Sink or swim? Modernization of mussel farming methods may negatively impact established seabird communities

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ABSTRACT

Marine aquaculture is the fastest growing sector of global food production and is projected to increase to meet future demand. Expansion and modernization of cultivation methods are needed to reach this target but a cost-benefit evaluation for biodiversity conservation is required to achieve sustainable aquaculture practices. We assess drivers of avian richness and abundance in a long-established seabird community present in a series of longline mussel farms in Italy and in response to a recent modernization process in the farming methodology. Over 2 years (24 surveys) we detected a remarkable diversity (15 species in 5 families) and abundance (n = 5858) of birds, of which 40% (n = 6) are regarded as species of international conservation importance. Our models highlighted that the strongest driver explaining variation in abundance and richness across sites was the type of buoy and the associated cultivation method applied. The older and fast-declining double headrope design, offered greater stability for birds to rest. Conversely, the newer and mechanizable single headrope design dominant method in our study site and projected to replace the older system, was unsuitable for birds. Our findings confirm the function of mussel farms as a sort of marine protected area where low anthropogenic disturbance, higher prey availability and suitable artificial structures promote the establishment of seabird communities with minimal impacts on harvest. However, we suggest that potential modernization of farming methods, important to meet future human demand, needs to be carefully assessed and compensated for, particularly where long-established seabird communities have formed in response to such practices.

1. Introduction

Over the past few decades, seafood production has grown at an unprecedented rate in response to human exploitation of wild fisheries beyond carrying capacity and to an increased demand for protein from a world population that is growing exponentially (FAO, 2018). Marine aquaculture is currently the fastest growing sector of global food production, supplying ca. 50% of the seafood consumed globally, and is projected to grow from 66.6 million metric tons (mmt) in 2012 to 93.2 mmt by 2030 (World Bank, 2013; FAO, 2018). However, to fill the gap between supply and future demand, significant improvements in aquaculture are required in ways that are socially and environmentally sustainable. These must take into account the biodiversity conservation perspective (Diana, 2009, Forrest et al., 2009, de Silva, 2012). Although not universal, aquaculture can negatively impact water quality (Pitta et al., 1998; La Rosa et al., 2002; Brooks et al., 2017), damage coastal habitats (Primavera, 2006; Forrest et al., 2009), introduce non-indigenous species (Savini et al., 2010), increase bycatch incidents (Barrett et al., 2019), and decrease the fitness of wild conspecifics through diseases and genetic pollution (Maury-Brachet et al., 2008; Johansen et al., 2011; Karlsson et al., 2016).

Of total global marine food production, about 14% consists of marine bivalves of which 89% is produced through aquaculture and only 11% from wild fisheries (Wijsman et al., 2019). Mussels are mostly farmed using the longline system, which consists of growing mussel larvae on ropes hanging from long, horizontal anchored lines suspended from buoys (Sdrigotti and Fonda Umani, 2002; Wall, 1996; Franzo et al., 2014). The ecological impacts of mussel farming ought to be minimal compared to fish farming because bivalves obtain food autonomously from the environment (i.e. filter feeding) whilst in fish farms the accumulation of organic matter as a consequence of uneaten food supplements can be high (Mazzola et al., 2000; Crawford et al.,

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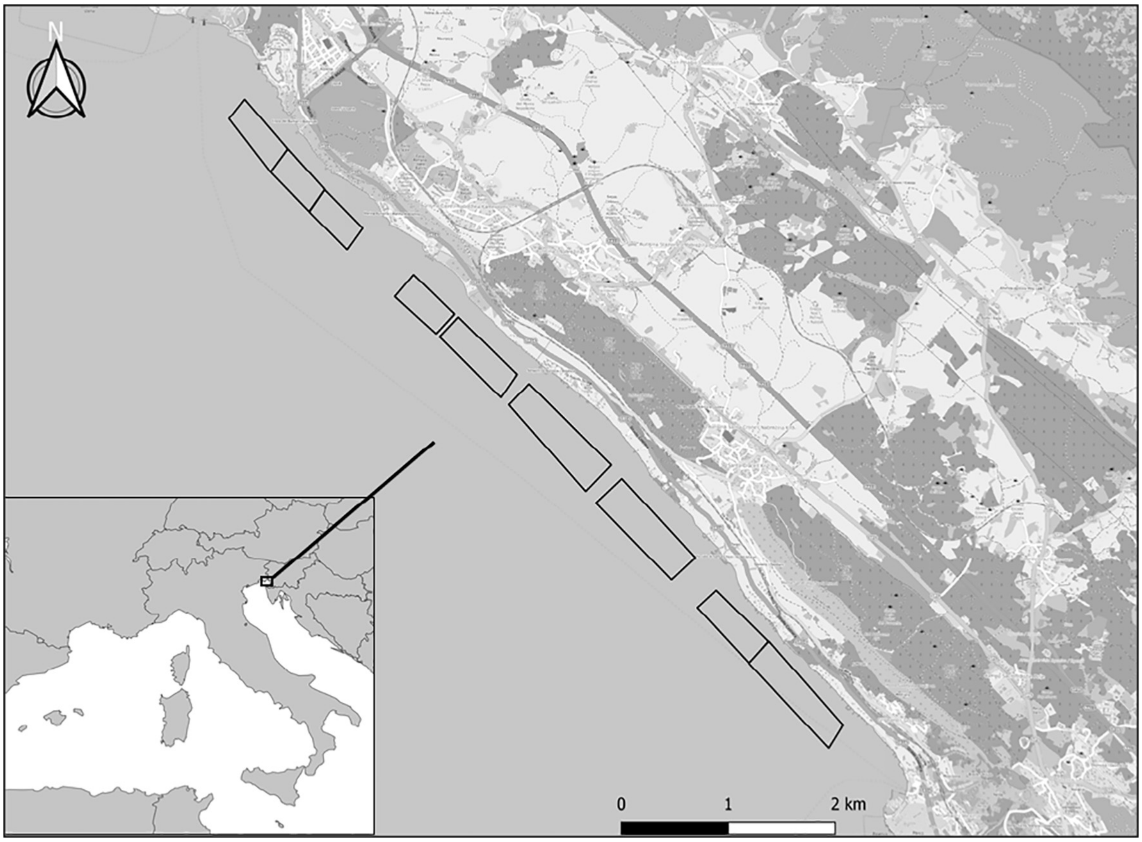

Fig. 1. Location of the study area in the Gulf of Trieste (Italy; bottom left map) and relative plots ($n = 9$) of mussel farms where bird counts and environmental sampling took place. © OpenStreetMap contributors.

2003; Danovaro et al., 2004). Various works have evaluated the contribution of mussel farms to ecosystem services with positive regulating services ranging from water purification and waste treatment (reducing algal blooms, improvement of seagrass and macroalgae growth; Lindahl et al., 2005, Peterson and Heck, 1999, Schröder et al., 2014, Waajen et al., 2016), carbon, nitrogen and phosphorus sequestration (used for shell and tissue growth; Srisunont and Babel, 2015, Clements and Comeau, 2019), reduction of erosion processes (i.e. currents velocity; Plew et al., 2005, Strohmeier et al., 2005, Stevens et al., 2008) and the provision of cultural services such as tourism, scientific and educational interactions, cultural activities and maintenance of community links with the marine environment (van der Schatte Olivier et al., 2018). Such regulation services seem to outweigh the negative impacts of disruption to water flow, to phytoplankton populations, depositional and benthic concerns and possible disruption to some cultural services (i.e. recreational, aesthetic and spiritual interactions; Seafood Safety Assessment Ltd., 2019). Mussels are also considered foundation species (Bruno and Bertness, 2001) as their aggregation creates physical architectures (aggregation devices or artificial reefs) which facilitate the formation of biogenic habitats for many species including those of conservation concern (Borthagaray and Carranza, 2007; Sanchez-Jerez et al., 2011; Theodorou et al., 2015; Díaz López and Methion, 2017). In addition, the development of aquaculture systems and the related urbanization of coastal areas has formed novel habitats as a result of the presence of new artificial structures (i.e. pontoon, buoys, bridges) with important consequences at a trophic level. Epifaunal assemblages that grow on artificial floating structures have been found to differ in composition, have greater density and growth rates and attract greater abundances of associated predators than nearby shorelines (Costa-Pierce and Bridger, 2002; Kirk et al., 2007; McKindsey et al., 2011).

An evaluation of the advantages and disadvantages provided by artificial structures has been mostly focused on sedentary and errant invertebrates and fish (People, 2006; Perkol-Finkel and Benayahu, 2007; Norrisey et al., 2006; Tallman and Forrester, 2007) whilst less attention has been paid to marine vertebrates such as birds or mammals (Würsig and Gailey, 2002). Studies describing the presence of these animals in aquaculture systems are generally focused on finding non-lethal methods for deterring predation and related economic losses on aquaculture products (Nash et al., 2000; Ross et al., 2001; Varennes et al., 2013), whilst descriptions of the conservation value of aquaculture for biodiversity are limited (Kirk et al., 2007; Barrett et al., 2019). Depending on the location and type of aquaculture, available literature describes bird assemblages encompassing various orders and families including swans, geese and ducks (Anatidae), divers (Gavidae), cormorants and shag (Phalacrocoracidae), herons (Ardeidae), grebes (Podicepedidae), raptors (Accipitridae, Pandionidae), waders, gulls and terns (Charadriiformes) and even passerines (Passeriformes) (see Callier et al., 2018, Barrett et al., 2019 and references within). These are sometimes of important conservation value as many seabird populations are declining globally (Croxall et al., 2012; Paleczny et al., 2015). Birds may be attracted by mussel farms as they provide a direct (e.g. predation on the farmed species) and indirect (e.g. acting as fish aggregation devices) source of food (Varennes et al., 2015; Callier et al., 2018). Furthermore, the presence of various types of artificial structures (i.e. buoys, ropes) can function as important sites for optimizing energy consumption i.e. perching during feeding events, roosting areas and stopover sites during migration (Fisher and Boren, 2012; Bordjan et al., 2013). As a result, mussel cultures may provide poorly understood hotspots for avian biodiversity, but little monitoring occurs in these systems and potential changes on site may have important consequences on the biodiversity that becomes established over time.

In this study, we examine drivers of avian diversity and abundance in well-established mussel farms set up in Italy in the 1970s, in response to a recent modernization in longline cultivation methods whilst controlling for various biotic and abiotic variables. In addition to patterns of abundance and richness, we intend investigating species-specific effects for the most abundant species on site, namely Mediterranean shag *Phalacrocorax aristotelis desmarestii* an endemic yet declining bird of conservation concern listed in the Annex I of the European Birds Directive (Directive 2009/147/EC) and for a common species such as the yellow-legged gull *Larus michahellis*. Due to a rapid rise in demand and need to increase the quantity and quality of the harvest, mussels farming techniques and structures have changed over time and across most continents (Theodorou et al., 2011, Spencer, 2002, Barrett et al., 2019). These changes are aimed at maximizing the resistance of these systems to adverse weather conditions, as well as increasing mussel productivity and the mechanization of the harvesting process (Sustersic, 2011; Rosland et al., 2011; Cubillo et al., 2012). So far, no evaluation on potential consequences of such changes for the long-term established avifauna (ca. 50 years) has yet been carried out.

2. Methods

2.1. Study site

Our study site is located in Italy in the Gulf of Trieste (Fig. 1; N 45° 39′, E 13° 47′), a shallow basin (average depth 17 m, max depth 25 m; Celio et al., 2002, Mozetič et al., 2002) of the Adriatic Sea, representing the northern most part of the Mediterranean. Seasonal variations in water temperature range from 8 to 24 °C at the surface and 8 to 20 °C in the bottom layers (Vidović et al., 2016). The salinity of the water is typically marine, ranging from 33 to 38.5%. (Ogorelec et al., 1991). The mean tidal range is about 1 m, and rarely 1.5 m. The coastal area is characterised by a rocky environment or sedimentary bottom with both sandy and muddy areas. Here, we studied a series of mussel farms covering an area of approximately 150 ha (length 8 km, 0.25 km width) about 0.5 km from the shore and present within the Miramare UNESCO Biosphere Reserve.

2.2. Changes in mussel farming methodologies

On our study site mussel farms date back to the middle of the nineteenth century when they were initially cultured for oyster *Ostrea* spp. (Mollusca: Bivalva) and later replaced by mussel cultivation, specifically the Mediterranean mussel *Mytilus galloprovincialis* (Mollusca: Bivalva; Melaku Canu and Solidoro, 2014). Initially, they were grown on wooden poles although these were later substituted (1970s) by longline floating systems with a double or triple longline design (healreinafter termed “*biventia*”; see Fig. 2). The *biventia* system is rapidly disappearing in our study site with a − 54.2% decline recorded in longline abundance between 1997 (n = 380) and 2019 (n = 174) in favour of the more recent *monoventia* design which is now dominant (n = 260) here (Franzosini, 1998; Solidoro et al., 2010; Sustersic, 2011; COGIUMAR, 2019). This change in practice can be attributed to the better resistance of *monoventia* to storm surges, encouraging greater individual mussel growth (lower intraspecific competition for food compared to *biventia*) and allows the incorporation of mechanized harvesting, thus reducing costs and increasing harvesting capacities (Rosland et al., 2011; Sustersic, 2011; Cubillo et al., 2012). These types of longline system designs are not specific to our study site but have been promoted by local authorities and occur in other Italian regions (i.e. Sardinia, Saba, 2012) as well as across various countries of the world (e.g. France, Slovenia, Albania, Greece, New Zealand, United Kingdom and North America; *pers. obser.*, Smith and Goddard, 1988, Spencer, 2002, Danioux et al., 2000, Theodorou et al., 2011). The *biventia* longline uses fiberglass barrels (length: 1.20-180 m, diameter: 0.5–0.65 m) which are joined together by two ropes keeping them in a horizontal and steady position, whilst the newer *monoventia* is represented by polyethylene floats (length: 1.45–1.50 m, diameter: 0.5–0.6 m) joined together by a single rope which keeps the float in a vertical position. Using up to date photographic evidence, in our study area we estimated approximately 4443 buoys, of which 1006 were of the *biventia* system and 3437 being of the *monoventia* system.

2.3. Bird surveys

We standardized taxonomic names following the Handbook of the Birds of the World and BirdLife International (2019).

In order to obtain measurements of bird richness and abundance (the sum of all species and individuals within a plot in a given event), we divided our study area into 9 plots with similar biogeochemical and geomorphological characteristics yet holding different proportions of buoy types (Fig. 1 and Table S.1). Plots were discerned in the field using available landmarks and consequently were slightly variable in shape and size. Bird surveys occurred over 24 months (from July 2016 to June 2018) when we performed monthly counts of bird species and their relative abundance per plot from a boat, with the aid of two surveyors (the same people throughout the study period) equipped with binoculars (10 × 42) and a camera with a telephoto lens (500 mm). Bird surveys across each plot occurred on the same day and were mostly in the afternoon (91.6%, n = 22/24) between 12:00 and 10:00 local time (CET), and only a few in the morning (8.3%, n = 2/24) between 09:00 and 11:00 CET, spending an equal amount of time (5 min) for each of the 9 plots when recording species richness and abundance. Bird counts included all individuals and species standing on buoys or floating on the water within a given plot. Birds occurring just a few meters outside the mussel farm were not included in the analyses. Movement between plots during surveys was carefully considered in order to avoid double-counts. All the surveys were carried out during calm sea conditions (average wind speed between 2.5 and 6.6 m/s) and fine weather (average air temperature 4–25 °C, atmospheric pressure between 1012.3 and 1026.7; MAMBO-1, OGS).

2.4. Statistical analysis

We modelled monthly estimates (n = 24) of abundance and richness within each plot (n = 9) as a function of i) proportion of buoy type (expressed as the proportional value of *biventia* relative to the total number of buoys in a given plot and included as linear term); ii) the sum of all buoys within a plot (linear); iii) plot size (linear); iv) tidal range (CNR-ISMAR, calculated as per Stravisi and Purga, 1997; linear and quadratic term); and v) time of day (transformed in proportional values as minutes after midnight; linear and quadratic term). Sea depth, which can influence bird presence (Sponza et al., 2010), was not included as a predictor because it did not differ among plots (one-way ANOVA: F = 1.932, p = .09, μ = 12.3 m, SE = 0.12). For the analysis on Mediterranean shag abundance we included only months when the species is most abundant in our study site which is during the non-breeding period (June–November; Sponza et al., 2013). All explanatory variables were standardized (i.e. centred on their mean value and scaled by their standard deviation) before analysis and models were tested for within-group collinearity by calculating the variance inflation factor (VIF) using the package ‘car’ (Fox and Weisberg, 2011). Collinearity between plot size and the proportion of *biventia* buoys to the total number of floats per plot was high (VIF > 3, Pearson r = 0.83) and the former was excluded from the analyses. This effect was highly expected due to the spatial design of longlines which are positioned approximately 20 m apart with buoys in the same line being 8-10 m apart (Sustersic, 2011; COGIUMAR, 2019). Analyses were conducted in R 3.5.2 environment (R Core Team, 2017) where we built generalized linear mixed models (GLMMs) with Poisson error distribution and a log link function to evaluate whether the type of buoy and its relative abundance, tidal conditions and time of the day influenced patterns of species richness and abundance as well as species-specific abundances whilst controlling for the non-independent nature of the survey by setting each plot and date (Julian date) as random factors (random

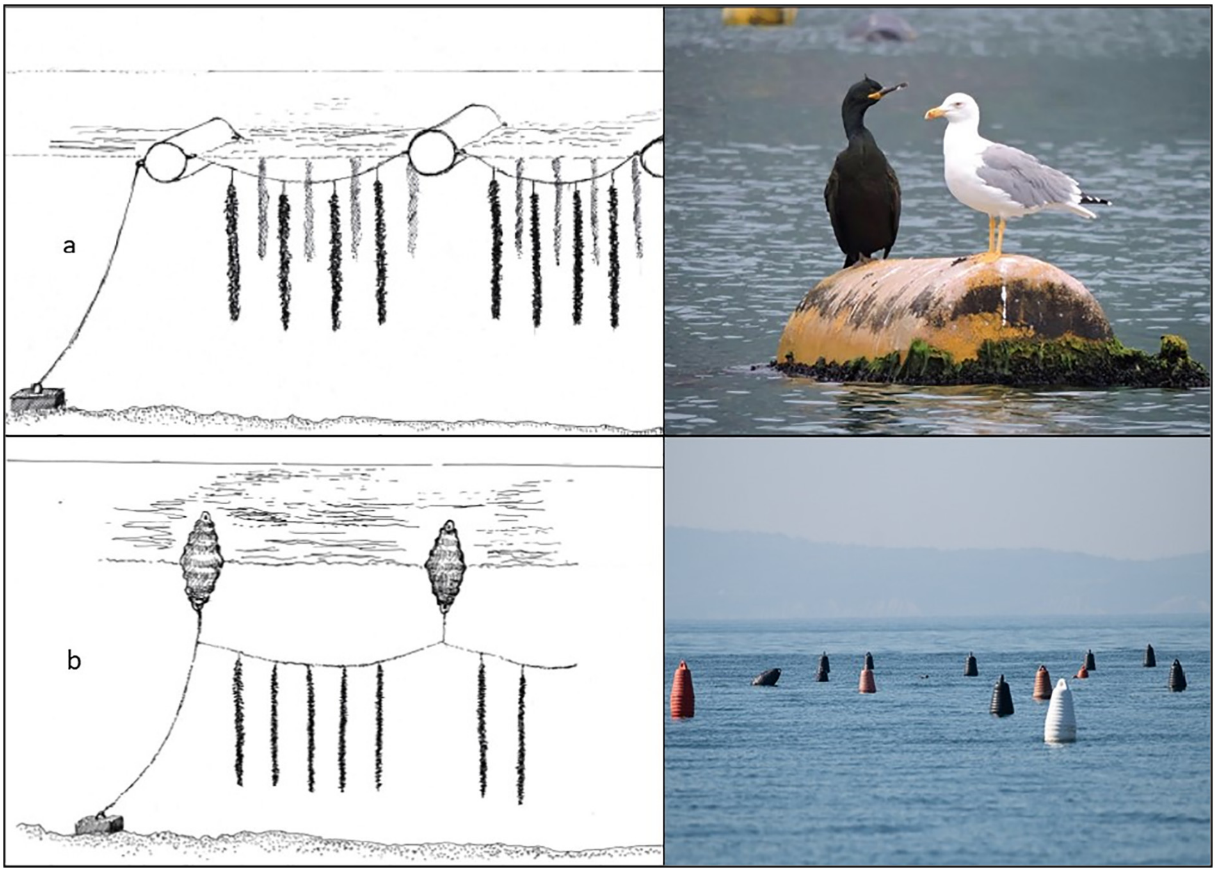

Fig. 2. a) the older and rapidly disappearing *biventia* longline design with floats joined together by two parallel ropes keeping the float in a horizontal position. This is in contrast to the more recent *monoventia* longline (b) where buoys are connected by a single rope keeping the float in a vertical position.

intercept model). To account for a minor overdispersion when modelling bird abundance and Mediterranean shag (tested with the package 'blmeco', Körner-Nievergelt et al., 2015), we incorporated in the model an observation-level random effect following Elston et al. (2001) and Harrison (2014). For each analyses, we performed a model selection procedure based on an information-theoretic approach (Burnham and Anderson, 2002), ranking all possible models within a group according to the Akaike Information Criterion corrected for small sample sizes (AICc) using the "dredge" function in the R package 'MuMIn' (Barton, 2018) and selecting the most parsimonious models (Δ AICc ≤ 2) whilst excluding 'uninformative parameters' (sensu Arnold, 2010). We then calculated marginal R^2 ("R^2m"; variance explained by fixed effects only) and conditional R^2 ("R^2c"; variance explained also by the random factor) following Nakagawa and Schielzeth (2013).

3. Results

Between 2016 and 2018 we recorded a total of 5858 birds belonging to 15 species of which 40% ($n = 6$) are listed in the Annex I of the European Birds Directive (2009/147/CE, see *Supporting Information* for species list). The most abundant species were Mediterranean shag ($n = 3077$), yellow-legged gull ($n = 2100$), black-headed gull *Larus ridibundus* ($n = 225$) and eider duck *Somateria mollissima* ($n = 60$). Species abundance peaked in the months of September ($\mu = 508.5$, SE = 133.5) and June ($\mu = 393$, SE = 123) whilst species richness was highest in January ($\mu = 10$, SE = 0).

As hypothesized, our models suggested a strong and overarching positive effect of the *biventia* design and a negative one for *monoventia* system across all measures of bird abundance and species richness, including on the abundances of Mediterranean shag and yellow-legged gull (Table 1, Fig. 3). The total number of buoys was a marginally supported variable in the model investigating bird abundance and Mediterranean shag abundance, although confidence intervals overlapped 0. Species richness was negatively correlated with time of the day, with more species recorded during late morning (10:00–11:00 CET) than late afternoon (18:00 CET). Shag abundance on mussel farms displayed a linear relationship with time, with higher counts occurring during late afternoon. We found no effect of tidal range in any of the analyses performed. Variance explained by both fixed and random effects was high in most models (bird abundance: R^2m = 0.6, R^2c = 0.9; species richness: R^2m = 0.2, R^2c = 0.3, shag abundance: R^2m = 0.6, R^2c = 0.9; yellow-legged gull: R^2m = 0.6, R^2c = 0.9).

4. Discussion

To our knowledge, this is one of the few works that describes the biological and ecological value of mussel farms for birds, with a high proportion of species detected in this study being of international conservation importance. All analyses revealed an overarching positive effect of the older *biventia* design on bird abundance and richness whilst it was highly negative for the newer *monoventia* system, thus highlighting that the on-going modernization of cultivation methods in our study site may ultimately have negative consequences for this long-established seabird community.

The ecological function of longline mussel farms is likely to vary, depending on the species considered, area investigated, and method employed but based on our study, we can suggest several mechanisms as to why birds might be attracted or repelled from these areas. Firstly, the presence of mussels themselves act directly as food source, particularly for sea ducks such as eider, a species rarely encountered during our observations and generally uncommon at this latitude therefore unlikely to cause considerable economic damage in these systems

Table 1

Top (AICc ≤2) and null models (last row) evaluating drivers of species abundance, richness and species-specific effects on the proportion of *biventia* buoys, total number of buoys per plot, tide and time of the survey (linear and quadratic effects). Intercept, beta coefficients and 95% confidence intervals (CI - in brackets) for fixed effects are shown (in bold are highlighted significant fixed effects where 95% CI do not include zero).

Intercept	*Biventia* buoys	Total buoys	Tide	Tide^2	Time	Time^2	logLik	AICc	Delta	Weight
Species abundance										
2.44 (2.01,2.85)	**1.22 (0.77,1.68)**	0.35 (−0.09,0.81)					−796.15	1604.7	0	0.559
2.43 (1.96,2.9)	**1.03 (0.59,1.48)**						−797.45	1605.2	0.49	0.438
2.43 (1.53,3.32)							−803.59	1615.4	10.7	0.002
Species richness										
0.7 (0.5,0.88)	**0.34 (0.15,0.55)**				**−0.11 (−0.19,−0.02)**		−326.58	661.4	0	0.841
0.7 (0.36,1.02)							−333.98	672	10.6	0.003
Mediterranean shag abundance										
1.69 (0.95,2.36)	**1.89 (1.44,2.74)**	0.57 (−0.2,1.35)			**0.513 (0.19,0.84)**		−337.761	690.6	0	0.473
1.68 (0.84,2.44)	**1.61 (0.87,2.42)**				**0.513 (0.19,0.84)**		−338.923	690.7	0.04	0.465
1.64 (0.01,3.12)							−348.38	705.1	14.5	0
Yellow-legged gull abundance										
1.81 (1.4,2.18)	**0.78 (0.59,1.11)**						−765.11	1538.4	0	0.991
1.8 (1.01,2.52)							−770.84	1547.8	9.4	0.009

(Perco et al., 1993; Kravos et al., 1999). Interestingly, most of the bird species detected were predominantly piscivorous (i.e. Mediterranean shag, terns, grebes, divers) or unable to dive and feed directly on mussels (i.e. gulls) from the submerged longlines. These high densities of birds with a predominantly piscivorous diet may be partially explained by the presence of mussel reefs on longlines which have been reported to attract higher abundances of fish than adjacent non-farmed areas, sometimes producing important economic damage due to predation (Šegvić-Bubić et al., 2011; Barrett et al., 2019). Unfortunately, due to the lack of surveys in an area without mussel farms, we were not able to test for this latter hypothesis. However, we can theorize that the potential losses of piscivorous birds from the areas (i.e. total conversion

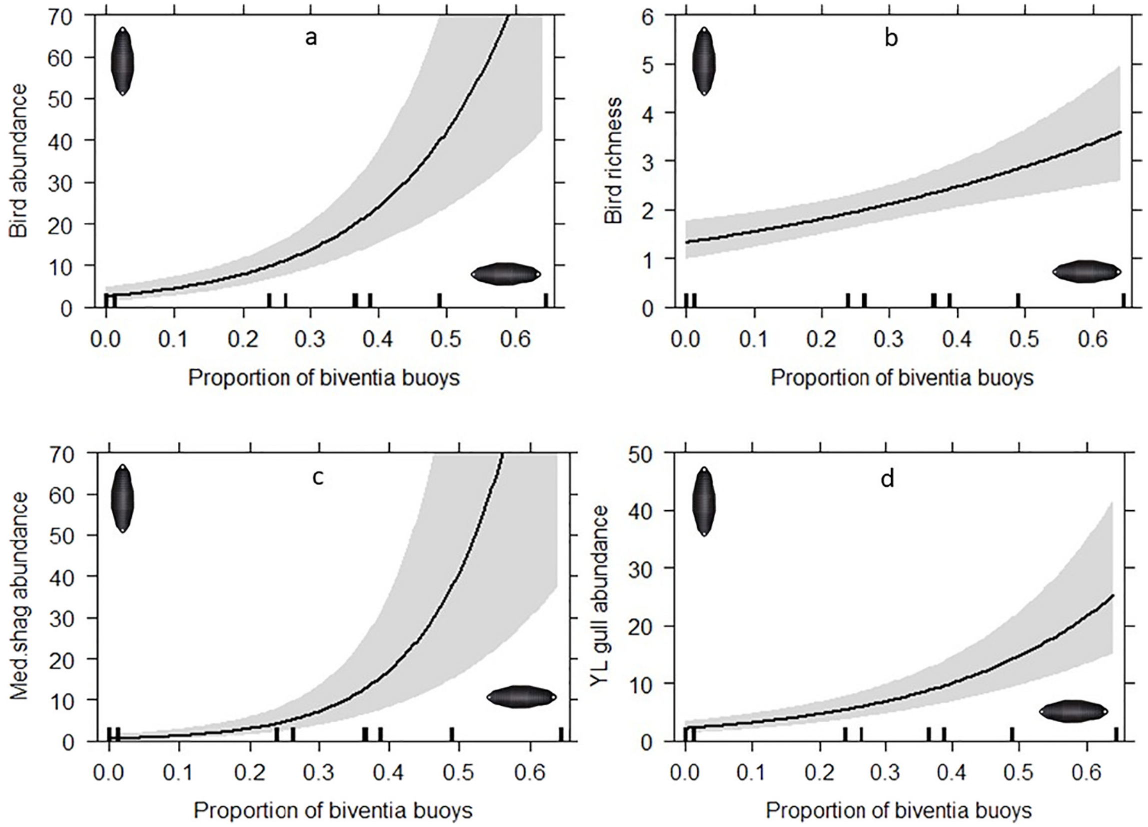

Fig. 3. Fitted relationship of the effect of *biventia* and *monoventia* floats on bird abundance (a), species richness (b), Mediterranean shag abundance (c) and yellow-legged gull abundance (d). Due to the variation in the quantity and type of buoy within each plot, we modelled the proportional value of *biventia* to the total number of floats (*monoventia* and *biventia*). In the horizontal axis, values < 0.5 represent a plot where the majority of buoys are *monoventia*, while values > 0.5 are plots holding greater proportions of *biventia* floats. Other predictors included the total number of buoys within a plot, tidal range, time and day of the survey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from *biventia* to *monoventia*) may increase economic losses to mussel farmers as a consequence of higher rates of predation of mussel by fish. Future studies are needed to confirm the value of birds as biological controllers of fish in these systems.

A second and stronger mechanism attracting birds to these areas is linked to the presence of artificial structures. According to our analyses, positive and negative associations of birds with these structures may be due to the differences in the design of the two cultivation methods. The *biventia* design employs two parallel ropes that keep buoys in a horizontal and stable position offering greater surface and a steady area for birds to perch. This contrasts with the unsteady, vertical and conically-shaped floats employed in the *monoventia* system, where little or no surface areas is available. Suitable structures, such as the *biventia* buoys, have been found to be a valuable roosting sites for many species of birds, including those that do not feed on the farmed product and therefore produce no economic damage (Forrest et al., 2007, Bordjan et al., 2013, Branco et al., 2001, Roycroft et al., 2004, Roycroft et al., 2007, Forrest et al., 2009, Callier et al., 2018). Apart from Mediterranean shag, other species such as eider duck, yellow-legged gull, cormorant *Phalacrocorax carbo*, black-headed gull *Larus ridibundus*, Mediterranean gull *Larus melanocephalus*, common gull *Larus canus*, common tern *Sterna hirundo* and Sandwich tern *Thalasseus sandvicensis* were observed roosting overnight at our study sites. We also found confirmation of this roosting behaviour also from our models in that Mediterranean shags abundance peaked towards late afternoon when birds used these structures as roost sites. These findings are consistent with Bordjan et al. (2013) who observed that Mediterranean shag in Slovenia roosted almost exclusively on horizontal *biventia* buoys. Apart for roosting, birds may also benefit from the floats as platforms to perch upon for comfort behaviours between foraging events. Roycroft et al. (2007) noted that various species of Laridae and Phalacrocoracidae use suspension buoys for maintenance behaviours such as preening, wing-drying and standing.

The final but fundamental effect is that mussel farms can act as a type of marine protected area where fishing is not allowed on site and boat traffic is limited. Human disturbance, which around our study area consists of recreational, commercial and fishing boat traffic and activities, is likely to reduce patterns of foraging activity, leading to a displacement of birds from optimal to suboptimal areas and ultimately impacting on various species' energy balance. For example, great cormorants flying off their nests as a consequence of an anthropogenic disturbance effect, entailed an additional consumption of 23 g fish per bird or ca. 23 kg per disturbance event for a typical colony (Grémillet et al., 1995). In Spain, boat disturbance caused European shags to exhibit a characteristic avoidance behaviour that resulted in a substantial reduction in foraging activity as levels of boat use increased (Velando and Munilla, 2011).

Our study area is subjected to rapid modernization in mussel farming methods, favouring more economically viable systems (i.e. *monoventia*). Between 1997 and 2019 more than half of all the *biventia* longlines (and associated floats) were replaced by the newer *monoventia* systems which is now the dominant method. We believe that this change, coupled with the strongly positive association of seabirds with the *biventia* system, may ultimately cause important losses of biodiversity locally and at wider scale. One of our study species of important conservation value, the Mediterranean shag, breeds in Croatia and migrates to the Gulf of Trieste to spend here the post-breeding period here (Sponza et al., 2010). These movements within the Adriatic began in the 1980s and since then they have increased consistently over time, peaking around 2011–2012 with estimates ranging from 6000 to 10,000 individuals (Škornik et al., 2011), representing 20–33% of the total non-breeding population (Wetlands International, 2004). Reasons behind this change in behaviour have been attributed to overfishing around the Croatian breeding areas (Sponza et al., 2013), the presence of suitable foraging areas in the Gulf of Trieste (Sponza et al., 2010; Cosolo et al., 2011) and the development of *biventia* longline mussel farms that have allowed the establishment of undisturbed roosts of this species along the otherwise highly populated coast of the Gulf of Trieste (Koce, 2018). We estimated that ca. 80% of the current population in the Gulf of Trieste (ca. 3.000 individuals; Sponza et al., 2013), roosts on *biventia* buoys (Utmar et al., 2018).

Future mussel farming plans in our study area are aiming at a total replacement of the *biventia* systems in favour of the *monoventia* one, thus leading to a potential disruption in long-established behavioural patterns and ultimately driving important losses of seabird populations at both a local and a European level. Alternative roosting habitats are likely to be a limiting factor in our study area, as alternative nearby areas are densely populated with few undisturbed sites available. Suitable floating structures are becoming valuable refuge areas for marine and costal species threatened by habitat loss due to the process of urbanization, climate change (i.e. sea level rise), erosion, subsidence and seawater ingress. In response to these threats, international conservation organisations are promoting a series of world-first trials aimed at providing alternatives roosting habitats for when other natural roosts may be submerged or inappropriate (i.e. Birdlife Australia, 2019). Negative impacts may not only include losses of biodiversity but also to economic ones, assuming the potential role of piscivorous birds as predators of fish species causing economical damage at mussel farms. If such modernization process must occur, future studies should be targeted to study the implementation of supplementary floating structures to compensate for the detrimental effects of losing the *biventia* system for this long-established seabird community. Given that mussel farms are a fast-growing feature worldwide, such changes are likely to occur unnoticed elsewhere in the world, as little information is generally available on this topic. To our knowledge, dedicated seabird surveys in these systems are scarce at global level and, as for our case, may harbour, important species of conservation concern.

CRediT authorship contribution statement

Davide Scridel:Conceptualization, Data curation, Formal analysis, Methodology, Writing - review & editing.**Paolo Utmar**:Conceptualization, Data curation, Methodology, Writing - review & editing.**Carlo Franzosini**:Validation, Writing - review & editing.**Marco Segarich**:Methodology, Writing - review & editing.**Sara Menon**:Methodology, Writing - review & editing.**Mihai Burca**:Data curation, Writing - review & editing.**Paolo Diviacco**:Data curation, Writing - review & editing.**Saul Ciriaco**:Validation, Writing - review & editing.**Paola del Negro**:Validation, Writing - review & editing.**Maurizio Spoto**:Conceptualization, Funding acquisition, Methodology, Validation, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2020.108458.

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