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High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries

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A B S T R A C T

Bycatch is a cause of mortality among marine mammals, sea turtles, fish and birds. For some species this mortality may be sufficient to cause population declines. The Baltic Sea is a global 'hotspot' for bird bycatch in gillnet fisheries and is globally important for wintering sea ducks, but no technical solution has been found yet to reduce bird bycatch in gillnet fisheries in the Baltic. Here, we report on trials conducted in the Baltic Sea to test whether two different gillnet modifications with visual stimuli can effectively reduce bird bycatch while maintaining volume of fish caught. We conducted paired trials of two types of visual stimuli attached to nets: 1) high contrast monochrome net panels and 2) net lights (constant green and flashing white LED lights). We measured the amount of fish and birds caught in standard nets and those modified with the visual stimuli. Neither of the two most commonly caught species, Long- tailed Ducks *(Clangula hyemalis)* and Velvet Scoters (*Melanitta fusca*), were deterred from lethal encounters with nets by either black-and-white panels or by steady green or flashing white net lights. Long-tailed Ducks were caught in larger numbers in nets equipped with flashing white net lights than in unmodified nets at the same location. Catch rates of commercial fish were not affected by net lights or net panels placed within the nets. Hence, while the deterrents that we tested successfully maintained fish catch, they failed to reduce bird bycatch and are therefore ineffective. We discuss likely avenues for future investigation of bycatch mitigation methods for gillnet fisheries, including species and location response to net lights, managed fishery closures, above-water distraction of birds and gear switching.

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1. Introduction

Bycatch, the unintended capture of animals by a fishery, is a cause of mortality among marine mammals, sea turtles, fish and birds (Lewison et al., 2004, 2014; Moore et al., 2009). For some species, bycatch mortality is sufficiently large to cause population declines (Michael et al., 2017; Phillips et al., 2016; Wanless et al., 2009; Jaramillo-Legorreta et al., 2017; Peckham et al., 2007; Dulvy et al., 2014).

Bycatch of seabirds was first documented in gillnet fisheries in the early 1970s (Tull et al., 1972), although it was not until the early 1990s that bycatch of several taxa in gillnets was recognised as a conservation concern (Northridge, 1991). Gillnets were banned in the high seas (United Nations, 1991), but are still used extensively within Exclusive Economic Zones (EEZs) across the world, where several hundreds of thousands of seabirds are accidentally caught and drowned every year (Žydelis et al., 2013). Effective mitigation measures that reduce the bycatch of seabirds have been developed for longline fisheries (Melvin et al., 2014; Sullivan et al., 2018; Žydelis et al., 2009b; ACAP, 2017b; ACAP, 2017a), but effective measures that reduce the bycatch of diving birds (seabirds, including sea ducks) in gillnets have not been developed (Melvin et al., 1999; Løkkeborg, 2011).

The Baltic Sea has been identified as a global ‘hotspot’ for bird bycatch in gillnet fisheries, with mortalities estimated to be in the tens of thousands annually (Žydelis et al., 2009a, 2013). Primarily, this mortality is comprised of benthivorous (sea ducks (Tribes Somateriini, Mergini) and piscivorous (sawbill ducks (Mergini), loons (Gaviidae), grebes (Podicipedidae), auks (Alcidae)) species, which are susceptible because their foraging frequently occurs in shallower water areas favoured for gillnet fishing.

The high incidence of bird bycatch in gillnets in the Baltic Sea is due to two factors; the global importance of the Baltic for wintering sea ducks, particularly Long-tailed Ducks *Clangula hyemalis* and Velvet Scoters *Melanitta fusca* (Skov et al. (2011)), BirdLife International (2018)); and the very large number of gillnets being used by many commercial and artisanal fishermen.

Populations of Long-tailed Duck and Velvet Scoter have undergone precipitous declines in the Baltic region in recent years. Between censuses in 1992–93 and 2007–09, declines of over 50% were recorded for Long-tailed Duck, Velvet Scoter, Common Eider *Somateria mollissima* and Steller's Eider *Polysticta stelleri* (Skov et al., 2011). Overall, among the 30 species of Baltic wintering birds that are particularly susceptible to bycatch in gillnets (Žydelis et al., 2013), 10 are listed vulnerable to critically endangered in the HELCOM red list of birds (HELCOM, 2013).

In 2017, Tarzia et al. (2017) estimated that around 1,000 sea ducks were killed in the area fished by the small-scale fleet of Lithuania alone - a country with a small coastline and one of the smaller gillnet fleets in the Baltic (89 registered small-scale vessels (EU Fleet Register on the Net, 2018)). Extrapolations of the total bycatch of birds in gillnets in the Lithuanian Baltic are as high as 2,500–5,000 birds annually, and slightly over 3,000 annually for the Polish gillnet fleet in the region of Puck Bay alone (Psuty et al., 2017). The magnitude of sea duck bycatch in gillnets across the entire Baltic Sea may therefore be sufficient to contribute significantly to the decline of sea duck populations (Almeida et al., 2017).

Given the potentially significant effect of gillnet bycatch on sea duck populations in the region, effective measures to reduce bycatch in gillnets are urgently needed. However, only few technical bycatch mitigation measures have been tested for gillnets (Løkkeborg, 2011). Melvin et al. (1999) trialled visual alerts in the form of high visibility net colouring and auditory alerts in the form of ‘pingers’, whilst Mangel et al. (2018) examined the use of green lights, attached to the floating line from which the net is suspended (hereafter: headline, Fig. 1), previously found to be successful at reducing sea turtle bycatch. The current best practice for minimising bird bycatch is the exclusion of gillnet fishing at times when and from areas where susceptible species are known to concentrate (Žydelis et al., 2013). However, such measures incur social and economic costs.

Martin and Crawford (2015) reviewed the sensory and perceptual capacity of birds to identify potential methods to reduce bycatch in gillnet fisheries. Based on their analysis, visual alerts are most likely to be detected by birds underwater. In view of the turbid and low light level conditions that often occur in coastal marine water it was argued that alerting stimuli should be large sized net panels that have high internal monochrome contrast. Visual cues, in the form of thick white mesh panels incorporated into nets, appeared to be successful in reducing bycatch of auks in drifting gillnets in Puget Sound. However, the degree of reduction differed between species and also resulted in a reduction in the target salmon catch (Melvin et al., 1999). While bycatch of some cetaceans (e.g Harbour Porpoise, *Phocoena phocoena*) can be reduced by acoustic deterrence devices (Trippel et al., 1999; Bjørge et al., 2013; Gearin et al., 1994), there is little evidence that this would be effective in aquatic birds, since (as with other terrestrial vertebrates whose hearing has evolved to function in air) there is no evidence that birds are able to communicate or navigate using acoustic cues under water (Gridi-Papp and Narins, 2008).

Recently, Mangel et al. (2018), working in the eastern Pacific, reported a significant reduction in the bycatch of Guanay Cormorants *Phalacrocorax bougainvillii* in gillnets to which green LED lights had been attached. The same lights had previously been shown to reduce turtle bycatch in the same fishery (Ortiz et al., 2016; Wang et al., 2010, 2013). This finding suggests that some form of visual signal may deter birds from approaching gillnets. In these cases, the deterrents were tested on visual pursuit predators (auks and cormorants). By contrast, sea ducks primarily exploit tactile information to detect benthic prey in waters of low visibility (Madge and Burn, 1988; Livezey, 1995). The coastal waters of the southern Baltic Sea are of relatively high turbidity year-round compared to oceanic waters (Sandén and Håkansson, 1996; Aarup, 2002). Hence, a practical field test is urgently needed to assess whether visual deterrents, such as high contrast net panels or lights attached to the nets, can effectively reduce the bycatch of sea ducks in the Baltic Sea, while maintaining the amount of fish caught in the modified nets.

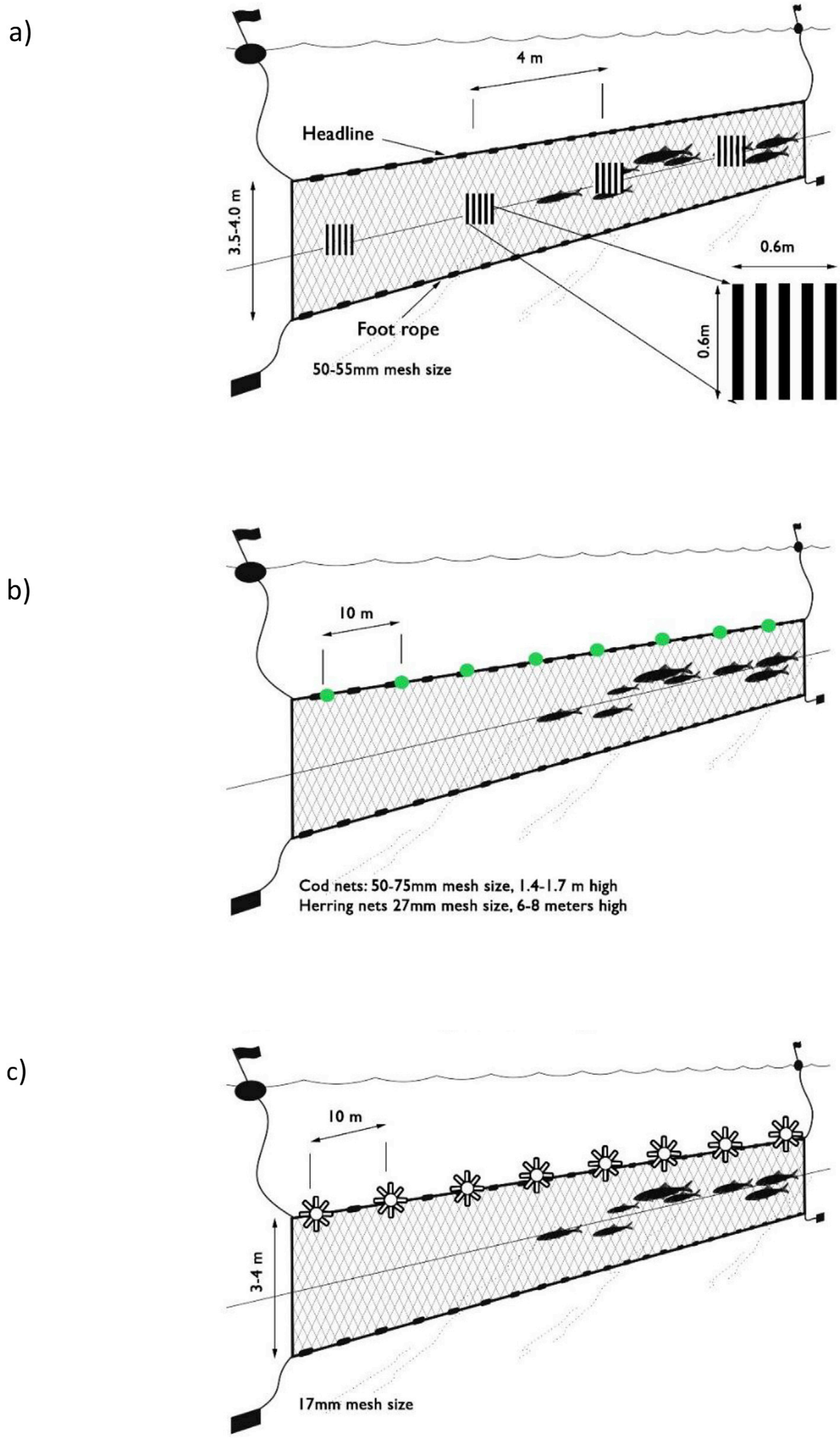

Fig. 1. Schematic of the bycatch mitigation measures trialled. a) Net panel used in Lithuanian bycatch mitigation trials. Panels measured 0.60 × 0.60 m and were attached every 4 m along each net, equidistant from the head and bottom lines; b) Green constant lights used in Polish trials, every 10 m along the headline; c) Flashing white lights, used in Lithuanian waters, every 10 m along the headline. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Here, we report on trials conducted in the Baltic Sea waters of Poland and Lithuania to test whether two different net modifications with visual stimuli can effectively reduce bird bycatch. We also investigated whether any net modifications would influence the volume of fish caught. To achieve this, we deployed control and experimental gillnets in collaboration with commercial fishers and measured the amount of target fish and birds caught in both control and experimental gillnets.

2. Methods

We conducted paired trials to determine the effects of the gear technology on bird bycatch and target fish catch. Two types of visual stimuli attached to nets were tested: 1) high contrast monochrome net panels and 2) net lights. Fishers who participated in our trials did not alter their fishing practices in any way other than the addition of bycatch mitigation measures. We did, however, work with fishers in areas known to be at risk of relatively high bycatch (i.e. Special Protection Areas off the Lithuanian and Polish coasts), in order to effectively test the mitigation measures, by exposing them to realistic levels of bycatch risk. The bycatch rates presented in this study should therefore not be considered as representative for the species across their ranges and should not be used to extrapolate gillnet bycatch across the whole Baltic Sea.

2.1. Net panels

Based on a design proposed in Martin and Crawford (2015), we tested high visibility net panels (Fig. 1a). Net panels were designed following a 'sensory ecology' approach to bycatch mitigation (Martin and Crawford, 2015) by maximising the likelihood of birds detecting the panels, and therefore nets. Panels measuring 0.6 m × 0.6 m, composed of vertically oriented alternate black and white stripes (60 mm wide) made of nylon, were attached every 4 m along the net and centrally in the vertical plane (Martin and Crawford, 2015). The stripes of the panel were cut into strips to allow the flow-through of water and reduce drag on the net (Fig. 1a).

Net panel trials were conducted in the winters of 2015/2016 and 2016/2017. Nine small vessels targeting Cod *Gadus morhua* in the coastal fishing blocks immediately west of the Lithuanian coast and the Curonian Spit (Fig. 2) used paired sets of multiple monofilament nylon gillnets of mesh size 50–55 mm, length 40–75 m, height 3.5–4 m (set length 165 m–600 m). Set lengths were determined by individual vessels but were kept consistent within each pair. Each pair of sets consisted of

Fig. 2. Location of inshore fishing zones where bycatch mitigation trials were carried out in the Baltic sea. A = Lithuanian Coast; B = Curonian Spit; C = Pomeranian Bay; D = Puck Bay. A & B in Lithuanian territorial waters, C & D in Polish territorial waters.

two identical sets, of which one was fitted with the net panels. For each set, the number and species of any birds bycaught were recorded, as was the total fish catch (species and total weight in kg) and the soak time and length of the set.

2.2. Net lights

Based on previous work (Mangel et al., 2018), we tested constant green battery-powered LED lights (model YML-1000, YM Fishing, Korea) and flashing white battery-powered LED lights (Fishtek, Devon, UK).

In the winters of 2016/17 and 2017/18, we tested these two types of net light as a technique to mitigate bird bycatch in two areas of the Baltic Sea.

1) Constant green net lights were tested in the Polish Baltic in the late winter fishing seasons of 2016 and 2017 (Fig. 2). Green lights were mounted in plastic carriers, the majority of light was within the waveband 500–550 nm with a narrow peak of intensity at 525 nm. Lights were attached to the headline of nets every 10 m (Fig. 1 b&c). Four small vessels (two in each of the Pomeranian Bay and Puck Bay fishing areas; Fig. 2), predominantly targeting Cod, Whitefish *Coregonus lavaretus*, Pikeperch *Sander lucioperca* and Flounder *Platichthys flesus* (net mesh 55–70 mm) were provided with green lights. Low catches of the initial target species with unmodified control nets forced fishers to refocus on Herring *Clupea harengus* (Pomeranian Bay only, net mesh 27 mm). Vessels deployed sets in pairs, one carrying lights and one without but otherwise identical. Cod sets were 322 m–588 m long comprised of individual nets (43–84 m in length and 1.4–1.7 m high), while Herring sets were 300 m–600 m in length comprised of individual nets of 50 m length and between 6 and 8 m high (Fig. 1b).
2) Flashing white net lights were tested in the eastern Baltic off the coast of Lithuania during the winter of 2017/18 (Fig. 2). White lights were mounted in clear thermoplastic elastomer carriers that were approximately 200 mm long and weighed 30g. The white net lights had a set flash sequence with increasing flash rates starting from 2 s flash intervals to 250 ms flash intervals. Flashes lasted 52 ms and flash sequences repeated every 16 s with a light output of 10 lumen. Three small vessels targeting Smelt (*Osmerus eperlanus)* were provided with the lights to attach to one of a pair of otherwise identical sets (210 m–300 m) comprising individual nets of mesh size 17 mm, of 30 m length and 3–4 m high (Fig. 1c).For each of the paired net deployments we collected data on fish catch, bird bycatch and effort as for the net panel trial described above.

2.3. Data analysis

Experiments were paired trials, with each treatment net being paired with an identical control net at the same time and location. Consequently, we did not use sophisticated statistical models that account for variability in bycatch across space and time and control for non-independence of bycatch during the same fishing trip (Gardner et al., 2008). Instead, we simply quantified the effect size of our treatment as the difference in the number of bycaught birds per trial. We calculated that difference for all trials and calculated 95% bootstrapped confidence intervals around the mean by randomly drawing n samples with replacement from all the trials, with n being the number of trials available for a given mitigation measure. We took the mean of 10,000 random draws and present the bootstrapped mean and the 95% confidence intervals (CI) of the change in seabird bycatch scaled to the mean set length and soak time. We first performed this calculation for all bird species together but given that there may be species-specific differences in the response to certain bycatch mitigation techniques (Melvin et al., 1999), we also conducted these analyses for the two most commonly caught sea ducks, Velvet Scoters and Long-tailed Ducks.

Similarly, we calculated the change in fish catch and present the bootstrapped mean and 95% confidence intervals of fish catch, scaled to the mean fish catch across all control nets in a given fishery.

If the 95% confidence intervals overlapped zero, we concluded that the effect of the bycatch mitigation measure was not statistically significant.

3. Results

3.1. Net panels

In winters of 2015/16 and 2016/17, 151 experimental net deployments (48,101m/days) resulted in 129 birds being caught, with 74 caught in control sets and 56 in experimental sets. Eight species were recorded as bycatch, with Velvet Scoters, Long-tailed Ducks and Red-throated Loons *Gavia stellata* the most numerous (Table 1). We excluded a single extreme event (where 27 birds were captured in a single 60 m control net and 12 birds in the paired treatment net of the same size) from our analysis because this single event disproportionally affected the mean catch rate. Excluding this event had no effect on our conclusion that there was no significant difference in the overall number of birds bycaught in the experimental (0.87 birds/1000m/day) and control nets (0.91 birds/1000m/day). However, there was a small increase in the number of Long-tailed Ducks bycaught when net panels were deployed (mean increase = 0.30 birds/1000 m net/day; 95% CI 0.08–0.53; 0.06 (in control sets) to 0.36

Table 1
Numbers of birds caught in experimental gillnets in the Lithuanian and Polish Baltic Sea between 2015 and 2018. Experimental gillnets were deployed in paired mitigation trial sets where three different mitigation measures were tested against unmodified control nets in the same set.

Species	Vernacular name	Net panels		Constant green lights		Flashing white lights	
		Control	Experiment	Control	Experiment	Control	Experiment
Aythya marila	Great Scaup	1	0	1	0		
Bucephala clangula	Goldeneye	1	0			0	1
Clangula hyemalis	Long-tailed Duck	3	23	43	29	8	30
Gavia arctica	Black-throated Loon			2	2		
Gavia stellata	Red-throated Loon	4	2	2	1		
Larus argentatus	Herring Gull	1	0				
Melanitta fusca	Velvet Scoter	62	28	2	3	1	1
Melanitta nigra	Common Scoter	2	0	1	4	4	3
Mergus merganser	Goosander					0	2
Phalacrocorax carbo	Great Cormorant			1	0		
Podiceps cristatus	Great Crested Grebe	0	1	2	2		
Uria aalge	Common Guillemot			1	2		
TOTAL		**74**	**56**	**55**	**43**	**13**	**37**

(in experimental sets) birds/1000m/day; Fig. 3). There was no consistent change in fish catch due to net panel use, with a mean change of −1.5% between experimental and control sets (95% CI: -14.6—12.1%, Fig. 4).

3.2. Net lights

1) Constant green net lights were tested in 78 net deployments (23,930m/days). The total bycatch was 98 birds, the majority of which (72) were Long-tailed Ducks, along with small numbers of seven other species (Table 1). Similar numbers of birds were caught in control (55) and experimental (43) sets (Table 1). The addition of green net lights therefore had no significant effect on bycatch of either all birds [0.73 (control) vs. 0.57 (experimental) birds/1000m/day] or that of Long-tailed Ducks [0.57 (control) vs. 0.39 (experimental) birds/1000m/day (Fig. 3)]. Fish catch also remained unchanged using green headline lights, with a mean change of 0.98% between experimental and control sets (95% CI: -9.0 − 12.5%, Fig. 4).
2) Flashing white net lights were tested in smaller mesh smelt nets during 39 net deployments (11,635m/days). The total bycatch was 50 birds, thirteen in control sets and 37 in sets with white net lights. The majority of these bycaught birds were Long-tailed Ducks, with a few Scoters and two Goosanders *Mergus merganser* (Table 1). There was an increase in the bycatch of all birds with flashing white net lights [mean increase = 2.13 birds/1000 m net/day; 95% CI 0.71–3.92; Fig. 3; 1.16 (control) to 3.29 (experimental) birds/1000m/day], mainly due to the increased bycatch of Long-tailed Ducks [mean increase = 1.96 birds/1000 m net/day; 95% CI 0.71–3.39; Fig. 3; 0.79 (control) to 2.75 (experimental) birds/1000m/day].

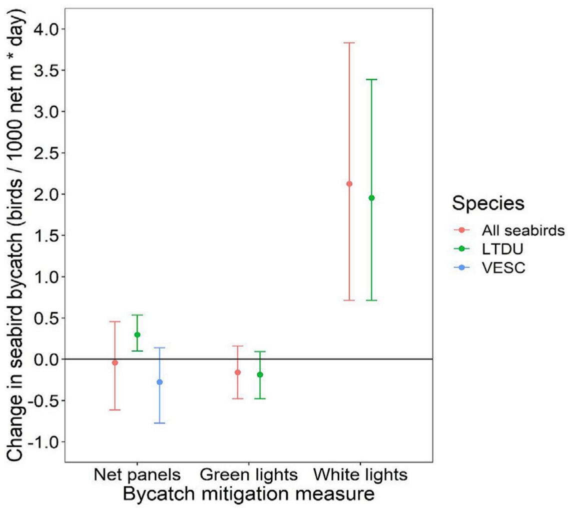

Fig. 3. Mean change in seabird and sea duck bycatch between control and treatment gillnets in the Lithuanian and Polish Baltic Sea between 2015 and 2018. Experimental gillnets were deployed in paired mitigation trial sets where three different mitigation measures were tested against unmodified control nets in the same set. Error bars are 95% confidence intervals. LTDU = Long-tailed Duck; VESC = Velvet Scoter.

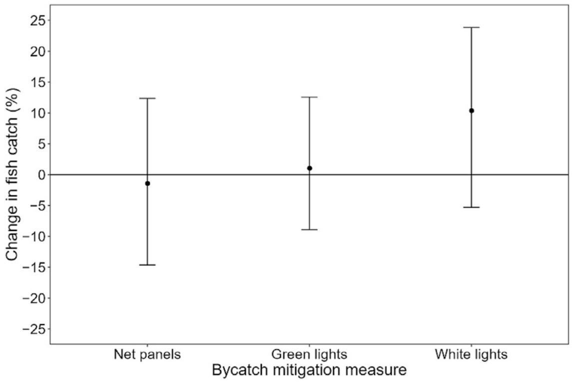

Fig. 4. Percentage change in target fish catch between control and treatment gillnets in the Lithuanian and Polish Baltic Sea between 2015 and 2018. Experimental gillnets were deployed in paired mitigation trial sets where three different mitigation measures were tested against unmodified control nets in the same set. Error bars are 95% confidence intervals.

Fish catch with the presence of lights showed a mean change of 10.4% between experimental and control sets but given the large variability in fish catch this effect was not statistically different from 0 (95% CI: -5.3 − 23.7%, Fig. 4).

4. Discussion

Our results suggest that neither net lights nor net panels were effective at reducing bird bycatch in Baltic set net fisheries. Moreover, the use of flashing white net lights increased bird bycatch. Catch rates of commercial fish were not affected by net lights or net panels placed within the nets. Neither of the two most commonly caught species, Long- tailed Ducks and Velvet Scoters, were deterred from lethal encounters with nets by either black-and-white panels or by steady green or flashing white net lights. More worryingly, Long-tailed Ducks seemed to be attracted to nets equipped with flashing white net lights.

Two previous studies suggested that increasing the visibility of nets using mesh or panels (Melvin et al., 1999) and the deployment of green net lights (Mangel et al., 2018) could potentially reduce seabird bycatch in gillnets. However, in Puget Sound thick white mesh was integrated into the net and had to be relatively broad to effectively reduce bycatch, with the adverse effect of simultaneously reducing salmon catch (Melvin et al., 1999). As with our trials in the Baltic sea, these Puget Sound trials were conducted in relatively turbid coastal fisheries, where visibility is likely to be limited for foraging animals.

The primary seabird bycatch interaction recorded by driftnet fishers in Puget Sound (Melvin et al., 1999) came from rafts of birds floating towards nets on currents. When drifting birds saw the headline of the net, their dive escape response resulted in capture, so increasing the visibility of the top portion of the net likely encouraged birds to fly or hop over the headline rather than to dive (Melvin et al., 1999). This interaction is fundamentally different to the bottom-set gillnet fishery in which sea ducks are caught in the Baltic Sea, explaining why our results did not confirm that increased net visibility would result in lower bird bycatch.

The net panels that we trialled covered a smaller proportion of the net surface (1–8%) compared to the Puget Sound trials (10–25%) (Melvin et al., 1999), and had no effect on fish catch, but are also not an effective means of reducing current bycatch rates. These panels were designed to be visible to diving birds given their underwater sensory capacities and the low light levels and turbid conditions (Sandén and Håkansson, 1996) that occur in many driftnet fisheries (Martin and Crawford, 2015). These panels may well be conspicuous to the birds, but they do not elicit an aversive/avoidance response. In fact, some birds could find them attractive. Long-tailed Ducks congregate in winter to find breeding partners, and adult birds in breeding plumage display high contrast black-and-white tracts of feathers (Madge and Burn, 1988). High contrast monochrome net panels may therefore be visible to Long-tailed Ducks and may elicit an attraction rather than an aversion response.

Indeed, we found that flashing white lights attached to the headline attracted more Long-tailed Ducks into gillnets than control nets. This suggests that sea ducks may have detected lights attached to the nets and may have been attracted to nets.

In the turbid waters of the coastal Baltic, one of the main issues with gillnets, and any mitigation techniques reliant on visual perception, is that vulnerable animals may be unlikely to perceive threats in time to avoid them. Alternatively, the dark-adapted state of their eyes may be disrupted by sudden exposure to a bright light, leaving them temporarily visually impaired and therefore less likely to be able to detect a net. For benthic-foraging species, the amount of time that can be spent on the bottom gathering food is limited by the amount of time needed to reach the bottom and return to the surface (Richman and Lovvorn, 2008; Nilsson, 1970). In dark and turbid waters, the return to the surface is likely accelerated by buoyancy and the attraction to light, which could potentially explain the increased catch rate of Long-tailed Ducks in nets equipped with white flashing lights.

Use of mitigation methods that reduce target species catch rates will deter fishers from their potential adoption. Therefore, it is imperative to assess the influence of mitigation techniques on bycatch rates on target species. The fact that the methods trialled in this study did not adversely affect fishing effectiveness is potentially useful, if an effective light-based method can be found that deters birds. For example, constant green lights in a set net fishery in Brazil effectively reduce bycatch of sea turtles and are popular with fishers as they also increase catches of lobster. The increase in lobster catches is possibly the reason for acceptance of technical mitigation methods in this fishery (R. Enever *personal observation*).

4.1. Future developments

The need to understand and reduce bird bycatch in gillnet fisheries remains urgent. Our current work and that of others have so far failed to find a universally effective solution to this problem. We suggest that future work on bycatch mitigation should explore at least four areas:

(1) *species and location response to net lights.* In our study the deployment of green headline lights elicited no significant effect on bird bycatch or target species catch rates. This is contrary to the finding that green lights reduced cormorant (Mangel et al., 2018) and sea turtle (Ortiz et al., 2016; Wang et al., 2010) bycatch in the Pacific Ocean. Given these conflicting findings, the use of green net lights may be a worthy avenue for future research, especially to understand apparent differences between species. In Peru, bycatch reductions of >80% were recorded for Guanay Cormorants in sets in which green lights were deployed. However, there was also an increase in the number of Peruvian Boobies *Sula variegata* caught and these may have been attracted by the lights (Mangel et al., 2018). A combination of more fundamental work on what sea ducks (and other seabirds) find aversive (potentially with captive populations) and further trials with the same lights in new locations (with other species vulnerable to bycatch) would help to better understand fundamental differences between species and locations. However, careful specification of the nature of the lights will be necessary to compare effects. For example, coloured lights should be specified by the wavelength band and intensity of their output, not just the human subjective description of their colour. Also, the effect of light flicker frequency should be investigated further.

(2) *managed fishery closures*. Comparing our results with those of Mangel et al. (2018) suggests that it is unlikely that a single mitigation measure will be effective to reduce all bird bycatch in fisheries around the world. Region- and fisheries-specific combinations of mitigation measures may be necessary to reduce bycatch to acceptable levels in particular locations. As suggested previously, spatial fishing closures in areas where birds vulnerable to gillnet bycatch congregate may be the most effective approach to reduce bycatch (Žydelis et al., 2013). This may be feasible given that the species vulnerable to gillnet bycatch have generally short foraging ranges within the locations where they come into conflict with fisheries. However, without careful management, fishery closures could displace fishing efforts and may increase bycatch in other areas resulting in no net benefit for bird populations (Agardy et al., 2011; Suuronen et al., 2010; Sen, 2010). Furthermore, the coincidence of foraging birds with fishing effort is likely to be high since similar resources are being targeted, therefore time area closures are likely to have significant economic consequences, and thus be difficult to enforce.

(3) *novel mitigation measures involving above-water distraction of birds*. The current state of knowledge supports the need to consider novel mitigation measures based on alternative strategies. A potential solution could be to focus on above-water measures. Such measures do not face the same limitations of understanding the light environment and the visual challenges faced by the birds below water. Evidence exists how to effectively distract birds of a range of species and in a range of situations (Woodroffe et al., 2005). Crop protection, fouling control, and airport area exclusion studies (Burger, 1983; Bishop et al., 2003; Haag-Wackernagel and Geigenfeind, 2008) may provide valuable insights for future research on a marine-based deterrent. The use of 'looming eyes' by Hausberger et al. (2018) has proven effective in deterring birds of prey and corvids whilst showing no signs of immediate habituation, highlighting the potential for utilising the same behavioural response that eyespot mimicry in prey provokes among predators (Stevens, 2005; Merilaita et al., 2011; De Bona et al., 2015). This could potentially be adapted into existing fishing gear, such as buoys, which could deter rafting seabirds from areas of gillnet fishing activity and would be undisruptive to fishing practices.

(4) *gear-switching.* Replacing gillnets with other fishing gear with lower bycatch has been tested. This has included switching to longlines (Vetemaa and Ložys, 2009; Mentjes and Gabriel, 1999), baited pots (Koschinski and Strempel, 2012), and fish traps (Vetemaa and Ložys, 2009). Results have been variable, but Lithuanian trials of herring trap nets did demonstrate zero bird bycatch and higher catch efficiency (Vetemaa and Ložys, 2009). Baited pots trials indicate substantial bird bycatch reductions, though fish catch has been impacted in some cases (Koschinski and Strempel, 2012). However, work conducted more recently by Hedgärde et al. (2016) suggests that with further refinement, catch efficiency could be improved in baited pots. Perhaps the biggest barriers to the adoption of gear-switching are economic and social, with capital outlay costs for new fishing equipment and the need to re-train in fishing with a new gear type. However, the encouraging results from these studies suggest that further exploration and development is merited, particularly in ways to promote uptake and lessen socio-economic resistance to the use of new gear types.

Conflicts of interest

RE is Head of Innovation and Uptake at Fishtek Marine, provider of lights for mitigation trials.

Role of the funding sources

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