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Original Article

Relative benthic disturbances of conventional and novel otter boards

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Reducing otter-board angle of attack (AOA) has been proposed as a way to limit the habitat impacts of demersal trawls, but there are few quantitative assessments. This study tested the hypothesis that a novel otter-board design, termed the "batwing" (comprising a 0.1-m wide sled with an offset sail at 20° AOA) would have relatively fewer bottom impacts than a conventional flat-rectangular otter board (35° AOA, with a similar hydrodynamic spreading force). Pairs of each otter board were suspended beneath a purpose-built rig comprising a beam and posterior semi-pelagic collection net and repeatedly deployed across established trawl grounds in an Australian estuary. Compared with the conventional otter boards, the batwings displaced significantly fewer empty shells (*Anadara trapezia* and *Spisula trigonella*) by 89% and school prawns (*Metapenaeus macleayi*) by up to 78%. These rates were similar to the difference in base-plate bottom contact (87%). Further, the batwing damaged proportionally fewer damaged shells, attributed to their displacement away from the board's surface area. Other debris (lighter pieces of wood) and benthic fish (bridled gobies, *Arenigobius bifrenatus*) were not as greatly mobilised (i.e. reduced by 50 and 25%, respectively); possibly due to their position on or slightly off the bottom, and a similar influence of hydrodynamic displacement by the hydro-vane surface areas. Although the consequences of reducing otter-board bottom contact largely remain unknown, low AOA designs like the batwing may represent a practical option for fisheries where trawling is perceived to be hazardous to sensitive habitats.

Keywords: batwing, habitats, hydrodynamic drag, impact, otter boards.

Introduction

Demersal trawling occurs throughout the world's oceans and is believed to have originated in the mid-14th century with a design called the "wondyrchoum"; essentially a precursor to modern beam trawls (Robinson, 1996; Kennelly and Broadhurst, 2002). Technology evolved to "otter trawling" in the late 19th century, which involves the nets being horizontally spread by the relative flow of water (from forward motion of the gear) acting on hydro vanes (or "otter boards"; Jones, 1992; Auster and Langton, 1999). Since the early 20th century, otter trawling has become established as the world's most widely used mobile fishing gear and is considered a principal source of anthropogenic disturbances to benthic habitats (Jones, 1992; Auster and Langton, 1999; Collie *et al.*, 2000; Kaiser *et al.*, 2002).

Many concerns about habitat impacts associated with demersal otter trawls have focused on the otter boards, which leave discernible marks on the substratum, and, in some cases, lead to unwanted ecosystem impacts (Dayton *et al.*, 1995; Auster and Langton, 1999; Kaiser *et al.*, 2002). Substrate type (e.g. hard or soft) and its mobility will dictate the impact of otter boards and recovery times, whereby soft sediments (e.g. mud and sandy-mud) with a low level of natural disturbance, will be most affected and take longer to recover than harder substrata (e.g. sand) (DeAlteris *et al.*, 1999, 2000; Dernie *et al.*, 2003).

Although otter-board impacts are a direct function of their weight and contact pressure (by necessity they have the greatest concentrated mass within demersal trawls), there are two other key factors that ultimately affect the substrate contact area. First is the height-to-length ratio, or aspect ratio of the foil, which determines the otter board's length for a given foil surface area (Patterson and Watts, 1985; Seafish *et al.*, 1993). Second is the operational angle of attack (AOA), which typically is between 30 and 45° (Patterson and Watts, 1985; Seafish *et al.*, 1993). Considering these two factors, an otter board's lateral span of seabed contact can be deduced from simple trigonometry to be the base-plate width, for an AOA of 0°, to a maximum of the base-plate length, for a hypothetical 90° AOA.

Many conventional demersal otter boards are flat and rectangular with a low aspect ratio to match their high AOA (>35°), which, although not required to adequately spread the trawls during fishing (i.e. 30° is most effective, whereas ~20° is the most efficient), ensures their stability during deployment (Sterling and Eayrs, 2010). A novel, high-aspect, otter-board design that achieves a consistent low AOA and has good stability is the "batwing" (Sterling and Eayrs, 2008; McHugh *et al.*, 2015). The batwing foil—comprising a polyurethane (PU) sail set on a stainless-steel boom and mast—acts like an independent kite with a single longitudinal connection to the trawl system via a heavy main sled made from mild and stainless steel. The batwing is configured so that the sled base-plate aligns to the tow direction, whereas the sail has a consistent AOA (20°) and rides on a PU "flap" that passes lightly over the seabed on a layer of high-pressure water for most of its length. Conceivably, because the batwing mostly contacts the seabed via its base-plate width (assuming the sail has minimal contact), it should evoke proportionally fewer habitat disturbances than conventional, low-aspect, and high AOA otter boards.

Identifying component-specific effects on habitats are difficult when using a complete trawl configuration (i.e. otter boards, net, ground gear, and associated gear; Gilkinson *et al.*, 1998). One method is via *in situ* observations (e.g. video and sonar imaging), although in some fisheries these are limited owing to low visibility and difficulties discerning trawl-mark longevity (existing or new; Smith *et al.*, 2007). Furthermore, proper experimental procedures require observations (e.g. video and sonar) to be collected before, during, and after planned experiments (Schwinghamer *et al.*, 1998), which can be a difficult task in established fisheries (Dayton *et al.*, 1995).

An alternative option involves assessing broad relative benthic disturbances among different otter boards in the same space and time, which can then be used as a proxy for determining the utility or otherwise of modified designs for conserving habitats. We follow this approach here using a purpose-built test rig comprising a posteriorly located collection net (analogous to a covered codend) to investigate the hypothesis of no differences in the relative substrate disturbances of conventional flat-rectangular and batwing otter boards. The rig was alternately deployed across flat (sandy-mud), previously trawled areas known to contain large areas of empty shell (*Anadara trapezia* and *Spisula trigonella*) and other macro-debris, so that their abundances in the collection net and any inflicted damage could be used as relative indices of disturbance.

Material and methods

The experiment was completed in Lake Wooloweyah (29°26′S 153°22′E; ~1–2 m depth), New South Wales, Australia, during the Austral autumn, 2014, using a 10-m penaeid trawler (104 kw) configured with two independent hydraulic winches to tow double rig. The trawler had a global positioning system (GPS; Lowrance, HDS5) to record speed over the ground (SOG in m s^{-1}) (every 60 s). The experiment was done at the end of the fishing season and with no other vessels present on the trawled area.

Otter boards and the testing assembly

Two otter-board pairs were assessed; both with 0.1-m base plates (Figures 1 and 2). The first otter-board pair was termed the "flat-rectangular" and represented a standard design used nationally and internationally, comprising a mild-steel frame with marine-grade plywood inserts (52.53 kg, 1.39 × 0.61 m, solid area of 0.77 m^2; Figure 1a). The second pair was the "batwing"; each with a main sled made from mild and stainless steel, and a PU sail on a stainless-steel boom and mast (60.74 kg, 1.12 × 1.23 m, 0.74 m^2) at a 20° AOA (Figures 1b and 2a).

Both otter-board pairs were deployed, one pair at a time on a purpose-built test rig comprising a 6-m beam secured at each end to sleds (1.07 × 0.76 × 0.1 m); inside which a "collection net" (a design described by McHugh *et al.*, 2015, and made from 32- and 12-mm polyethylene and polyamide mesh in the body and codend, respectively) was posteriorly attached (Figure 2). The collection net had a 20-cm diameter float attached in the centre of its headline to maximise the vertical opening posterior to the otter boards, but no ground gear. Rather, the lower frame line was attached 0.1 m above and inside the sled base plates so that it could not contact (nor disturb) the substrate, nor collect any entrained material from the sled (Figure 2). We validated this lack of substrate contact in earlier work, when the configuration was fished without the attached otter boards (Broadhurst *et al.*, 2015).

The flat-rectangular and batwing otter boards were bolted at their conventional fishing orientations (35 and 0° base-plate AOA, providing total lateral bottom contacts of 1.60 and 0.20 m, respectively) to independent aluminium frames that could be secured immediately below the beam and 1-m either side of the centre line, so that the base plates were on the same plane as the sleds, and in front of the collection net (Figure 2). The beam assembly was attached via a 7-m bridle to the towing warps on one side of the vessel, and a conventional otter trawl was operated on the other side (to balance the vessel during towing).

Although the tip of the batwings extended slightly higher than the collection net, we did not consider that this would confound the estimates of collected debris. Logic for this statement is based on previous underwater video observations, which revealed that unlike flat-rectangular otter boards which disturb the substratum via the base-plate AOA and immediately create quite high sand and debris plumes, the 0° AOA of the batwing base plate and only slight contact of the sail foot on the seabed limits the posterior plume in the water column to the lower section (Sterling and Eayrs, 2008).

On each fishing day, an otter-board pair was suspended below the beam and deployed for 10 min along independent tracks (Figure 2). The otter-board pairs were alternately deployed among four days and also within 2 days, providing a total of 36 replicates of each.

Data collected and statistical analyses

Data collected during each deployment were restricted to the test rig and collection net and included: the total distance (m) trawled

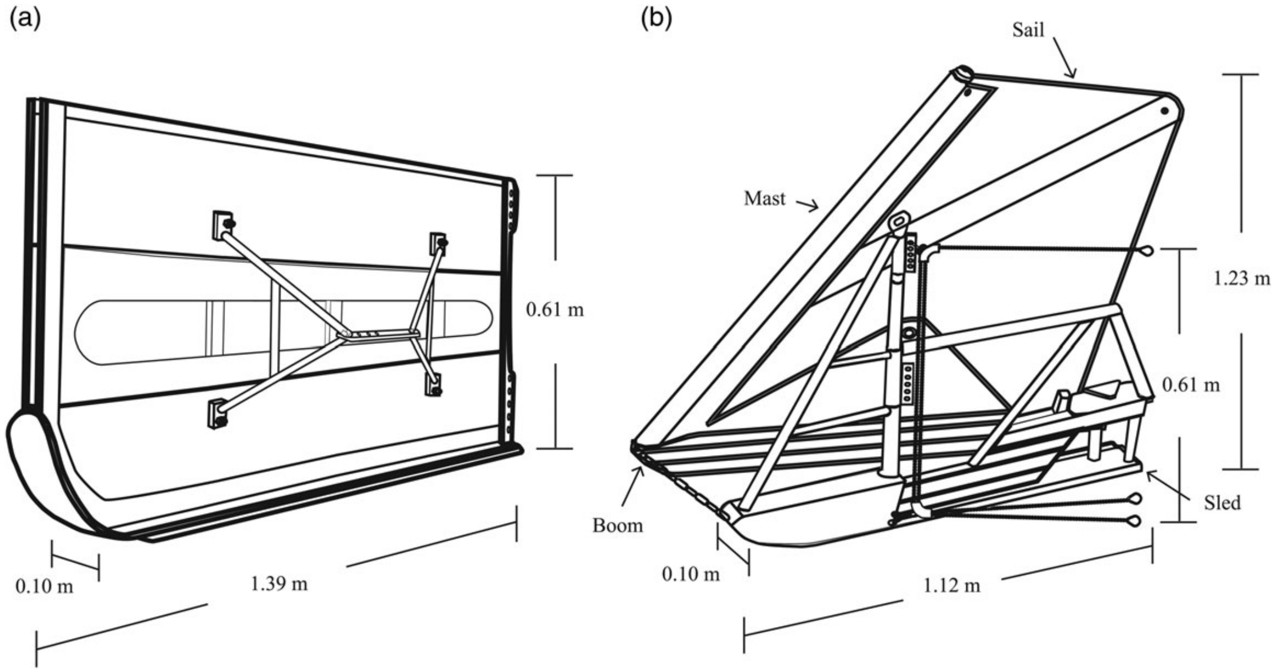

Figure 1. Three-dimensional representation of the (a) flat-rectangular (1.39 × 0.61 m; 52.53 kg) and (b) batwing otter boards (1.12 × 1.23 m; 60.74 kg) tested in the study.

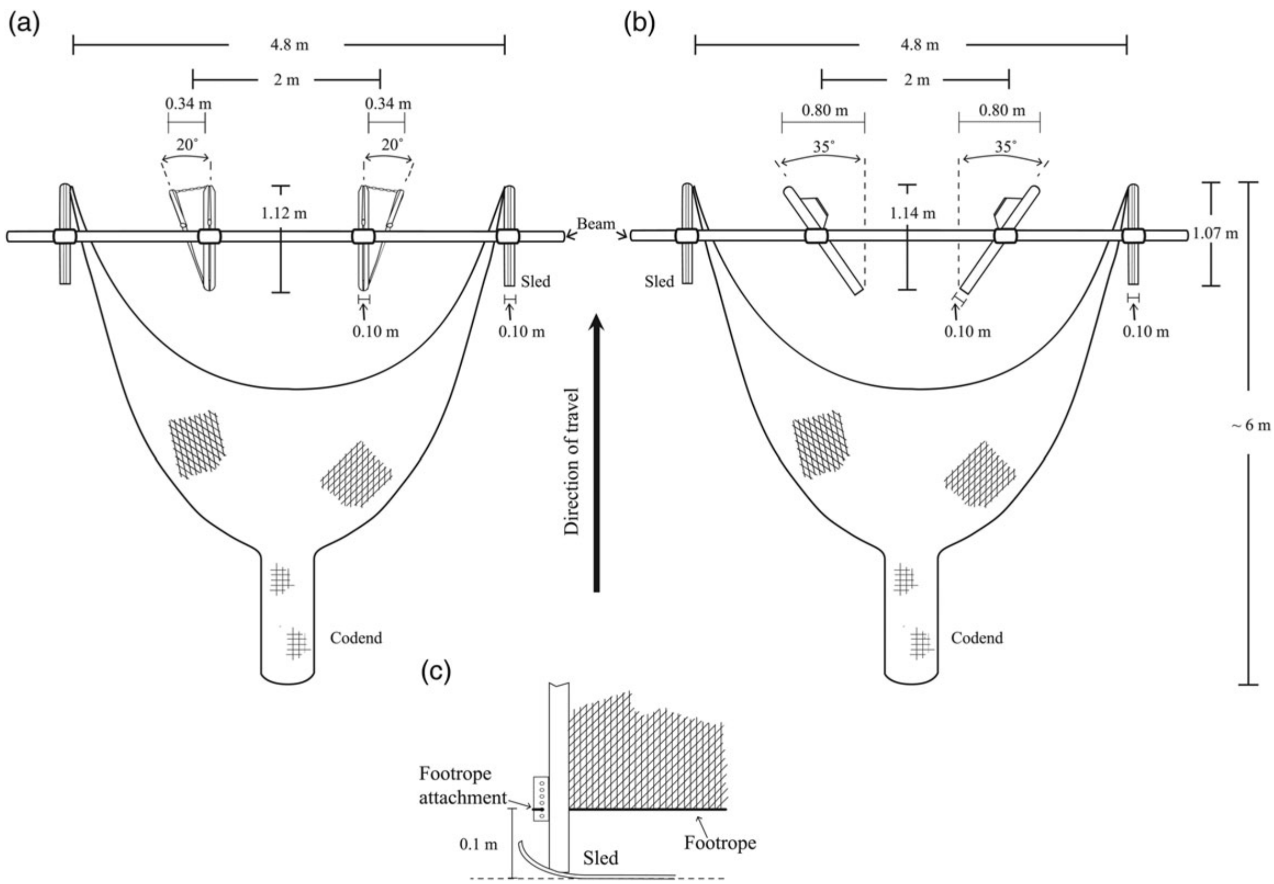

Figure 2. Top view of the test-rig frame, collection net, and (a) batwing and (b) flat-rectangular otter-board pairs. The highlighted section (c) shows the footrope attachment point (0.1 m from the substrate) on the leading edge of the beam-trawl sled. The recorded lengths [of the fixed and solid structures in (a) and (b)] are proportional, but owing to variable dynamics, the net shape and length were estimated.

(rig on and off the bottom—obtained from the GPS); SOG (m s^{-1}); total catch weight; the numbers and weights of individual fauna; sizes of key species (carapace length, CL, for prawns and total length, TL, for fish to the nearest 1 mm); and the weights of shells and other debris (mostly water-saturated wood). Estimates of faunal abundance were derived using a 500-g subsample of the total catch, processed in the laboratory. Empty shells were also classified as "damaged" (i.e. broken pieces) or "undamaged" (structurally complete). Owing to difficulties in identifying prawns to the species level, two groups were classified: individuals >5-mm CL (entirely school prawns, *Metapenaeus macleayi*) and those <5-mm CL (some school prawns, but mostly glass shrimp, *Acetes* spp.), termed "misc. Dendrobranchiata".

All data were separately analysed in linear mixed models (LMMs), with some standardised before analyses. Catch numbers and weights were analysed as log-transformed data, after being standardised to per 500-m deployment (because of differences in the distance towed—Results). All other data, including the mean CL of school prawns (>5-mm CL), ratio of damaged and undamaged shells, and deployment distance were analysed in their raw form.

All LMMs included "otter-board pair" as a fixed effect, whereas "days", "deployments", and, where relevant, their interaction were included as random terms. All models were fitted using ASReml (Gilmour *et al.*, 2006) in the R software package (R Core Development Team, 2014). The null hypothesis of no difference between otter boards was tested using a Wald *F*-test, which is a modification of the standard Wald test to provide better inference about fixed effects in mixed models. Specifically, the Wald *F*-test is derived by dividing the standard Wald test statistic by the denominator degrees-of-freedom following Kenward and Roger (1997).

Results

A total catch of 87.82 kg was retained in the collection net, comprising school prawns (3.97 kg), misc. Dendrobranchiata (6.29 kg), shells (50.28 kg), wooden debris (12.71 kg), blue blubber jellyfish, *Catostylus* spp. (9.71 kg), and teleosts (4.86 kg). The latter included 23 species, but five comprised 85% of the total (by number): southern herring, *Herklotsichthys castelnaui* (38%); pink-breasted siphonfish, *Siphamia roseigaster* (17%); whitebait, *Hyperlophus vittatus* (15%); Australian anchovy, *Engraulis australis* (11%); and bridled goby, *Arenigobius bifrenatus* (4%).

We attempted to tow the test rig with the batwing and flat-rectangular pairs at similar SOGs (ranging between 1.17 and 1.53 m s^{-1}) but, while comparable, the mean ± SE deployment distances (833 ± 4.17 and 821 ± 4.17 m) were significantly different (LMM, $p < 0.05$; Table 1). Consequently, all numbers and weights are discussed per standardised distance trawled (to 500 m for convenience). Based on the deployment distances, the mean total substrate contacts of the batwing and flat-rectangular pairs were 166.68 ± 0.98 and 1312.86 ± 5.26 m^2, respectively.

Compared with the flat-rectangular otter board's 500-m deployment^{-1}, the net behind the batwing pair had significantly lower: weights of total catch (predicted mean reduced by 80%), empty shells (by 89%) and debris (by 50%); numbers and weights of school prawns (by 78 and 72%); and numbers of bridled gobies (by 25%; LMM, $p < 0.05$; Figure 3a–e; Table 1). The batwing pair also damaged relatively fewer empty shells (28 ± 3.0 vs. 40 ± 3.0% of the total), but directed more (91%) whitebait 500 m

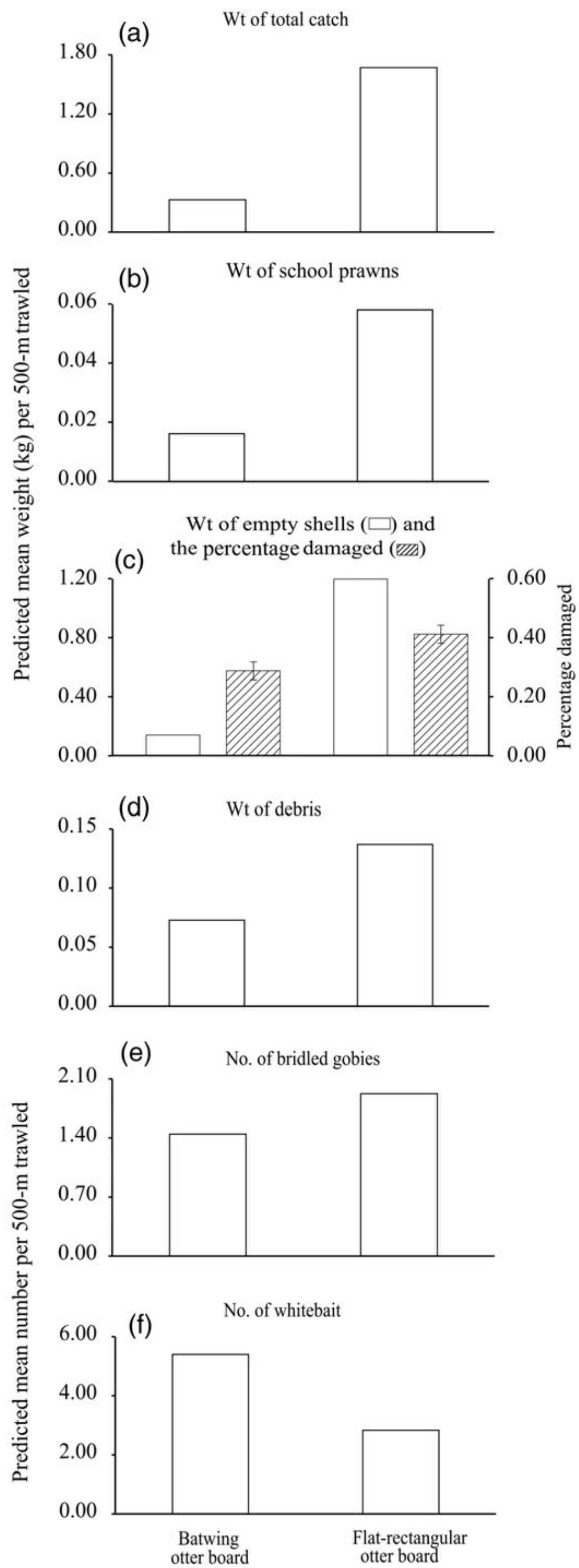

Figure 3. Significant differences in predicted mean catches in the collection net per 500 m deployment between the flat-rectangular and batwing otter-boards pairs for the weights of (a) total catch, (b) school prawns, *M. macleayi*, (c) empty shells (*A. trapezia* and *S. trigonella*, with the percentage damaged, ± SE), and (d) debris and the numbers of (e) bridled gobies, *A. bifrenatus*, and (f) whitebait, *H. vittatus*.

Table 1. Summaries of Wald *F*-values from LMMs assessing the importance of the fixed effect of otter-board pair (batwing vs. flat rectangular) in explaining variability among catches in the collection net.

Variables	Wt (kg)	No.	Wald *F*
Deployment distance	–	–	4.76*
Wt of total catch 500 m^{-1}	53.51	–	26.83***
Wt of school prawns, *M. macleayi* 500 m^{-1}	2.42	–	21.56**
No. of school prawns 500 m^{-1}	–	4 794	13.32*
Wt of misc. Dendrobranchiata 500 m^{-1}	3.79	–	2.94
No. of misc. Dendrobranchiata 500 m^{-1}	–	13 219	0.57
Mean CL of school prawns >5 mm	–	–	2.58
Wt of empty shell 500 m^{-1}	30.93	–	27.61***
Proportion of empty shell damaged	–	–	11.5*
Wt of debris 500 m^{-1}	7.74	–	6.30*
Wt of total teleost bycatch 500 m^{-1}	2.95	–	0.47
No. of whitebait, *H. vittatus* 500 m^{-1}	–	185	6.94*
No. of bridled goby, *A. bifrenatus* 500 m^{-1}	–	55	5.89*
No. of southern herring, *H. castelnaui* 500 m^{-1}	–	473	0.61
No. of pink-breasted siphonfish, *S. roseigaster* 500 m^{-1}	–	211	0.05
No. of Australian anchovy, *E. australis* 500 m^{-1}	–	140	0.05

Numbers and weights are presented in their raw form and before analyses were standardised to per 500-m trawled and then log-transformed. CL, carapace length; –, not relevant.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

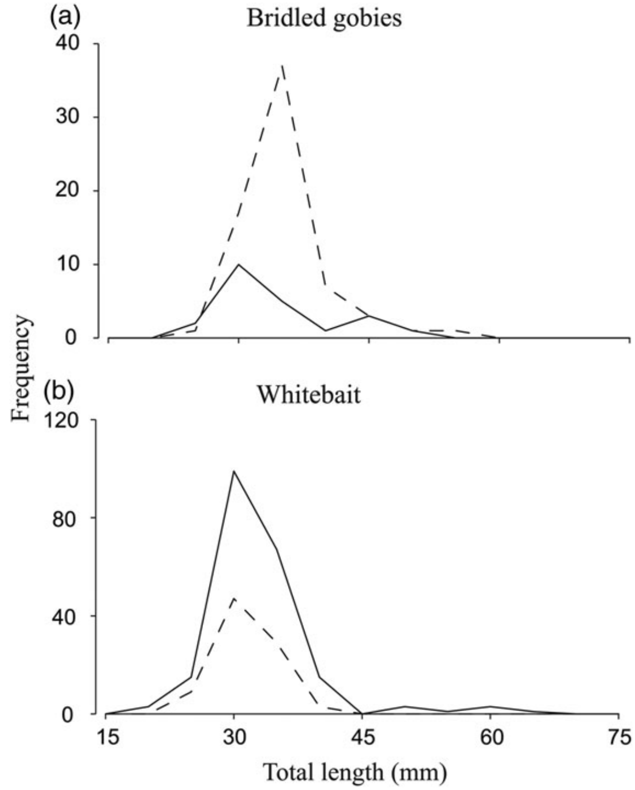

Figure 4. Size-frequency plots of (a) bridled gobies, *A. bifrenatus*, and (b) whitebait, *H. vittatus* in the collection net per absolute deployment for the flat-rectangular (dashed lines) and batwing (solid lines) otter-board pairs.

deployment^{-1} into the collection net, than the flat-rectangular configuration (LMM, $p < 0.05$; Figure 3f; Table 1).

There was no significant difference in school prawn mean sizes (>5-mm CL) collected behind the batwing (10.31 ± 0.26 mm CL) or flat-rectangular (9.76 ± 0.26 mm CL) otter-board pairs (LMM, $p > 0.05$; Table 1). Although insufficient individuals were caught to enable analyses of mean TL among deployments, the pooled size frequencies of bridled gobies and whitebait were also similar between configurations (Figure 4). There were no other significant differences between treatments (LMM, $p > 0.05$; Table 1).

Discussion

This study represents an innovative approach to describing the reductions in bottom contact and associated habitat disturbances that can be achieved via modifications to otter-board design. The observed relative differences in live catches and non-motile entrained material can be explained by behavioural responses and density-dependent mechanisms related to the substrate contact and AOA of the otter boards.

The results suggest efficiency differences between the flat-rectangular and batwing otter boards, but it should be noted that there was an experimental-design artefact which could confound the interpretation of some variables. Specifically, the otter boards were inside the collection-net wings and closer to the opening than typical trawl configurations. Further, the necessary width of the collection net (i.e. 4.8 m in total) would have meant some organisms were caught, irrespective of the otter boards. Nevertheless, the significant increase in numbers of whitebait, but fewer bridled gobies in the net behind the batwing may reflect its greater aspect ratio and lesser bottom contact. Specifically, whitebait is a schooling species that might have more easily avoided the net behind the flat-rectangular otter boards owing to their large projected area (a function of the 35° AOA) and the associated visual stimulus (e.g. greater sand clouds). In contrast, bridled gobies are benthic and therefore more likely to be affected by the reduced bottom contact of the batwing.

The observed differences in school prawn catches support the latter hypothesis, with relatively fewer in the net behind the batwing pair and at a rate (72–78%) almost proportional to the concomitant reduction in otter-board base-plate contact (87%). The same effects were hypothesised to account for significant differences in school prawn catches between beam (i.e. just sleds) and otter trawls previously tested in the same lake (Broadhurst *et al.*, 2012), but did not extend to the batwing when conventionally rigged to otter trawls (McHugh *et al.*, 2015). Such differences possibly reflect spatial or temporal variability in school-prawn behaviour in terms of their level of activity and catchability (emergence from the substrate). Dendrobranchiata catches were not similarly affected here, but the glass shrimp were probably dispersed higher in the water column. Further, the small size of glass shrimp would have precluded any sustained swimming ability (e.g. Daniel and Meyhofer, 1989) or active escape response.

The relationship between entrained material and base-plate contact was further supported by the non-motile catches, and especially shells. For example, the batwing pair displaced 89% fewer shells into the collection net than the flat rectangular, almost exactly the same as the reduction in base-plate contact (87%). Further, the batwing damaged proportionally fewer shells, which may reflect the mechanism of displacement. The flat-rectangular otter board would have displaced shells along the length of the base plate with its intense ploughing action and guided some of the shells into the collection net by contact with the timber-and-steel hydro vane. In contrast, the batwing would have displaced fewer shells with the ramped, leading edge of the base plate, with only some then contacting the PU sail.

Although physical contact is an important factor affecting the displacement of dense material/organisms, otter boards also mobilise sediment via their hydrodynamic action (Main and Sangster, 1981; O'Neill and Summerbell, 2011). For example, the amount of material entrained by an otter board can be related to its hydrodynamic drag (O'Neill and Summerbell, 2011), because this is a measure of the rate at which energy is imparted by the otter board to the otherwise stationary water. This effect—an otter board's AOA and resulting hydrodynamic drag—is evident from observations by Sterling and Eayrs (2008), where the water flow around a batwing's low AOA sail did not separate and entrained less material (predominantly near its base) than a conventionally rigged flat-rectangular otter board (from which plumes filled the immediately posterior water column).

The relative difference in lighter displaced debris (mostly wood) between designs (e.g. 50%) may reflect the difference in drag of the otter boards and the energy contained in the water turbulence surrounding them while they produce a spreading force. Specifically, perhaps while the hydrodynamic effects of both boards were not sufficient to displace shells from the sediment, it was nevertheless the key force behind the disturbance/mobilisation of less dense material (like wood) into the collection net, and the extent reflects the relative hydrodynamic drag of the boards.

The results present a useful comparison of habitat disturbance between two contrasting otter-board designs; however, it is important to consider that the consequences in terms of actual ecological impacts remain unknown. Further, the test rig precluded replicating some aspects of conventional operations, including variations in otter-board contact weight and orientation with respect to pitch (tilt) or roll (heel). Notwithstanding the limitations, we believe the method replicated commercially representative otter-board–seabed interactions and provided accurate relative indications of the characteristics of the two designs.

Considering the above, low AOA and high-aspect otter boards like the batwing clearly have the potential to displace less benthic material and for bivalves, at least, with considerably less physical damage. Further research is required to examine the ecological implications of such reductions in various trawling environments, but the principles developed here might offer practical solutions where trawling in sensitive areas is considered problematic. A concomitant benefit of the batwing design is reduced drag, which has the potential to make trawling more energy efficient (e.g. McHugh *et al.*, 2015).

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