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REPORT

A quantitative comparison of recreational spearfishing and linefishing on the Great Barrier Reef: implications for management of multi-sector coral reef fisheries

A. J. Frisch · R. Baker · J-P. A. Hobbs · L. Nankervis

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Abstract This study compared the catch composition, catch per unit effort, and incidental impacts of spearfishers and linefishers engaged in a structured fishing program whereby fishing effort was standardized across time, space and skill level. It was found that (1) the catch composition of both groups of fishers overlapped considerably, (2) the numbers of target fish caught by spearfishers (156) and linefishers (168) were not significantly different, (3) the mean size of target fish caught by spearfishers (1.95 ± 0.1 kg, ±SE) was significantly larger than the mean size of target fish caught by linefishers (1.27 ± 0.06 kg), and (4) spearfishers retained 43% more biomass of target species than did linefishers (304 versus 213 kg, respectively). However, linefishers used ~1 kg of bait for every 3 kg of target fish that were captured. Linefishers also caught far more undersized, undesirable, or protected fishes (i.e., bycatch) and caused far more pollution (i.e., lost gear) than did spearfishers. It is concluded that the overall impacts of recreational spearfishing and linefishing on fishery resources of the Great Barrier Reef are broadly equivalent (per unit of fishing effort), and that management regulations should be applied equitably across both fishing sectors. A management strategy of this type will simplify enforcement of fisheries regulations and avoid discrimination of particular fishers in local communities where both fishing methods are socially or culturally important.

Keywords Spearfishing · Linefishing · Catch per unit effort · Selectivity · Coral trout · Bycatch

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Introduction

Overfishing is deemed to be one of the greatest threats to the future of coral reefs (Jackson et al. 2001; Bellwood et al. 2004; Newton et al. 2007). Understanding and managing the effects and yields of reef fisheries is therefore crucial for conserving coral reefs, and for bringing wealth and stability to the tens of millions of people who use or depend on coral reefs as a source of food or income (Pauly et al. 2002; Newton et al. 2007). An important step in this direction is to understand how various fishing methods impact upon both target and non-target organisms.

Two of the most common reef-fishing methods used in the Indo-Pacific region are linefishing, otherwise known as angling, and spearfishing (Hundloe 1985; Wright and Richards 1985; Dalzell et al. 1996; Pet-Soede et al. 2001; Cinner and McClanahan 2006). Linefishing typically involves the use of a baited steel hook attached to a weighted nylon line. Spearfishing typically involves the use of a rubber-propelled spear, as well as associated dive gear such as mask, snorkel and fins. Although SCUBA is used in a few places, the vast majority of spearfishing is performed by breath-hold divers (Dalzell et al. 1996; Gillett and Moy 2006). In most places, both linefishing and spearfishing are conducted from small (4 to 6 m), outboard-powered boats with 1–5 fishers per boat (Hundloe 1985; Wright and Richards 1985; Myers 1993; Dalzell et al. 1996).

Even in developing nations, most reef fishers have the option of either spearfishing or linefishing, since both methods are relatively simple and require little capital investment (Dalzell et al. 1996). In places where management regulations exist (e.g., Australia), spearfishing and linefishing tend to be managed uniformly (i.e., the same input and output controls), mainly because of the lack of specific information pertaining to each fishing method. However, it is crucial for reef fishery managers to acquire intimate knowledge of the selectivity, catch per unit effort (CPUE) and incidental impacts of both spearfishing and linefishing. This is to enable formulation and implementation of fishing regulations that (1) ensure target species are exploited on a sustainable basis, (2) encourage fishing methods that minimize bycatch, habitat degradation, and fishing-associated pollution, and (3) allow shared fishery resources to be allocated equitably among different user groups (King 1995; Walters and Martell 2004). Given the current concern over the sustainability of reef fisheries (Pauly et al. 2002; Bellwood et al. 2004; Newton et al. 2007), there are remarkably few studies on the relative impacts of spearfishing and linefishing with respect to coral reef species (McClanahan and Mangi 2004).

Because spearfishers choose the fish they shoot, this form of fishing is regarded as highly selective, both in terms of species and size (Dalzell 1996; Mann et al. 1997; Harper et al. 2000). One advantage of this selectivity is that spearfishing has minimal impact on non-target species (Eckersley 1997). Another noteworthy characteristic of breath-hold spearfishing is that it is limited to shallow water. Hence, the proportion of target fishes available to spearfishers is typically less than the proportion available to linefishers (Mann et al. 1997). Despite this limitation, spearfishing is often perceived to be more efficient (in terms of CPUE) than linefishing (Long 1957; Eckersley 1997; Gillett and Moy 2006), although this is yet to be substantiated. The range of previous estimates of CPUE for spearfishing and linefishing overlap considerably (Hundloe 1985; Wright and Richards 1985; Dalzell 1996; Dalzell et al. 1996; Harper et al. 2000; Pet-Soede et al. 2001; McClanahan and Mangi 2004). Furthermore, these estimates vary (within method) by at least an order of magnitude. This variability is probably attributable to the fact that data were collected at different times and places, using different types of fishers (commercial, artisanal, subsistence or recreational). Additionally, most of the data were collected indirectly, either by boat-ramp surveys, which tend not to accurately quantify fishing effort (Wright and Richards 1985), or by questionnaires and personal logbooks, techniques that are often biased and unreliable (Tarrant and Manfredo 1993; King 1995; Connolly and Brown 1995). Together, these problems prevent meaningful, quantitative comparisons of spearfishing and linefishing using available data.

The aim of this study, therefore, was to compare the catch composition, CPUE and incidental impacts of recreational spearfishing and linefishing in the context of a coral reef fishery. To do this, small teams of spearfishers and linefishers were engaged in a program of structured fishing on the Great Barrier Reef (GBR), Queensland, Australia. Importantly, both groups of fishers participated concurrently at the same reef site, thereby avoiding any spatial or temporal biases. Also, catch and effort data were recorded directly (i.e., “on site”) to maximize accuracy.

Materials and methods

Field surveys

Two teams of fishers, one consisting of two linefishers (one hook and line per person) and the other consisting of two spearfishers (one spear or speargun per person; no SCUBA) conducted normal fishing activities aboard two small (4–6 m) boats (one team per boat). To standardize fishing effort among teams and over time, linefishers and spearfishers operated concurrently during synchronized “sessions” which were 1.5 h in duration. A total of 45 sessions were conducted during twelve one-day “trips” (3–4 sessions per trip) that were spread across 14 months (May 2005 to July 2006). Consecutive sessions during the same trip were separated by a short recess (0.25–1 h) and all sessions were completed between 0800 and 1700 hours. Given that some locations may favor one or other fishing method (Long 1957; Connell and Kingsford 1998), each session was conducted at a different site (i.e., an arbitrary area of coral reef that was approximately 1 km^2). Sites were chosen haphazardly and both teams fished the same site at the same time. Sites were spread across seven coral reefs in the Townsville region of the GBR (Fig. 1) where local fish assemblages are considered to be relatively intact (Pandolfi et al. 2003; Wilkinson 2004). For a complete description of the habitat, as well as estimates of the distribution and abundance of target fish species, see Done (1982) and Newman et al. (1997). To standardize access to reef habitats at each location, fishing was restricted to depths of $\leq$15 m (approximately the maximum working depth of most spearfishers). Since the focus of this study was on reef fishing, all participants were discouraged from targeting pelagic species such as mackerel (*F. Scombridae*) and trevally (*F. Carangidae*).

Sampling considerations

Most popular food fishes are non-uniformly distributed across small spatial scales (Newman et al. 1997; Connell

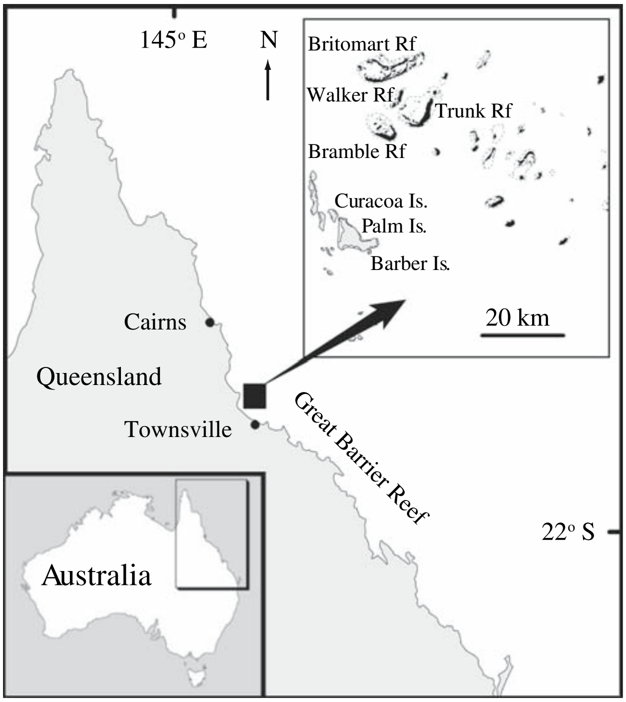

Fig. 1 Map of the study area. Fishing effort was spread across seven reefs (see *inset*, *upper right*) in the Townsville region of the Great Barrier Reef, Australia

and Kingsford 1998), a source of variability that may confound potential differences between fishing methods. Thus, it would have been desirable to engage multiple boats per fishing method. This was not possible, however, because only two boats were ever available at any one time. Nonetheless, the use of only one boat per method was considered unlikely to alter the project's outcomes because (1) both teams of fishers were highly mobile and thus capable of moving to a new location (within each site) if local fish abundances were considered unsatisfactory, and (2) any advantage or disadvantage to one or other method was likely to be limited to a single session and each session constituted only a small proportion (2.2%) of total effort. It should also be noted that the number of fishers per boat was limited to two, thereby allowing estimation of intra-method variability while minimizing the potential for bias associated with competition between fishers in the same boat.

Given that catch rates are greatly influenced by a fisher's skill (Hundloe 1985; Lincoln-Smith et al. 1989; Mann et al. 1997), fishing ability was standardized by selecting only those people who (1) regarded themselves as competent fishers, (2) had several years of experience in the relevant fishing method, and (3) had been reef fishing within the last 6 months. Also, as many different fishers as could be recruited were engaged in the study. Hence, there were nine different fishers per method ($N = 18$), and the median number of trips per fisher was two.

Data collection

The identity, size, number and fate of all captured fish were recorded shortly after capture (n.b. a fish was defined as any vagile fishery resource, including finfish, crustaceans and cephalopods). Where possible, fish were identified to species level according to Randall et al. (1990) or Jones and Morgan (1994). Some of the less abundant species were identified to the genus or family level only. Body size (±0.5 cm) was recorded as total length (TL), carapace length (CL) or mantle length (ML) for finfish, crustaceans and cephalopods, respectively, and the fate of each fish was categorized into one of the following groups: A = kept to eat; B = kept for bait; C = released in good condition (i.e., no major injury and able to swim without difficulty); D = released or escaped in poor condition (includes any animal that sustained spear-induced injuries); E = discarded dead. Fish that were temporarily hooked on a line but escaped before landing were disregarded. Incidental impacts of fishing were also recorded. This included the amount of pollution (lost gear), the quantity of bait used, and the number of times that fishers deployed their vessel's anchor (i.e., the number of "hangs").

Data analysis

Fish catches were compared in terms of the taxonomic composition, number, length and weight of fish, the latter of which was estimated using length–weight conversion formulae (Kulbicki et al. 2005; Froese and Pauly 2007). If this information was not available (or the species could not be identified), the conversion formula of a morphometrically-similar, congeneric species was used. Importantly, formula substitutions were considered unlikely to influence overall results because relevant fish were rare and constituted only a small proportion of the total catch.

The numbers of fish retained by each fisher group were compared using a χ^2 goodness-of-fit test, while length–frequency distributions of target species were analyzed using a Kolmogorov–Smirnov test (Zar 1999). A Student's t test was used to compare mean fish weights, although data were initially transformed ($\log_{10}[x + 1]$) to overcome heteroscedasticity (Zar 1999). A Student's t test was also used to compare mean CPUEs of legal (≥minimum legal size; MLS) fish, both in terms of the number and biomass of captured fish. To calculate CPUE, the number or biomass of fish that were captured during each 'trip' was divided by the amount of time spent fishing, thus giving units of either fish h^{-1} or kg h^{-1} (per fisher).

To determine which factor(s) had the greatest influence on fish catches, least-squares classification and regression tree (CART) analysis was used to examine the CPUE of legal fish (excluding bycatch) in relation to trip, fisher and method (De'ath and Fabricius 2000). This type of analysis successively "splits" the data into increasingly homogenous clusters by minimizing the residual sums of squares for each split, analogous to least squares regression (De'ath and Fabricius 2000). In separate analyses, the CPUE of all legal fish and of legal coral trouts (*Plectropomus* spp.) only, were used as dependant variables, while combinations of trip, fisher and (in all analyses) method were used as explanatory variables. In each case, the "best" tree models were chosen by bootstrapped cross-validation using both the minimum and minimum + one standard error (1SE) rules (Breiman et al. 1984). Coral trouts were analyzed separately as a single group because all species of *Plectropomus* are equally sought-after and many fishers cannot distinguish between them (Frisch and van Herwerden 2006).

CART analyses were performed using S-PLUS 2000 computer software with the TREEs Plus supplement (Mathsoft, Seattle, USA). All other statistical analyses were performed using SPSS computer software (SPSS, Chicago, USA). For each test, the relevant assumptions were checked a priori and a significant difference was considered to exist if $P < 0.05$ (Zar 1999). All data listed in the text and figures are the (untransformed) arithmetic mean ± 1SE.

Results

Catch composition

A total of 648 fish from ≥45 species were captured during 135 h of spearfishing and linefishing (Table 1). Spearfishers caught 163 fish belonging to 21 species, while linefishers caught 485 fish belonging to ≥32 species. Most (65%) of the line-caught fish were regarded as bycatch (Table 1). This included large numbers (140) of blue-spotted rockcod (*Cephalopholis cyanostigma*) as well as two each of barramundi cod (*Cromileptes altivelis*) and red bass (*Lutjanus bohar*), both of which are protected by law (Anon. 2003). Most of the bycatch was subsequently released, although some species were often used as bait (predominantly fusilier, *Caesio cuning*). Excluding bycatch and bait, the numbers of fish retained by spearfishers (156) and linefishers (168) did not differ significantly from a 1:1 ratio (Table 2).

For both groups of fishers, the retained portion of the catch was dominated by coral trouts: *Plectropomus leopardus*, *Plectropomus maculatus* and *Plectropomus laevis* (Fig. 2). Together, these three species comprised 62% of spearfishers' catch and 73% of linefishers' catch (excluding bycatch). Aside from coral trouts, spearfishers also caught significant quantities of spiny lobsters (F. Palinuridae; 17%), rockcods (F. Serranidae; 6%), parrotfish (F. Scaridae; 6%) and snappers (F. Lutjanidae; 4%). In contrast, linefishers caught (and retained) notable quantities of snappers (14%) and emperors (F. Lethrinidae; 11%), but they did not catch any spiny lobsters, parrotfish or legal-size rockcods (Fig. 2).

Size distribution

The mean weight of fish caught by spearfishers (1.95 ± 0.1 kg, ±SE) was significantly greater than the mean weight of fish caught by linefishers (1.27 ± 0.06 kg, excluding bycatch) ($t_{322} = 7.0$, $P < 0.001$) (Table 2). Similarly, the total biomass of fish retained by spearfishers (304 kg) was greater than the total biomass of fish retained by linefishers (213 kg, excluding bait). With regard to the dominant target species (*Plectropomus* spp.), the mean length of individuals caught by spearfishers (48.9 ± 0.7 cm TL) was significantly greater than the mean length of individuals caught by linefishers (42.9 ± 0.5 cm TL) ($t_{258} = 6.9$, $P < 0.001$) (Fig. 3). Approximately 23% of *Plectropomus* caught by linefishers were below the MLS, while only 3% of *Plectropomus* caught by spearfishers were below the MLS. The length–frequency distributions of *Plectropomus* captured by spearfishers and linefishers were significantly different (Kolmogorov–Smirnov $Z = 3.14$, $P < 0.001$) (Fig. 3). This result did not change even when undersize (<MLS) *Plectropomus* were excluded from the analysis (Kolmogorov–Smirnov $Z = 2.38$, $P < 0.001$).

Catch per unit effort

The CPUE of spearfishers (1.08 ± 0.12 fish h^{-1}, ±SE) was not significantly different to the CPUE of linefishers (1.17 ± 0.15 fish h^{-1}) in terms of the number of fish captured (excluding bycatch) (Table 2). In contrast, the CPUE of spearfishers (2.22 ± 0.23 kg h^{-1}) was significantly greater than the CPUE of linefishers (1.57 ± 0.20 kg h^{-1}) in terms of the biomass of fish captured (excluding bycatch) ($t_{46} = 2.16$, $P = 0.036$). However, CART analyses revealed that CPUE varied more among trips, or among fishers (within trips), than among fishing methods, regardless of which catch component ("all legal fish" or "legal coral trout only"), dependent variable (fish h^{-1} or kg h^{-1}), or combination of explanatory variables (trip, fisher, method) were used in the analyses. In all cases, two-leaf trees were the best models, as indicated by the minimum and minimum + 1SE rules (Table 3).

Incidental impacts

Spearfishers landed and retained 76% of the fish they attempted to catch. The remaining fish either escaped with spear-induced injuries (21%) or were discarded dead (3%) (Fig. 4). The latter occurred when a speared fish was found to be <MLS or when a speared spiny lobster was found to

Table 1 Summary of linefishers' and spearfishers' catch after 135 h of structured fishing on the Great Barrier Reef. All fish sizes are listed as cm Total Length (TL), unless otherwise noted

Taxon	Target species?[a]	Minimum legal size[b]	Spearfishing		Linefishing	
			Number caught	Size range (mean) cm	Number caught	Size range (mean) cm
Serranidae (rockcods and coral trout)						
Cephalopholis boenak	No	38	0	–	5	17–27 (22)
Cephalopholis cyanostigma	No	38	0	–	140	16–34 (25)
Cromileptes altivelis	No	No take	0	–	2	48–50 (49)
Epinephelus caeruleopunctatus	Yes	38	4	39–53 (47)	0	–
Epinephelus coioides	Yes	35	1	51	0	–
Epinephelus fasciatus	No	38	0	–	5	26–29 (28)
Epinephelus fuscoguttatus	Yes	50	5	59–92 (70)	2	42–42 (42)
Epinephelus merra	No	38	0	–	5	25–37 (31)
Epinephelus ongus	No	38	0	–	9	23–33 (29)
Epinephelus polyphekadion	Yes	50	1	47	0	–
Plectropomus laevis	Yes	50	7	45–65 (58)	1	49
Plectropomus leopardus	Yes	38	84	36–61 (48)	154	29–62 (43)
Plectropomus maculatus	Yes	38	9	46–58 (50)	5	33–66 (46)
Lethrinidae (emperors)						
Lethrinus atkinsoni	Yes	25	1	44	10	29–41 (35)
Lethrinus laticaudis	Yes	30	0	–	1	44
Lethrinus lentjan	No	25	0	–	2	30–30 (30)
Lethrinus miniatus	Yes	38	1	53	10	34–53 (46)
Unidentified Lethrinidae	No	25	0	–	9	31–39 (35)
Lutjanidae (snappers)						
Aprion virescens	Yes	38	0	–	1	53
Lutjanus argentimaculatus	Yes	35	3	52–61 (57)	0	–
Lutjanus bohar	No	No take	0	–	2	31–48 (40)
Lutjanus carponotatus	Yes	25	3	31–37 (34)	19	21–37 (31)
Lutjanus fulviflamma	No	25	0	–	9	25–30 (28)
Lutjanus quinquelineatus	No	25	0	–	4	21–23 (22)
Lutjanus russelli	Yes	25	1	41	7	28–35 (33)
Lutjanus sebae	Yes	55	1	46	8	33–50 (40)
Unidentified Lutjanidae	No	25	0	–	2	23–28 (26)
Palinuridae (spiny lobsters)						
Panulirus longipes	Yes	–	4	9–10 (9)[c]	0	–
Panulirus penicillatus	Yes	–	2	12–13 (13)[c]	0	–
Panulirus versicolor	Yes	–	22	8–14 (12)[c]	0	–
Miscellaneous						
Caesio cuning	No	–	0	–	49	24–33 (27)
Carangoides spp.	No	–	0	–	6	43–77 (59)
Choerodon venustus	Yes	30	2	38–52 (45)	0	–
Echeneis naucrates	No	–	0	–	1	50
Grammatorcynus bicarinatus	Yes	50	0	–	2	80–81 (81)
Naso unicornis	Yes	25	1	49	0	–
Opistognathus sp.	No	–	0	–	1	36
Plectorhinchus chaetodontoides	Yes	25	1	60	0	–
Scarus microrhinus	Yes	25	9	40–51 (45)	0	–
Synodus sp.	No	–	0	–	1	24

Table 1 continued

Taxon	Target species?[a]	Minimum legal size[b]	Spearfishing		Linefishing	
			Number caught	Size range (mean) cm	Number caught	Size range (mean) cm
Unidentified Labridae	No	25	0	–	10	21–25 (24)
Nebrius ferrugineus (shark)	No	–	0	–	1	85
Triaenodon obesus (shark)	No	–	0	–	1	90
Octopus sp. (octopus)	No	–	0	–	1	–
Sepia sp. (squid)	Yes	–	1	15[d]	0	–
Live rock or coral	No	–	0	–	2	–

[a] Target species were those that fishers usually retained to eat

[b] Many non-target species have a minimum legal size by default under Queensland State law (Anon. 2003)

[c] Carapace length (cm)

[d] Mantle length (cm)

Table 2 Catch statistics for spearfishers and linefishers after 135 h of structured fishing on the Great Barrier Reef

	Spearfishing	Linefishing
Diversity of catch (no. of species)	21	≥32[a]
Total catch (no. of fish)	163[b]	485
Legal catch[c] (no. of fish)	156	168
Biomass of legal catch[c] (kg)	304	213
Mean fish weight[c] (kg) ± SE	1.95 ± 0.10**	1.27 ± 0.06**
CPUE[c] (fish h^{-1}) ± SE	1.08 ± 0.12	1.17 ± 0.15
CPUE[c] (kg h^{-1}) ± SE	2.22 ± 0.23*	1.57 ± 0.20*
Bait consumption (kg pilchards)	–	52.8
Bait consumption (kg reef fish)	–	19.4
Pollution (lost gear)	1 knife, 2 spear tips, 1 gun rubber	96 hooks (plus associated lead weights and nylon line)
Number of hangs[d]	70	155

Levels of significance are denoted by asterisks (* $P < 0.05$; ** $P < 0.001$)

[a] The exact number of species was unknown because some fish were grouped into families or genera

[b] Excludes organisms that escaped injured (i.e., category D)

[c] Excludes organisms that were smaller than the minimum legal size (see Anon. 2003) or regarded as bycatch (i.e., not usually retained after capture, unless used for bait)

[d] Refers to the total number of times that fishers deployed their vessel's anchor

bear eggs, in which case it was protected by law (Anon. 1995). Linefishers retained 35% of their catch for the purpose of eating. A further 12% were retained for bait. The remaining fish were either released in good condition (47%), released in poor condition (5%), or discarded dead (1%) (Fig. 4). Fish in the latter two groups generally suffered from hook-induced injuries and (or) barotrauma. Whilst the exact amount of collateral mortality could not be determined (due to the prospect of delayed effects), it was found that at least 87 reef fish were incidentally killed or substantially injured as a result of linefishing (i.e., sum of categories B, D and E, Fig. 4). In contrast, 51 reef fish were incidentally killed or injured as a result of spearfishing (i.e., sum of categories D and E, Fig. 4).

During the study, linefishers used 72.2 kg of baitfish. This consisted of 19.4 kg of reef fish (predominantly *C. cuning*) and 52.8 kg of pre-purchased pilchards (*Sardinops* spp.) (Table 2). Assuming a mean pilchard weight of 45 g (Froese and Pauly 2007), the total number of fish used for bait (including reef fish) was ~1,233. This equates to 2.5 baitfish for each fish that was captured, or 7.3 baitfish for each fish that was kept to eat.

With regard to fishing-associated pollution, spearfishers lost four items of fishing gear, while linefishers lost 96 hooks plus associated lead weights and nylon line (Table 2). Seventy-seven of these hooks were lost when they became "snagged" on the substrate. The remaining 19 hooks were lost when "hooked" fish subsequently

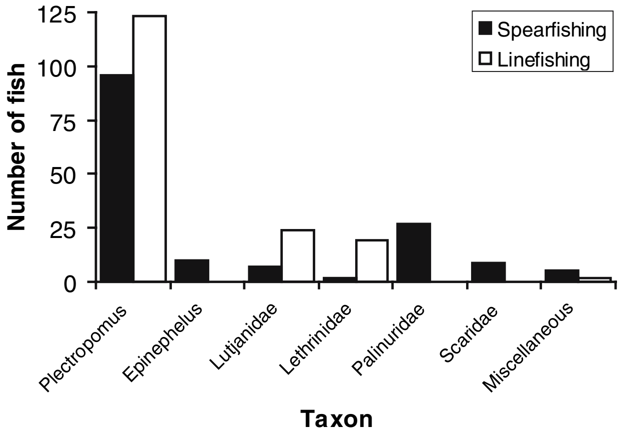

Fig. 2 The composition of spearfishers' and linefishers' catch after 135 h of structured fishing on the Great Barrier Reef. Data exclude organisms that were smaller than the minimum legal size (see Anon. 2003) or regarded as bycatch (i.e., not usually retained after capture, unless used for bait)

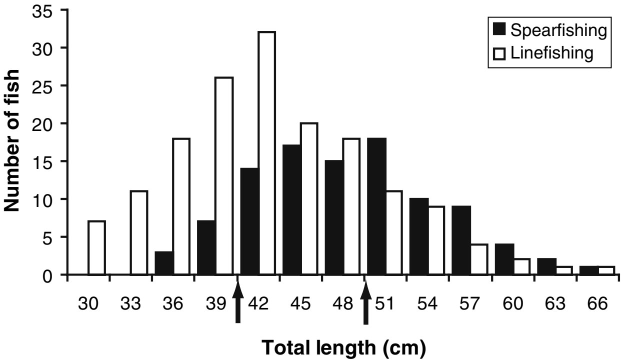

Fig. 3 Size distribution of coral trout (*Plectropomus* spp.) that were captured during 135 h of structured spearfishing and linefishing on the Great Barrier Reef. The *x*-axis labels represent size-class midpoints. *Arrows* illustrate the minimum legal sizes of *Plectropomus leopardus* (38 cm), *Plectropomus maculatus* (38 cm) and *Plectropomus laevis* (50 cm). Species-specific sample sizes for *P. leopardus*, *P. maculatus* and *P. laevis* were 84, 9 and 7 (respectively) for spearfishing and 154, 5 and 1 (respectively) for linefishing

broke the line. The ultimate fates of these fish were unknown.

Linefishers moved their boat more frequently during each fishing session than did spearfishers. The mean duration of each hang was ~58 min for spearfishers and ~26 min for linefishers. As such, linefishers deployed their anchor more than double the number of times than did spearfishers (Table 2).

Table 3 Summary of classification and regression tree (CART) analyses of spearfishers' and linefishers' catch per unit effort (CPUE)

Catch component	Dependant variable	Explanatory variables	Tree size[a]	Split[b]
All legal fish[c]	fish h^{-1}	Method, fisher, trip	2	fisher
	fish h^{-1}	Method, trip	2	trip
	kg h^{-1}	Method, fisher, trip	2	fisher
	kg h^{-1}	Method, trip	2	trip
Legal coral trout only[d]	fish h^{-1}	Method, fisher, trip	2	fisher
	fish h^{-1}	Method, trip	2	trip
	kg h^{-1}	Method, fisher, trip	2	fisher
	kg h^{-1}	Method, trip	2	trip

[a] The number of homogeneous clusters ("leaves") in the best tree model

[b] The explanatory variable that accounted for the greatest amount of variability among clusters

[c] Excludes organisms that were smaller than the minimum legal size (see Anon. 2003) or regarded as bycatch (i.e., not usually retained after capture, unless used for bait)

[d] Includes all *Plectropomus* spp. that were larger than the minimum legal size (see Anon. 2003)

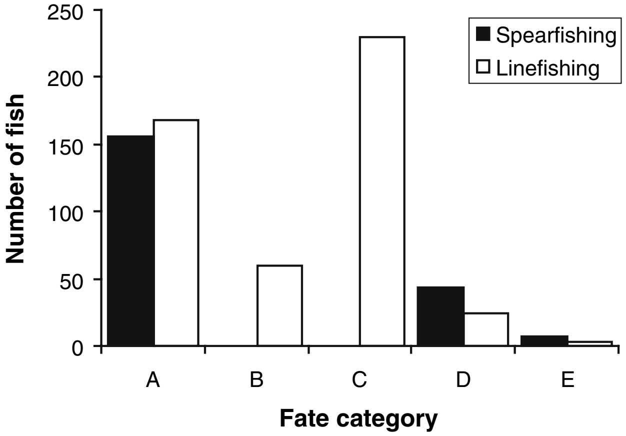

Fig. 4 The fate of fish that were captured during 135 h of structured spearfishing and linefishing on the Great Barrier Reef (*A* kept to eat; *B* kept for bait; *C* released in good condition; *D* released or escaped in poor condition; *E* discarded dead)

Discussion

It is widely perceived that spearfishing is more efficient than linefishing with respect to exploiting shared fishery resources (Long 1957; Eckersley 1997; Mann et al. 1997; Gillett and Moy 2006). However, the efficiencies of these two fishing methods have never been compared directly, at least not without the potential for bias associated with boat-ramp surveys, questionnaires or logbooks (Wright and Richards 1985; Tarrant and Manfredo 1993; King 1995; Connolly and Brown 1995). The results of this study thus provide the empirical data that are necessary for reef managers to make informed decisions regarding equitable allocation of shared fishery resources among different fishing sectors.

The findings of this study do not support the perception that spearfishing is more efficient at capturing target fish than is linefishing. Both groups of fishers were found to harvest similar numbers of target fish, as well as exploit a similar biomass of fisheries resources (i.e., when bait consumption was included; see below). Additionally, because of the considerably larger bycatch, as well as the loss of substantial amounts of fishing gear, it seems that linefishing has the potential to inflict greater incidental impacts on GBR ecosystems per unit of effort than does spearfishing.

Catch composition

Although the diversity of food fishes on the GBR is very large (Randall et al. 1990; Grant 1997), it is evident that both spearfishers and linefishers caught and retained only a small number (20) of the available species, and that there was a high degree of overlap with respect to the catch composition of both fishing sectors (Table 1). These results suggest, firstly, that spearfishers and linefishers have strong preferences for a select few species and secondly, that spearfishers and linefishers compete for many of the same fish. In reef fisheries elsewhere, there tends to be much less overlap in species composition, and species preferences are often obscure (Dalzell et al. 1996; Harper et al. 2000; McClanahan and Mangi 2004). This is probably because most popular species (e.g., groupers and other apex predators) are no longer abundant on many coral reefs (Roberts 1995; Jennings and Lock 1996; Sadovy et al. 2003), which forces local fishers to retain most (or all) of the other fish they catch (Dalzell et al. 1996; McClanahan and Mangi 2004; Author’s personal observation).

Coral trouts (*Plectropomus* spp.) were the principal target species of both fisher groups, a result that reflects the fact that these fishes are highly esteemed, relatively common, and vulnerable to both spearfishing and linefishing (Heemstra and Randall 1993; Sadovy et al. 2003). Species other than coral trouts were not generally targeted, but were captured opportunistically according to their respective vulnerabilities to each fishing method. For example, spiny lobsters were not caught by linefishing because these organisms do not take commonly used baits (Frisch 2007). Similarly, few snappers and emperors were caught by spearfishing because these organisms are relatively timid and difficult to approach underwater (Personal communication, reef fishers).

Size distribution

It is evident that spearfishers generally caught larger fish than did linefishers (Table 2). This pattern indicates that the two fishing methods have different size selectivities (King 1995; Dalzell 1996), although the difference was probably exaggerated by minimum size limits. Because estimating fish size can be difficult underwater and inadvertently spearing an under-size fish is considered to be wasteful (Personal communication, reef fishers), spearfishers tend to avoid fish that appear close the MLS (Fig. 3). Linefishers, on the other hand, have the potential to accurately measure a captured fish’s size without substantially harming it. Hence, linefishers are more likely than spearfishers to retain smaller fish that approach the MLS.

In ecological terms, it may be beneficial to target larger fish, since it increases the proportion of the population that reproduce before recruitment to the fishery (King 1995). However, it is also undesirable to target very large fish, because they make a disproportionately large contribution to the reproductive output of the population (Sadovy 1996; Birkeland and Dayton 2005). It is therefore pertinent to consider the relative sizes of fish caught by each fishing method. The mean sizes of coral trouts (*Plectropomus* spp.) caught by spearfishing and linefishing were 48.9 and 42.9 cm TL, respectively. These fishes attain sexual maturity at ~35 cm TL and normally grow to ≥70 cm TL (Heemstra and Randall 1993; Ferreira 1995). The mean size difference of fish caught by spearfishing and linefishing (i.e., 6 cm TL) was therefore small relative to the potential size of the fish. As such, the difference between methods with regard to fish size is unlikely to be ecologically significant.

Catch per unit effort

Excluding bycatch, the CPUEs of spearfishers and linefishers were similar with respect to the number of fish captured, but different with respect to the biomass of fish captured, since spearfishers generally caught larger fish than did linefishers (Table 2). However, CART analyses revealed that the variability in CPUE among fishing methods was small in comparison to the variability in CPUE among trips, or among fishers (Table 3). This suggests that the temporal and spatial aspects of fishing effort were more important determinants of CPUE, measured in terms of either the number or biomass of fish, than which fishing method was employed. Whilst it is possible that some of the variability in CPUE was a result of differences in skill among fishers (Hundloe 1985; Lincoln-Smith et al. 1989; Mann et al. 1997) or the spatial heterogeneity of target fish populations (Newman et al. 1997; Connell and Kingsford 1998), it is unlikely that these influences were significant given the criteria for selecting fishers and the structured nature of the sampling design (respectively) (see “Materials and methods”).

An interesting (but anecdotal) observation was that the CPUE (fish h^{-1}) of spearfishers was often lower than that of linefishers during sessions when fishing was generally regarded as “good”, but that the pattern was reversed during sessions when fishing was generally regarded as “bad”. One explanation is that spearfishers experienced “gear saturation” during “good” sessions. In other words, the time required to shoot, retrieve and store a fish may have been limiting for spearfishers when target fish were abundant (n.b., some spearfishers individually returned each captured fish to the boat in order to avoid attracting sharks). Another explanation, which is not mutually exclusive, is that spearfishing was more efficient than linefishing when target fish were scarce, or were not concentrated in predictable areas, perhaps because spearfishers actively searched for fish by swimming over a broad area, while linefishers generally selected discrete “spots” in which to deploy their baited hooks.

Studies of other shallow reef fisheries across the Indo-Pacific indicate that spearfishers typically catch 0.4–8.5 kg h^{-1}, while linefishers typically catch 0.5–5.1 kg h^{-1} (Wright and Richards 1985; Dalzell et al. 1996; Pet-Soede et al. 2001; McClanahan and Mangi 2004). Although those studies engaged artisanal fishers and are thus not directly comparable to this study, it is noteworthy that the CPUEs observed here (2.22 and 1.57 kg h^{-1} for spearfishing and linefishing, respectively) were within the range of previously reported values. It is also interesting that among those studies, the degree of variation within each fishing method was much greater than the degree of variation between fishing methods, which is congruent with the findings of the present study.

Incidental impacts

In general, spearfishing was found to be much more selective than linefishing, both in terms of species and size. As a result, the total number of undersized, undesirable or protected fishes captured by spearfishers (7) was far less than the number captured by linefishers (257). However, spearfishers’ bycatch was always released dead, while linefishers’ bycatch was generally released in good condition (Fig. 4). Furthermore, spearfishers injured an additional 44 fish that escaped before capture (category D, Fig. 4). Whilst the fate of these fish is not known, it seems likely that a significant proportion of them subsequently died as a result of their injuries. Similarly, it is likely that a significant proportion of line-caught fish that were released in seemingly good condition (category C, Fig. 4) also died, perhaps as a result of post-release predation, stress, delayed barotrauma, or apparently minor mouth injuries (Cooke and Schramm 2007; Rudershausen et al. 2007). The proportion of fish that suffer significant effects or die as a result of fishing-induced injuries contributes to the incidental impacts of spearfishing and linefishing and thus should be integrated into any contemporary management regime. Unfortunately, post-release mortality rates are not available for any of the species encountered here. Estimation of these parameters is therefore considered an important topic for future research.

Bait consumption represents a significant collateral impact of linefishing, because small fishes such as fusiliers often provide important ecosystem functions (Hobson 1991; Graham et al. 2003). In general, linefishers used 1 kg of bait for every 3 kg of fish that were kept to eat. Although it was mentioned earlier that spearfishers exploited a significantly greater biomass of fish compared to linefishers (304 versus 213 kg, respectively), the difference was small when the biomass of bait used by linefishers (72.2 kg) was added to their tally. Additionally, baitfish are often supplied from geographically distant fisheries (Western Australia, California or India in the case of pilchards; Authors’ personal observation), thus extending the impacts of linefishing to areas that are well beyond local fishing grounds.

Both spearfishers and linefishers were responsible for some degree of pollution. In the case of spearfishers, this consisted of four pieces of lost spearfishing gear (two spear tips, one knife, one gun rubber). However, gear of this nature is unlikely to harm reef organisms when it is lost at sea. In contrast, the gear lost by linefishers (96 hooks plus associated lead weights and nylon line) may potentially cause collateral mortality of other fish, sharks, turtles and seabirds, either by ingestion of steel hooks or by entanglement in nylon line (Matsuoka et al. 2005). Incidentally, if the rate of hooks lost during this project (i.e., 1 hook per 1.71 kg of “legal” coral trouts) is representative of the entire GBR linefishery, it is estimated that approximately one million hooks are lost annually on the GBR, since the total catch of coral trouts is estimated to be 1805 t (Williams 2002).

It is well recognized that coral reefs can be adversely affected by anchor damage, and that the amount of damage is proportional to (among other things) the number of times an anchor is deployed and retrieved (Davis 1977; Dinsdale and Harriott 2004). In the present study, linefishers recorded more than double the number of hangs than spearfishers did, suggesting that linefishers potentially cause a greater amount of anchor damage per unit of fishing effort. This difference is related to the fact that linefishers must retrieve their anchor each time they wish to move to a new area, while spearfishers generally select a single anchorage and thereafter swim between areas.

In summary, spearfishers and linefishers were found to catch similar numbers of target fish. They were also found to exploit a similar biomass of fishery resources (i.e., when bait consumption was included). Together, these results suggest that spearfishers and linefishers have equivalent access to shared fishery resources, and that the direct impacts of each fishing method are not vastly different. It thus seems appropriate that management regulations be implemented equitably across both sectors of the GBR recreational fishery. This will simplify enforcement of fisheries regulations and avoid discrimination of particular fishers in local communities where both fishing methods are socially or culturally important. However, this type of management strategy may need to be reviewed once further information is obtained about the incidental impacts of fishing (e.g., post-release mortality rates and the effects of lost gear). Lastly, two cautions are issued with regard to extrapolating the results of this study to other reef fisheries. Due to differences in skill, behavior and motivation of recreational versus artisanal or subsistence fishers (Ruddle 1996), the conclusions presented here may not be applicable to reef fisheries outside of developed nations such as Australia. Secondly, this study applies only to reef fisheries where SCUBA is prohibited, because without the limitations imposed by breath-hold diving, the CPUE of spearfishing is likely to be substantially greater than that reported here.

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References

Anon Fisheries regulation (1995) Queensland Government, Brisbane, Australia (http://www.legislation.qld.gov.au)

Anon Fisheries management plan (2003) Queensland Government, Brisbane, Australia (http://www.legislation.qld.gov.au)

Bellwood DR, Hughes TP, Folke C, Nystrom M (2004) Confronting the coral reef crisis. Nature 249:827–833

Birkeland A, Dayton PK (2005) The importance in fishery management of leaving the big ones. Trends Ecol Evol 20:356–358

Breiman L, Friedman JH, Olshen RA, Stone CG (1984) Classification and regression trees. Wadsworth International Group, Belmont

Cinner JE, McClanahan TR (2006) Socioeconomic factors that lead to overfishing in small-scale coral reef fisheries of Papua New Guinea. Environ Conserv 33:73–80

Connell SD, Kingsford MJ (1998) Spatial, temporal and habitat related variation in the abundance of large predatory fish at One Tree Reef, Australia. Coral Reefs 17:49–57

Connolly NA, Brown TL (1995) Use of angler diaries to examine biases associated with 12-months recall on mail questionnaires. Trans Am Fish Soc 124:413–442

Cooke SJ, Schramm HL (2007) Catch-and-release science and its application to conservation and management of recreational fisheries. Fish Manag Ecol 14:73–79

Dalzell P (1996) Catch rates, selectivity, and yields of reef fishing. In: Polunin NVC, Roberts C (eds) Reef fisheries. Chapman and Hall, London, pp 161–192

Dalzell P, Adams TJH, Polunin NVC (1996) Coastal fisheries in the Pacific Islands. Oceanogr Mar Biol Annu Rev 34:395–531

Davis GE (1977) Anchor damage to a coral reef on the coast of Florida. Biol Conserv 11:29–34

De'ath G, Fabricius KE (2000) Classification and regression trees: a powerful yet simple technique for ecological analysis. Ecology 81:3178–3192

Dinsdale EA, Harriott VJ (2004) Assessing anchor damage on coral reefs: a case study in selection of environmental indicators. Environ Manage 33:126–139

Done TJ (1982) Patterns in the distribution of coral communities across the central Great Barrier Reef. Coral Reefs 1:95–107

Eckersley Y (1997) War beneath the waves: spearfishing debate surfaces. Geo Australasia 19:18–26

Ferreira BP (1995) Reproduction of the common coral trout *Plectropomus leopardus* (Serranidae: Epinephelinae) from the central and northern Great Barrier Reef. Bull Mar Sci 56:653–669

Frisch AJ (2007) Growth and reproduction of the painted spiny lobster (*Panulirus versicolor*) on the Great Barrier Reef (Australia). Fish Res 85:61–67

Frisch AJ, van Herwerden L (2006) Field and experimental studies of hybridization between coral trouts, *Plectropomus leopardus* and *Plectropomus maculatus* (Serranidae), on the Great Barrier Reef, Australia. J Fish Biol 68:1013–1025

Froese R, Pauly D (2007) FishBase. International centre for living aquatic resource management, Manila (http://www.fishbase.org)

Gillett R, Moy W (2006) Spearfishing in the Pacific islands: current status and management issues. Food and Agriculture Organisation of the United Nations, Rome

Graham NAJ, Evans RD, Russ GR (2003) The effects of marine reserve protection on the trophic relationships of reef fishes on the Great Barrier Reef. Environ Conserv 30:200–208

Grant E (1997) Guide to fishes. E.M. Grant Publishers, Scarborough

Harper DE, Bohnsack JK, Lockwood BR (2000) Recreational fisheries in Biscayne National Park, Florida, 1976–1991. Mar Fish Rev 62:8–26

Heemstra PC, Randall JE (1993) Groupers of the world. FAO Species Catalogue 16. Food and Agriculture Organization of the United Nations, Rome

Hobson ES (1991) Trophic relationships of fishes specialized to feed on zooplankters above coral reefs. In: Sale PF (ed) The ecology of fishes on coral reefs. Academic Press, San Diego, pp 69–95

Hundloe T (1985) Fisheries of the Great Barrier Reef. Prestige Litho Printing, Brisbane

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner RR (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629–637

Jennings S, Lock J (1996) Population and ecosystem effects of fishing. In: Polunin NVC, Roberts C (eds) Reef fisheries. Chapman and Hall, London, pp 193–218

Jones DS, Morgan GJ (1994) A field guide to crustaceans of Australian waters. Reed, Chatswood

King M (1995) Fisheries biology, assessment and management. Blackwell Science, Oxford

Kulbicki M, Guillemot N, Amand M (2005) A general approach to length–weight relationships for New Caledonian lagoon fishes. Cybium 29:235–252

Lincoln-Smith MP, Bell JD, Pollard DA, Russell BC (1989) Catch and effort of competition spearfishermen in southeastern Australia. Fish Res 8:45–61

Long EJ (1957) Anglers versus spearmen. Sea Front 3:130–141

Mann BQ, Scott GM, Mann-Lang JB, Brouwer SL, Lamberth SJ, Sauer WHH, Erasmus C (1997) An evaluation of participation in and management of the South African spearfishery. S Afr J Mar Sci 18:179–193

Matsuoka T, Nakashima T, Nagasawa N (2005) A review of ghost fishing: scientific approaches to evaluation and solutions. Fish Sci 71:691–702

McClanahan TR, Mangi SC (2004) Gear-based management of a tropical artisanal fishery based on species selectivity and capture. Fish Manag Ecol 11:51–60

Myers RF (1993) Guam's small-boat-based fisheries. Mar Fish Rev 55:117–128

Newman SJ, Williams AM, Russ GR (1997) Patterns of zonation of assemblages of the Lutjanidae, Lethrinidae and Serranidae (Epinephelinae) within and among mid-shelf and outer-shelf reefs in the central Great Barrier Reef. Mar Freshw Res 48:119–128

Newton K, Cote IM, Pilling GM, Jennings S, Dulvy NK (2007) Current and future sustainability of island coral reef fisheries. Curr Biol 17:655–658

Pandolfi JM, Bradbury RH, Sala E, Hughes TP, Bjorndal KA, Cooke RG, McArdle D, McClenachan L, Newman MJH, Peredes G, Warner RR, Jackson JBC (2003) Global trajectories of the long-term decline of coral reef ecosystems. Science 301:955–958

Pauly D, Christensen V, Guenette S, Pitcher TJ, Sumaila UR, Walters CJ, Watson R, Zeller D (2002) Towards sustainability in world fisheries. Nature 418:689–695

Pet-Soede C, van Densen WLT, Pet JS, Machiels MAM (2001) Impact of Indonesian coral reef fisheries on fish community structure and the resultant catch composition. Fish Res 51:35–51

Randall JE, Allen GR, Steene RC (1990) Fishes of the Great Barrier Reef and Coral Sea. Crawford House Press, Bathurst

Roberts CM (1995) Effects of fishing on the ecosystem structure of coral reefs. Conserv Biol 9:988–995

Ruddle K (1996) Geography and human ecology of reef fisheries. In: Polunin NVC, Roberts C (eds) Reef fisheries. Chapman and Hall, London, pp 137–160

Rudershausen PJ, Buckel JA, Williams EH (2007) Discard composition and release fate in the snapper and grouper commercial hook-and-line fishery in North Carolina, USA. Fish Manag Ecol 14:103–113

Sadovy YJ (1996) Reproduction of reef fishery species. In: Polunin NVC, Roberts C (eds) Reef fisheries. Chapman and Hall, London, pp 15–59

Sadovy Y, Donaldson TJ, Graham TR, McGilvray F, Muldoon GJ, Phillips MJ, Rimmer MA, Smith A, Yeeting B (2003) While stocks last: the live reef food fish trade. Asian Development Bank, Manila

Tarrant MA, Manfredo MJ (1993) Digit preference, recall bias, and non-response bias in self reports of angling participation. Leisure Sci 15:231–238

Walters CJ, Martell SJD (2004) Fisheries ecology and management. Princeton University Press, Princeton

Wilkinson C (2004) Status of coral reefs of the world. Australian Institute of Marine Science, Townsville

Williams LE (2002) Queensland's fisheries resources: current condition and recent trends 1988–2000. Department of Primary Industries, Brisbane

Wright A, Richards AH (1985) A multi-species fishery associated with coral reefs in the Tigak Islands, Papua New Guinea. Asian Mar Biol 2:69–84

Zar JH (1999) Biostatistical Analysis. Prentice-Hall, London