MR. LUKE T BARRETT (Orcid ID : 0000-0002-2820-0421)

Article type : Review

Impacts of marine and freshwater aquaculture on wildlife: a global meta-analysis

Luke T Barrett*, Stephen E Swearer and Tim Dempster

School of BioSciences, University of Melbourne, Victoria 3010, Australia

* Corresponding author: barrett.luke@gmail.com

Abstract

The global expansion of aquaculture has raised concerns about its environmental impacts, including effects on wildlife. Aquaculture farms are thought to repel some species and function as either attractive population sinks ('ecological traps') or population sources for others. We conducted a systematic review and meta-analysis of empirical studies documenting interactions between aquaculture operations and vertebrate wildlife. Farms were associated with elevated local abundance and diversity of wildlife, although this overall effect was strongly driven by aggregations of wild fish at sea cages and shellfish farms (abundance: 72x; species richness: 2.0x). Birds were also more diverse at farms (1.1x), but other taxa showed variable and comparatively small effects. Larger effects were reported when researchers selected featureless or unstructured habitats as reference sites. Evidence for aggregation 'hotspots' is clear in some systems, but we cannot determine if farms act as ecological traps for most taxa, as few studies assess either habitat preference or fitness in wildlife. Fish collected near farms were larger and heavier with no change in body condition,

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1111/raq.12277](https://doi.org/10.1111/raq.12277)

but also faced higher risk of disease and parasitism. Birds and mammals were frequently reported preying on stock, but little data exists on the outcomes of such interactions for birds and mammals – farms are likely to function as ecological traps for many species. We recommend researchers measure survival and reproduction in farm-associated wildlife to make direct, causal links between aquaculture and its effects on wildlife populations.

Key words: attraction; ecological traps; environmental impact; fitness; predation; wild population

INTRODUCTION

Aquaculture infrastructure (farms hereafter) presents a novel environment for wild animal populations. High stocking densities within farms aggregate biomass far beyond natural levels (commonly 5-45 kg m⁻³ final biomass: FAO Fisheries and Aquaculture 2018), and in open systems, provide considerable trophic subsidies for animals that take advantage of the opportunity, potentially benefitting some wildlife. However, there are also deleterious effects associated with proximity to farms, and the net impact of aquaculture on productivity and persistence of wildlife populations will depend both on behavioural responses to farms and the fitness consequences of those responses. Where individuals are attracted to a habitat that confers poorer fitness outcomes than other available habitats, they have fallen into an ‘ecological trap’ (Robertson & Hutto 2006; Hale & Swearer 2016). While the concept is defined at the individual level, trap habitats have population-level consequences by drawing individuals from surrounding habitats into attractive population sinks (Hale *et al.* 2015). Even in the absence of an ecological trap, changes in the abundance and spatial distribution of influential species may indirectly affect other species and drive large-scale shifts in biodiversity and ecosystem function (Gamfeldt *et al.* 2015).

A range of attractive and repulsive mechanisms for wildlife can occur simultaneously at farms (Callier *et al.* 2017). The primary attractive mechanism in most systems is probably food availability, either in the form of direct predation on stock, or an indirect trophic subsidy in the form of farm waste (spilled feed, faeces and dead stock). Birds, pinnipeds and otters are well-documented predators of stock at sea cage or pond fish farming systems (Carss 1993; Pitt & Conover 1996; Adámek *et al.* 2003; Güçlüsoy & Savas 2003; Quick *et al.* 2004; Freitas *et al.* 2007; Dorr *et al.* 2012; Sepúlveda *et al.* 2015), while farm waste from sea cages

also attracts significant aggregations of opportunistic wild fish (Dempster *et al.* 2002, 2009; Tuya *et al.* 2006; Sanchez-Jerez *et al.* 2011). A high local abundance of fish is likely to lead to secondary attraction of large predators, such as dolphins (Diaz López 2006; Piroddi *et al.* 2011). Shellfish and algae farming do not require inputs of feed, but high densities of filter feeding shellfish in farms do accumulate biomass, attracting wild fish and invertebrate species (Dealteris *et al.* 2004; Powers *et al.* 2007; McKindsey *et al.* 2011; Segvic-Bubic *et al.* 2011), while algae farming attracts wild herbivores (Hehre & Meeuwig 2016). Farm structures themselves may also be attractive, functioning in a similar manner to fish aggregation devices or artificial reefs (Tallman & Forrester 2007; Sanchez-Jerez *et al.* 2011). Farm structures provide three-dimensional habitat complexity, and associated light, noise and novel biofouling communities may all be attractive to a range of wild taxa (Dumont *et al.* 2011; Callier *et al.* 2017). Paradoxically, many of these environmental changes associated with farms, such as light, noise, eutrophication and high densities of predators, may have repulsive effects on wary or functionally specialised taxa (Markowitz *et al.* 2004; Becker *et al.* 2011).

Attraction to farms may increase or decrease the fitness of wildlife. One expectation is that increased food availability will lead to faster growth, higher body condition and increased reproductive output. Accordingly, there is some evidence that farm-associated wild fish have higher body condition and reproductive investment indices than fish from reference sites (Dempster *et al.* 2011), but little is known about potential benefits for other taxa. In broadcast spawning taxa, high local population densities at farms are likely to confer greater mating efficiency (Inglis & Gust 2003). Such benefits for farm-associated wildlife are likely to be at least partially counteracted by potential deleterious fitness effects related to dietary shifts, contamination, disease, parasitism, and elevated mortality rates. For example, a shift from fish oils to terrestrially-derived ingredients in aquaculture feed may result in deficiencies of long-chain polyunsaturated fatty acids in animals that feed regularly at farms (eg. Salze *et al.* 2005; Fernandez-Jover *et al.* 2007a; Gonzalez-Silvera *et al.* 2017). Additionally, farm waste can create an anoxic environment with significant effects on benthic and estuarine communities (Wu 1995; Yucel-Gier *et al.* 2007; Herbeck *et al.* 2013; Valdemarsen *et al.* 2015), while in some areas, wildlife may also accumulate elevated tissue loadings of contaminants such as antibiotics, pyrethroid parasiticides, metals and organohalogens (Samuelson *et al.* 1992; Boyd & Massaut 1999; BurrIDGE *et al.* 2010; Bustnes *et al.* 2010) with potentially nontrivial effects (e.g. Crump & Trudeau 2009; Berg *et al.* 2016). For fish,

the primary concern may be the effect of proximity to farms on disease and parasitism rates: high population densities within farms create favourable conditions for outbreaks of diseases and parasites such as sea lice (Krkosek *et al.* 2005, 2006; Costello 2009; Lafferty *et al.* 2015; Krkošek 2017). Wild fish populations may also act as reservoirs for parasites and diseases, and as they move between cages to take advantage of feeding opportunities, they act as potential transmission vectors that may increase reinfection rates for farms, driving positive feedbacks (Uglen *et al.* 2009; Hayward *et al.* 2011).

Despite this suite of environmental concerns, the aquaculture industry is the world's fastest-growing food production sector (FAO Fisheries and Aquaculture 2015). For this growth to be sustainable in terms of environmental impacts and 'social license' to operate, the industry must grapple with issues arising from interactions between aquaculture activities and the natural environment and develop solutions to minimise negative effects on wildlife (and vice versa). The first step should be to assess the state of knowledge on these issues and identify the most severe effects. Recent reviews have outlined the range of interactions that occur between aquaculture activities and wild fauna (e.g. Uglen *et al.* 2014; Taranger *et al.* 2015; Glover *et al.* 2017; Callier *et al.* 2017), but there has been not yet been a quantitative global synthesis of the impacts of aquaculture on wildlife. Here, we conduct a systematic review and meta-analysis of studies documenting interactions between aquaculture activities and wildlife, primarily to quantify the effects of these interactions on abundance, diversity, and fitness of farm-associated wildlife, and secondarily to highlight potential drivers of conflict between wildlife and aquaculture. Thereafter, we recommend directions for future research to address key knowledge gaps in this area.

MATERIALS AND METHODS

Literature search and systematic review

Primary publications up to November 2017 were discovered by searching for the following terms using the ISI Web of Science: (aquaculture OR mariculture OR "fish farm*" OR "shellfish farm*" OR "mussel farm*" OR "oyster farm*" OR "sea cage*" OR "net pen*" OR "fish pond*" OR "seaweed farm*" OR "macroalgal farm*" OR "algal farm*") AND (attract* OR avoid* OR wild OR aggreg* OR impact* OR depredat* OR predat* OR disease) AND

(wildlife OR animal* OR fauna* OR fish* OR shark* OR mammal* OR dolphin* OR cetacean* OR otter* OR seal* OR sea lion* OR bird* OR avian OR reptile* OR snake* OR amphibian* OR frog*). >9000 results were manually screened on an individual basis, by title and abstract alone where the topic was clearly irrelevant, or else after accessing the full text. Additional articles missed by our initial search were discovered using informal exploratory searches using Google Scholar, and by reading the reference lists of all relevant articles returned by our initial search. Our search focused on interactions with vertebrate wildlife (defined here as fish, birds, mammals and reptiles), as these animals are typically highly mobile and are therefore more able to make decisions about whether to reside at and interact with farms.

For inclusion, publications were required to have provided empirical field data on at least one of the following: (1) distribution, behaviour, condition, disease or mortality of wildlife in the vicinity of aquaculture sites, or (2) direct interactions between wildlife and stock at aquaculture sites (e.g. predation of stock). To minimise potential duplication of data, we only included peer-reviewed English-language journal articles.

To document the distribution of research effort in the field, we recorded the year, country, region, environment, culture system, culture taxa and the wild taxa for each study.

Meta-analysis

Studies were included in the subsequent meta-analysis if they provided quantitative data sufficient to calculate effect sizes for variables at aquaculture sites relative to ‘natural’ or ‘reference’ sites. We extracted a range of quantitative variables that were representative of the dominant types of interactions between aquaculture operations and wild vertebrates, relating to spatial distribution (Abundance, Species Richness), size structure (Length, Weight), food availability (Body Condition, Stomach Fullness), disease and parasite infection levels – either infection loads on individuals or prevalence of infected individuals in the population (Infection Level), as well as direct measures of Mortality and Fertility. Reproductive condition metrics (e.g. relative gonad size) were considered a component of Body Condition.

Natural log response ratios were calculated for each variable: $RR = \ln(F/R)$, where F is the trait mean at farm sites and R is the trait mean at reference sites. Taking the natural log of the response ratio normalises the error distribution by reducing the influence of positive responses (Hedges *et al.* 1999). Studies employed a variety of sampling designs, including random or matched farm and reference sites, and stocked or unstocked farms. All were treated as random for the purposes of this meta-analysis, with RR calculated from the mean trait values across all farm and reference sites regardless of how sites were selected by the authors. Where multiple complementary measures were available for a response variable, we took the mean of those measures (for example, Fulton's K, hepatosomatic index and gonadosomatic index all contribute to the Body Condition variable). Where a study provided data on a response variable from multiple species or sites, we combined data to provide a single replicate, except where data spanned multiple culture systems (e.g. cages and ponds), taxonomic classes (e.g. birds and mammals), environments (e.g. marine and freshwater), or countries. No article contributed more than two studies to our database. This was done to prevent studies that provided data on numerous species from having a disproportionate influence on our findings, and to ensure spatial independence between replicates given the high mobility of most species studied. Where data was provided for farms with and without exclusion measures (e.g. fenced and unfenced sites), we used data from sites without exclusion measures.

Some variables were not easily quantified for statistical analysis but were nonetheless important in understanding interactions between farms and wild fauna. These included changes in tissue fatty acid profiles, trace elements and stable isotopes, contamination from antibiotics, heavy metals and other substances, and behavioural data such as residence time or visitation rates. For these variables, we recorded the response ratio if possible, otherwise we noted the direction or nature of the effect.

Statistical analyses

To test for a significant effect of farm-association on response variables, we checked normality before conducting one sample t-tests on RR data (mean RR under null hypothesis of no farm effect = 0) using R software (R Core Team 2017).

Exploratory model selection was used to determine which of the following factors best predicted effects of farms on wildlife (abundance and species richness responses only, as remaining responses had insufficient sample sizes for exploratory analysis): Year, Country, Continent, Environment (*Marine, Freshwater*), Culture System (*Cage, Pond, Longline, Rack, Bed*), Cultured Taxa (*Fish, Shellfish, Crustacean, Alga*), Wild Taxa (*Fish, Bird, Mammal, Reptile, Amphibian*), and Reference Habitat (*Structured, Unstructured*). We fitted a global general linear model using R, and employed the dredge() function in the MuMIn package (Barton 2016) to compare the second-order Akaike's Information Criterion (AIC_C) score of every possible subset of the global model. AIC_C includes a correction for finite sample sizes and yields more conservative models than AIC (Burnham and Anderson 2002). We selected the model with the lowest AIC_C score, and then used the likelihood ratio to test whether the selected model offered a significantly better fit than the null (intercept only) model, tested the significance of model terms, and then conducted post-hoc tests with a Tukey correction to test pairwise effects within significant model terms.

There was orders-of-magnitude variation in RRs for abundance and species richness among studies and systems, and accordingly, the overall trends that we report may be strongly influenced by a small number of studies with unusually large RRs. To test this possibility, we conducted a sensitivity analysis by ranking studies (replicates) according to the absolute value of the RR, removing the studies with the largest RR in a stepwise fashion, and rerunning the model between each removal (Bancroft *et al.* 2007; Kroeker *et al.* 2010). We then report the number of studies that can be removed from the dataset without altering the statistical significance of the farm effect.

To test whether the geographic distribution of research effort on this topic corresponds to the distribution of aquaculture production, we fitted a zero-inflated Poisson model (using the pscl package for R: Zeileis *et al.* 2008) to compare the number of studies contributed by each country with the reported aquaculture production (t) by that country (FAO Fisheries and Aquaculture 2017). To account for the large disparity in peer-reviewed English language research output between developed and developing nations, we also included the United Nations Human Development Index as a model term (United Nations Development Programme 2017).

RESULTS

Our searches discovered 204 relevant studies across 191 articles published between 1978 and 2017 (Appendix I). 91 studies provided comparative data on wildlife populations at farms and reference sites suitable for inclusion in the meta-analysis of log response ratios (RR).

Distribution of research effort

There was a clear geographical bias in research effort within our database, with 114 peer-reviewed English language studies conducted in Europe and 46 in North America (Fig. 1). Among nations, Norway, the United States and Spain accounted for the most research (Fig. 1). Research effort across nations was significantly predicted by an interaction between the size of the nation's aquaculture industry and the developmental index of the nation ($p = 0.03$, Table S1), wherein highly developed nations (especially those in Europe and North America: Fig. 2) with large production contributed more studies than those with low production ($p < 0.0001$, Table S1). Several major aquaculture-producing nations were either poorly represented or entirely absent from our database: most notably, mainland China is by an order of magnitude the largest aquaculture producer in the world (FAO Fisheries and Aquaculture 2017), yet was entirely absent from our database. Other leading producers, namely Indonesia, India, Vietnam, Philippines and Bangladesh, were also either absent or represented by only a single study.

Most studies in our database assessed interactions with wildlife in marine or estuarine environments (Fig. 1), despite global animal aquaculture production being considerably higher in freshwater environments (47 cf. 27 million t in 2014) (FAO Fisheries and Aquaculture 2015). 105/144 studies in the marine environment took place at sea cage farms, while 49/60 freshwater systems were pond-based (Fig. 1). Fish were the most common cultured taxa studied (163 studies) – primarily salmonids (69 studies) in western Europe and the Americas, and sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) in southern Europe (43 studies). The research effort on environmental effects of salmon farming is in line with the predominance of salmonids in the marine fish farming sector, although freshwater cyprinid culture is the most productive pisciculture sector overall (FAO Fisheries and Aquaculture 2015). Sea bream, sea bass and marine shellfish systems are overrepresented in our dataset relative to the size of these sectors, perhaps due to their importance for nations

with high marine research activity (particularly Spain). Algal and crustacean culture (5 and 3 studies, respectively) were dramatically underrepresented here relative to the size of the sectors (FAO Fisheries and Aquaculture 2015).

Most studies reported interactions with wild fish (108 studies), followed by birds (53 studies), mammals (38 studies), reptiles (3 studies) and amphibians (2 studies) (Fig. 1).

Effects on wildlife

Abundance

We discovered 65 studies that quantified the abundance of wildlife at aquaculture farming sites compared to reference sites, using various forms of Control-Impact (CI), Before-After (BA) and Control-Impact-Before-After (BACI) designs. These studies used a variety of sampling methods, including visual census, catch-per-unit-effort and tagging/tracking. 17 studies reported a lower abundance near farms, two no difference, and 46 a higher abundance. The mean effect was a 49x increase in abundance near farms ($RR = 1.05$, $t_{64} = 4.3$, $p < 0.0001$), but this value was strongly influenced by a few outlier studies reporting very large aggregations of wild fish around sea cages (for example, a mean 1327x increase over three sampling dates at one Australian offshore farm compared to featureless mid-water reference sites: Dempster *et al.*, 2004). Fish demonstrated the largest abundance changes, while changes in bird and mammal abundance were highly variable in both effect size and direction and not significantly different to zero (Fig. 3, Table 1). We were not able to calculate RR for an additional six studies reporting differential abundance at farms (fish: 2/2 higher; mammals: 1/2 higher; birds: 2/2 higher).

A sensitivity analysis revealed that it was possible to conduct stepwise removal of 25/65 replicates with the largest effect sizes without losing statistical significance, indicating that the overall trend was robust. However, when studies that assessed changes in wild fish abundance at sea cage systems were omitted from the analysis, the remaining studies did not provide support for an overall effect of aquaculture on wildlife abundance ($t_{38} = 0.81$, $p = 0.42$), indicating that wild fish aggregations around sea cages were largely responsible for this overall effect.

Model selection indicated that differential abundance was best predicted by a model containing Environment, Cultured Taxa and Reference Habitat ($R^2 = 0.33$, $F = 7.4$, $p < 0.0001$; Table S2). The Cultured Taxa term was significant ($p = 0.0001$), as was Reference Habitat ($p = 0.003$), while Environment was not ($p = 0.12$). Post-hoc testing revealed that increases in abundance of wild fauna tended to be higher at fish farms than at shellfish farms ($p = 0.001$) and that studies comparing abundance at farm sites to unstructured or featureless reference sites (e.g, sandy seabed or open ocean) generally found a larger response than those that chose natural reef, unstocked farms or other structured habitats as reference sites ($p = 0.006$; Table S3).

Species richness

Most studies only assessed a limited number of target species, but 37 studies provided useful data on species richness at farms and reference sites. Of these, all but six reported higher species richness at farm sites, with a mean 1.7x increase ($RR = 0.30$, $t_{36} = 3.1$, $p = 0.004$). This effect was strongest in fish ($RR = 0.43$) but was also significant in birds ($RR = 0.13$) (Table 1). Only one study in our database quantified differential species richness in mammals, and one in amphibians (Roycroft *et al.* 2004; Kloskowski 2010, Table 1).

There was large variation in effect size and direction across studies, but a sensitivity analysis found the overall trend to be remarkably robust (25/37 studies removed without losing statistical significance). As with abundance, the effect was not significant when sea cage systems were omitted from the analysis ($t_{21} = 1.6$, $p = 0.11$).

Species richness effects were best predicted by a model containing Reference Habitat and Wild Taxa ($R^2 = 0.27$, $F = 4.3$, $p = 0.007$; Table S2). Post-hoc testing revealed that the only significant pairwise effect was between fish and amphibians, with fish species richness positively affected and amphibian species richness negatively affected by the presence of aquaculture sites in their respective environments ($p = 0.03$; Table S4).

Size structure, body condition and stomach fullness

Wild fish collected near aquaculture sites were on average 1.2x larger and 1.7x heavier than their counterparts from reference sites (Table 1), but no size comparisons were available for non-fish taxa.

Most studies (11) reported trends toward higher condition metrics in farm-associated wildlife, while two found no difference and two lower condition metrics at farms, although there was no significant effect overall (Table 1). Similarly, 8/11 studies found higher rates of stomach fullness in farm-associated wildlife, but these effects tended to be small and were not significant overall (Table 1). All but two comparisons of body condition or stomach fullness data concerned wild marine fish, while Gregory and Nelson (1991) estimated a 1.9x higher rate of stomach fullness in snakes at fish hatcheries, and Kloskowski *et al.* (2017) reported higher physiological stress indicators (=lower condition for our purposes) in grebes nesting on fish ponds.

Physiological changes

All 16/17 studies that reported looking for physiological or dietary changes in farm-associated wild fish relative to those from reference sites found evidence of dietary shifts, while the remainder found only minor differences in stable isotopes (Johnston *et al.* 2010). Evidence for dietary shift included farm feed pellets in the stomachs of farm-associated wild fish (Skog *et al.* 2003; Fernandez-Jover *et al.* 2011; Arechavala-Lopez *et al.* 2011), taxonomic changes in stomach contents (Demétrio *et al.* 2012; Fernandez-Jover & Sanchez-Jerez 2015), higher tissue fat content and altered tissue fatty acid profiles that reflected the terrestrial-origin of lipids in farm feed (Skog *et al.* 2003b, Fernandez-Jover *et al.* 2007, 2011, Arechavala-Lopez *et al.* 2011, 2015, Abaad *et al.* 2016). Arechavala-Lopez *et al.* (2015) also reported differing trace element profiles in saithe near and far from salmon farms, while two studies reported altered taste and other metrics of quality (Skog *et al.* 2003; Bogdanović *et al.* 2012).

Contamination

Comparisons of contaminant levels in the tissues of farm-associated and non-associated fish revealed mixed results. All three studies that tested for antimicrobial contamination in farm-associated wild fish at farms where antimicrobials were in use found evidence of

antimicrobial residue in the majority of fish sampled, including oxytetracycline (0.2-1.3 $\mu\text{g g}^{-1}$ muscle tissue: Björklund *et al.* 1990), oxolinic acid (0.4-4.4 $\mu\text{g g}^{-1}$ muscle tissue at two farms: Samuelsen *et al.* 1992) and flumequine (1.0-4.9 $\mu\text{g g}^{-1}$ muscle tissue: Ervik *et al.* 1994). In each case, mean concentrations for positive samples exceed the current European Union limits for these substances in skin and muscle of finfish for human consumption: oxytetracycline: 0.1 $\mu\text{g g}^{-1}$; oxolinic acid: 0.1 $\mu\text{g g}^{-1}$; flumequine: 0.6 $\mu\text{g g}^{-1}$ (European Union 2010). It should be noted that the development of new vaccines has allowed fish farmers in some areas (e.g. salmonid farms in Norway and Scotland) to largely cease antimicrobial use despite rapid expansion of the industry, but use remains high in other regions (Watts *et al.* 2017). It remains unclear whether antimicrobial residue impacts fitness in farm-associated wild fish, whether through toxicity, loss of gut microbiota or antimicrobial resistance in pathogens.

There have also been assessments of organohalogens and metals in the tissues of farm-associated wild fish. One study reported significantly higher levels of organochlorines and polybrominated diphenyl ethers in farm-associated fish relative to those from reference sites (1.5x higher in cod, 1.2x higher in saithe: Bustnes *et al.* 2010). Another reported higher levels (2.1x) of mercury in tissues of farm-associated rockfish (*Sebastes* spp.), potentially related to an increase in trophic level near farms (DeBruyn *et al.* 2006). In the most comprehensive study to date, Bustnes *et al.* (2011) measured concentrations of 30 elements in cod and saithe livers from three regions in Norway. In saithe, Hg (2.0x), U (1.4x), Cr (1.9x) and Mn (1.6x) concentrations were significantly higher in farm-associated fish, while Se, Zn, Cd, Cs and As were higher at reference sites. In cod, U (1.4x), Al (1.5x) and Ba (1.9x) were higher in farm-associated fish, while Se, Zn, Cd, Cs and As were higher at reference sites. While there is evidence that some metals accumulate in sediments under fish farms, there is little evidence so far that farm-associated wild fish are accumulating high concentrations in their tissues.

Infection rates

We discovered 22 studies that empirically investigated viral, bacterial or parasite transmission between farmed and wild populations. In all cases, the authors concluded that the risk of infection was either unchanged or elevated by interactions between farms and wild fish populations. Of the 11 studies that quantified changes in infection levels with the presence of active fish farms, all found higher levels of infection in farm-associated wild fish,

with a mean 16x increase overall ($RR = 2.1$, $t_{10} = 5.5$, $p = 0.0003$). This large effect was primarily driven by eight studies of sea louse infection loads on wild salmonids near salmon farms (3.5-73x increase, $RR = 2.5$). One study reported higher infection densities of external parasites but lower densities of internal parasites in farm-associated gadids, probably as a result of consuming fewer infected wild fish and invertebrates in favour of commercial feed (Dempster *et al.* 2011). Three studies provided molecular evidence for likely viral or bacterial transmission between cultured and wild fish in the Mediterranean Sea (Zlotkin *et al.* 1998; Diamant *et al.* 2000; Colorni *et al.* 2002), and a molecular analysis of stomach contents revealed that wild cod consumed escaped salmon stock infected with piscine reovirus (Glover *et al.* 2013). However, molecular evidence did not always support the transmission hypothesis: Mladineo *et al.* (2009) reported that monogenean and isopod parasites were not transmitted between wild and farmed fish at one Mediterranean Sea farm.

Survivorship and fertility rates

Only two studies in our database estimated differential mortality rates in farm-associated fauna. Kilambi *et al.* (1978) used age structure to infer a 21 % increase in survivorship of largemouth bass following the establishment of cage culture in a freshwater lake, while in contrast, Broyer *et al.* (2017) recorded 39 % higher mortality of ducklings at fish ponds. In sea cage systems, elevated external parasitism rates (especially sea louse infections on salmonids) may increase mortality in farm-associated fish, but to our knowledge, differential mortality between farm and reference sites has not yet been empirically demonstrated. A further six studies quantified culling of numerous birds at farms but did not compare mortality rates at farms to those at reference sites. Two others reported dolphins being accidentally drowned in anti-predator nets (Kemper & Gibbs 2001; Diaz López & Bernal-Shirai 2007), but again, did not benchmark these against natural mortality rates. Several studies noted higher fishing effort adjacent to sea cages, although we are only aware of two studies that quantified fishing effort and catch rates (Akyol & Ertosluk 2010; Bacher & Gordo 2016), and none assessed fishing mortality rates among farm-associated fish.

Estimates of fertility (i.e. reproductive success) for wildlife at farms are similarly rare, but two recent examples were returned by our search, both documenting probable ecological traps: Kloskowski (2012) reported that fledging rates of grebes nesting on fish ponds stocked with +1 carp were only 37 % of those nesting on unstocked ponds, while Broyer *et al.* (2017)

found that high food availability was outweighed by high predation rates for ducks nesting on stocked ponds (Table 1).

Conflict with aquaculture operations

Birds were usually predators of stock. 45/53 studies that documented interactions with birds considered predation on stock to be the major habitat use, whether in cages, ponds, shellfish beds or longlines. The most common avian predators were cormorants and herons. 24/38 studies of interactions with wild mammals considered predation to be the major habitat use, in most cases by otters in ponds or sea cages (12 studies) or pinnipeds in sea cages (10 studies). Five studies reported herbivorous fishes inhabiting algae farms, but only one presented clear evidence of fish consuming algal crops (Anyango *et al.* 2017). One study reported predation of farmed mussels by wild fish (Segvic-Bubic *et al.* 2011), while three reported snakes taking stock from hatchery ponds (Plummer & Goy 1984; Gregory & Nelson 1991; Nelson & Gregory 2000).

Of the 77 studies that reported predation on stock or damage to infrastructure, only 11 quantified stock losses as a proportion of potential production, with a mean loss of 15 % (range 0-50 %). The lower end of that range was due to mammals taking only dead or moribund fish from hatcheries (Pitt & Conover 1996), while the upper was due to predation by cormorants in fish ponds (Barlow & Bock 1984). Other studies quantified consumption of stock by individual predators without placing it in the context of potential production (e.g. Glahn *et al.* 1999). In addition to predating stock, pinnipeds were reported to damage nets and cause fish escapes (e.g. Güçlüsoy & Savas 2003; Sepúlveda & Oliva 2005).

DISCUSSION

Responses to aquaculture by wildlife vary greatly across taxonomic groups and culturing systems, but our systematic review and meta-analysis reveals several key and well-supported trends within taxonomic groups and culturing systems and identifies clear knowledge gaps to inform future research.

Are wildlife attracted to aquaculture?

Fish

Multiple lines of evidence suggest that many fish species prefer aquaculture sites over natural habitats, and on average, farms are associated with a much higher density and diversity of wild fish. The few available tracking studies indicate that farm-associated wild fish tend to be either residents or regular visitors (Otterå & Skilbrei 2014; Arechavala-Lopez *et al.* 2015a; Loiseau *et al.* 2016; Tsuyuki & Umino 2017), with spilled feed and waste likely to be the major attractive cues driving wild fish aggregations (Tuya *et al.* 2006; Ballester-Moltó *et al.* 2015; Bacher *et al.* 2015). Effects on fish abundance and diversity are also likely to depend on the functional group being assessed, with most surveys of fish populations at farms and reference sites targeting mobile generalist carnivores (either by design or through choice of sampling method).

Birds

Studies of bird abundance revealed highly variable responses to farms, but our meta-analysis indicates that aquaculture sites are associated with higher bird species richness overall. Numerous studies documented large bird populations at farms without comparing them to natural waterways, making it difficult to draw conclusions about the influence of farms on the spatial distribution of wildlife. Furthermore, little work has been done to assess responses at the individual level (i.e. migration or site fidelity) that can assist in inferring habitat preferences (Robertson & Hutto 2006), but it is likely that many bird species (especially herons, cormorants and gulls) find the availability of prey at fish and crustacean farms highly attractive (Barlow & Bock 1984; Stickley *et al.* 1992, 1995; Carss 1993; Glahn *et al.* 1999; Harrison 2009). Shellfish farms also increase local abundance of generalist or molluscivorous bird functional groups (Roycroft *et al.* 2004; Kirk *et al.* 2007), but others, such as invertivorous wading birds, may be displaced by shellfish farm infrastructure or associated ecological changes (Kelly *et al.* 1996; Godet *et al.* 2009; Broyer & Calenge 2010).

Mammals

Marine mammals (pinnipeds and dolphins) also showed highly variable responses to the presence of aquaculture, ranging from resident nuisance animals (Pemberton & Shaughnessy

1993; Hume *et al.* 2002; Güçlüsoy & Savas 2003; Sepúlveda and Oliva 2005), to periodic visitors (Díaz López 2012, 2017; Díaz López and Methion 2017), to active avoidance of farms (Markowitz *et al.* 2004; Watson-Capps & Mann 2005; Pearson 2009; Becker *et al.* 2011). Otters were common at freshwater fish ponds (Kłoskowski 2005; Kortan *et al.* 2007) and estuarine sea cages in Europe (Freitas *et al.* 2007; Sales-Luis *et al.* 2009), but our search did not reveal any data on abundance or attraction to farms relative to natural waterways.

How does aquaculture affect fitness of wildlife?

Fish

Our meta-analysis indicated that farm-associated fish tend to be larger and heavier, a finding that is consistent with either aggregation of adult fish or higher growth rates due to a trophic subsidy. This larger average size, together with greater abundance overall, results in a very high local biomass of farm-associated wild fish. Despite this, farm-associated fish had similar or higher body condition metrics and rates of stomach fullness than fish from reference sites (Fernandez-Jover *et al.* 2007a; Dempster *et al.* 2011), indicating that farm environments may have a higher carrying capacity for wild fish than reference sites. However, any potential positive effects—such as higher reproductive potential—may be opposed by orders of magnitude higher infection loads near farms (especially sea lice on salmonids: Krkošek 2017) and possible impacts of a dietary shift from marine-derived to terrestrially-derived fatty acids in commercial aquaculture feed (Lavens *et al.* 1999; Mazorra *et al.* 2003; Salze *et al.* 2005; Borgevik *et al.* 2012; Arechavala-Lopez *et al.* 2015b). Little is known about how the plurality of environmental changes at farms combine to influence survival and reproduction in wild fish. Mortality rates are difficult to measure directly, but Kilambi *et al.* (1978) compared age structure and recapture rates in a lake before and after the commencement of cage farming and inferred that survivorship had increased with farming.

In this study, we only assessed direct interactions between aquaculture activities and wildlife, but indirect interactions also occur, and are likely to have a considerable bearing on outcomes for fish populations in farming areas. Dietary shifts may occur indirectly via benthic nutrient loading and subsequent ecological changes across multiple trophic levels (Brown *et al.* 1987; Wu 1995; Yucel-Gier *et al.* 2007; White *et al.* 2017), and potential deleterious effects of direct or indirect dietary shifts or other changes may be most apparent in eggs or offspring of

farm-associated fish (Salze *et al.* 2005; Barrett *et al.* 2018). Aggregations of large predators around sea cages may also reduce survivorship of fishes that inhabit the same area (Güçlüsoy & Savas 2003). Fish that escape from farms can reduce fitness in native populations through disease transmission (Arechavala-López *et al.* 2013; Glover *et al.* 2013), genetic mixing (Glover *et al.* 2017), and interference with spawning or competition with offspring and adults (Jensen *et al.* 2010; Sundt-Hansen *et al.* 2015).

Birds

In birds, the effects of farm proximity on fitness are even less clear; only in a few cases were we able to extract usable data on direct or indirect fitness metrics. Numerous studies reported birds taking stock from ponds and cages, but none in our database compared feeding rates to those on natural waterways. Nonetheless, we expect food availability to be high provided that birds are able to access suitable food items (e.g. feed, stock or wild prey co-occurring at farms). However, predatory birds also experience high mortality from culling and anti-predator net entanglements where such methods are employed, potentially causing fish farms to act as ecological traps for birds if mortality rates outweigh any benefits of higher food availability (Carss 1994; Belant *et al.* 2000; Blackwell *et al.* 2000; Bechard & Márquez-Reyes 2003; Quick *et al.* 2004). Negative effects will be exacerbated if food availability is lower than advertised, for example if piscivores are attracted to fish ponds but cannot access fish due to anti-predator nets, or if stocking regimes lead to cohorts of fish that are too large to be consumed. This latter scenario was observed by Kloskowski (2012), who reported that European carp farms were acting as ecological traps for red-necked grebes, as farmed fish were too large for fledglings to consume leading to starvation. Predation risk for clutches may also be elevated at farms: Broyer *et al.* (2017) observed high densities of breeding pairs and high food availability, but also high offspring mortality – a probable ecological trap. Conversely, tuna ranching in Australia was associated with a population boom for silver gulls and appears to be a clear case of fish farms functioning as a strong population source for wildlife – reproductive success for the gulls was dramatically increased by the trophic subsidy obtained by exploiting farm feed (Harrison 2009). Similarly, long term trends in wading bird populations closely tracked the scale of crayfish aquaculture in the southern USA (Fleury & Sherry 1995).

Mammals

Effects of aquaculture on mortality and reproduction of aquatic mammals are little known, but as with piscivorous birds, are probably determined by the trade-off between high food availability and high risk from culling and entanglements. Cetaceans may benefit from easy food when they visit farms (Díaz López 2017) and culling and entanglements are relatively rare (Díaz López & Bernal-Shirai 2007; Callier *et al.* 2017). As a result, attraction to farms may be an adaptive trait that results in increased fitness on balance, although we lack direct evidence for this. In contrast to cetaceans, pinnipeds experience heavy mortality from culling (Güçlüsoy & Savas 2003; Quick *et al.* 2004; Callier *et al.* 2017) and are more vulnerable to accidental entanglement (Callier *et al.* 2017). High mortality rates are likely to outweigh any increase in food availability for a long-lived, slow breeding animal, such that seals that are attracted to farms may be vulnerable to ecological traps driven by culling at farms.

Conflict and potential mutualism between aquaculture and wildlife

Our meta-analysis revealed that the nature of interactions between wild fauna and aquaculture were highly dependent on the taxon. Wild fish generally do not interact directly with stock unless small enough to enter sea cages through the mesh (although in rare cases wild fish may damage nets: Moe *et al.* 2007, Sanchez-Jerez *et al.* 2008). Of more concern is the role that wild populations play as reservoirs for pathogens and parasites, facilitating reinfection of farms (Uglen *et al.* 2014b). This is an inevitable risk of farming in open systems, but research is underway to lower infection rates by minimising spatiotemporal overlap between stock and zones of high infection risk (Samsing *et al.* 2016; Wright *et al.* 2017). Together with post-infection treatments, such measures also minimise the role that farms play as amplifiers of pathogen and parasite populations.

Most studies returned by our search concluded that predation or damage by birds and mammals is an ongoing problem for managers, but stock losses were rarely quantified (but see some recent examples: Sun *et al.* 2004; Sepúlveda & Oliva 2005; Morrison & Vogel 2009; Dorr *et al.* 2012) Where suitably habituated, pinnipeds have a propensity to become ‘nuisance animals’, damaging nets (leading to fish escapes) and consuming or stressing stock (Kemper *et al.* 2003; Quick *et al.* 2004; Sepúlveda & Oliva 2005). Such problems are difficult to solve. Culling is undesirable as it increases environmental impacts and negatively affects public perceptions of aquaculture. Relocation is expensive and often ineffective

(Hume *et al.* 2002) and scaring devices have a limited effective lifespan before animals are desensitised. Exclusion using steel mesh appears to be the only viable option in some cases (Pemberton & Shaughnessy 1993).

While there tends to be a focus on negative interactions between farms and wild fauna, wild fish can provide ecosystem services to aquaculture operations by increasing animal welfare and reducing local environmental impacts of farming. Invertivorous fish that are small enough to gain access to sea cages (such as wrasse and lumpfish in Norwegian salmon farms) can act as cleaner fish and significantly reduce parasite loads on stock. Cleaner fish are now being deployed in large numbers for this purpose (Imsland *et al.* 2014; Skiftesvik *et al.* 2014). Wild fish and invertebrates ameliorate and disperse benthic nutrient loads by consuming spilled feed, faeces and dead stock (Vita *et al.* 2004; Felsing *et al.* 2005; Fernandez-Jover *et al.* 2007b). However, resident populations of large predators at fish farms may impede this waste amelioration service by scaring or consuming wild fish (Diaz López 2006), resulting in more severe benthic impacts, but such predators also prey on escaped fish, potentially reducing the risk of genetic introgression from farmed to wild fish populations (Glover *et al.* 2017).

For fish farming to continue to grow, farmers need to demonstrate environmental sustainability and good animal welfare standards. Protecting wild fish aggregations to take advantage of the ecosystem services they provide may be an important part of achieving these goals. Continued development of non-lethal bird and pinniped exclusion methods will be a necessary step.

Recommendations for future research on impacts of aquaculture on wildlife

Simply documenting behaviour of wildlife at farms or changes in wildlife abundance provides little information on the effects of aquaculture on persistence of wildlife populations. Aquaculture can have qualitatively distinct effects on wildlife that are superficially indistinguishable in the absence of data on habitat selection decisions, movement or fitness. For example, an elevated density of wildlife at a farm relative to a reference site may support various contradictory hypotheses, including but not limited to: (a) high survivorship or fertility causing the farm to function as a productive population source, with or without strong attraction, and typically with density-dependent spillover to

surrounding areas (Pulliam 1988), or (b) strong attraction to the farm habitat but high mortality rates or low reproductive success for residents. The latter scenario describes an attractive population sink (ecological trap) that draws animals in from surrounding areas and causes deleterious population effects disproportionate to its area (Hale *et al.* 2015). Our meta-analysis reveals that in most cases we do not have sufficient data on fitness outcomes, either direct or indirect, and as a result cannot distinguish between attractive or productive population effects, or their resultant positive or negative effects on wild populations.

Conceptual frameworks have been developed to distinguish between these two (non-mutually-exclusive) processes on artificial reefs and fish aggregation devices (Osenberg *et al.* 2002; Brickhill *et al.* 2005; Reubens *et al.* 2013), and may be applied to aquaculture sites. Evidence for attraction without significant production of wild fauna at aquaculture sites may include: (i) rarity of younger cohorts relative to older cohorts, (ii) population declines at adjacent reference sites corresponding to increases at farms, (iii) high mortality or reproductive failure rates at farms, or (iv) tracking, microchemistry, tissue fatty acid or stable isotope analysis indicating recent immigration to farms. Conversely, evidence for high individual fitness leading to productive wild populations at farms may include, depending on the taxa: (i) successful breeding pairs residing at farms, (ii) high densities of larvae or juveniles, (iii) increases in abundance at farms followed by increases at adjacent reference sites consistent with density-dependent spillover, (iv) tracking, microchemistry, tissue fatty acid and stable isotope analysis indicating that most individuals are not recent immigrants.

Importantly, the above criteria for separating attraction and production are most relevant when compared to reference habitats (i.e. is residing at a farm a good decision for an individual, or likely to lead to an ecological trap?). Only 91/204 studies included in our database allowed us to infer changes in at least one variable in farm-associated wildlife by making comparison to reference sites or timepoints. In many cases, changes in distribution or health of wildlife were not central to the study, but in other cases, there was a lost opportunity to understand more about these interactions. Where relevant, we recommend that studies of abundance or fitness of wild fauna at farms should benchmark their findings against reference sites or timepoints (Underwood 1994; Osenberg *et al.* 2002; Brickhill *et al.* 2005). Reference sites should be appropriate for the hypotheses being tested. For example, our meta-analysis revealed that inferred increases in population densities at sea cage fish farms vary by orders of magnitude depending on whether the reference habitat is a nearby natural reef or

featureless open water. Accordingly, researchers should be clear in their reasons for selecting a given reference habitat.

Most importantly, we have highlighted the paucity of data on mortality rates and reproductive success in farm-associated fauna. Such data are central to our understanding of the environmental impacts of aquaculture but can be difficult to obtain. Population-level metrics can be effective in closed or semi-closed systems (Kilambi *et al.* 1978), and researchers have long been capable of tracking mortality and breeding success in birds, including at aquaculture sites (Kloskowski 2012; Broyer *et al.* 2017). Open systems with highly mobile taxa (such as wild fish associated with sea cage aquaculture) present a greater challenge, but in coastal environments, acoustic tags in conjunction with external tags can provide excellent data on spatiotemporal movement and mortality rates in areas with differing levels of farm activity (Olsen & Moland 2011; Olsen *et al.* 2012; Fernández-Chacón *et al.* 2015).

It is now well established that wild fish are typically more abundant at sea cage fish farms than reference sites, and that such fish are likely to consume farm waste, experience nutritional shifts and depending on the system, be exposed to elevated parasite loads. The challenge now is to develop an equivalent state of knowledge for other wild taxa and aquaculture systems, and to obtain more direct measures of the effects of farm-association on wildlife populations.

DATA ACCESSIBILITY

See Appendix I for a full list of research articles included in this study.

REFERENCES

- Abaad M, Tuset VM, Montero D, Lombarte A, Otero-Ferrer JL and Haroun R (2016) Phenotypic plasticity in wild marine fishes associated with fish-cage aquaculture. *Hydrobiologia* **765**: 343–358.
- Adámek Z, Kortan D, Lepič P and Andreji J (2003) Impacts of otter (*Lutra lutra* L) predation on fishponds: A study of fish remains at ponds in the Czech Republic. *Aquaculture*

- International* **11**: 389–396.
- Akyol O and Ertosluk O (2010) Fishing near sea-cage farms along the coast of the Turkish Aegean Sea. *Journal of Applied Ichthyology* **26**: 11–15.
- Anyango JO, Mlewa CM and Mwaluma J (2017) Abundance diversity and trophic status of wild fish around seaweed farms in Kibuyuni, South Coast Kenya. *International Journal of Fisheries and Aquatic Studies* **5**: 440–446.
- Arechavala-Lopez P, Izquierdo-Gomez D, Uglem I and Sanchez-Jerez P (2015a) Aggregations of bluefish *Pomatomus saltatrix* (L) at Mediterranean coastal fish farms: seasonal presence daily patterns and influence of farming activity. *Environmental Biology of Fishes* **98**: 499–510.
- Arechavala-Lopez P, Sæther B-S, Marhuenda-Egea F, Sanchez-Jerez P and Uglem I (2015b) Assessing the influence of salmon farming through total lipids fatty acids and trace elements in the liver and muscle of wild saithe *Pollachius virens*. *Marine and Coastal Fisheries* **7**: 59–67.
- Arechavala-Lopez P, Sanchez-Jerez P, Bayle-Sempere JT, Fernandez-Jover D, Martinez-Rubio L, Lopez-Jimenez JA and Martinez-Lopez FJ (2011) Direct interaction between wild fish aggregations at fish farms and fisheries activity at fishing grounds: a case study with *Boops boops*. *Aquaculture Research* **42**: 996–1010.
- Arechavala-López P, Sánchez-Jerez P, Bayle-Sempere JT, Uglem I and Mladineo I (2013) Reared fish farmed escapees and wild fish stocks—a triangle of pathogen transmission of concern to Mediterranean aquaculture management. *Aquaculture Environment Interactions* **3**: 153–161.
- Bacher K and Gordo A (2016) Does marine fish farming affect local small-scale fishery catches? A case study in the NW Mediterranean Sea. *Aquaculture Research* **47**: 2444–2454.
- Bacher K, Gordo A and Sagué O (2015) Feeding activity strongly affects the variability of wild fish aggregations within fish farms: a sea bream farm as a case study. *Aquaculture Research* **46**: 552–564.
- Ballester-Moltó M, Sanchez-Jerez P, Garcia-Garcia B and Aguado-Giménez F (2015) Husbandry and environmental conditions explain temporal variability of wild fish assemblages aggregated around a Mediterranean fish farm. *Aquaculture Environment Interactions* **7**: 193–203.
- Bancroft BA, Baker NJ and Blaustein AR (2007) Effects of UVB radiation on marine and freshwater organisms: a synthesis through meta-analysis. *Ecology Letters* **10**: 332–345.

- Barlow CG and Bock K (1984) Predation of fish in farm dams by cormorants *Phalacrocorax* spp. *Australian Wildlife Research* **11**: 559–566
- Barrett LT, Swearer SE, Harboe T, Karlsen Ø, Meier S and Dempster T (2018) Limited evidence for differential reproductive fitness of wild Atlantic cod in areas of high and low salmon farming density. *Aquaculture Environment Interactions* doi: 10.3354/aei00275
- Barton K (2016) MuMIn: multi-model inference R package version 1.15.6. URL: <https://cran.r-project.org/package=MuMIn>
- Bechard MJ and Márquez-Reyes C (2003) Mortality of wintering ospreys and other birds at aquaculture facilities in Colombia. *Journal of Raptor Research* **37**: 292–298.
- Becker BH, Press DT and Allen SG (2011) Evidence for long-term spatial displacement of breeding and pupping harbour seals by shellfish aquaculture over three decades. *Aquatic Conservation: Marine and Freshwater Ecosystems* **21**: 247–260.
- Belant JL, Tyson LA and Mastrangelo PA (2000) Effects of lethal control at aquaculture facilities on populations of piscivorous birds. *Wildlife Society Bulletin* **28**: 379–384.
- Berg V, Kraugerud M, Nourizadeh-Lillabadi R *et al.* (2016) Endocrine effects of real-life mixtures of persistent organic pollutants (POP) in experimental models and wild fish. *Journal of Toxicology and Environmental Health Part A* **79**: 538–548.
- Björklund H, Bondestam J and Bylund G (1990) Residues of oxytetracycline in wild fish and sediments from fish farms. *Aquaculture* **86**: 359–367.
- Blackwell BF, Dolbeer RA and Tyson LA (2000) Lethal control of piscivorous birds at aquaculture facilities in the northeast United States: effects on populations. *North American Journal of Aquaculture* **62**: 300–307.
- Bogdanović T, Šimat V, Frka-Roić A and Marković K (2012) Development and application of quality index method scheme in a shelf-life study of wild and fish farm affected bogue (*Boops boops* L.). *Journal of Food Science* **77**: S99–S106.
- Bogevik AS, Natário S, Karlsen Ø, Thorsen A, Hamre K, Rosenlund G and Norberg B (2012) The effect of dietary lipid content and stress on egg quality in farmed Atlantic cod *Gadus morhua*. *Journal of fish biology* **81**: 1391–405.
- Boyd CE and Massaut L (1999) Risks associated with the use of chemicals in pond aquaculture. *Aquacultural Engineering* **20**: 113–132.
- Brickhill MJ, Lee SY and Connolly RM (2005) Fishes associated with artificial reefs: attributing changes to attraction or production using novel approaches. *Journal of Fish Biology* **67**: 53–71.

- Brown JR, Gowen RJ and McLusky DS (1987) The effect of salmon farming on the benthos of a Scottish sea loch. *Journal of Experimental Marine Biology and Ecology* **109**: 39–51.
- Broyer J and Calenge C (2010) Influence of fish-farming management on duck breeding in French fish pond systems. *Hydrobiologia* **637**: 173–185.
- Broyer J, Chavas G and Chazal R (2017) The effects of cessation of fish farming on duck breeding in French fishpond systems. *Hydrobiologia* **788**: 47–53.
- Burnham KP and Anderson DR (2002) *Model selection and multimodel inference: a practical information-theoretic approach*, 2nd edn. Springer, New York, NY.
- Burridge L, Weis JS, Cabello F, Pizarro J and Bostick K (2010) Chemical use in salmon aquaculture: a review of current practices and possible environmental effects. *Aquaculture* **306**: 7–23.
- Bustnes JO, Lie E, Herzke D, Dempster T, Bjørn PA, Nygård T and Uglem I (2010) Salmon farms as a source of organohalogenated contaminants in wild fish. *Environmental Science & Technology* **44**: 8736–43.
- Bustnes JO, Nygård T, Dempster T, Ciesielski T, Jenssen BM, Bjorn PA and Uglem I (2011) Do salmon farms increase the concentrations of mercury and other elements in wild fish? *Journal of Environmental Monitoring* **13**: 1687–1694.
- Callier MD, Byron CJ, Bengtson DA *et al.* (2017) Attraction and repulsion of mobile wild organisms to finfish and shellfish aquaculture: a review. *Reviews in Aquaculture* doi: 10.1111/raq.12208
- Carss DN (1993) Grey heron *Ardea cinerea* L predation at cage fish farms in Argyll western Scotland. *Aquaculture and Fisheries Management* **24**: 29–45.
- Carss DN (1994) Killing of piscivorous birds at Scottish fin fish farms, 1984–87. *Biological Conservation* **68**: 181–188.
- Colorni A, Diamant A, Eldar A, Kvitt H and Zlotkin A (2002) Streptococcus iniae infections in Red Sea cage-cultured and wild fishes. *Diseases of Aquatic Organisms* **49**: 165–170.
- Costello MJ (2009) How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. *Proceedings of the Royal Society B* **276**: 3385–3394.
- Crump KL and Trudeau VL (2009) Mercury-induced reproductive impairment in fish. *Environmental Toxicology and Chemistry* **28**: 895.
- Dealteris JT, Kilpatrick BD and Rheault RB (2004) A comparative evaluation of the habitat value of shellfish aquaculture gear, submerged aquatic vegetation and a non-vegetated

- seabed. *Journal of Shellfish Research* **23**: 867–874.
- DeBruyn AMH, Trudel M, Eyding N *et al.* (2006) Ecosystemic effects of salmon farming increase mercury contamination in wild fish. *Environmental Science & Technology* **40**: 3489–3493.
- Demétrio JA, Gomes LC, Latini JD and Agostinho AA (2012) Influence of net cage farming on the diet of associated wild fish in a Neotropical reservoir. *Aquaculture* **330**: 172–178.
- Dempster T, Sanchez-Jerez P, Bayle-Sempere JT and Giménez-Casalduero F (2002) Attraction of wild fish to sea-cage fish farms in the south-western Mediterranean Sea: spatial and short-term temporal variability. *Marine Ecology Progress Series* **242**: 237–252.
- Dempster T, Sanchez-Jerez P, Bayle-Sempere JT and Kingsford M (2004) Extensive aggregations of wild fish at coastal sea-cage fish farms. *Hydrobiologia* **525**: 245–248.
- Dempster T, Sanchez-Jerez P, Fernandez-Jover D, Bayle-Sempere JT, Nilsen R, Bjørn PA and Uglem I (2011) Proxy measures of fitness suggest coastal fish farms can act as population sources and not ecological traps for wild gadoid fish. *PLOS ONE* **6**: e15646.
- Dempster T, Uglem I, Sanchez-Jerez P, Fernandez-Jover D, Bayle-Sempere J and Nilsen R (2009) Coastal salmon farms attract large and persistent aggregations of wild fish: an ecosystem effect. *Marine Ecology Progress Series* **385**: 1–14.
- Diamant A, Banet A, Ucko M, Colorni A, Knibb W and Kvitt H (2000) Mycobacteriosis in wild rabbitfish *Siganus rivulatus* associated with cage farming in the Gulf of Eilat, Red Sea. *Diseases of Aquatic Organisms* **39**: 211–219.
- Diaz López B (2006) Bottlenose dolphin (*Tursiops truncatus*) predation on a marine fin fish farm: some underwater observations. *Aquatic Mammals* **32**: 305–310.
- Diaz López B (2012) Bottlenose dolphins and aquaculture: interaction and site fidelity on the north-eastern coast of Sardinia (Italy). *Marine Biology* **159**: 2161–2172.
- Diaz López B (2017) Temporal variability in predator presence around a fin fish farm in the Northwestern Mediterranean Sea. *Marine Ecology* **38**: e12378.
- Diaz López B and Bernal-Shirai JA (2007) Bottlenose dolphin (*Tursiops truncatus*) presence and incidental capture in a marine fish farm on the north-eastern coast of Sardinia (Italy). *Journal of the Marine Biological Association of the UK* **87**: 113–117.
- Díaz López B and Methion S (2017) The impact of shellfish farming on common bottlenose dolphins' use of habitat. *Marine Biology* **164**: 83.
- Dorr BS, Burger LW, Barras SC and Godwin KC (2012) Economic impact of double-crested cormorant *Phalacrocorax auritus* depredation on channel catfish *Ictalurus punctatus*

- aquaculture in Mississippi, USA. *Journal of the World Aquaculture Society* **43**: 502–513.
- Dumont CP, Gaymer CF and Thiel M (2011) Predation contributes to invasion resistance of benthic communities against the non-indigenous tunicate *Ciona intestinalis*. *Biological Invasions* **13**: 2023–2034
- Ervik A, Thorsen B, Eriksen V, Lunestad BT and Samuelsen OB (1994) Impact of administering antibacterial agents on wild fish and blue mussels *Mytilus edulis* in the vicinity of fish farms. *Diseases of Aquatic Organisms* **18**: 45–51.
- European Union (2010) Commission Regulation (EU) No 37/2010 of 22 December 2009 on pharmacologically active substances and their classification regarding maximum residue limits in foodstuffs of animal origin Brussels European Union. URL: https://eur-lex.europa.eu/food/plant/pesticides/max_residue_levels_en
- FAO Fisheries and Aquaculture (2015) FAO Yearbook - Fishery and Aquaculture Statistics (2014).
- FAO Fisheries and Aquaculture (2017) Fishery and Aquaculture Statistics - Global aquaculture production 1950-2015 (FishstatJ). URL: <http://www.fao.org/fishery/statistics/software/fishstatj/en>
- FAO Fisheries and Aquaculture (2018) Cultured aquatic species fact sheets. URL: <http://www.fao.org/fishery/culturedspecies/search/en>
- Felsing M, Glencross B and Telfer T (2005) Preliminary study on the effects of exclusion of wild fauna from aquaculture cages in a shallow marine environment. *Aquaculture* **243**: 159–174.
- Fernández-Chacón A, Moland E, Espeland SH and Olsen EM (2015) Demographic effects of full vs partial protection from harvesting: inference from an empirical before-after control-impact study on Atlantic cod. *Journal of Applied Ecology* **52**: 1206–1215.
- Fernandez-Jover D, Jimenez JA, Sanchez-Jerez P, Bayle-Sempere JT, Giménez-Casaldueiro F, Lopez FJM and Dempster T (2007a) Changes in body condition and fatty acid composition of wild Mediterranean horse mackerel (*Trachurus mediterraneus* Steindachner 1868) associated to sea cage fish farms. *Marine Environmental Research* **63**: 1–18.
- Fernandez-Jover D, Martinez-Rubio L, Sanchez-Jerez P *et al.* (2011) Waste feed from coastal fish farms: a trophic subsidy with compositional side-effects for wild gadoids. *Estuarine Coastal and Shelf Science* **91**: 559–568.
- Fernandez-Jover D and Sanchez-Jerez P (2015) Comparison of diet and otolith growth of

- juvenile wild fish communities at fish farms and natural habitats. *ICES Journal of Marine Science* **72**: 916–929.
- Fernandez-Jover D, Sanchez-Jerez P, Bayle-Sempere J, Carratala A and Leon VM (2007b) Addition of dissolved nitrogen and dissolved organic carbon from wild fish faeces and food around Mediterranean fish farms: Implications for waste-dispersal models. *Journal of Experimental Marine Biology and Ecology* **340**: 160–168.
- Fleury BE and Sherry TW (1995) Long-term population trends of colonial wading birds in the southern United States: the impact of crayfish aquaculture on Louisiana populations. *Auk* **112**: 613–632.
- Freitas D, Gomes J, Luis TS *et al.* (2007) Otters and fish farms in the Sado estuary: ecological and socio-economic basis of a conflict. *Hydrobiologia* **587**: 51–62.
- Gamfeldt L, Lefcheck JS, Byrnes JEK, Cardinale BJ, Duffy JE and Griffin JN (2015) Marine biodiversity and ecosystem functioning: what's known and what's next? *Oikos* **124**: 252–265.
- Glahn JF, Tomsa T and Preusser KJ (1999) Impact of great blue heron predation at trout-rearing facilities in the northeastern United States. *North American Journal of Aquaculture* **61**: 349–354.
- Glover KA, Solberg MF, McGinnity P *et al.* (2017) Half a century of genetic interaction between farmed and wild Atlantic salmon: status of knowledge and unanswered questions. *Fish and Fisheries* doi: 10.1111/faf.12214
- Glover KA, Sørvik AGE, Karlsbakk E, Zhang Z and Skaala Ø (2013) Molecular genetic analysis of stomach contents reveals wild Atlantic cod feeding on piscine reovirus (PRV) infected Atlantic salmon originating from a commercial fish farm. *PLOS ONE* **8**: e60924.
- Godet L, Toupont N, Fournier J, Le Mao P, Retiere C and Olivier F (2009) Clam farmers and oystercatchers: effects of the degradation of *Lanice conchilega* beds by shellfish farming on the spatial distribution of shorebirds. *Marine Pollution Bulletin* **58**: 589–595.
- Gonzalez-Silvera D, Guardiola FA, Cordero H, Cuesta A, Esteban MA, Martínez-López FJ and López-Jiménez JA (2017) The short-term effects of farmed fish food consumed by wild fish congregating outside the farms. *Marine Pollution Bulletin* **114**: 689–698.
- Gregory PT and Nelson KJ (1991) Predation on fish and intersite variation in the diet of common garter snakes *Thamnophis sirtalis* on Vancouver Island. *Canadian Journal of Zoology* **69**: 988–994.
- Güçlüsoy H and Savas Y (2003) Interaction between monk seals *Monachus monachus*

- (Hermann 1779) and marine fish farms in the Turkish Aegean and management of the problem. *Aquaculture Research* **34**: 777–783.
- Hale R and Swearer SE (2016) Ecological traps: current evidence and future directions. *Proceedings of the Royal Society B* **283**: 494–499.
- Hale R, Trembl EA and Swearer SE (2015) Evaluating the metapopulation consequences of ecological traps. *Proceedings of the Royal Society B* **282**: 20142930
- Harrison SJ (2009) Interactions between Silver Gulls (*Larus novaehollandiae*) and Southern Bluefin Tuna (*Thunnus maccoyii*) aquaculture in the Port Lincoln area. PhD thesis. Flinders University, Australia.
- Hayward CJ, Svane I, Lachimpadi SK, Itoh N, Bott NJ and Nowak BF (2011) Sea lice infections of wild fishes near ranches southern bluefin tuna (*Thunnus maccoyii*) in South Australia. *Aquaculture* **320**: 178–182.
- Hedges LV, Gurevitch J and Curtis PS (1999) The meta-analysis of response ratios in experimental ecology. *Ecology* **80**: 1150–1156.
- Hehre EJ and Meeuwig JJ (2016) A global analysis of the relationship between farmed seaweed production and herbivorous fish catch. *PLOS ONE* **11**: e0148250.
- Herbeck LS, Unger D, Wu Y and Jennerjahn TC (2013) Effluent nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China. *Continental Shelf Research* **57**: 92–104.
- Hume F, Pemberton D, Gales R, Brothers N and Greenwood M (2002) Trapping and relocating seals from salmonid fish farms in Tasmania 1990-2000: was it a success? *Papers and Proceedings of the Royal Society of Tasmania* **136**: 1–6.
- Immsland AK, Reynolds P, Eliassen G, Hangstad TA, Foss A, Vikingstad E and Elvegård TA (2014) The use of lumpfish (*Cyclopterus lumpus* L) to control sea lice (*Lepeophtheirus salmonis* Krøyer) infestations in intensively farmed Atlantic salmon (*Salmo salar* L). *Aquaculture* **424–425**: 18–23.
- Inglis GJ and Gust N (2003) Potential indirect effects of shellfish culture on the reproductive success of benthic predators. *Journal of Applied Ecology* **40**: 1077–1089.
- Jensen Ø, Dempster T, Thorstad EB, Uglem I and Fredheim A (2010) Escapes of fishes from Norwegian sea-cage aquaculture: causes consequences and prevention. *Aquaculture Environment Interactions* **1**: 71–83.
- Johnston TA, Keir M and Power M (2010) Response of native and naturalized fish to salmonid cage culture farms in northern Lake Huron, Canada. *Transactions of the American Fisheries Society* **139**: 660–670.

- Kelly JP, Evens JG, Stallcup RW and Wimpfheimer D (1996) Effects of aquaculture on habitat use by wintering shorebirds in Tomales Bay, California. *California Fish and Game* **82**: 160–174.
- Kemper C, Pemberton D, Cawthorn M *et al.* (2003) Aquaculture and marine mammals: co-existence or conflict? In: Gales N, Hindell M and Kirkwood R (ed.) *Marine Mammals: Fisheries Tourism and Management Issues*, pp. 208–225. CSIRO Publishing, Collingwood.
- Kemper CM and Gibbs SE (2001) Dolphin interactions with tuna feedlots at Port Lincoln, South Australia and recommendations for minimising entanglements. *Journal of Cetacean Research and Management* **3**: 283–292.
- Kilambi RV, Adams JC and Wickizer WA (1978) Effects of cage culture on growth abundance and survival of resident largemouth bass (*Micropterus salmoides*). *Journal of the Fisheries Research Board of Canada* **35**: 157–160.
- Kirk M, Esler D and Boyd WS (2007) Morphology and density of mussels on natural and aquaculture structure habitats: implications for sea duck predators. *Marine Ecology Progress Series* **346**: 179–187.
- Kloskowski J (2010) Fish farms as amphibian habitats: factors affecting amphibian species richness and community structure at carp ponds in Poland. *Environmental Conservation* **37**: 187–194.
- Kloskowski J (2012) Fish stocking creates an ecological trap for an avian predator via effects on prey availability. *Oikos* **121**: 1567–1576.
- Kloskowski J (2005) Otter *Lutra lutra* damage at farmed fisheries in southeastern Poland II: exploitation of common carp *Cyprinus carpio*. *Wildlife Biology* **11**: 257–261.
- Kloskowski J, Kaczanowska E, Krogulec J and Grela P (2017) Hematological indicators of habitat quality: erythrocyte parameters reflect greater parental effort of red-necked grebes under ecological trap conditions. *The Condor* **119**: 239–250.
- Kortan D, Adámek Z and Poláková S (2007) Winter predation by otter *Lutra lutra* on carp pond systems in South Bohemia (Czech Republic). *Folia Zoologica* **56**: 416.
- Krkošek M (2017) Population biology of infectious diseases shared by wild and farmed fish. *Canadian Journal of Fisheries and Aquatic Sciences* **74**: 620–628.
- Krkosek M, Lewis MA, Morton A, Frazer LN and Volpe JP (2006) Epizootics of wild fish induced by farm fish. *Proceedings of the National Academy of Sciences of the USA* **103**: 15506–15510.
- Krkosek M, Lewis MA and Volpe JP (2005) Transmission dynamics of parasitic sea lice

- from farm to wild salmon. *Proceedings of the Royal Society B* **272**: 689–96.
- Kroeker KJ, Kordas RL, Crim RN and Singh GG (2010) Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters* **13**: 1419–1434.
- Lafferty KD, Harvell CD, Conrad JM *et al.* (2015) Infectious diseases affect marine fisheries and aquaculture economics. *Annual Review of Marine Science* **7**: 471–496.
- Lavens P, Lebegue E, Jaunet H, Brunel A, Dhert P and Sorgeloos P (1999) Effect of dietary essential fatty acids and vitamins on egg quality in turbot broodstocks. *Aquaculture International* **7**: 225–240.
- Loiseau N, Kiszka JJ, Bouveroux T, Heithaus MR, Soria M and Chabanet P (2016) Using an unbaited stationary video system to investigate the behaviour and interactions of bull sharks *Carcharhinus leucas* under an aquaculture farm. *African Journal of Marine Science* **38**: 73–79.
- Markowitz TM, Harlin AD, Wursig B and Mcfadden CJ (2004) Dusky dolphin foraging habitat: overlap with aquaculture in New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems* **14**: 133–149.
- Mazorra C, Bruce M, Bell JG *et al.* (2003) Dietary lipid enhancement of broodstock reproductive performance and egg and larval quality in Atlantic halibut (*Hippoglossus hippoglossus*). *Aquaculture* **227**: 21–33.
- McKindsey CW, Archambault P, Callier MD and Olivier F (2011) Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: a review. *Canadian Journal of Zoology* **89**: 622–646.
- Mladineo I, Segvic T and Grubisic L (2009) Molecular evidence for the lack of transmission of the monogenean *Sparicotyle chrysophrii* (Monogenea, Polyopisthocotylea) and isopod *Ceratothoa oestroides* (Crustacea, Cymothoidae) between wild bogue (*Boops boops*) and cage-reared sea bream (*Sparus aurata*). *Aquaculture* **295**: 160–167.
- Moe H, Dempster T, Sunde LM, Winther U and Fredheim A (2007) Technological solutions and operational measures to prevent escapes of Atlantic cod (*Gadus morhua*) from sea cages. *Aquaculture Research* **38**: 91–99.
- Morrison SS and Vogel P (2009) Aquaculture ponds a Jamaican study: The impact of birds on fish production. *African Journal of Agricultural Research* **4**: 1447–1454.
- Nelson KJ and Gregory PT (2000) Activity patterns of garter snakes *Thamnophis sirtalis* in relation to weather conditions at a fish hatchery on Vancouver Island, British Columbia. *Journal of Herpetology* **34**: 32.

- Olsen EM, Heupel MR, Simpfendorfer CA and Moland E (2012) Harvest selection on Atlantic cod behavioral traits: implications for spatial management. *Ecology and Evolution* **2**: 1549–1562.
- Olsen EM and Moland E (2011) Fitness landscape of Atlantic cod shaped by harvest selection and natural selection. *Evolutionary Ecology* **25**: 695–710.
- Osenberg C, St Mary CM, Wilson JA and Lindberg WJ (2002) A quantitative framework to evaluate the attraction-production controversy. *ICES Journal of Marine Science* **59**: S214–S221.
- Otterå H and Skilbrei OT (2014) Possible influence of salmon farming on long-term resident behaviour of wild saithe (*Pollachius virens* L). *ICES Journal of Marine Science* **71**: 2484–2493.
- Pearson HC (2009) Influences on dusky dolphin (*Lagenorhynchus obscurus*) fission-fusion dynamics in Admiralty Bay, New Zealand. *Behavioral Ecology and Sociobiology* **63**: 1437–1446.
- Pemberton D and Shaughnessy PD (1993) Interaction between seals and marine fish-farms in Tasmania and management of the problem. *Aquatic Conservation: Marine and Freshwater Ecosystems* **3**: 149–158.
- Piroddi C, Bearzi G and Christensen V (2011) Marine open cage aquaculture in the eastern Mediterranean Sea: a new trophic resource for bottlenose dolphins. *Marine Ecology Progress Series* **440**: 255–266.
- Pitt WC and Conover MR (1996) Predation at Intermountain West fish hatcheries. *The Journal of Wildlife Management* **60**: 616–624.
- Plummer M V and Goy JM (1984) Ontogenetic dietary shift of water snakes (*Nerodia rhombifera*) in a fish hatchery. *Copeia* **1984**: 550.
- Powers M, Peterson C, Summerson H and Powers S (2007) Macroalgal growth on bivalve aquaculture netting enhances nursery habitat for mobile invertebrates and juvenile fishes. *Marine Ecology Progress Series* **339**: 109–122.
- Pulliam HR (1988) Sources sinks and population regulation. *The American Naturalist* **132**: 652–661.
- Quick NJ, Middlemas SJ and Armstrong JD (2004) A survey of antipredator controls at marine salmon farms in Scotland. *Aquaculture* **230**: 169–180.
- R Core Team (2017) R: A language and environment for statistical computing. URL: <http://www.r-project.org/>
- Reubens JT, Vandendriessche S, Zenner AN, Degraer S and Vincx M (2013) Offshore wind

- farms as productive sites or ecological traps for gadoid fishes? Impact on growth condition index and diet composition. *Marine Environmental Research* **90**: 66-74.
- Robertson BA and Hutto RL (2006) A framework for understanding ecological traps and an evaluation of existing evidence. *Ecology* **87**: 1075–1085.
- Roycroft D, Kelly TC and Lewis LJ (2004) Birds seals and the suspension culture of mussels in Bantry Bay a non-seaduck area in Southwest Ireland. *Estuarine Coastal and Shelf Science* **61**: 703–712.
- Sales-Luis T, Freitas D and Santos-Reis M (2009) Key landscape factors for Eurasian otter *Lutra lutra* visiting rates and fish loss in estuarine fish farms. *European Journal of Wildlife Research* **55**: 345–355.
- Salze G, Tocher DR, Roy WJ and Robertson DA (2005) Egg quality determinants in cod (*Gadus morhua* L): egg performance and lipids in eggs from farmed and wild broodstock. *Aquaculture Research* **36**: 1488–1499.
- Samsing F, Johnsen I, Stien LH, Oppedal F, Albretsen J, Asplin L and Dempster T (2016) Predicting the effectiveness of depth-based technologies to prevent salmon lice infection using a dispersal model. *Preventive Veterinary Medicine* **129**: 48–57.
- Samuelsen OB, Lunestad BT, Husevag B, Holleland T and Ervik A (1992) Residues of oxolinic acid in wild fauna following medication in fish farms. *Diseases of Aquatic Organisms* **12**: 111–119.
- Sanchez-Jerez P, Fernandez-Jover D, Bayle-Sempere J, Valle C, Dempster T, Tuya F and Juanes F (2008) Interactions between bluefish *Pomatomus saltatrix* (L) and coastal sea-cage farms in the Mediterranean Sea. *Aquaculture* **282**: 61–67.
- Sanchez-Jerez P, Fernandez-Jover D, Uglem I *et al.* (2011) Coastal fish farms as fish aggregation devices (FADs). In: Bortone SA, Brandini FP, Fabi G and Otake S (ed.) *Artificial Reefs in Fishery Management*, pp. 187–208. Taylor & Francis Group, Florida.
- Segvic-Bubic T, Grubisic L, Karaman N, Ticina V, Jelavic KM and Katavic I (2011) Damages on mussel farms potentially caused by fish predation – self service on the ropes? *Aquaculture* **319**: 497–504.
- Sepúlveda M, Newsome SD, Pavez G, Oliva D, Costa DP and Hueckstaedt LA (2015) Using satellite tracking and isotopic information to characterize the impact of South American sea lions on salmonid aquaculture in southern Chile. *PLOS ONE* **10**: e0134926–e0134926.
- Sepúlveda M and Oliva D (2005) Interactions between South American sea lions *Otaria flavescens* (Shaw) and salmon farms in southern Chile. *Aquaculture Research* **36**: 1062–

- 1082 1068.
- 1083 Skiftesvik AB, Blom G, Agnalt A-L *et al.* (2014) Wrasse (Labridae) as cleaner fish in
 1084 salmonid aquaculture – the Hardangerfjord as a case study. *Marine Biology Research*
 1085 **10**: 289–300.
- 1086 Skog T-E, Hylland K, Torstensen BE and Berntssen MHG (2003) Salmon farming affects the
 1087 fatty acid composition and taste of wild saithe *Pollachius virens* L. *Aquaculture*
 1088 *Research* **34**: 999–1007.
- 1089 Stickley AR, Glahn JF, King JO and King DT (1995) Impact of great blue heron depredations
 1090 on channel catfish farms. *Journal of the World Aquaculture Society* **26**: 194–199.
- 1091 Stickley AR, Warrick GL and Glahn JF (1992) Impact of double-crested cormorant
 1092 depredations on channel catfish farms. *Journal of the World Aquaculture Society* **23**:
 1093 192–198.
- 1094 Sun YH, Wu HJ and Wang Y (2004) Tawny fish-owl predation at fish farms in Taiwan.
 1095 *Journal of Raptor Research* **38**: 326–333.
- 1096 Sundt-Hansen L, Huisman J, Skoglund H and Hindar K (2015) Farmed Atlantic salmon
 1097 *Salmo salar* L parr may reduce early survival of wild fish. *Journal of Fish Biology* **86**:
 1098 1699–1712.
- 1099 Tallman JC and Forrester GE (2007) Oyster grow-out cages function as artificial reefs for
 1100 temperate fishes. *Transactions of the American Fisheries Society* **136**: 790–799.
- 1101 Taranger GL, Karlsen Ø, Bannister RJ *et al.* (2015) Risk assessment of the environmental
 1102 impact of Norwegian Atlantic salmon farming. *ICES Journal of Marine Science* **72**:
 1103 997–1021.
- 1104 Tsuyuki A and Umino T (2017) Spatial movement of black sea bream *Acanthopagrus*
 1105 *schlegelii* around the oyster farming area in Hiroshima Bay, Japan. *Fisheries Science* **83**:
 1106 235–244.
- 1107 Tuya F, Sanchez-Jerez P, Dempster T, Boyra A and Haroun RJ (2006) Changes in demersal
 1108 wild fish aggregations beneath a sea-cage fish farm after the cessation of farming.
 1109 *Journal of Fish Biology* **69**: 682–697.
- 1110 Uglem I, Dempster T, Bjørn PA, Sanchez-Jerez P and Økland F (2009) High connectivity of
 1111 salmon farms revealed by aggregation residence and repeated movements of wild fish
 1112 among farms. *Marine Ecology Progress Series* **384**: 251–260.
- 1113 Uglem I, Karlsen Ø, Sanchez-Jerez P and Sæther B (2014) Impacts of wild fishes attracted to
 1114 open-cage salmonid farms in Norway. *Aquaculture Environment Interactions* **6**: 91–103
- 1115 Underwood AJ (1994) On Beyond BACI: sampling designs that might reliably detect

- environmental disturbances. *Ecological Applications* **4**: 3–15.
- United Nations Development Programme (2017) International Human Development Indicators. Available at: <http://hdrundporg/en/countries> [Accessed October 30 2017].
- Valdemarsen T, Hansen PK, Ervik A and Bannister RJ (2015) Impact of deep-water fish farms on benthic macrofauna communities under different hydrodynamic conditions. *Marine Pollution Bulletin* **101**: 776–783.
- Vita R, Marin A, Madrid JA, Jimenez-Brinquis B, Cesar A and Marin-Guirao L (2004) Effects of wild fishes on waste exportation from a Mediterranean fish farm. *Marine Ecology Progress Series* **277**: 253–261.
- Watson-Capps JJ and Mann J (2005) The effects of aquaculture on bottlenose dolphin (*Tursiops* sp) ranging in Shark Bay, Western Australia. *Biological Conservation* **124**: 519–526.
- Watts JEM, Schreier HJ, Lanska L and Hale MS (2017) The rising tide of antimicrobial resistance in aquaculture: sources sinks and solutions *Marine Drugs* **15**: 158.
- White CA, Bannister RJ, Dworjanyn SA, Husa V, Nichols PD, Kutti T and Dempster T (2017) Consumption of aquaculture waste affects the fatty acid metabolism of a benthic invertebrate. *Science of The Total Environment* **586**: 1170–1181.
- Wright DW, Stien LH, Dempster T, Vågseth T, Nola V, Fosseidengen J-E and Oppedal F (2017) “Snorkel” lice barrier technology reduced two co-occurring parasites the salmon louse (*Lepeophtheirus salmonis*) and the amoebic gill disease causing agent (*Neoparamoeba perurans*) in commercial salmon sea-cages. *Preventive Veterinary Medicine* **140**: 97–105.
- Wu RSS (1995) The environmental impact of marine fish culture: towards a sustainable future. *Marine Pollution Bulletin* **31**: 159–166.
- Yucel-Gier G, Kucuksezgin F and Kocak F (2007) Effects of fish farming on nutrients and benthic community structure in the Eastern Aegean (Turkey). *Aquaculture Research* **38**: 256–267.
- Zeileis A, Kleiber C and Jackman S (2008) Regression models for count data in R. *Journal of Statistical Software* **27**. doi: 10.18637/jss.v027.i08
- Zlotkin A, Hershko H and Eldar A (1998) Possible transmission of *Streptococcus iniae* from wild fish to cultured marine fish. *Applied and Environmental Microbiology* **64**: 4065–4067.

TABLES

Table 1. Mean effects of aquaculture sites on wildlife populations. F:W = mean at farms / mean at reference sites. $RR = \ln(F:W)$. Positive RR indicates metric is higher at aquaculture sites. t-stat and p refer to one sample t-test comparing RR data to null expectation of $RR = 0$. Taxa are omitted where no comparative data are available. Asterisk indicates variables for which higher RR corresponds to poorer outcomes.

	N	F:W	RR $\pm$ SE	t-stat	p
Abundance					
Fish	44	72	1.65 $\pm$ 0.29	5.7	<0.0001
Birds	13	1.8	0.13 $\pm$ 0.31	0.40	0.70
Mammals	7	1.1	-0.68 $\pm$ 0.67	-1.0	0.35
Amphibians	1	0.31	-1.17	–	–
All taxa	65	49	1.05 $\pm$ 0.24	4.3	<0.0001
Species richness					
Fish	28	2.0	0.43 $\pm$ 0.11	3.9	0.0005
Birds	7	1.1	0.13 $\pm$ 0.04	3.3	0.02
Mammals	1	0.50	-0.69	–	–
Amphibians	1	0.32	-1.15	–	–
All taxa	37	1.7	0.30 $\pm$ 0.10	3.1	0.004
Size (length)					
Fish	18	1.2	0.15 $\pm$ 0.03	4.6	0.0002
Size (weight)					
Fish	12	1.7	0.40 $\pm$ 0.13	3.0	0.01
Condition metrics					
Fish	14	1.3	0.17 $\pm$ 0.09	1.9	0.08
Birds	1	0.7	-0.31	–	–
All taxa	15	1.2	0.14 $\pm$ 0.09	1.5	0.15
Stomach fullness					
Fish	10	1.4	0.04 $\pm$ 0.30	0.13	0.90
Reptiles	1	1.9	0.66	–	–
All taxa	11	1.5	0.10 $\pm$ 0.28	0.35	0.73
Infection level*					
Fish	11	16	2.09 $\pm$ 0.38	5.5	0.0003
Fertility					

Birds	2	0.60	-0.60 ± 0.40	-1.5	0.37
Mortality⁺					
Fish	1	0.82	-0.20	–	–
Bird	1	1.4	0.33	–	–

FIGURE CAPTIONS

Figure 1. Distribution of research effort in terms of the number of studies that met the criteria for inclusion in our database, according to (A) Country, (B) Culture system, (C) Region, (D) Culture taxa, (E) Environment, and (F) Wild taxa.

Figure 2. Distribution of research effort on interactions between aquaculture sites and wild fauna among countries and territories. Production data taken from the Fishstatj database (FAO Fisheries and Aquaculture Department 2017).

Figure 3. Summary statistics for log response ratios (RR) for each variable in our meta-analysis. All taxa are included. Boxes denote median, lower (25 %) and upper (75 %) quartiles, whiskers denote 1.5x interquartile range. Data points are ‘jittered’ for clarity. Asterisk indicates variables for which higher RR corresponds to poorer outcomes.

Figure 1.

Figure 2.

Figure 3.

Appendix I. List of 191 articles included in systematic review and meta-analysis.

- Abaad, M., Tuset, V.M., Montero, D., Lombarte, A., Otero-Ferrer, J.L. and Haroun, R. (2016) Phenotypic plasticity in wild marine fishes associated with fish-cage aquaculture. *Hydrobiologia* 765, 343–358.
- Adámek, Z., Kortan, D., Lepič, P. and Andreji, J. (2003) Impacts of otter (*Lutra lutra* L.) predation on fishponds: A study of fish remains at ponds in the Czech Republic. *Aquaculture International* 11, 389–396.
- Anyango, J.O., Mlewa, C.M. and Mwaluma, J. (2017) Abundance, diversity and trophic status of wild fish around seaweed farms in Kibuyuni, South Coast Kenya. *International Journal of Fisheries and Aquatic Studies* 5, 440–446.
- Arechavala-Lopez, P., Izquierdo-Gomez, D., Uglem, I. and Sanchez-Jerez, P. (2015a) Aggregations of bluefish *Pomatomus saltatrix* (L.) at Mediterranean coastal fish farms: seasonal presence, daily patterns and influence of farming activity. *Environmental Biology of Fishes* 98, 499–510.
- Arechavala-Lopez, P., Sæther, B.-S., Marhuenda-Egea, F., Sanchez-Jerez, P. and Uglem, I. (2015b) Assessing the influence of salmon farming through total lipids, fatty acids, and trace elements in the liver and muscle of wild saithe *Pollachius virens*. *Marine and Coastal Fisheries* 7, 59–67.
- Arechavala-Lopez, P., Sanchez-Jerez, P., Bayle-Sempere, J., Fernandez-Jover, D., Martinez-Rubio, L., Lopez-Jimenez, J.A. and Martinez-Lopez, F.J. (2011) Direct interaction

- between wild fish aggregations at fish farms and fisheries activity at fishing grounds: a case study with *Boops boops*. *Aquaculture Research* 42, 996–1010.
- Arechavala-Lopez, P., Uglem, I., Sanchez-Jerez, P., Fernandez-Jover, D., Bayle-Sempere, J.T. and Nilsen, R. (2010) Movements of grey mullet *Liza aurata* and *Chelon labrosus* associated with coastal fish farms in the western Mediterranean Sea. *Aquaculture Environment Interactions* 1, 127–136.
- Avery, M.L., Eiselman, D.S., Young, M.K., Humphrey, J.S. and Decker, D.G. (1999) Wading bird predation at tropical aquaculture facilities in central Florida. *North American Journal of Aquaculture* 61, 64–69.
- Bacher, K. and Gordo, A. (2016) Does marine fish farming affect local small-scale fishery catches? A case study in the NW Mediterranean Sea. *Aquaculture Research* 47, 2444–2454.
- Bacher, K., Gordo, A. and Sague, O. (2012) Spatial and temporal extension of wild fish aggregations at *Sparus aurata* and *Thunnus thynnus* farms in the north-western Mediterranean. *Aquaculture Environment Interactions* 2, 239–252.
- Bacher, K., Gordo, A. and Sagué, O. (2015) Feeding activity strongly affects the variability of wild fish aggregations within fish farms: a sea bream farm as a case study. *Aquaculture Research* 46, 552–564.
- Bagdonas, K., Humborstad, O.-B. and Løkkeborg, S. (2012) Capture of wild saithe (*Pollachius virens*) and cod (*Gadus morhua*) in the vicinity of salmon farms: three pot types compared. *Fisheries Research* 134–136, 1–5.
- Ballester-Moltó, M., Sanchez-Jerez, P. and Aguado-Giménez, F. (2017) Consumption of particulate wastes derived from cage fish farming by aggregated wild fish. An experimental approach. *Marine Environmental Research* 130, 166–173.
- Ballester-Moltó, M., Sanchez-Jerez, P., Garcia-Garcia, B. and Aguado-Giménez, F. (2015) Husbandry and environmental conditions explain temporal variability of wild fish assemblages aggregated around a Mediterranean fish farm. *Aquaculture Environment Interactions* 7, 193–203.
- Baltrūnaitė, L. (2009) Diet of otters in fish farms in Lithuania. *Acta Zoologica Lituanica* 19, 182–187.
- Barlow, C.G. and Bock, K. (1984) Predation of fish in farm dams by cormorants, *Phalacrocorax* spp. *Australian Wildlife Research* 11, 559–566.
- Bechard, M.J. and Márquez-Reyes, C. (2003) Mortality of wintering ospreys and other birds at aquaculture facilities in Colombia. *Journal of Raptor Research* 37, 292–298.

- Becker, B.H., Press, D.T. and Allen, S.G. (2011) Evidence for long-term spatial displacement of breeding and pupping harbour seals by shellfish aquaculture over three decades. *Aquatic Conservation-Marine and Freshwater Ecosystems* 21, 247–260.
- Belant, J.L., Tyson, L.A. and Mastrangelo, P.A. (2000) Effects of lethal control at aquaculture facilities on populations of piscivorous birds. *Wildlife Society Bulletin* 28, 379–384.
- Bergman, K.C., Svensson, S. and Ohman, M.C. (2001) Influence of algal farming on fish assemblages. *Marine Pollution Bulletin* 42, 1379–1389.
- Beynon, J.L., Hutchins, D.L., Rubino, A.J., Lawrence, A.L. and Chapman, B.R. (1981) Nocturnal activity of birds on shrimp mariculture ponds. *Journal of the World Mariculture Society* 12, 63–70.
- Björdal, Å. and Johnstone, A.D.F. (1993) Local movements of saithe (*Pollachius virens* L.) in the vicinity of fish farm cages. In: *ICES Mar Sci Symp*, Vol. 196. pp 143–146.
- Björklund, H., Bondestam, J. and Bylund, G. (1990) Residues of oxytetracycline in wild fish and sediments from fish farms. *Aquaculture* 86, 359–367.
- Bjørn, P.-A., Uglem, I., Kerwath, S., Sæther, B.-S. and Nilsen, R. (2009) Spatiotemporal distribution of Atlantic cod (*Gadus morhua* L.) with intact and blocked olfactory sense during the spawning season in a Norwegian fjord with intensive salmon farming. *Aquaculture* 286, 36–44.
- Bjørn, P.A., Finstad, B. and Kristoffersen, R. (2001) Salmon lice infection of wild sea trout and Arctic char in marine and freshwaters: the effects of salmon farms. *Aquaculture Research* 32, 947–962.
- Blackwell, B.F., Dolbeer, R.A. and Tyson, L.A. (2000) Lethal control of piscivorous birds at aquaculture facilities in the northeast United States: effects on populations. *North American Journal of Aquaculture* 62, 300–307.
- Bogdanović, T., Šimat, V., Frka-Roić, A. and Marković, K. (2012) Development and application of quality index method scheme in a shelf-life study of wild and fish farm affected bogue (*Boops boops*, L.). *Journal of Food Science* 77, S99–S106.
- Bonizzoni, S., Furey, N.B., Pirotta, E., Valavanis, V.D., Wuersig, B. and Bearzi, G. (2014) Fish farming and its appeal to common bottlenose dolphins: modelling habitat use in a Mediterranean embayment. *Aquatic Conservation-Marine and Freshwater Ecosystems* 24, 696–711.

- Boyra, A., Sanchez-Jerez, P., Tuya, F., Espino, F. and Haroun, R. (2004) Attraction of wild coastal fishes to an Atlantic subtropical cage fish farms, Gran Canaria, Canary Islands. *Environmental Biology of Fishes* 70, 393–401.
- Brandt, M.J., Höschle, C., Diederichs, A., Betke, K., Matuschek, R., Witte, S. and Nehls, G. (2013) Far-reaching effects of a seal scarer on harbour porpoises, *Phocoena phocoena*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 23, 222–232.
- Brehmer, P., Gerlotto, F., Guillard, J., Sanguinède, F., Guénnegan, Y. and Buestel, D. (2003) New applications of hydroacoustic methods for monitoring shallow water aquatic ecosystems: the case of mussel culture grounds. *Aquatic Living Resources* 16, 333–338.
- Bridgman, G.K., Rave, E.H. and Rafferty, J.M. (2000) Piscivorous bird depredation at northern Minnesota aquaculture facilities. *Prairie Naturalist* 32, 17–28.
- Broyer, J. and Calenge, C. (2010) Influence of fish-farming management on duck breeding in French fish pond systems. *Hydrobiologia* 637, 173–185.
- Broyer, J., Chavas, G. and Chazal, R. (2017) The effects of cessation of fish farming on duck breeding in French fishpond systems. *Hydrobiologia* 788, 47–53.
- Bustnes, J.O., Lie, E., Herzke, D., Dempster, T., Bjørn, P.A., Nygård, T. and Uglem, I. (2010) Salmon farms as a source of organohalogenated contaminants in wild fish. *Environmental Science & Technology* 44, 8736–43.
- Bustnes, J.O., Nygard, T., Dempster, T., Ciesielski, T., Jenssen, B.M., Bjorn, P.A. and Uglem, I. (2011) Do salmon farms increase the concentrations of mercury and other elements in wild fish? *Journal of Environmental Monitoring* 13, 1687–1694.
- Caldow, R., Beadman, H., McGrorty, S., Kaiser, M., Goss-Custard, J., Mould, K. and Wilson, A. (2003) Effects of intertidal mussel cultivation on bird assemblages. *Marine Ecology Progress Series* 259, 173–183.
- Carss, D.N. (1990) Concentrations of wild and escaped fishes immediately adjacent to fish farm cages. *Aquaculture* 90, 29–40.
- Carss, D.N. (1993a) Cormorants *Phalacrocorax carbo* at cage fish farms in Argyll, western Scotland. *Seabird* 15, 38–44.
- Carss, D.N. (1993b) Grey heron, *Ardea cinerea* L., predation at cage fish farms in Argyll, western Scotland. *Aquaculture and Fisheries Management* 24, 29–45.
- Carss, D.N. (1994) Killing of piscivorous birds at Scottish fin fish farms, 1984–87. *Biological Conservation* 68, 181–188.

- Cartier, L.E. and Carpenter, K.E. (2014) The influence of pearl oyster farming on reef fish abundance and diversity in Ahe, French Polynesia. *Marine Pollution Bulletin* 78, 43–50.
- de Carvalho, L.L., de Souza, E.G.A., da Mata Júnior, M.R. and Villaga, R.C. (2017) Assessment of rocky reef fish assemblages close to seaweed farming. *Aquaculture Research* 48, 481–493.
- Cervenci, A., Troost, K., Dijkman, E., de Jong, M., Smit, C.J., Leopold, M.F. and Ens, B.J. (2015) Distribution of wintering common eider *Somateria mollissima* in the Dutch Wadden Sea in relation to available food stocks. *Marine Biology* 162, 153–168.
- Chesney, E.J. and Iglesias, J. (1979) Seasonal distribution, abundance and diversity of demersal fishes in the inner Ria de Arosa, Northwest Spain. *Estuarine and Coastal Marine Science* 8, 227–239.
- Clynick, B.G., McKindsey, C.W. and Archambault, P. (2008) Distribution and productivity of fish and macroinvertebrates in mussel aquaculture sites in the Magdalen islands (Québec, Canada).
- Colorni, A., Diamant, A., Eldar, A., Kvitt, H. and Zlotkin, A. (2002) *Streptococcus iniae* infections in Red Sea cage-cultured and wild fishes. *Diseases of Aquatic Organisms* 49, 165–170.
- Connolly, L.M. and Colwell, M.A. (2005) Comparative use of longline oysterbeds and adjacent tidal flats by waterbirds. *Bird Conservation International* 15, 237–255.
- D'Amours, O., Archambault, P., McKindsey, C.W. and Johnson, L.E. (2008) Local enhancement of epibenthic macrofauna by aquaculture activities. *Marine Ecology Progress Series* 371, 73–84.
- Dealteris, J.T., Kilpatrick, B.D. and Rheault, R.B. (2004) A comparative evaluation of the habitat value of shellfish aquaculture gear, submerged aquatic vegetation and a non-vegetated seabed. *Journal of Shellfish Research* 23, 867–874.
- DeBruyn, A.M.H., Trudel, M., Eyding, N., et al. (2006) Ecosystemic effects of salmon farming increase mercury contamination in wild fish. *Environmental Science & Technology* 40, 3489–3493.
- Demétrio, J.A., Gomes, L.C., Latini, J.D. and Agostinho, A.A. (2012) Influence of net cage farming on the diet of associated wild fish in a Neotropical reservoir. *Aquaculture* 330, 172–178.
- Dempster, T., Fernandez-Jover, D., Sanchez-Jerez, P., Tuya, F., Bayle-Sempere, J., Boyra, A. and Haroun, R.J. (2005) Vertical variability of wild fish assemblages around sea-cage

- fish farms: implications for management. *Marine Ecology Progress Series* 304, 15–29.
- Dempster, T., Sanchez-Jerez, P., Bayle-Sempere, J.T. and Kingsford, M. (2004) Extensive aggregations of wild fish at coastal sea-cage fish farms. *Hydrobiologia* 525, 245–248.
- Dempster, T., Sanchez-Jerez, P., Fernandez-Jover, D., Bayle-Sempere, J.T., Nilsen, R., Bjørn, P.-A. and Uglem, I. (2011) Proxy measures of fitness suggest coastal fish farms can act as population sources and not ecological traps for wild gadoid fish. *PLoS ONE* 6, e15646.
- Dempster, T., Sanchez-Jerez, P., Uglem, I. and Bjørn, P.-A. (2010) Species-specific patterns of aggregation of wild fish around fish farms. *Estuarine, Coastal and Shelf Science* 86, 271–275.
- Dempster, T., Uglem, I., Sanchez-Jerez, P., Fernandez-Jover, D., Bayle-Sempere, J. and Nilsen, R. (2009) Coastal salmon farms attract large and persistent aggregations of wild fish: an ecosystem effect. *Marine Ecology Progress Series* 385, 1–14.
- Diamant, A., Banet, A., Ucko, M., Colorni, A., Knibb, W. and Kvitt, H. (2000) Mycobacteriosis in wild rabbitfish *Siganus rivulatus* associated with cage farming in the Gulf of Eilat, Red Sea. *Diseases of Aquatic Organisms* 39, 211–219.
- Diaz López, B. (2006) Bottlenose dolphin (*Tursiops truncatus*) predation on a marine fin fish farm: some underwater observations. *Aquatic Mammals* 32, 305–310.
- Diaz López, B. (2012) Bottlenose dolphins and aquaculture: interaction and site fidelity on the north-eastern coast of Sardinia (Italy). *Marine Biology* 159, 2161–2172.
- Diaz López, B. (2017) Temporal variability in predator presence around a fin fish farm in the Northwestern Mediterranean Sea. *Marine Ecology* 38, e12378.
- Diaz López, B. (2009) The bottlenose dolphin *Tursiops truncatus* foraging around a fish farm: effects of prey abundance on dolphins' behavior. *Current Zoology* 55, e11221–e11221.
- Diaz López, B. and Bernal-Shirai, J.A. (2007) Bottlenose dolphin (*Tursiops truncatus*) presence and incidental capture in a marine fish farm on the north-eastern coast of Sardinia (Italy). *Journal of the Marine Biological Association of the United Kingdom* 87, 113–117.
- Diaz López, B. and Bernal-Shirai, J.A. (2008) Marine aquaculture and bottlenose dolphins' (*Tursiops truncatus*) social structure. *Behavioral Ecology and Sociobiology* 62, 887–894.

- Dorr, B.S., Burger, L.W., Barras, S.C. and Godwin, K.C. (2012) Economic impact of double-crested cormorant, *Phalacrocorax auritus*, depredation on channel catfish, *Ictalurus punctatus*, aquaculture in Mississippi, USA. *Journal of the World Aquaculture Society* 43, 502–513.
- Draulans, D. and van Vesseem, J. (1985) The effect of disturbance on nocturnal abundance and behaviour of grey herons (*Ardea cinerea*) at a fish-farm in winter. *Journal of applied ecology*, 19–27.
- Dunthorn, A.A. (1971) The predation of cultivated mussels by eiders. *Bird Study* 18, 107–11.
- Eklöf, J.S., de la Torre-Castro, M., Nilsson, C. and Rönnbäck, P. (2006) How do seaweed farms influence local fishery catches in a seagrass-dominated setting in Chwaka Bay, Zanzibar? *Aquatic Living Resources* 19, 137–147.
- Erbland, P.J. and Ozbay, G. (2008) A comparison of the macrofaunal communities inhabiting a *Crassostrea virginica* oyster reef and oyster aquaculture gear in Indian River Bay, Delaware. *Journal of Shellfish Research* 27, 757–768.
- Ervik, A., Thorsen, B., Eriksen, V., Lunestad, B.T. and Samuelsen, O.B. (1994) Impact of administering antibacterial agents on wild fish and blue mussels *Mytilus edulis* in the vicinity of fish farms. *Diseases of Aquatic Organisms* 18, 45–51.
- Fernandez-Jover, D., Faliex, E., Sanchez-Jerez, P., Sasal, P. and Bayle-Sempere, J.T. (2010) Coastal fish farming does not affect the total parasite communities of wild fish in SW Mediterranean. *Aquaculture* 300, 10–16.
- Fernandez-Jover, D., Jimenez, J.A.L., Sanchez-Jerez, P., Bayle-Sempere, J.T., Giménez-Casaldueiro, F., Lopez, F.J.M. and Dempster, T. (2007a) Changes in body condition and fatty acid composition of wild Mediterranean horse mackerel (*Trachurus mediterraneus*, Steindachner, 1868) associated to sea cage fish farms. *Marine Environmental Research* 63, 1–18.
- Fernandez-Jover, D., Martinez-Rubio, L., Sanchez-Jerez, P., et al. (2011) Waste feed from coastal fish farms: a trophic subsidy with compositional side-effects for wild gadoids. *Estuarine, Coastal and Shelf Science* 91, 559–568.
- Fernandez-Jover, D. and Sanchez-Jerez, P. (2015) Comparison of diet and otolith growth of juvenile wild fish communities at fish farms and natural habitats. *ICES Journal of Marine Science* 72, 916–929.
- Fernandez-Jover, D., Sanchez-Jerez, P., Bayle-Sempere, J., Carratala, A. and Leon, V.M. (2007b) Addition of dissolved nitrogen and dissolved organic carbon from wild fish

- faeces and food around Mediterranean fish farms: Implications for waste-dispersal models. *Journal of Experimental Marine Biology and Ecology* 340, 160–168.
- Fernandez-Jover, D., Sanchez-Jerez, P., Bayle-Sempere, J.T., Arechavala-Lopez, P., Martinez-Rubio, L., Lopez Jimenez, J.A. and Martinez Lopez, F.J. (2009) Coastal fish farms are settlement sites for juvenile fish. *Marine environmental research* 68, 89–96.
- Fernandez-Jover, D., Sanchez-Jerez, P., Bayle-Sempere, J.T., Valle, C. and Dempster, T. (2008) Seasonal patterns and diets of wild fish assemblages associated with Mediterranean coastal fish farms. *ICES Journal of Marine Science* 65, 1153–1160.
- Fleury, B.E. and Sherry, T.W. (1995) Long-term population trends of colonial wading birds in the southern United States: The impact of crayfish aquaculture on Louisiana populations. *Auk* 112, 613–632.
- Freitas, D., Gomes, J., Luis, T.S., et al. (2007) Otters and fish farms in the Sado estuary: ecological and socio-economic basis of a conflict. *Hydrobiologia* 587, 51–62.
- Gabrielsen, S.-E. (1999) Effects of fish-farm activity on the limnetic community structure of brown trout, *Salmo trutta*, and Arctic charr, *Salvelinus alpinus*. *Environmental biology of fishes* 55, 321–332.
- Gaitán-Espitia, J.D., Gómez, D., Hobday, A.J., Daley, R., Lamilla, J. and Cárdenas, L. (2017) Spatial overlap of shark nursery areas and the salmon farming industry influences the trophic ecology of *Squalus acanthias* on the southern coast of Chile. *Ecology and evolution* 7, 3773–3783.
- Giannoulaki, M., Machias, A., Somarakis, S. and Karakassis, I. (2005) Wild fish spatial structure in response to presence of fish farms. *Journal of the Marine Biological Association of the United Kingdom* 85, 1271–1277.
- Glahn, J.F., Rasmussen, E.S., Tomsa, T. and Preusser, K.J. (1999a) Distribution and relative impact of avian predators at aquaculture facilities in the northeastern United States. *North American Journal of Aquaculture* 61, 340–348.
- Glahn, J.F., Tomsa, T. and Preusser, K.J. (1999b) Impact of great blue heron predation at trout-rearing facilities in the northeastern United States. *North American Journal of Aquaculture* 61, 349–354.
- Glover, K.A., Sørvik, A.G.E., Karlsbakk, E., Zhang, Z. and Skaala, Ø. (2013) Molecular genetic analysis of stomach contents reveals wild Atlantic cod feeding on piscine reovirus (PRV) infected Atlantic salmon originating from a commercial fish farm. *PLoS ONE* 8, e60924.

- Godet, L., Toupoint, N., Fournier, J., Le Mao, P., Retiere, C. and Olivier, F. (2009) Clam farmers and oystercatchers: effects of the degradation of *Lanice conchilega* beds by shellfish farming on the spatial distribution of shorebirds. *Marine Pollution Bulletin* 58, 589–595.
- Goodbrand, L., Abrahams, M. V and Rose, G.A. (2013) Sea cage aquaculture affects distribution of wild fish at large spatial scales. *Canadian Journal of Fisheries and Aquatic Sciences* 70, 1289–1295.
- Gregory, P.T. and Nelson, K.J. (1991) Predation on fish and intersite variation in the diet of common garter snakes, *Thamnophis sirtalis*, on Vancouver Island. *Canadian Journal of Zoology* 69, 988–994.
- Güçlüsoy, H. and Savas, Y. (2003) Interaction between monk seals *Monachus monachus* (Hermann, 1779) and marine fish farms in the Turkish Aegean and management of the problem. *Aquaculture Research* 34, 777–783.
- Hayward, C.J., Svane, I., Lachimpadi, S.K., Itoh, N., Bott, N.J. and Nowak, B.F. (2011) Sea lice infections of wild fishes near ranched southern bluefin tuna (*Thunnus maccoyii*) in South Australia. *Aquaculture* 320, 178–182.
- Hehre, E.J. and Meeuwig, J.J. (2016) A global analysis of the relationship between farmed seaweed production and herbivorous fish catch. *PLoS ONE* 11, e0148250.
- Hume, F., Pemberton, D., Gales, R., Brothers, N. and Greenwood, M. (2002) Trapping and relocating seals from salmonid fish farms in Tasmania, 1990-2000: was it a success? *Papers and Proceedings of the Royal Society of Tasmania* 136, 1–6.
- Iglesias, J. (1981) Spatial and temporal changes in the demersal fish community of the Ria de Arosa (NW Spain). *Marine Biology* 65, 199–208.
- Hilgerloh, G., Halloran, J.O., Kelly, T.C. and Burnell, G.M. (2001) A preliminary study on the effects of oyster culturing structures on birds in a sheltered Irish estuary. *Hydrobiologia* 465, 175–180.
- Jacobs, S.R. and Terhune, J.M. (2000) Harbor seal (*Phoca vitulina*) numbers along the New Brunswick coast of the Bay of Fundy in autumn in relation to aquaculture. *Northeastern Naturalist* 7, 289–296.
- Jimenez, J.E., Arriagada, A.M., Fonturbel, F.E., Camus, P.A. and Avila-Thieme, M.I. (2013) Effects of exotic fish farms on bird communities in lake and marine ecosystems. *Naturwissenschaften* 100, 779–787.

- Johansson, T., Hakanson, L., Borum, K. and Persson, J. (1998) Direct flows of phosphorus and suspended matter from a fish farm to wild fish in lake southern Bullaren, Sweden. *Aquacultural Engineering* 17, 111–137.
- Johnston, T.A., Keir, M. and Power, M. (2010) Response of native and naturalized fish to salmonid cage culture farms in northern Lake Huron, Canada. *Transactions of the American Fisheries Society* 139, 660–670.
- Kelly, J.P., Evens, J.G. and Stallcup, R.W. (1996) Effects of aquaculture on habitat use by wintering shorebirds in Tomales Bay, California. *California Fish and Game* 82, 160–174.
- Kemper, C.M. and Gibbs, S.E. (2001) Dolphin interactions with tuna feedlots at Port Lincoln, South Australia and recommendations for minimising entanglements. *Journal of Cetacean Research and Management* 3, 283–292.
- Kilambi, R. V., Adams, J.C. and Wickizer, W.A. (1978) Effects of cage culture on growth, abundance, and survival of resident largemouth bass (*Micropterus salmoides*). *Journal of the Fisheries Research Board of Canada* 35, 157–160.
- Kloskowski, J. (2010) Fish farms as amphibian habitats: factors affecting amphibian species richness and community structure at carp ponds in Poland. *Environmental Conservation* 37, 187–194.
- Kloskowski, J. (2012) Fish stocking creates an ecological trap for an avian predator via effects on prey availability. *Oikos* 121, 1567–1576.
- Kloskowski, J. (2005) Otter *Lutra lutra* damage at farmed fisheries in southeastern Poland, II: exploitation of common carp *Cyprinus carpio*. *Wildlife Biology* 11, 257–261.
- Kloskowski, J. (2009) Size-structured effects of common carp on reproduction of pond-breeding amphibians. *Hydrobiologia* 635, 205–213.
- Kloskowski, J., Grendel, A. and Wronka, M. (2000) The use of fish bones of three farm fish species in diet analysis of the Eurasian otter, *Lutra lutra*. *Folia Zoologica* 49, 183–190.
- Kloskowski, J., Kaczanowska, E., Krogulec, J. and Grela, P. (2017) Hematological indicators of habitat quality: erythrocyte parameters reflect greater parental effort of red-necked grebes under ecological trap conditions. *The Condor* 119, 239–250.
- Kloskowski, J., Nieoczym, M., Polak, M. and Pitucha, P. (2010) Habitat selection by breeding waterbirds at ponds with size-structured fish populations. *Naturwissenschaften* 97, 673–682.

- Kortan, D., Adámek, Z. and Poláková, S. (2007) Winter predation by otter, *Lutra lutra* on carp pond systems in South Bohemia (Czech Republic). *Folia Zoologica* 56, 416.
- Krkosek, M., Lewis, M.A., Morton, A., Frazer, L.N. and Volpe, J.P. (2006) Epizootics of wild fish induced by farm fish. *Proceedings of the National Academy of Sciences of the United States of America* 103, 15506–15510.
- Krkosek, M., Lewis, M.A. and Volpe, J.P. (2005) Transmission dynamics of parasitic sea lice from farm to wild salmon. *Proceedings. Biological sciences* 272, 689–96.
- Laffargue, P., Begout, M. and Lagardere, F. (2006) Testing the potential effects of shellfish farming on swimming activity and spatial distribution of sole (*Solea solea*) in a mesocosm. *ICES Journal of Marine Science* 63, 1014–1028.
- Lanszki, J., Pallos, Z.S., Nagy, D. and Yoxon, G. (2007) Diet and fish choice of Eurasian otters (*Lutra lutra* L.) in fish wintering ponds in Hungary. *Aquaculture international* 15, 393–402.
- Lin, H.-J., Shao, K.-T., Hsieh, H.-L., Lo, W.-T. and Dai, X.-X. (2009) The effects of system-scale removal of oyster-culture racks from Tapong Bay, southwestern Taiwan: model exploration and comparison with field observations. *ICES Journal of Marine Science* 66, 797–810.
- Loiseau, N., Kiszka, J.J., Bouveroux, T., Heithaus, M.R., Soria, M. and Chabanet, P. (2016) Using an unbaited stationary video system to investigate the behaviour and interactions of bull sharks *Carcharhinus leucas* under an aquaculture farm. *African Journal of Marine Science* 38, 73–79.
- Ludwig, G.X., Hokka, V., Sulkava, R. and Ylönen, H. (2002) Otter *Lutra lutra* predation on farmed and free-living salmonids in. *Wildlife Biology* 8.
- Machias, A., Karakassis, I., Giannoulaki, M., Papadopoulou, K.N., Smith, C.J. and Somarakis, S. (2005) Response of demersal fish communities to the presence of fish farms. *Marine Ecology Progress Series* 288, 241–250.
- Machias, A., Karakassis, I., Labropoulou, M., Somarakis, S., Papadopoulou, K.N. and Papaconstantinou, C. (2004) Changes in wild fish assemblages after the establishment of a fish farming zone in an oligotrophic marine ecosystem. *Estuarine Coastal and Shelf Science* 60, 771–779.
- MacKenzie, K., Longshaw, M., Begg, G.S. and McVicar, A.H. (1998) Sea lice (Copepoda: Caligidae) on wild sea trout (*Salmo trutta* L.) in Scotland. *ICES Journal of Marine Science* 55, 151–162.

- Manikowska-Ślepowrońska, B., Szydzik, B. and Jakubas, D. (2016) Determinants of the presence of conflict bird and mammal species at pond fisheries in western Poland. *Aquatic Ecology* 50, 87–95.
- Marengi, F.P. and Ozbay, G. (2010) Floating oyster, *Crassostrea virginica* Gmelin 1791, aquaculture as habitat for fishes and macroinvertebrates in Delaware Inland Bays: the comparative value of oyster clusters and loose shell. *Journal of Shellfish Research* 29, 889–904.
- Markowitz, T.M., Harlin, A.D., Wursig, B. and Mcfadden, C.J. (2004) Dusky dolphin foraging habitat: overlap with aquaculture in New Zealand. *Aquatic Conservation-marine and Freshwater Ecosystems* 14, 133–149.
- Marques, C., Rosalino, L.M. and Santos-Reis, M. (2007) Otter predation in a trout fish farm of central-east Portugal: preference for “fast-food”? *River Research and Applications* 23, 1147–1153.
- McAllister, P.E. and Owens, W.J. (1992) Recovery of infectious pancreatic necrosis virus from the faeces of wild piscivorous birds. *Aquaculture* 106, 227–232.
- McConnell, A., Routledge, R. and Connors, B. (2010) Effect of artificial light on marine invertebrate and fish abundance in an area of salmon farming. *Marine Ecology Progress Series* 419, 147–156.
- McPeck, K.C., McDonald, P.S. and VanBlaricom, G.R. (2015) Aquaculture disturbance impacts the diet but not ecological linkages of a ubiquitous predatory fish. *Estuaries and Coasts* 38, 1520–1534.
- Middlemas, S.J., Fryer, R.J., Tulett, D. and Armstrong, J.D. (2013) Relationship between sea lice levels on sea trout and fish farm activity in western Scotland. *Fisheries Management and Ecology* 20, 68–74.
- Mladineo, I., Segvic, T. and Grubisic, L. (2009) Molecular evidence for the lack of transmission of the monogenean *Sparicotyle chrysophrii* (Monogenea, Polyopisthocotylea) and isopod *Ceratothoa oestroides* (Crustacea, Cymothoidae) between wild bogue (*Boops boops*) and cage-reared sea bream (*Sparus aurata*). *Aquaculture* 295, 160–167.
- Morrissey, D.J., Cole, R.G., Davey, N.K., Handley, S.J., Bradley, A., Brown, S.N. and Madarasz, A.L. (2006) Abundance and diversity of fish on mussel farms in New Zealand. *Aquaculture* 252, 277–288.
- Morrison, S.S. and Vogel, P. (2009) Aquaculture ponds, a Jamaican study: The impact of birds on fish production. *African Journal of Agricultural Research* 4, 1447–1454.

- Morton, A., Routledge, R. and Krkosek, M. (2008) Sea louse infestation in wild juvenile salmon and Pacific herring associated with fish farms off the east-central coast of Vancouver Island, British Columbia. *North American Journal of Fisheries Management* 28, 523–532.
- Morton, A., Routledge, R., McConnell, A. and Krkosek, M. (2011) Sea lice dispersion and salmon survival in relation to salmon farm activity in the Broughton Archipelago. *ICES Journal of Marine Science* 68, 144–156.
- Morton, A., Routledge, R., Peet, C. and Ladwig, A. (2004) Sea lice (*Lepeophtheirus salmonis*) infection rates on juvenile pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon in the nearshore marine environment of British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 61, 147–157.
- Morton, A., Routledge, R.D. and Williams, R. (2005) Temporal patterns of sea louse infestation on wild Pacific salmon in relation to the fallowing of Atlantic salmon farms. *North American Journal of Fisheries Management* 25, 811–821.
- Mott, D.E. and Flynt, R.D. (1995) Evaluation of an electric fence system for excluding wading birds at catfish ponds. *The Progressive Fish-Culturist* 57, 88–90.
- Nelson, K.J. and Gregory, P.T. (2000) Activity patterns of garter snakes, *Thamnophis sirtalis*, in relation to weather conditions at a fish hatchery on Vancouver Island, British Columbia. *Journal of Herpetology* 34, 32.
- Neofitou, N. (2016) Waste feed from fish farms of the eastern Mediterranean and attraction of wild fish. *Universal Journal of Geoscience* 4, 112–115.
- Oakes, C.T. and Pondella, D.J. (2009) The value of a net-cage as a fish aggregating device in southern California. *Journal of the World Aquaculture Society* 40, 1–21.
- Otterå, H. and Skilbrei, O.T. (2014) Possible influence of salmon farming on long-term resident behaviour of wild saithe (*Pollachius virens* L.). *ICES Journal of Marine Science* 71, 2484–2493.
- Özgül, A. and Angel, D. (2013) Wild fish aggregations around fish farms in the Gulf of Aqaba, Red Sea: implications for fisheries management and conservation. *Aquaculture Environment Interactions* 4, 135–145.
- Parkhurst, J.A., Brooks, R.P. and Arnold, D.E. (1992) Assessment of predation at trout hatcheries in central Pennsylvania. *Wildlife Society Bulletin (1973-2006)* 20, 411–419.
- Pemberton, D., Brothers, N. and Copson, G. (1991) Predators on marine fish farms in Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 125, 33–35.

- Pemberton, D. and Shaughnessy, P.D. (1993) Interaction between seals and marine fish-farms in Tasmania, and management of the problem. *Aquatic Conservation-marine and Freshwater Ecosystems* 3, 149–158.
- Pitt, W.C. and Conover, M.R. (1996) Predation at intermountain west fish hatcheries. *The Journal of Wildlife Management* 60, 616–624.
- Plummer, M. V. and Goy, J.M. (1984) Ontogenetic dietary shift of water snakes (*Nerodia rhombifera*) in a fish hatchery. *Copeia* 1984, 550.
- Powers, M., Peterson, C., Summerson, H. and Powers, S. (2007) Macroalgal growth on bivalve aquaculture netting enhances nursery habitat for mobile invertebrates and juvenile fishes. *Marine Ecology Progress Series* 339, 109–122.
- Quick, N.J., Middlemas, S.J. and Armstrong, J.D. (2004) A survey of antipredator controls at marine salmon farms in Scotland. *Aquaculture* 230, 169–180.
- Radomski, A.A. and Zimba, P. V (2010) Does pond water reflectance influence double-crested cormorant selection of aquaculture ponds? *Journal of the World Aquaculture Society* 41, 430–437.
- Ramos, I.P., Brandão, H., Zanatta, A.S., Zica, E. de O.P., da Silva, R.J., de Rezende-Ayroza, D.M.M. and Carvalho, E.D. (2013) Interference of cage fish farm on diet, condition factor and numeric abundance on wild fish in a Neotropical reservoir. *Aquaculture* 414, 56–62.
- Ribeiro, S., Viddi, F.A., Cordeiro, J.K. and Freitas, T.R.O. (2007) Fine-scale habitat selection of Chilean dolphins (*Cephalorhynchus eutropia*): interactions with aquaculture activities in southern Chiloe Island, Chile. *Journal of the Marine Biological Association of the United Kingdom* 87, 119–128.
- Riera, R., Tuset, V.M., Rodríguez, M., Monterroso, Ó. and Lombarte, A. (2017) Analyzing functional diversity to determine the effects of fish cages in insular coastal wild fish assemblages. *Aquaculture* 479, 384–395.
- Robinson, S., Gales, R., Terauds, A. and Greenwood, M. (2008a) Movements of fur seals following relocation from fish farms. *Aquatic Conservation-marine and Freshwater Ecosystems* 18, 1189–1199.
- Robinson, S., Terauds, A., Gales, R. and Greenwood, M. (2008b) Mitigating fur seal interactions: relocation from Tasmanian aquaculture farms. *Aquatic Conservation-marine and Freshwater Ecosystems* 18, 1180–1188.
- Ross, B., Lien, J. and Furness, R.W. (2001) Use of underwater playback to reduce the impact of eiders on mussel farms. *ICES Journal of Marine Science* 58, 517–524.

- Roycroft, D., Kelly, T.C. and Lewis, L.J. (2004) Birds, seals and the suspension culture of mussels in Bantry Bay, a non-seaduck area in Southwest Ireland. *Estuarine, Coastal and Shelf Science* 61, 703–712.
- Roycroft, D., Kelly, T.C. and Lewis, L.J. (2007) Behavioural interactions of seabirds with suspended mussel longlines. *Aquaculture International* 15, 25–36.
- Sales-Luis, T., Freitas, D. and Santos-Reis, M. (2009) Key landscape factors for Eurasian otter *Lutra lutra* visiting rates and fish loss in estuarine fish farms. *European Journal of Wildlife Research* 55, 345–355.
- Samuelsen, O.B., Lunestad, B.T., Husevag, B., Holleland, T. and Ervik, A. (1992) Residues of oxolinic acid in wild fauna following medication in fish farms. *Diseases of Aquatic Organisms* 12, 111–119.
- Sandilyan, S. (2017) A preliminary assessment on the role of abandoned shrimp farms on supporting waterbirds in Pichavaram mangrove, Tamilnadu, Southern India. *Journal of Coastal Conservation* 21, 255–263.
- Sanz-Lázaro, C., Belando, M.D., Navarrete-Mier, F. and Marín, A. (2011) Effects of wild fish and motile epibenthic invertebrates on the benthos below an open water fish farm. *Estuarine, Coastal and Shelf Science* 91, 216–223.
- Schramm JR, H.L., French, B. and Ednoff, M. (1984) Depredation of channel catfish by Florida double-crested cormorants. *The Progressive Fish-Culturist* 46, 41–43.
- Segvic-Bubic, T., Grubisic, L., Karaman, N., Ticina, V., Jelavic, K.M. and Katavic, I. (2011) Damages on mussel farms potentially caused by fish predation - self service on the ropes? *Aquaculture* 319, 497–504.
- Segvić Bubić, T., Grubišić, L., Tičina, V. and Katavić, I. (2011) Temporal and spatial variability of pelagic wild fish assemblages around Atlantic bluefin tuna *Thunnus thynnus* farms in the eastern Adriatic Sea. *Journal of Fish Biology* 78, 78–97.
- Sepúlveda, F., Marin, S.L. and Carvajal, J. (2004) Metazoan parasites in wild fish and farmed salmon from aquaculture sites in southern Chile. *Aquaculture* 235, 89–100.
- Sepúlveda, M., Newsome, S.D., Pavez, G., Oliva, D., Costa, D.P. and Hueckstaedt, L.A. (2015) Using satellite tracking and isotopic information to characterize the impact of South American sea lions on salmonid aquaculture in southern Chile. *PLoS ONE* 10, e0134926–e0134926.
- Sepúlveda, M. and Oliva, D. (2005) Interactions between South American sea lions *Otaria flavescens* (Shaw) and salmon farms in southern Chile. *Aquaculture Research* 36, 1062–1068.

- Sepúlveda, M., Pavez, G., Santos-Carvalho, M., Balbontín, C., Pequeño, G. and Newsome, S.D. (2017) Spatial, temporal, age, and sex related variation in the diet of South American sea lions in southern Chile. *Marine Mammal Science* 33, 480–495.
- Skilbrei, O.T. and Otterå, H. (2016) Vertical distribution of saithe (*Pollachius virens*) aggregating around fish farms. *ICES Journal of Marine Science: Journal du Conseil* 73, 1186–1195.
- Skog, T.-E., Hylland, K., Torstensen, B.E. and Berntssen, M.H.G. (2003) Salmon farming affects the fatty acid composition and taste of wild saithe *Pollachius virens* L. *Aquaculture Research* 34, 999–1007.
- Snow, M., Black, J., Matejusova, I., McIntosh, R., Baretto, E., Wallace, I.S. and Bruno, D.W. (2010) Detection of salmonid alphavirus RNA in wild marine fish: implications for the origins of salmon pancreas disease in aquaculture. *Diseases of Aquatic Organisms* 91, 177–188.
- Stickley, A.R., Glahn, J.F., King, J.O. and King, D.T. (1995) Impact of great blue heron depredations on channel catfish farms. *Journal of the World Aquaculture Society* 26, 194–199.
- Stickley, A.R., Warrick, G.L. and Glahn, J.F. (1992) Impact of double-crested cormorant depredations on channel catfish farms. *Journal of the World Aquaculture Society* 23, 192–198.
- Strictar-Pereira, L., Agostinho, A.A. and Gomes, L.C. (2010) Cage culture with tilapia induces alteration in the diet of natural fish populations: the case of *Auchenipterus osteomystax*. *Brazilian Journal of Biology* 70, 1021–1030.
- Sudirman, H.H., Jompa, J., Zulfikar, Iswahyudin and McKinnon, A.D. (2009) Wild fish associated with tropical sea cage aquaculture in South Sulawesi, Indonesia. *Aquaculture* 286, 233–239.
- Sun, Y.H., Wu, H.J. and Wang, Y. (2004) Tawny fish-owl predation at fish farms in Taiwan. *Journal of Raptor Research* 38, 326–333.
- Tallman, J.C. and Forrester, G.E. (2007) Oyster grow-out cages function as artificial reefs for temperate fishes. *Transactions of the American Fisheries Society* 136, 790–799.
- Tsuyuki, A. and Umino, T. (2017) Spatial movement of black sea bream *Acanthopagrus schlegelii* around the oyster farming area in Hiroshima Bay, Japan. *Fisheries Science* 83, 235–244.

- Tuckett, Q.M., Ritch, J.L., Lawson, K.M. and Hill, J.E. (2017) Landscape-scale survey of non-native fishes near ornamental aquaculture facilities in Florida, USA. *Biological Invasions* 19, 223–237.
- Tully, O., Gargan, P., Poole, W.R. and Whelan, K.F. (1999) Spatial and temporal variation in the infestation of sea trout (*Salmo trutta* L.) by the caligid copepod *Lepeophtheirus salmonis* (Krøyer) in relation to sources of infection in Ireland. *Parasitology* 119, 41–51.
- Tuya, F., Sanchez-Jerez, P., Dempster, T., Boyra, A. and Haroun, R.J. (2006) Changes in demersal wild fish aggregations beneath a sea-cage fish farm after the cessation of farming. *Journal of Fish Biology* 69, 682–697.
- Uglen, I., Dempster, T., Bjørn, P.-A., Sanchez-Jerez, P. and Økland, F. (2009) High connectivity of salmon farms revealed by aggregation, residence and repeated movements of wild fish among farms. *Marine Ecology Progress Series* 384, 251–260.
- Ulenaers, P. and Dhondt, A.A. (1994) Great crested grebe *Podiceps cristatus* chick mortality in relation to parental fishing. *Bird Study* 41, 211–220.
- Ulenaers, P. and van Vesse, J. (1994) Impact of great crested grebes (*Podiceps cristatus* L.) on fish ponds. *Hydrobiologia* 279, 353–366.
- Valle, C., Bayle-Sempere, J.T., Dempster, T., Sanchez-Jerez, P. and Gimenez-Casalduero, F. (2007) Temporal variability of wild fish assemblages associated with a sea-cage fish farm in the south-western Mediterranean Sea. *Estuarine Coastal and Shelf Science* 72, 299–307.
- Valtonen, E.T. and Koskivaara, M. (1994) Relationships between the parasites of some wild and cultured fishes in two lakes and a fish farm in central Finland. *International Journal for Parasitology* 24, 109–118.
- Vita, R., Marin, A., Madrid, J.A., Jimenez-Brinquis, B., Cesar, A. and Marin-Guirao, L. (2004) Effects of wild fishes on waste exportation from a Mediterranean fish farm. *Marine Ecology Progress Series* 277, 253–261.
- Wallace, I.S., Donald, K., Munro, L.A., et al. (2015) A survey of wild marine fish identifies a potential origin of an outbreak of viral haemorrhagic septicaemia in wrasse, Labridae, used as cleaner fish on marine Atlantic salmon, *Salmo salar* L., farms. *Journal of Fish Diseases* 38, 515–521.
- Wallace, I.S., Gregory, A., Murray, A.G., Munro, E.S. and Raynard, R.S. (2008) Distribution of infectious pancreatic necrosis virus (IPNV) in wild marine fish from Scottish

- waters with respect to clinically infected aquaculture sites producing Atlantic salmon, *Salmo salar* L. *Journal of Fish Diseases* 31, 177–186.
- Watson-Capps, J.J. and Mann, J. (2005) The effects of aquaculture on bottlenose dolphin (*Tursiops* sp.) ranging in Shark Bay, Western Australia. *Biological Conservation* 124, 519–526.
- Wisniowska, L. (2007) Otter (*Lutra lutra* L.) damage in commercial carp ponds of southern Poland. *Hystrix, the Italian Journal of Mammalogy* 17.
- Yasue, M. and Dearden, P. (2009) The importance of supratidal habitats for wintering shorebirds and the potential impacts of shrimp aquaculture. *Environmental Management* 43, 1108–1121.
- Zlotkin, A., Hershko, H. and Eldar, A. (1998) Possible transmission of *Streptococcus iniae* from wild fish to cultured marine fish. *Applied and Environmental Microbiology* 64, 4065–4067.
- Žydelis, R., Esler, D., Kirk, M. and Sean Boyd, W. (2009) Effects of off-bottom shellfish aquaculture on winter habitat use by molluscivorous sea ducks. *Aquatic Conservation: Marine and Freshwater Ecosystems* 19, 34–42.

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Barrett, LT;Swearer, SE;Dempster, T

Title:

Impacts of marine and freshwater aquaculture on wildlife: a global meta-analysis

Date:

2019-11-01

Citation:

Barrett, L. T., Swearer, S. E. & Dempster, T. (2019). Impacts of marine and freshwater aquaculture on wildlife: a global meta-analysis. *REVIEWS IN AQUACULTURE*, 11 (4), pp.1022-1044. <https://doi.org/10.1111/raq.12277>.

Persistent Link:

<http://hdl.handle.net/11343/284441>