mainly by being gilled in the nets. This species is a pelagic carnivore that is dependent on a strong swimming thrust for catching prey. Once gilled, they would be expected to drive forward firmly into the net and to become wedged. The low number of wedged fish for this species may be a result of their firm flesh, which is not easily compressed by the mesh and which may prevent them from entering the net further. Larger fish, despite their greater swimming thrust (Lander, 1969), cannot enter the small mesh sizes far enough to become wedged.

Odax pullus were mostly gilled and wedged in the nets. The low number of *O. pullus* that become tangled was likely the result of the soft fin rays, fused teeth, and small scales typical of this species (Paulin et al., 1989), all of which offer little that will snag on

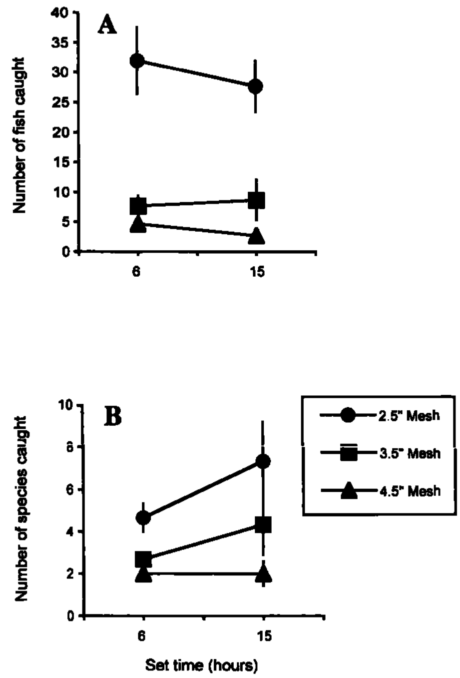

Figure 3
The mean number of fish (A) (±1 SE) and the mean number of species (B) (±1 SE) landed by the three mesh sizes against time.

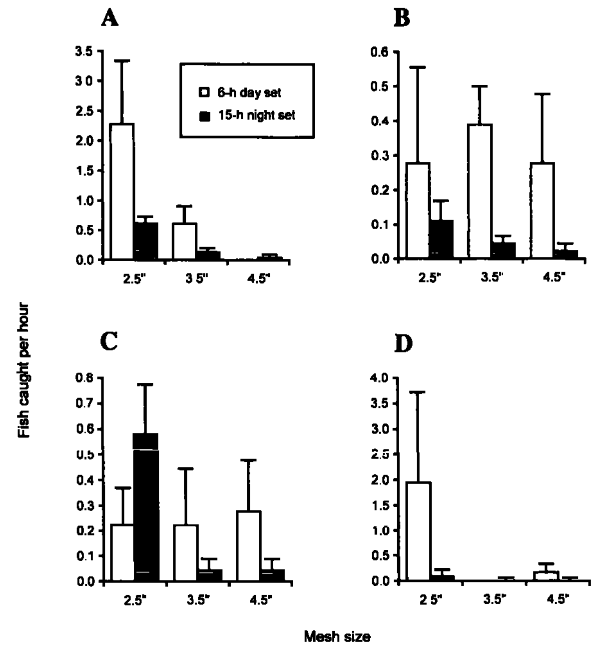

Figure 4
The mean number of fish caught per hour (+1 SE) for four common species in three mesh sizes and in two set durations.

the mesh. However, several other characteristics unique to *O. pullus* make this species very vulnerable to capture by gill nets. The fusiform body shape of this species allows even large individuals to enter the mesh of a gill net to about half their body length before further forward movement is prevented. Their sinuous swimming motion and weak pectorals do not allow them to swim backwards out of a gill net or to stop quickly. This, coupled with the tendency of *O. pullus* to swim below the algal canopy where they are likely to have difficulty detecting the mesh, makes this species one of the most vulnerable to gill nets.

Aplodactylus arctidens were mostly gilled and tangled when caught in the nets. This mode of capture may be due to the strong dorsal spines in this species' anterior dorsal fin which prevent the mesh from passing further along the fish's body. The differences between mesh sizes in the proportions of *A. arctidens* caught by each method may be a result of mesh selectivity. The great number of fish tangled in the 2.5" mesh is probably a result of larger fish becoming tangled by their fins and spines. Small fish caught initially in equivalent numbers in the larger mesh sizes are able to pass through the net unhindered.

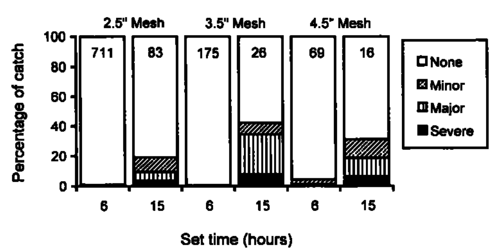

Figure 5
The percentage composition of the catch from nets of three mesh sizes in terms of condition of fish after various set times. n = the number of fish landed by each mesh size after each set duration. See Table 2 for damage categories.

Notolabrus fucicola, a labrid species, were mostly gilled when caught in the nets. This is likely to be a result of their labriform swimming motion, which enables them to swim backwards out of the net rather than having to force their way through the mesh. If a labrid's backward motion is not prevented by its gills becoming snagged, it invariably escapes from the mesh. Labrids have also been observed to display a unique rolling motion when first tangled in the net (Hickford and Schiel, 1995), a motion that often results in a fish freeing itself from the net.

The deep-bodied *Latridopsis ciliaris* were mostly tangled and gilled. The small number of this species that were found wedged in net mesh is probably due to none of the mesh sizes being large enough to allow larger blue moki to enter the nets any further than their gills. The significantly greater number of fish tangled in the 2.5" mesh is a result of larger fish becoming tangled by their large fins and protruding fin rays. Large, laterally compressed fish, such as *L. ciliaris* and *Nemadactylus macropterus*, are not strong swimmers (Doak, 1991). They rely on muscular undulations from head to tail in order to swim, and they brake with their pectoral fins. This weak swimming ability, coupled with their large spiny fins, resulted in *L. ciliaris* often becoming entangled by a single fin rather than being truly enmeshed in the net.

Winters and Wheeler (1990) stated that the difference in fishing power between nets of various mesh sizes may be a result of differences in the proportion of fish caught by each entanglement mode in each mesh size. They stated that the three modes of capture have different fishing powers that may vary with mesh size, but in general, wedging is more effective than gilling, and both these modes are much more effective than tangling. However, the results of our study show that for total fish numbers caught in all mesh sizes combined, most fish were gilled (60%), whereas wedged (17%) and tangled (23%) fish made up significantly lower proportions of the catch. This result suggests that, in the case of our study, gill nets do in fact "gill" fish rather than capture them by tangling or wedging.

Mesh-size selectivity was evident from the mean length of fish captured by each method in each mesh size. Although the fork length of gilled and wedged fish increased with increasing mesh size, the fork length of tangled fish was less uniform in its relationship with mesh size.

The results of our study show that tangling is not the result solely of size selection and is not consistent across mesh sizes. The proportions of *Odax pullus* caught by each method, when plotted against fork length, show a clear transition as fork length increases from most fish being wedged to the majority being tangled. This transition would not occur if the size of tangled fish were independent of mesh size, because fish of all sizes would then become tangled in any given mesh size.

Although the concept of gill net "saturation," or diminishing returns with increasing effort, is generally recognized as a limiting factor in catch per unit of time (Minns and Hurley, 1988), there have been relatively few studies directed at exploring the mechanisms that limit the catch. Our study shows evidence of a set-time saturation effect with all three mesh sizes. Neither the number of fish caught nor the number of species caught were significantly different between the six and fifteen hour sets. However, these different set times had only a small overlap diurnally and saturation may have been influenced by differing periods of fish activity. There was no evidence in either the gill nets or in both underwater observations and videos (Hickford and Schiel, unpubl. data) that predators affected catches.

Space limitation in the gill net itself is regarded as a major component of the saturation effect. Once a fish has been captured, the particular cell that it occupies and the cells immediately surrounding it are not capable of catching other fish. Koike and Takeuchi (1982) examined this feature and found that fish were repulsed around a captured individual for some but not all mesh sizes. Kennedy (1951) cited additional ways in which the efficiency of a gill net decreases with time. These included the presence of captured, struggling fish (which makes the net more obvious and could frighten other fish away) and the presence of dead fish (which may cause other fish to avoid the area). Kennedy speculated that the greater the catch during the initial time period, the greater the difference between the initial (observed) and final (expected) catches.

The effect of set time on total and species catches in gill nets has a direct bearing on the use of this gear in assessing the abundance and species diversity of fish populations. Some studies have focused on comparing multi- to one-night catches (Richards and Schnute, 1986; Minns and Hurley, 1988).The evidence presented here, however, suggests that net saturation can occur during a single night, although this may be confounded by the varying behaviors of the fish species present.

The apparent similarity in catch rates of *Odax pullus*, *Arripis trutta*, *Aplodactylus arctidens*, and *Latridopsis ciliaris* during day and night sets was unexpected. These species are more active during the day and would be expected to be caught in significantly greater numbers in the day sets. Greater average numbers of these species were caught during the daytime, but the catches were so variable that any patterns may have been masked.

The condition of fish in the landed catch is closely related to the length of time a net is in the water. The catch of nets set for longer than six hours will contain a high proportion of damaged fish. The relation between set time and condition is confounded by the fact that nets set for periods longer than six hours were usually left in the water overnight. During the hours of darkness, lobsters (*Jasus edwardsii*) feed more actively (Gunson, 1983) and can severely damage fish. However, lobsters often become tangled in nets while feeding on dead or dying fish in the bottom region of the nets and were frequently caught during nighttime sets in this study. Most intertidal and subtidal marine isopods also peak in their activity rates during the hours of darkness (Jones and Naylor, 1970; Fincham, 1973). Sea lice can completely devour all but the skin and calcified structures of a fish. The fact that both these predators feed predominantly at night means that damage incurred by fish would be greater for overnight sets.

In our study, few fish were damaged in the six hour sets, but up to 40% of fish were damaged in the fifteen hour sets. Therefore, any increase in the number of fish caught beyond six hours may be offset by more fish being severely damaged.

Gill nets do not representatively sample the fish population at reef sites; none of the species in this study was caught in its proportional occurrence in nearshore habitats (Hickford and Schiel, 1995). Behavioral traits, such as swimming motion, and morphological characteristics, such as spines or large fins, act to make some species more vulnerable than others to the fishing action of gill nets. The 2.5" mesh is clearly the most effective at catching most species of fish and is particularly effective at capturing juvenile and resident reef fish. Nets of this small mesh size are commonly available to amateur fishermen in New Zealand, who use them in nearshore waters. Our study clearly shows that although commercially valuable species, such as *Odax pullus, Latridopsis ciliaris,* and *Arripis trutta,* can be caught in great numbers around coastal reefs, the bycatch of resident species, such as *Aplodactylus arctidens, Notolabrus fucicola,* and a broad range of others, is considerable. Most of these species are of no commercial value, but their removal from nearshore waters may well have long-term consequences on resident fish populations in areas where considerable gill netting occurs, such as around the Kaikoura Peninsula.

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