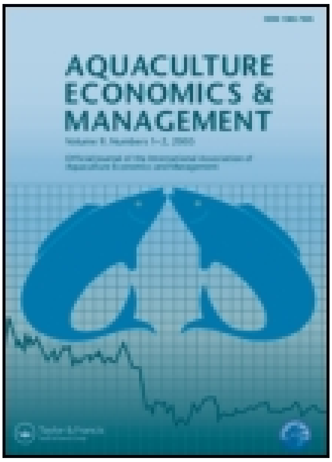
This article was downloaded by: [Universitetbiblioteket I Trondheim NTNU]
On: 28 July 2014, At: 01:03
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Aquaculture Economics & Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uaqm20

FISHY FISH? THE ECONOMIC IMPACTS OF ESCAPED FARMED FISH

Yajie Liu [a], Jon Olaf Olaussen [b] & Anders Skonhoft [c]

[a] SINTEF Fisheries and Aquaculture (Fiskeri og havbruk), Trondheim, Norway

[b] Trondheim Business School, Sør-Trøndelag University College (HiST), Trondheim, Norway

[c] DELATE: Centre for Economic Research, Department of Economics, Norwegian University of Science and Technology (NTNU), Dragvoll University Campus, Trondheim, Norway

Published online: 16 Jul 2014.

To cite this article: Yajie Liu, Jon Olaf Olaussen & Anders Skonhoft (2014) FISHY FISH? THE ECONOMIC IMPACTS OF ESCAPED FARMED FISH, Aquaculture Economics & Management, 18:3, 273-302, DOI: 10.1080/13657305.2014.926466

To link to this article: http://dx.doi.org/10.1080/13657305.2014.926466

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Aquaculture Economics & Management, 18:273–302, 2014
Copyright © Taylor & Francis Group, LLC
ISSN: 1365-7305 print/1551-8663 online
DOI: 10.1080/13657305.2014.926466

FISHY FISH? THE ECONOMIC IMPACTS OF ESCAPED FARMED FISH

Yajie Liu[1], Jon Olaf Olaussen[2], and Anders Skonhoft[3]
[1]*SINTEF Fisheries and Aquaculture (Fiskeri og havbruk), Trondheim, Norway*
[2]*Trondheim Business School, Sør-Trøndelag University College (HiST), Trondheim, Norway*
[3]*DELATE: Centre for Economic Research, Department of Economics, Norwegian University of Science and Technology (NTNU), Dragvoll University Campus, Trondheim, Norway*

☐ *The escape of cultured fish from a marine aquaculture facility is a type of biological invasion that may lead to a variety of potential ecological and economic effects on native fish. This article develops a general invasive species impact model to capture explicitly both the ecological and economic effects of invasive species, especially escaped farmed fish, on native populations and harvests. First, the possible effects of escaped farmed fish on the growth and stock size of a native fish are examined. Next, a bioeconomic model to analyze changes in yield, benefit distribution, and overall profitability is constructed. Different harvesting scenarios, such as commercial, recreational, and joint commercial and recreational fishing are explored. The model is illustrated by a case study of the interaction between native and farmed Atlantic salmon in Norway. The results suggest that both the harvest and profitability of a native fish stock may decline after an invasion, but the total profits from the harvest of both native and farmed stocks may increase or decrease, depending on the strength of the ecological and economic parameters.*

Keywords biological invasion, ecological and economic effects, escaped farmed fish, invasive fish

INTRODUCTION

During the last few decades, concerns have been increasing about the effects of invasive species, especially invasive fish. Invasive species can be introduced intentionally into a new environment for recreational or commercial purposes (Williams et al., 1995). In other cases, human activities have allowed intruders to become established indirectly. For example, global warming causes organisms to migrate to higher latitudes (Carlton, 2000), and transportation and shipping carries organisms across the oceans (Enserink, 1999). Small-scale events such as wastewater discharges and

Address correspondence to Yajie Liu, SINTEF Fisheries and Aquaculture (Fiskeri og havbruk), Postboks 4762, Sluppen, 7465 Trondheim, Norway. E-mail: yajie.liu@sintef.no

farming activities may release organisms into the surrounding environment. Regardless of its origins, an invasive species (including fish) potentially generates risks to and effects on native species, local communities, and ecosystems (Mooney & Hobbs, 2000).

The potential economic effects of invasive species consist of damages to economic enterprises, food safety and human health, markets, particularly seafood markets, and international trade (Lovell, Stone, & Fernandez, 2006; Olsen, 2006). These economic impacts can be severe. In addition to economic impacts, invasive species also generate ecological impacts, including losses to biodiversity and changes in the structures and functions of individual populations and ecosystems (Mooney & Hobbs, 2000). Holmes (1998) argued that invasive species are the second-most important cause of biodiversity losses worldwide, just after habitat degradation.

In this article, we analyze another potential concern associated with invasive fish, namely the ecological and economic impacts on native fish of invasive fish from aquaculture facilities. Farmed species are reared in confined facilities in locations that provide suitable conditions for growth and are accessible to markets. Due to natural disasters, accidents, or human error, farmed animals can escape from their facilities into the surrounding environment, potentially creating ecological and economic impacts, especially when there are interactions with native fish.

The escaped fish interact with native fish in a variety of ways. Ecologically, they may interact through competition, predation, hybridization, colonization, or the spread of disease or parasites. Ecological interactions may lead to both positive and negative effects on native fish. If escaped cultured fish are able to survive in the natural environment, they become part of the ecosystem, and they interact directly (and indirectly) with the native fish. For example, escaped farmed salmon compete with native salmon, and escaped farmed cod and halibut migrate to the open ocean to interact with native inhabitants, including their congeners. Competition over natural habitat, food sources, and mates may result in changes in the structure and productivity of a native stock (Naylor et al., 2005).

In the case of escaped farmed salmon, it has been reported that successful interbreeding between escaped farmed and native salmon reduces fitness and productivity (McGinnity et al., 2003), dilutes genetic gene pools (McGinnity et al., 2004; Roberge et al., 2008), and threatens the survival of native salmon offspring (Hindar et al., 2006). Also, escaped farmed salmon may spread disease and parasites, thereby increasing the mortality of native salmon (Bjørn & Finstad, 2002; Gargan, Tully, & Poole, 2002; Krkošek et al., 2006).

If the number of escaped farmed fish is small, the effects may be negligible; the effects increase in severity as the number of escaped farmed fish grows. Some vulnerable native populations potentially could go extinct with repeated invasions. Escaped farmed fish can also create economic impacts in seafood markets. For example, depending on the ecological impact, invasive farmed fish could change (increase or decrease) the overall stock (native and escaped farmed) available for harvest.

In this article, we develop a general bioeconomic model to capture both the ecological and economic effects of invasive farmed fish on native stocks and harvests. The framework discussed here is transferable to other situations where escaped fish mix with their native counterparts, or where an ecosystem, for any reason, faces a yearly influx of invasive fish. The increasing aquaculture production worldwide of both salmon and other species such as cod and halibut highlights the importance of this issue.

The article is organized as follows. A review of the literature on the economics of invasive species with an emphasis on aquatic species invasions is presented. We derive the mechanisms of ecological and economic impacts of invasive farmed fish on native fish. We first introduce an ecological model of an invasive farmed fish. Next, the flow of service costs and benefits are taken into account. We analyze the unified planning solution in equilibrium and apply the framework to Atlantic salmon in Norway to illustrate the ecological and economic effects of escaped farmed salmon on native salmon stocks and fisheries under different scenarios, which concludes the article.

LITERATURE REVIEW

The economic analysis of an invasion includes estimating the actual or potential damage costs resulting from an invasion and the costs associated with management measures such as prevention, control, and mitigation (Hoagland & Jin, 2006). The economics of pest management and disease control have been extensively studied in agriculture, forestry, and fisheries, but less attention has been directed to measuring the costs associated with invasions (Perrings, Williamson, & Dalmazzone, 2000). This limitation is due to a lack of data as well as uncertainties and measurement problems. However, there is an extensive literature on multiple species interactions, such as predator-prey and biological competition. For instance, Hannesson (1983) has explored the optimal harvesting of a two-species predator-prey system, Flaaten (1991) has investigated the sustainable harvesting of two competing species, and Strobele and Wacker (1991) have explored the optimal harvesting of two species under various types of interactions. A recent detailed review of integrated ecological-economic models can be found in Tschirhart (2009).

A general conceptual bioeconomic model of the economic impacts of an invasion has been developed by Knowler and Barbier (2000) and

Barbier (2001). These authors specify two principles that should be followed. First, the exact interaction between the invader and the native species should be examined, and, second, the correct measure of the economic impacts is to compare the *ex post* and *ex ante* economic values (i.e., profits) of invasion scenarios. The first principle is the essential step. Their conceptual model includes both diffusion and interspecies competition. The authors consider a situation in which the invader is a pest without commercial value and the native fish is commercially harvested.

Knowler and Barbier (2000) illustrate a special case by focusing only on interspecies competition. They model the predator-prey relationship between a native anchovy species and an invading comb-jellyfish in the Black Sea. The anchovy is the prey for the comb-jelly fish, whose invasion leads to a decline in the productivity of anchovy. The study concludes that the introduction of a comb-jellyfish is destructive to the local fishing communities dependent on the anchovy fishery for sustaining their livelihoods.

Knowler, Barbier and Strand (2002) and Knowler and Barbier (2005) apply the predator-prey model to examine the interactions among nutrient enrichment, invasive comb-jelly fish, and native anchovy in the Black Sea under different management strategies. The anchovy benefits from the nutrient abatement, and suffers from competition and predation by comb-jellyfish. They show that the outbreak of comb-jellyfish resulting from nutrient enrichment can dilute the benefits raised by pollution abatement.

Similarly, Settle and Shogren (2002) examine the introduction of exotic lake trout into Yellowstone Lake based on predator-prey relationships among lake trout, cutthroat trout, bears, birds, and human beings. The authors find that if the invasive lake trout is uncontrolled, the native cutthroat trout population would dramatically decline, even go extinct, which further affects the grizzly bear population. The bioeconomic models in these studies are founded on predator-prey relationships between invasive and native fish.

Viewed as a form of biological pollution, an invasion generates externalities on economic activities such as commercial and recreational fishing. For example, McConnell and Strand (1989) analyze the social returns to commercial fisheries when water quality influences the demand and supply of commercial fish products under both open access and efficient allocation.

They show theoretically that water quality affects fish growth through reproduction and carrying capacity and affects total fishing costs through changes in fish stocks. Following this framework, Kataria (2007) applies a cost-benefit analysis to examine the introduction of signal crayfish to a fresh watercourse where native noble crayfish resides. The analysis suggests that the introduction of signal crayfish can generate positive net benefits if the two species have different population growth parameters. With similar growth parameters, on the other hand, the author shows that the introduction of signal crayfish would wipe out native noble crayfish because the two species cannot coexist.

In the case of fisheries and aquaculture, however, the literature dealing with the economic impacts of farmed fish on native fish is quite limited. Earlier work by Anderson (1985a, 1985b) addressed the interaction between native capture and ranched salmon in terms of common property problems and competitive markets. Recent work by Olaussen and Skonhoft (2008a) studies the economic impacts of escaped farmed Atlantic salmon on a recreational salmon fishery.

Expanding the models by Knowler and Barbier (2000) and McConnell and Strand (1989), they incorporate both ecological and economic effects and specify four general mechanisms that may affect economically valuable species (i.e., salmon) when exposed to biological invasions, namely, *ecological level, ecological growth, economic quantity,* and *economic quality.* Ecologically, escaped farmed salmon impose negative impacts on the growth but lead to positive impacts on the stock of native salmon. Economically, escaped farmed salmon lead to positive impacts on the supply (quantity) of and negative impacts on the demand (quality) for native salmon.

Other studies have explored the economic impacts of aquaculture on native fish species in general. For example, Hoagland, Jin, and Kite-Powell (2003) analyze the effects of aquaculture on native fish species through fish habitat and supply in the product market. They assume the carrying capacity of a fish stock is a downward sloping linear function of the area devoted to aquaculture, and the farmed product competes in the same market as native fish products. The results suggest that the commercial fish stock declines because more space is devoted to aquaculture. Under an open-access fishery, it is economically efficient for aquaculture to displace the fishery completely. An ocean area could be allocated exclusively for either aquaculture or fisheries at an economic optimum when aquaculture exerts a significant negative impact on the fishery.

The ecological-economic model we develop here differs from previous studies in several ways. First, we explicitly model the effects of an invasive fish species on the growth and stock size of a native fish species using a logistic growth model. We assume that both the growth and stock effects on the native fish are negative, and we treat native and farmed fish species as separate stocks with separate growth functions. This approach is in contrast to that of Olaussen and Skonhoft (2008a), who regard farmed salmon as a single exogenous flow into the system. Given our simplified biological model, we do not capture explicitly genetic interactions between native and escaped fish. Second, in contrast to Knowler, Barbier, and Strand (2002) and Knowler and Barbier (2005), we consider the escaped farmed fish as a potentially commercially valuable species.

Additionally, farmed fish coexist with native fish, unlike the crayfish case in which the native fish are displaced (Kataria, 2007). A nonselective harvesting strategy is applied to both escaped and native fish. Third, instead of using cultured area or aquaculture production as dependent variable to alter the carrying capacity (Hoagland et al., 2003), we hold the carrying capacity unchanged, and we use the biomass of escaped farmed fish as a *deterministic* variable to translate the ecological risks and effects into growth and stock variables for a native stock. Fourth, we assume that the growth of the invasive fish depends upon both own and native fish biomass.

BIOLOGICAL MODEL

In absence of an invasive fish, the natural growth of a native fish population x, measured in biomass, or number of fish, at time t (the time subscript is omitted) is given by $F(X)$. The natural growth function may typically be a one-peaked value function and is specified as the standard logistic one:

$$F(X) = rX\left(1 - \frac{X}{K_X}\right) \tag{1}$$

where r is the intrinsic growth rate and K_X. is the carrying capacity of a specific habitat, or population's natural equilibrium size. This growth model suggests that the population growth depends on the population size, or density, given a specific habitat, and basically combines two ecological processes: reproduction and competition. The intrinsic growth rate r represents reproduction, or reproductive abilities, while the population size per carrying capacity X/K_X represents competition since carrying capacity can be interpreted as the maximum number of fish the habitat can support.

As previously indicated, once established in the natural environment, escaped farmed fish becomes part of the ecosystem and interacts with native fish. Hence, incorporating the escaped farmed fish, the growth function changes to $F(X, Y)$, where Y is the stock size of the escaped farmed fish, or an invasive fish stock in general, also measured in the number of fish (or in biomass). Typically, a larger escaped farmed fish stock means lower natural growth and productivity in the native population, in other words, $\frac{\partial F(X,Y)}{\partial Y} = F_Y < 0$.

This negative growth effect may work through different channels. Based on the logistic growth function, we consider two effects that are represented through the intrinsic growth rate and through the carrying capacity. First, we consider the *stock effect* where the classical Lotka–Volterra interspecific competition model is modified and employed. This model takes into account the effects of intraspecific competition between the two types of fish, i.e., native and escaped farmed fish. Here the competition of an escaped farmed fish with a native fish is added into the logistic growth model of native fish by the term βY., with β as the competition coefficient. The same principle is applied to the competition effects of native fish on escaped farmed fish, see Equation (4).

In line with the Lotka–Volterra interspecific competition model, our population growth models generally allow for different carrying capacity for the different types of fish. The reason for using different carrying capacity for the two fish populations is that we consider the situation where the escaped farmed fish is quite similar to the native, but where it may, or may not, make use of the same habitat. Hence, in the special case where the escaped farmed populations are very similar (e.g., when domesticated fish escape and compete with its native congeners) and use the exact same habitat as the native population, the carrying capacities would be identical. Modifying Equation (1), we then obtain:

$$F(X, Y) = \tilde{r}X\left(1 - \frac{X + \beta Y}{K_X}\right) \tag{2}$$

When $0 < \beta \leq 1$, the effect of the escaped farmed fish on the native stock is less than the effect of the native stock on itself. On the other hand, when $\beta > 1$, the effect of the escaped farmed fish on the native stock is greater than the effect of the native stock on itself.[1] The maximum native natural growth is now given by $\tilde{r}(K_X - \beta Y)^2/4$ when the stock size at the maximum growth (*MSY*) is reduced to $X = X^{msy} = (K_X - \beta Y)/2$. In other words, both the maximum growth and the stock size that yields this peak growth are reduced (see Figure 1, dark dotted curve).

As previously mentioned, escaped organisms may interbreed with native individuals, which may potentially deteriorate the genetic makeup and reduce the fitness of the native stock. We couple this reproductive effect into the intrinsic growth rate, referring to it as a *growth effect*. The intrinsic growth rate is redefined as $\tilde{r} = \tilde{r}(X, Y) = r\left(1 - e^{\frac{\gamma X}{Y}}\right)$, where $\gamma > 0$ is a scaling parameter representing the magnitude of effects of escaped fish on native fish. This formula indicates that the intrinsic growth rate declines with the increasing biomass of the escaped fish in a non-linear fashion with $\tilde{r} = \tilde{r}(X, 0) = r$ and $\tilde{r} = \tilde{r}(X, \infty) = 0$ for all $X > 0$. In addition, we have $\tilde{r} > 0$ for all $0 < Y < \infty$. It should be noted that especially in cases where the escaped and native fish interbreed, the interbreeding may induce accumulated genetic effects from generation to generation.

Taking such effects into account would require a more complicated model that explicitly takes the gene flow into account, which is beyond the scope of this article. However, one of the reasons for including a *growth*

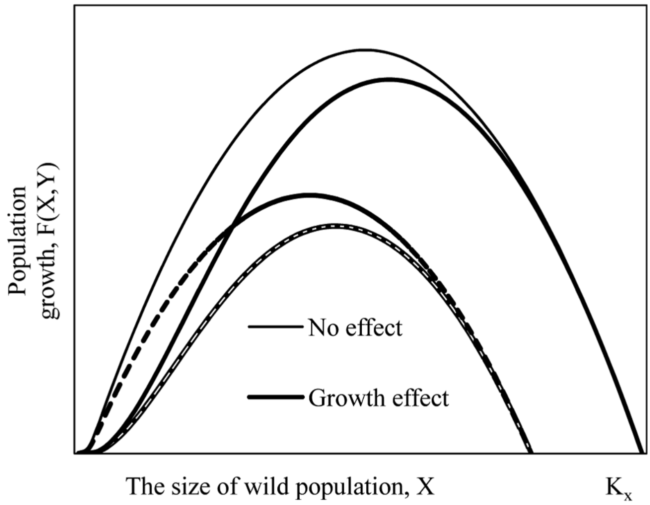


FIGURE 1 The growth and stock effects of escapees on the native stock growth. Light solid curve represents the growth without any effects; heavy solid curve represents growth effect; dotted curve represents stock effect and dashed curve represents both stock and growth effects.

effect is that the intrinsic growth rate may be reduced due to the influence of genes less suited for the native habitat. In fact, in the post invasion case, the intrinsic growth rate r is reduced due to the "hybrid wild" salmon affected by escaped fish. The degree of hybridization is determined by the parameter value of γ and the number of escaped farmed fish. However, we assume that the wild genotype fish still dominates this "hybrid" stock, thus, for simplicity we will keep referring to this salmon stock as the wild or native stock, even if there will always be degrees of wild and farmed fish in the post-invasion case (except when $\gamma = 0$).

Now, incorporating both the *stock* and *growth* effects into the logistic growth function (1), we obtain[2]

$$F(X,Y) = r\left(1 - e^{\frac{\gamma X}{Y}}\right) X \left(1 - \frac{X + \beta Y}{K_X}\right) \tag{3}$$

Figure 1 demonstrates both the stock and growth effect on the native fish growth. Notice that while the stock effect shifts the peak value to the left (dotted curve), the growth effect shifts it to the right (dark solid curve). In both cases the maximum natural growth is reduced. The magnitude of effects depends on the value of β, γ and Y. The larger β, γ and Y, the stronger the effects.

So far, we have assumed that invasive fish in general, and escaped fish in particular, have negative ecological effects on native fish (see Note 1). However, in some instances the effects may be positive. Japanese Seaweed, *Sargassum muticum,* for example, an invasive seaweed species, can enhance local diversity and the ecosystem function. This is because this species can provide an additional habitat for bottom species and food for some invertebrates and native fish species (Sánchez, Fernández, & Arrontes, 2005). Another example is invasive zebra mussels which have mixed effects on the environment and native fauna. On the one hand, they can improve the water quality and the richness of macro-invertebrates in lakes; on the other hand, they foul the underwater structures and devices (Ricciardi, 2003).

Nevertheless, most marine species selected for aquaculture are generally high-value such as salmon, sea bass, halibut, and cod. These species are top predators situated at, or near, the top of the food chain. Therefore, they rarely become the prey of other commercially exploited species. On the other hand, escaped fish are also harvested, and since the escaped fish increase the stock available for harvest *ceteris paribus,* they may also have a positive economic effect. Salmon enhancement in Norway, Canada, Japan and the United States are good examples of this *ceteris paribus* positive economic effect (e.g., Anderson, 1985a).

Additionally, the growth of escaped farmed fish as a part of the ecosystem has to be considered. Like native fish, escaped fish growth is assumed to be density dependent. Moreover, we assume that there is also a feedback effect from the native fish on escaped fish similar to the effect of the escaped fish on native fish. Therefore, the growth of escaped fish follows a growth function similar to that of the native, specified as:

$$G(Y, X) = s\left(1 - e^{\frac{aY}{X}}\right)Y\left(1 - \frac{Y + bX}{K_Y}\right) \tag{4}$$

s is the intrinsic growth rate of farmed species, K_Y is the carrying capacity, yet a and b are equivalent to γ and β in the native fish growth function (Equation (3)), representing the scaling parameter and competition coefficient, respectively. In the same manner as for the wild fish previously discussed, we assume that the farmed genotype controls this salmon stock, thus, we will refer to this population as the escaped (farmed) fish, even if there are degrees of hybridization for all $a > 0$.

The stock dynamic models of the native and escaped fish are completed when harvest and the flow of newly escaped fish are introduced. If h_t and q_t denote the harvests of the native and farmed species at time t, respectively, and m_t is the *annual* stream of newly escaped fish, the stock dynamics of the native and escaped fish are written as:

$$X_{t+1} - X_t = F(X_t, Y_t) - h_t \tag{5}$$

and

$$Y_{t+1} - Y_t = G(Y_t, X_t) - q_t + m \tag{6}$$

respectively.[3] In an ecological equilibrium, the natural growth of the native fish stock must exactly be balanced by its harvest, while the natural growth plus the flow of a newly escaped farmed fish should be equal to the harvest of the escaped fish. Thus, in equilibrium, we have $F(X, Y) = h$ and $G(Y, X) + m = q$. Note that this implies an assumption of a continuous and constant stream of invaders over time.

COSTS AND BENEFITS

Native fish provide various values, including direct and indirect use values, and non-use values such as option, existence, or intrinsic values. Here, we consider only the values directly related to the harvesting of native or escaped farmed fish. Thus, within our unified planner framework, the objective of the planner is to maximize the net surplus of harvesting both native and escaped fish. As already indicated, two types of harvesting activities are considered: harvests by commercial fishermen and harvests by recreational anglers. The net benefit of commercial harvest is determined by the meat value and the fishing costs, while the net benefit of recreational fishing is determined by the price of fishing permits and the number of fishing permits sold, together with the cost of supplying fishing permits.

Commercial Fishing

The harvest functions are assumed to be of the standard Schaefer type where $h_t = \theta E_t X_t$ and $q_t = \psi E_t Y_t$ are the harvests of native and escaped fish, respectively, with θ as the (fixed) catchability coefficient for native and ψ for escaped, and E_t as the effort measured in net fishing days (fishing days times number of nets). Note that these specifications imply non-selectivity in harvest. With identical catchability coefficients, $\theta = \psi$, the harvest will only differ due to the different abundance of native and escaped fish, and the harvest ratio will always be equal to the stock ratio; that is, $h_t / q_t = X_t / Y_t$.

With $p > 0$ and $v > 0$ as the harvest prices of the native and invasive fish, respectively, both assumed fixed and independent of the amount fished, and c is the unit effort cost, also assumed to be fixed, the current profit is defined as

$$\pi_t = p\theta E_t X_t + v\psi E_t Y_t - cE_t \tag{7}$$

As indicated by Equation (7), the invasive fish also may be harvested for its economic value. In some instances, however, this economic value may be absent due to less desire in the market. With a low, or even zero, fish price, $v = 0$, the invasive fish is merely a pest, like the jellyfish case in Knowler, Barbier, and Strand (2002) and Knowler and Barbier (2005). Fishing then occurs mainly for pest control, but it takes place as a by-product of fishing for native fish because of non-selectivity in harvest. These different cases are analyzed later.

Recreational Fishing

Besides commercial fishing, there may also be recreational fishing. Indeed, in some instances, the recreational fishery is more important. This is the case for the Norwegian Atlantic Salmon fishery explored further in this article. Although the commercial fishing of salmon takes place in the fjords and inlets, salmon also is harvested in the rivers during their upstream spawning migration in the summer and autumn. The fishing activity in Norwegian rivers is almost exclusively recreational in nature, dominated by recreational anglers with fishing rods. Each angler purchases a time-restricted fishing permit from a landowner/river manager, who is authorized by the state to sell fishing permits. A permit may be issued for as little as a few hours or as long as a season. The most common permits are issued on a 24-h basis (Olaussen & Skonhoft, 2008b).

Most rivers are managed by a single landowner, or a cooperation of landowners, acting as a single principal. The willingness to pay for a recreational fishing permit typically decreases in the number of permits (Anderson, 1993). Assuming that the fishing permit price I_t also depends on the stock sizes X_t or Y_t, an inverse demand function may be written as $I_t = I(D_t, X_t, Y_t)$ and where D_t is the number of fishing permits, or number of fishing days.[4] The overall surplus from recreational fishing in the rivers is made up of landowner profits from selling fishing permits plus angler surpluses, defined as:

$$U_t = \int_0^{D_t} I(\xi_t, X_t, Y_t)\, d\xi_t - zD_t \qquad (8)$$

when the unit cost of providing fishing permits is fixed by z.

The permit price declines in the number of fishing permits, $I_D < 0$. It is assumed to increase in the size of the native stock, $I_X > 0$, as a higher fish stock indicates a higher quality of the river (see, e.g., Olaussen & Skonhoft, 2008b). On the other hand, the permit price could either increase or decrease in the abundance of escaped farmed fish. It is increasing, $I_Y > 0$, if the stock size available for harvest is all that matters; that is, if the anglers consider a fish as a fish. This may be due to preferences or simply to difficulties in distinguishing between escaped farmed and native fish. On the other hand, the permit price shifts down with the size of the escaped farmed stock if the abundance of escaped farmed salmon decreases the utility of the anglers. In this case, the anglers simply prefer to harvest pure natives.

Economic Effects of Invasion

As in Knowler and Barbier (2000) and Barbier (2001), the economic net effect of an invasion is determined by comparing pre- and post-invasion scenarios. That is, the economic effect is the difference between the net benefits yielded from harvesting a native fish *before* and a native and a farmed species *after* invasion. If $\pi_{0,\ t}$ is the net current value of pre-invasion fishing for the commercial fishery, and $U_{0,\ t}$ for the recreational fishing, the current invasive economic impact B_t for commercial and recreational fishing may be expressed as:

$$B_{C,t} = \pi_t - \pi_{0,t} = [p\theta E_t X_t + v\psi E_t Y_t - cE_t] - [p\theta E_{0,t} X_{0,t} - cE_{0,t}] \tag{9}$$

and

$$B_{R,t} = U_t - U_{0,t} = \left[\int_0^{D_t} I(\xi_t, X_t, Y_t)\, d\xi_t - zD_t\right] - \left[\int_0^{D_{0,t}} I(\xi_{0,t}, X_{0,t})\, d\xi_{0,t} - zD_{0,t}\right] \tag{10}$$

respectively.

EXPLOITATION

The management of the ecological system under consideration is analyzed when the present-net benefit is maximized by a single planner. We first consider commercial harvest. The planner then aims to maximize $\sum_{t=0}^{\infty} \rho^t (p\theta E_t X_t + v\psi E_t Y_t - cE_t)$, where $\rho = \frac{1}{1+\delta}$ is the discount factor with $\delta \geq 0$ as the discount rate, subject to the population dynamics constraints (5) and (6), a constraint on the harvest, or effort $E_t \geq 0$, and the given initial stock conditions. The Lagrangian of this problem may be written as:

$$\begin{aligned} L = \sum_{t=0}^{\infty} \rho^t \{ & (p\theta E_t X_t + v\psi E_t Y_t - cE_t) - \rho\lambda_{t+1}[X_{t+1} - X_t - F(X_t, Y_t) + \theta E_t X_t] \\ & - \rho\mu_{t+1}[Y_{t+1} - Y_t - G(Y_t, X_t) - m + \psi E_t Y_t] \} \end{aligned} \tag{11}$$

where $\lambda_t > 0$ and μ_t are the shadow prices of the native and farmed species, respectively.

The first-order necessary conditions when $X_t > 0$ and $Y_t > 0$ are:

$$\frac{\partial L}{\partial E_t} = p\theta X_t + v\psi Y_t - c - \rho\left(\lambda_{t+1}\theta X_t + \mu_{t+1}\psi Y_t\right) \leq 0;\ \ 0 \leq E_t \tag{12}$$

$$\frac{\partial L}{\partial X_t} = p\theta E_t + \rho\lambda_{t+1}\left(1 + F_X(X_t, Y_t) - \theta E_t\right) - \lambda_t + \rho\mu_{t+1}G_X(X_t, Y_t) = 0 \tag{13}$$

and

$$\frac{\partial L}{\partial Y_t} = v\psi E_t + \rho\lambda_{t+1}F_Y(X_t, Y_t) + \rho\mu_{t+1}[1 + G_Y(Y_t, X_t) - \psi E_t] - \mu_t = 0 \tag{14}$$

Control condition (12) indicates that it is optimal to increase fishing effort up to the point where the marginal revenue is equal to the total marginal costs, which are made up by the effort costs plus the costs of reduced stocks evaluated at their shadow prices. Therefore, if the marginal revenue is less than the total marginal costs, fishing should not take place. Moreover, the upper limit on fishing effort level, E, would be set when the harvest rate is approaching (or equal) to 1.

Condition (13) states that the number of native fish should be maintained so that the value of one more fish on the margin should equalize its marginal cost minus the marginal value of an invasive fish, both measured at their respective shadow prices. Condition (14) has the same interpretation for the invasive fish. In this solution, the coexistence of both species is assumed. Otherwise, one species will be driven to extinction.

These conditions are also sufficient if the Lagrangian is concave in the states and control variables. Because the Lagrangian is linear in the control variable, the sufficiency conditions boil down to $\frac{\partial^2 L}{\partial X_t^2} = L_{XX} = \lambda_{t+1}F_{XX} + \mu_{t+1}G_{XX} \leq 0, \frac{\partial^2 L}{\partial Y_t^2} = L_{YY} = \lambda_{t+1}F_{YY} + \mu_{t+1}G_{YY} \leq 0$ and $\frac{\partial^2 L}{\partial X_t Y_t} = L_{XX}L_{YY} - L_{XX}^2 = \left(\lambda_{t+1}F_{XX} + \mu_{t+1}G_{XX}\right)\left(\lambda_{t+1}F_{YY} + \mu_{t+1}G_{YY}\right) - \left(\lambda_{t+1}F_{XY} + \mu_{t+1}G_{XY}\right)^2 \geq 0$, which are not generally satisfied for the given properties of the natural growth functions and the values of the shadow prices (see below). However, they hold for sure if the solutions are found on the concave parts of the natural growth functions, when the competition effects are small or modest such that F_{XY} and G_{XY} are small in values and the shadow prices are positive. Part of this reasoning indicates that the total value of biomass lost due to competition cannot be 'too large' (see, e.g., Hannesson, 1983, for an economic analysis, and Maynard Smith, 1974 for a basic ecological discussion).

Next we discuss some properties of the steady state solution under certain simplifying assumptions. However, how to approach the steady state in an optimal way is complicated. The complexity of finding the optimal approach paths in multi-dimensional models, which are linear in the control variable(s), is exemplified by the predator-prey model of Mesterton–Gibbons (1996). The author shows that a Most Rapid Approach (or "bang-bang") together with a singular control is not generally optimal in this type of two species system. The same type of complexity will also be present here. However, we may suspect that because of the high degree of linearity in the model together with density dependent regulation through both fish stocks, the optimal stable steady state is achieved quite fast. Later we find that this happens when the discount rate is low.

We look at the steady state under the assumption of zero discount rate, $\delta = 0$, or $\rho = 1$, because the solution then coincides with that of maximizing the sustainable rent (e.g., Clark, 1990). The steady state is defined when $X_t = X$, $Y_t = Y$, $E_t = E$, $\lambda_t = \lambda$ and $\mu_t = \mu$. Omitting the time subscripts and rewriting (13) yields then $\lambda = (p\theta E + \mu G_X)/(\theta E - F_X)$. Therefore, it is seen that $\lambda > 0$ when the marginal harvest value dominates the invasive stock cost effect $p\theta E + \mu G_X > 0$ under the assumption that the harvest function θEX intersects with the native fish natural growth function $F(.)$.

Moreover, rewriting Equation (14) when $\delta = 0$ still holds as $\mu = (v\psi E + \lambda F_Y)/(\psi E - G_Y)$, it is first observed that $\psi E - G_Y > 0$ also must hold for the same reason. We then find that $\mu \geq 0$ if $v\psi E \geq -\lambda F_Y$. Therefore, the escaped fish shadow price is positive, suggesting that its harvest price v is "high" together with a "small" negative effect on the native fish growth; that is, F_Y is small in value. This is the "value" case of the escaped fish. In the opposite case, we have a 'pest', or 'nuisance' situation with a negative shadow price, $\mu < 0$.[5] Irrespective of whether escaped fish are pests or commercially valuable, it is always optimal to harvest escaped fish due to the non-selective nature of the fishery.

When the control condition (12) with $\delta = 0$ is rewritten as $(p - \lambda)\theta X + (v - \mu)\psi Y = c$, it is seen that $p < \lambda$ holds when the difference between the market price and the shadow price of the invasive fish is "large." Equation (13) written as $(p - \lambda)\theta E = -(\lambda F_X + \mu G_Y)$ indicates that F_X is strictly positive in an optimal program if μG_Y is 'small' in value. In this case, for a given optimal number of invasive fish, the optimal native stock size will be located to the left hand side of the peak value of the natural growth function, or X^{msy} (cf., Figure 1).

If the invasive harvesting price is 'low' and $\mu < 0$ together with 'low' fishing cost c, we have $F_X > 0$ for certain. As demonstrated next this is the baseline result in the numerical simulations, in contrast to the standard one-species Gordon-Schaefer equilibrium harvesting model (Clark, 1990). On the other hand, a "high" c combined with a "low" value of the native fish catchability coefficient θ, we typically end up with a "large" optimal native stock and a solution to the right-hand side of X^{msy}.

Next, we consider the recreational fishery. Harvest is still defined through the Schaefer functions $h = \varphi D_t X_t$ and $q = \omega D_t Y_t$ where effort is given in number of fishing days, or equivalently, number of licenses (see above), with φ and ω as the recreational catchability coefficient for the native and invasive fish, respectively. Therefore, just as in the commercial case, with equal catchability coefficients, i.e., $\varphi = \omega$, we find that the harvest ratio is similar to the fish abundance ratio. The Lagrangian function now reads:

$$L = \sum_{t=0}^{\infty} \rho^t \int_0^{D_t} \{[I(\xi_t, X_t, Y_t) d\xi_t - zD_t] - \rho\lambda_{t+1}[X_{t+1} - X_t - F(X_t, Y_t) + \varphi D_t X_t] \\ - \rho\mu_{t+1}[Y_{t+1} - Y_t - G(Y_t, X_t) - m + \omega D_t Y_t]\} \tag{15}$$

The first-order conditions with coexistence of both species $X_t > 0,\ Y_t > 0$ are

$$\frac{\partial L}{\partial D_t} = I(D_t, X_t, Y_t) - z - \rho\left(\lambda_{t+1}\varphi X_t + \mu_{t+1}\omega Y_t\right) \leq 0;\ \ 0 \leq D_t \tag{16}$$

$$\frac{\partial L}{\partial X_t} = \int_0^{D_t} I_X(\xi_t, X_t, Y_t)\, d\xi_t + \rho\lambda_{t+1}[1 + F_X(X_t, Y_t) - \varphi D_t] \\ - \lambda_t + \rho\mu_{t+1} G_X(X_t, Y_t) = 0 \tag{17}$$

and

$$\frac{\partial L}{\partial Y_t} = \int_0^{D_t} I_Y(\xi_t, X_t, Y_t)\, d\xi_t + \rho\lambda_{t+1} F_Y(X_t, Y_t) + \rho\mu_{t+1}[1 + G_Y(Y_t, X_t) - \omega D_t] \\ - \mu_t = 0 \tag{18}$$

The interpretations of these conditions are analogous to the commercial fishing Equations (12)–(14). The only important difference is that the willingness to pay for fishing permits, and hence the fish price, depends on the stocks of the native and invasive fish and the number of permits. Thus, in contrast to the commercial fishery, the price is endogenous in the recreational case.

The cost structure is also different as there are no direct harvesting costs included in the recreational case. The landowner has a fixed unit cost of providing permits, but even in the presence of this fixed cost, condition (16) indicates that the landowner's profit generally is positive; at least when both shadow prices are positive. Just as in the commercial model, we may end up with a native stock located to the right-hand side as well as the left-hand side of X^{msy}. Intuitively, the first outcome can occur when the native demand stock value effect is substantial while the second may occur if, say, the catchability coefficient is high or the willingness to pay for permits is high.

In a steady state, the first-order conditions (16)–(18) together with the equilibrium conditions $F(X, Y) = \varphi DX$ and $G(Y, X) + m = \omega DY$ yield five equations determining the size of the two fish stocks, the effort, and the two shadow prices. In addition, the equilibrium native fish harvest follows as $h = \varphi DX = F(X, Y)$ and the invasive harvest as $q = \omega DY = G(Y, X) + m$. Combining these two equilibrium conditions yields $\frac{F(X,Y)}{G(Y,X)+m} = \varphi X/\omega Y$. Therefore, the effects of the yearly inflow of escaped fish m on the fish abundance are channeled directly through this composite equilibrium condition.

Differentiation now yields $\left(\frac{1}{\varphi X}\right)\left[\left(F_X - \frac{F}{X}\right) - \left(\frac{\varphi X}{\omega Y}\right)G_X\right]dX - \left(\frac{1}{\omega Y}\right)\left\{\left[G_Y - \frac{G+m}{Y}\right] - \left(\frac{\omega Y}{\varphi X}\right)F_Y\right\}dY = \left(\frac{1}{\omega Y}\right)dm$. Suppose now that $F(X, Y)$ is concave in X at the optimum such that $\left(F_X - \frac{F}{X}\right) < 0$, and the invasive stock function is concave in Y as well, $\left(G_Y - \frac{G+m}{Y}\right) < 0$. Therefore, if the optimal size of the escaped fish stock increases with a higher inflow, we find that the native stock may also increase when the negative ecological effect from the escaped to the native stock F_Y is "small" in value.

On the other hand, the native stock size will, not surprisingly, become lower in the new equilibrium with a higher inflow if this ecological effect is "large" in value and the negative ecological effect from the native to the invasive stock G_X is "small" in value. Recall that the size of the ecological effects is contingent upon a growth effect and a stock effect, and each is affected by two separate parameters in the specific functional form. We demonstrate that these parameters, and hence the magnitude of F_Y, have strong effects on the economics of this fishery.

A combined commercial and recreational fishery management may also be an option. The present-value net benefit of both fisheries together $(\pi_t + U_t) = (p\theta E_t X_t + v\psi E_t Y_t - cE_t) + \left[\int_0^{D_t} I(\xi_t, X_t, Y_t)d\xi_t - zD_t\right]$ is then maximized subject to the ecological constraints. The first-order control conditions of this problem are:

$$\frac{\partial L}{\partial E_t} = p\theta X_t + v\psi Y_t - c - \left(\lambda_{t+1}\theta X_t + \mu_{t+1}\psi Y_t\right) \leq 0;\ 0 \leq E_t \tag{19}$$

and

$$\frac{\partial L}{\partial D_t} = I(D_t, X_t, Y_t) - z - \left(\lambda_{t+1}\varphi X_t + \mu_{t+1}\omega Y_t\right) \leq 0;\ 0 \leq D_t \tag{20}$$

while the stock conditions $\frac{\partial L}{\partial X_t} = 0$ and $\frac{\partial L}{\partial Y_t} = 0$ simply add up from the previous two separate harvest situations.

If the willingness to pay for recreational fishing is ‘high’ relative to the commercial market fish price, we typically end up with a corner solution with recreational fishing only. That is, condition (20) holds as an equation while Equation (19) holds as an inequality due to the Kuhn-Tucker theorem. This analysis of a combined fishery tacitly implies that recreational and commercial fishing take place simultaneously. In reality, however, there may be sequential fishing (cf., the Norwegian Atlantic salmon fishery considered further in the discussion).

Such a scheme complicates the analysis further, as the biological constraints have to be adjusted accordingly. In addition, since commercial salmon fishing in Norway is subsistent in nature, and the economic value from commercial harvest is almost negligible compared to the values from recreational fishing, we typically end up with a corner solution involving recreational angling only. Consequently, the sequential harvest model seems superfluous in this specific case. Moreover, the models we construct here are generic in the sense that they may be applicable to other cases, not only salmon. Thus, some fisheries may be for commercial harvest (typically sea fisheries) only and some may be for recreational fishing (some freshwater fisheries) only. A sequential fishery is not pursued further in this article (but see Olaussen & Skonhoft, 2008a).

AN EMPIRICAL APPLICATION TO SALMON

Data and Specific Functional Forms

The methodological framework previously discussed will be illustrated empirically using the case of Atlantic salmon (*Salmo salar*) for a typical Norwegian salmon river. Atlantic salmon has become one of the most successful farmed species, and salmon aquaculture is one of the fastest growing food producing sectors in the world. In just over three decades from 1970 to 2008, farmed salmon production increased from 500 to over 1.5 million tons (Food and Agriculture Organization of the United Nations [FAO], 2010). Farmed salmon production has exceeded native production worldwide since 1998.

In contrast, native salmon stocks have declined in most areas, particularly in the North Atlantic. Some argue that salmon aquaculture has contributed to this decline because it triggers a reduction in the survival of native salmon (e.g., Ford & Myers, 2008), the spread of diseases and parasites (Bjørn & Finstad, 2002; Gargan, Tully, & Poole, 2002; Krkošek et al., 2006), and interbreeding (e.g., Naylor et al., 2005; Hindar et al., 2006). Norway has been the world’s number one farmed salmon producer since its beginning. Today, escaped farmed salmon is one of the most severe challenges facing the salmon aquaculture industry and native salmon stocks (e.g., Esmark, Stensland, & Lilleeng, 2005).

Atlantic salmon is an anadromous fish with a complex life cycle. Its spawning and juvenile development takes place in freshwater, and it feeds and grows in the sea before returning to its natal rivers to spawn. Native salmon is commonly harvested by two sectors: commercial fishing and recreational fishing. Commercial fishermen harvest salmon in the fjords and inlets as salmon migrate toward their spawning ground, and recreational anglers target salmon in the rivers. Commercial harvests are conducted for meat value while recreational fishing is conducted by individuals for sport and leisure with the possibility of personal consumption. Escaped farmed salmon in the fjords and rivers also are caught by commercial fishermen and recreational anglers.

The inverse demand function in the recreational fishery is specified as: $I(D, X, Y) = \alpha + \eta[1 - e^{-\kappa(\varphi X + \omega Y)}] - \phi D$. Here $\alpha > 0$ and $\phi > 0$ are the standard choke and slope parameters, respectively, and $\eta > 0$ and $\kappa > 0$ describe how the size of the fish stock, or river quality, translates into demand, and where κ indicates the strength of this changing stock demand effect. The stock demand effect is approximated by total catch per unit effort (or catch rate), i.e., $\frac{h+q}{D} = \frac{(\varphi DX + \omega DY)}{D} = \varphi X + \omega Y$, and where we assume the same quality effect of both native and escaped salmon. This demand specification implies that when fish abundance is small the permit choke price approaches α, and when the fish abundance is high it approaches its maximum value $(\alpha + \eta)$.

The baseline values for the ecological and economic parameters are shown for a typical Norwegian river in Table 1. Some of the parameter values are calibrated based on general fishing and farming practice in Norway. These values may vary to some degree dependent on environmental conditions and practice, and thus sensitivity analyses are presented for the most important parameters. It should also be noted that the ecological effects of the escapees on native salmon is assumed to be the same as the effects of native on escaped salmon, thus, $r = a$ and $\beta = b$.

The catchability coefficient for native and farmed salmon are assumed to be identical since there is no evidence that they are different, hence $\theta = \psi$ and $\varphi = \omega$. The carrying capacities of the stocks X and Y are also assumed to be similar, $K_x = K_y$ and the intrinsic growth rates for native and escaped farmed salmon are different. Experimental and field research show that farmed and hybrid salmon are competitively and reproductively inferior, resulting in lower survival rates and reproductive success than native fish, i.e., $r > s$ (Fleming et al., 1996, 2000; McGinnity et al., 2003, 2004). The annual inflow of escaped farmed salmon m is directly related to the size of the farmed production in the net-pens, farm management practice, and natural conditions, such as the frequency of storms and so forth.

TABLE 1 Baseline Values Ecological and Economic Parameters

Parameter	Description	Value	Reference
K_X, K_Y	Carrying capacity	25,000 (# of salmon)	Assumed
r	Intrinsic growth rate, native salmon	0.26	Fishbase
s	Intrinsic growth rate, farmed salmon	0.12	Estimated*
β	Habitat competition coefficient, native	1	Calibrated
γ	Scaling factor growth effect, native	5	Calibrated
b	Habitat competition coefficient, farmed	1	Calibrated
a	Scaling factor growth effect, farmed	5	Calibrated
m	Yearly influx escaped farmed salmon	400 (# of salmon)	Calibrated
θ	Catchability coefficient, native, commercial	0.003 (1/day)	NOU
ψ	Catchability coefficient, farmed, commercial	0.003 (1/day)	Calibrated
φ	Catchability coefficient, native, recreational	0.000015(1/day)	OS
ω	Catchability coefficient, farmed, recreational	0.000015(1/day)	Calibrated
α	Choke price, recreational	500 (NOK/day)	OS
ϕ	Slope effect recreational demand	0.12 (NOK/day^2)	OS
p	Price, native salmon, commercial	50 (NOK/salmon)	OS
v	Price, farmed salmon, commercial	50 (NOK/salmon)	OS
z	Marginal cost, recreational	50 (NOK/day)	OS
c	Unit cost, commercial	100 (NOK/day)	NOU
η	Recreational demand translation parameter	500 (NOK/day)	Calibrated
κ	Recreational quality effect parameter	3.33 (1/salmon)	Calibrated
δ	Discount rate	0	Assumed

Note. Exchange rate: 1 USD = 6.00 NOK (June 2014).

Data sources: Fishbase = www.fishbase.org, OS = Olaussen and Skonhoft (2008a), and NOU = NOU (1999). The intrinsic growth rate for farmed salmon is estimated based on reproductive traits such as fecundity, survival rate, and generation time (Fleming et al., 1996, 2000, 2006; McGinnity et al., 2003, 2004).

For these and other reasons, m changes from year to year (see Olaussen & Skonhoft, 2008a, for evidence). In our analysis, m is assumed constant and may hence be interpreted to be an average over a period of years. Its baseline value is set at $m = 400$ fish. Additionally, the baseline prices for farmed and native are assumed to be equal, $p = v$ although native salmon may command a higher price than escaped farmed salmon if appropriately labeled and people are well informed. We assume zero discount rate in the baseline scenario. As already discussed, this means that the steady state of the dynamic optimization problems coincides with the problems of maximizing current benefit in biological equilibrium. This enables a more straightforward economic interpretation of our economic results.

RESULTS

We first present the basic dynamic results from the commercial fishery in Figure 2. Although we solve the model for a time horizon of 60 years, we only present results for the first 40 years. This long time

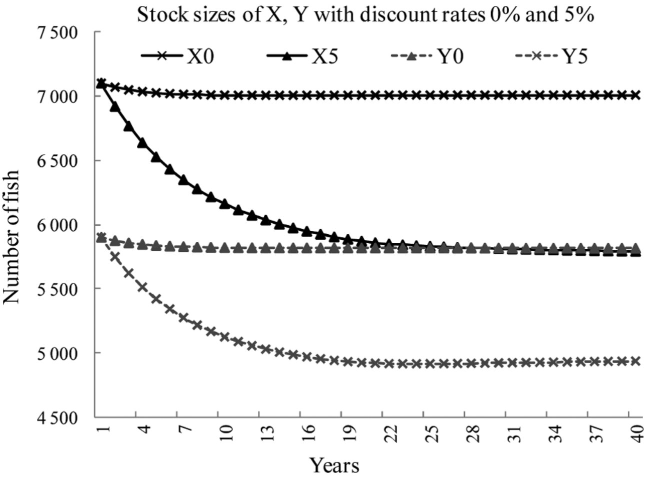


FIGURE 2 Stock sizes dynamic fishing pattern commercial fishing. Discount rates of 0% ($\delta = 0.00$) and 5% ($\delta = 0.05$). X_0 and X_5 are the wild salmon stock sizes, and Y_0 and Y_5 are the farmed salmon stock sizes with discount rates of 0% and 5%, respectively.

horizon for solving the model ensures that the reported solutions will be numerically indistinguishable from the infinite horizon solution reported for 40 years. We start with stock values slightly higher than their steady-state values. As already indicated, because of the high degree of linearity in the model together with density-dependent regulation in the natural growth functions, the model approaches a stable equilibrium without any overshooting/undershooting quite fast.

Given the initial stock sizes, the harvest pattern over time is very similar to the stock development; that is, the harvest first decreases fast and then gradually slows down until reaching the steady-state harvest state. Therefore; the transitional dynamics have similarities with saddle path dynamics. The effects of other initial situations were examined as well. Most importantly, we solved the model with low initial stock values, also starting with values on the convex part of the natural growth function (cf., Figure 1). In all cases the same steady state was achieved, indicating that the maximum solution is unique, at least within the scope of reasonable parameter values. We find that increasing the discount rate, as expected, reduces the stock sizes, and we also find that the time to reach the new steady state increases. However, the dynamics do not change qualitatively.

Table 2 reports the detailed steady state pre- and post-invasion results for the commercial fishery. For the baseline parameter values the native and farmed salmon coexist with the native dominating the ecological system. Further, for the optimal size of the invasive stock, the stock value representing the peak of the native stock growth function is $X^{msy} = 9593$. Hence, the optimal size of the native stock is located to the left-hand side

TABLE 2 Steady-State Commercial Fishing

	Pre-invasion	Post-invasion	Difference
Stock size native salmon, X	12833	7010	−5823 (45%)
Stock size farmed salmon, Y	–	5813	–
Harvest of native salmon, h	1624	886	−738 (45%)
Harvest of farmed salmon, q	–	734	–
Fishing effort, E	42	42	–
Profit of native salmon (‘000 NOK)	77	40	−37 (48%)
Profit of farmed salmon (‘000 NOK)	–	33	–

Note. Exchange rate: 1 USD = 6.00 NOK (June 2014).
Baseline parameter values.

of this peak. We find that $\mu = -3$ (NOK/salmon), and therefore $(p - \mu) = 53$. The native salmon shadow value $\lambda = 90$ (NOK/salmon) is quite high. This outcome typically implies a rather large gap between the harvest price of the invasive fish and its shadow value. On the other hand, as expected, we find the optimal stock size to be above $X^{msy} = \frac{K_X}{2} = 12500$ in the pre-invasive case (see also Table 1). Although the native stock intrinsic growth rate is 0.26 in the pre-invasive situation, it reduces marginally to $\tilde{r} = \tilde{r}(X, Y) = 0.26 * \left(1 - e^{-5*\frac{7010}{5813}}\right) = 0.259$ in the post-invasive case (Table 1). On the other hand, the stock effect given by the term, $\beta Y = 1{*}5813 = 5813$ is about 17% below that of the optimal native salmon stock (5813/7010).

Altogether these two effects combined mean that the optimal native stock becomes significantly lower than in the pre-invasion case. Hence, the steady state native salmon fishery profit declines due to the invasive escaped farmed salmon, dropping from NOK 77 (‘000) pre-invasion to NOK 40 (‘000). Nevertheless, the total profit remains quite stable with NOK 73 (‘000). Therefore, any native salmon profit loss is mostly compensated for by the profits attained from harvesting escaped farmed salmon.

If the escaped salmon harvest price is zero, $v = 0$, and we keep all the other parameter values unchanged, escaped farmed salmon has a negative shadow price $\mu = -53$ and is harvested just as a pest by-product due to the non-selectivity of the fishery and for the benefit of the native salmon stock. The steady-state total profit now declines significantly from NOK 77 (‘000) to NOK 40 (‘000) in this post-invasion pest case. Therefore, the escaped harvest price gives small and negligible quantity effects and the profit reduction is basically related to the missing invasive harvest value.

In the recreational fishing case, we only present results from the steady states (dynamic results are available upon request). For the baseline parameter values, the native stock as well as the invasive stock becomes higher than in the commercial case. Like the commercial baseline case, the optimal native stock size is located at the left hand side of X^{msy} in the post-invasion case. As previously discussed this may typically indicate a rather 'high' permit demand, and/or a "high" recreational fishery catchability coefficient. The results reported in Table 3 show that the size of the native stock and its harvest decrease by more than 50% after the invasion. However, the total harvest and surplus are kept relatively stable as the total stock size just slightly changes. The relatively stable total stock size also leads to small differences in permit prices and fishing days between pre- and post-invasion since the native and escaped salmon are treated equally in the demand function.

For the given ecological parameter values and the fixed annual inflow of escaped farmed salmon, the results suggest that the ecological and economic effects of escaped farmed salmon on native salmon are substantial, i.e., F_Y is "large" in value. As a consequence, the harvest and profit of native salmon decline after escaped farmed salmon enter the environment. However, escaped farmed salmon yield supplementary harvests and profit and surplus to fishermen and anglers. These supplements compensate in whole or in part the losses of native salmon harvest. The reason for this is that the same quality effect is assumed for fishing wild and farmed fish among the anglers, which is an important limiting assumption (see Liu et al., 2012).

Salmon is at present harvested by both commercial and recreational fishing sectors in Norway. Due to the high total surplus generated by the recreational fishery, however, our results yield a corner solution where the whole stock is destined for recational fishing, i.e., $E = 0$ and $D > 0$ as the optimal solution. See conditions (19) and (20). Thus, the mixed fishing case is not considered here.

Sensitivity Analysis

The robustness of the results due to changes in some key ecological and economic parameters are tested. Since recreational fishing generates

TABLE 3 Steady-State Recreational Fishing

	Pre-invasion	Post-invasion	Difference
Stock size native salmon, X	17136	7870	−9266 (-54%)
Stock size farmed salmon, Y	–	9118	–
Harvest of native salmon, h	1401	647	−647(-54%)
Harvest of farmed salmon, q	–	750	–
Permit price, I (NOK/day)	133	128	−5 (4%)
Fishing days, D	5452	5481	29 (0.5%)
Angler surplus ('000 NOK)	1784	1802	18 (1%)
Landowner profit ('000 NOK)	455	430	−25 (5%)
Total surplus, U ('000 NOK),	2239	2232	−7 (0.3%)

Note. Exchange rate: 1 USD = 6.00 NOK (June 2014).
Baseline parameter values.

higher economic surplus, this seems to be the more interesting fishery to look at when we demonstrate these effects. We start to look at changes in the annual inflow of escaped salmon, m, where we used 400 salmon in the baseline scenario, see Figure 3. Such changes may be due to various reasons. We find that the equilibrium native and farmed stocks and harvests change dramatically with a shifting annual inflow of escaped farmed salmon (upper panel). When $m = 0$, the native stock becomes dominant because of its higher intrinsic growth rate while the escaped farmed fish disappear.

On the other hand, with $m = 600$ the native stock goes extinct, and only farmed salmon remains. Therefore, for that high value of inflow, the native stock is simply outcompeted. The angler surplus changes slightly while the

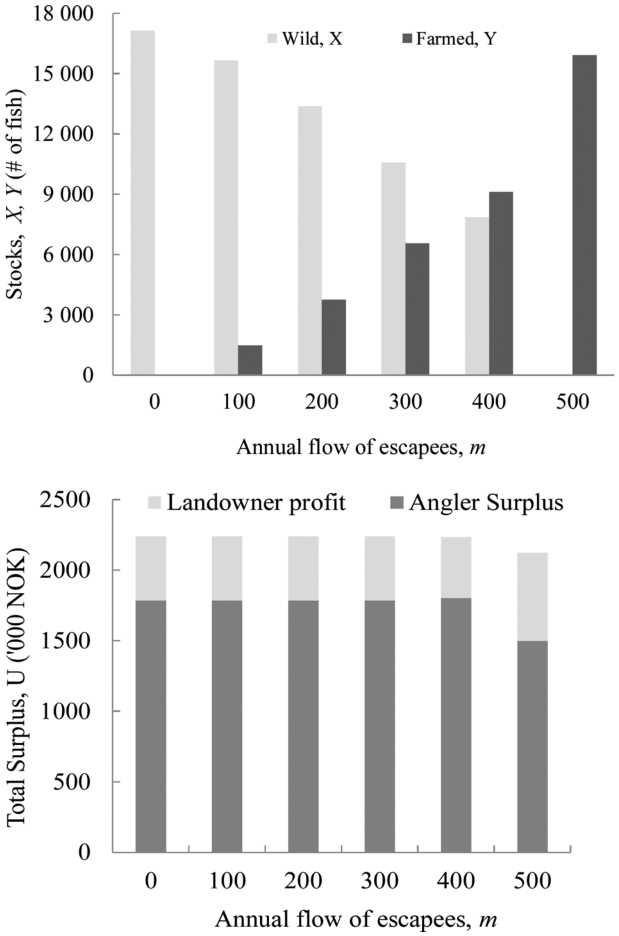


FIGURE 3 Steady-state recreational fishing. Effects of different yearly influx of farmed escapees m. Upper panel: stocks of native and farmed salmon. Lower panel: landowner profit and angler surplus.

total profit virtually remains at the same level except for a small decline when $m = 600$ (lower panel). These results are related to the fairly steady permit price and the number of fishing days, but most important to the assumption of similar demand quality effect of native and escaped fish.

We next study changes in the parameters β and b which steer the intensity of the habitat competition between the native and escaped farmed salmon. A higher β indicates that escaped farmed salmon has a stronger negative stock effect on native salmon, i.e., F_Y increases in value, while a higher value of b works in a similar manner on farmed salmon. The results in Table 4 where both these parameters are shifted simultaneously show that the steady state biomass loss to competition increases, and the optimal native salmon stock declines rapidly with increasing stock competition.

When $\beta = 1.2$, the stocks no longer coexist; the native salmon goes extinct and only the farmed salmon remains. This occurs irrespective of the significant higher native salmon intrinsic growth rate, and is mainly due to the annual inflow of escaped farmed salmon. The numbers of fishing days and the permit price are strongly influenced as well. As a consequence, the total surplus and benefit distribution change. For example, when changing β and b from the baseline value of 1 to 1.2, the total surplus declines from NOK 2332 to NOK 2067 ('000) while the landowner profit increases from NOK 430 to NOK 639 ('000). The lower number of permits sold by the landowners is more than outweighed by a higher permit price.

The effects of changing the intrinsic growth rates are also studied (results available upon request). Keeping the intrinsic growth rate of native salmon constant, we change the intrinsic growth rate of farmed salmon. When s becomes smaller, the stock size of native salmon increases while the stock size of farmed salmon decreases. The total steady-state stock size also reduces with a lower value of s. As a consequence, we find lower permit prices and more fishing days. Therefore, angler surplus increases and landowner profit decreases whereas the total surplus decreases. If s gradually

TABLE 4 Steady-State Recreational Fishing

	$\beta = b = 0.5$	$\beta = b = 0.8$	$\beta = b = 1$	$\beta = b = 1.1$	$\beta = b = 1.2$
Stock size native salmon, X	11965	9750	7870	6387	–
Stock size farmed salmon, Y	9772	9067	9118	9208	15226
Harvest of native salmon, h	1012	807	647	546	–
Harvest of farmed salmon, q	826	751	750	787	1114
Permit price, I (NOK/day)	155	143	128	87	181
Fishing days, D	5638	5519	5481	5670	4879
Angler surplus ('000 NOK)	1907	1827	1802	1949	1428
Landowner profit ('000 NOK)	591	511	430	210	639
Total surplus, U ('000 NOK)	2498	2338	2232	2159	2067

Note. Exchange rate: 1 USD = 6.00 NOK (June 2014).
Effects of changed habitat competition coefficientβ and b. Baseline values $\beta = b = 1$.

increases, the stock size of native salmon decreases while the stock size of escaped farmed salmon increases. When s approaches r, the escaped farmed salmon gradually replace native salmon which disappears eventually, analogous to what has been observed for crayfish (Kataria, 2007).

Changes in the choke price α are also considered. Shifts here may be attributed to changing income conditions of the anglers as well as changing preferences for recreational fishing. Table 5 indicates that both the optimal size of native and escaped salmon stocks respond rapidly to changing demand conditions while the total harvest and profit are enhanced as the increasing reservation price implies a higher demand.

Finally we studied the effects of shifts in the recreational fishery catchability coefficients φ and ω (not reported, but available upon request). Such shifts may be related to changes in gear restrictions and gear use (fly fishing, fishing lure, spinning bait). When the catchability coefficient increases, we find, not surprisingly, lower steady state stock sizes both of the escaped farmed and the native salmon, and higher harvest and total surplus. The fishing effort in number of fishing days changes slightly, and the combined effects of smaller stocks and higher catchability coefficient yield a higher fishing price. As a consequence, we find increased landowner profit while angler surplus remains almost unchanged. The more or less unchanged value of the equilibrium angler surplus is due to a two-sided effect. On the one hand, more efficient technology means smaller stocks which shift the demand function inwards through the stock sizes in the demand function. This effect is, however, counteracted through the catch per effort stock effect.

In sum, changes in the annual inflow of escaped farmed salmon, m, and changes in the habitat competition parameters β and b yield the strongest effects on the stock sizes of native and farmed species among the tested parameters. The effects of changing the intrinsic growth rate of farmed salmon and of changing the choke price α are greater on farmed than

TABLE 5 Steady-State Recreational Fishing

	$\alpha = 400$	$\alpha = 500$	$\alpha = 600$	$\alpha = 800$
Stock size native salmon, X	7348	7870	8013	7695
Stock size farmed salmon, Y	10390	9118	8127	6705
Harvest of native, h	539	647	733	846
Harvest of farmed, q	762	750	743	737
Permit price, I (NOK/day)	107	128	145	178
Fishing days, D	4889	5481	6099	7325
Angler surplus (‘000 NOK)	1434	1802	2232	3220
Landowner profit (‘000 NOK)	281	430	580	935
Total surplus U (‘000 NOK)	1715	2232	2811	4154

Note. Exchange rate: 1 USD = 6.00 NOK (June 2014).

Effects of changed choke price α. Baseline value $\alpha = 500$ (NOK/day).

on native salmon. The shifts in the recreational fishery catchability coefficients φ and ω have similar effect on both native and farmed species.

CONCLUDING REMARKS

In this article we have developed a general invasion impact model capturing both ecological and economic effects of invasive fish on native fish. More specially, we model the effects of an escaped farmed fish on native fish. Ecologically, two effects, namely growth and stock, are specified and incorporated into the logistic growth functions of native and escaped fish. Both lower the natural growth. Economically, the benefit associated with native and escaped fish are explored. A native fish is exploited for commercial values, while an escaped farmed fish is harvested either for commercial value or as a pest. Two different harvesting models are developed, and where the theoretical underpinnings of the commercial fishery as well as the recreational fishery are explored. Both fisheries take place with nonselective harvesting technologies.

A case study of Atlantic salmon in Norway illustrates the interaction between native and escaped farmed salmon. We first look at some basic dynamics of the models, and where we show that the stock sizes approach a stable equilibrium without any overshooting/undershooting. We find that increasing the discount rate, as expected, lowers the stock sizes, but does not change the dynamics qualitatively. More detailed steady state results are demonstrated for the commercial fishery and recreational fishery, respectively. We find that the ecological effects of invasion seem to be quite dramatic with respects to the stock, growth, and harvest of native fish. On the other hand, economically it turns out that the total net benefits received by fishermen and/or anglers and landowners decline only slightly.

In some cases they can even be better off from harvesting both native and farmed species than solely catching native fish. This highlights an important feature of escaped farmed salmon. Since these escaped fish contribute to the available stock for harvest, the incentives among fishermen, anglers, and landowners to reduce escaped farmed fish may be rather weak. For these reasons, the potential long term negative impacts through ecological mechanisms might be neglected by the various stakeholders. In our baseline numerical analysis, it is assumed that there is no distinction between native and farmed salmon to anglers. *A fish is just a fish* to them. This might not always be the case, and results from Olaussen and Liu (2011) indicate that anglers are willing to pay substantially more for fishing native than farmed salmon.

As indicated earlier, there are some limitations to our analysis. In this article, lumped natural growth functions are used. Thus, the accumulated effects of interbreeding between native and farmed species are not explicitly modeled. The preferred model to incorporate such accumulated genetic effects would be an age-structured dynamic model like the one developed by Hindar et al. (2006), which is studied through simulations. Such a simulation model would require a large amount of parameters and associated values that are unavailable in most cases. For a bioeconomic attempt to model the genetic effects of interbreeding, see Liu et al. (2012). Further, the economic analysis includes only the market values from harvest of wild and escaped fish. Other values, such as the native stock's intrinsic value, have not been included here. In the end, since all models, by definition, represent simplifications and abstractions of the real world, we must always be aware that the process of simplifications involves assumptions and imposes limitations.

ACKNOWLEDGMENTS

This research was conducted at the Centre for Economic Research, Department of Economics Norwegian University of Science and Technology (NTNU) where the first author was employed as a research associate. The authors would like to thank the participants at the Bioecon conference in Cambridge, 2013, for their helpful comments and suggestions. Special appreciation is also extended to the editor of the journal and two anonymous reviewers for their valuable and constructive suggestions which greatly improved an earlier version of this manuscript.

FUNDING

The research is funded by the Research Council of Norway through the program of Norwegian Environmental Research Towards 2015 (Miljø 2015). The opinions expressed here, certainly, are those of the authors and not those of the funding agency.

NOTES

1. In some cases, escaped fish may have positive effects on native fish when the native stock is so low that it cannot sustain its growth, and hence the presence of an escaped fish improves its growth (the 'Allee effect' in the ecological literature). In this case, the value of β is negative. This possible case is not considered here.
2. As already indicated, for a fixed intrinsic growth rate, our model has the same structure as the basic Lotka–Volterra model where the competition loss of our native fish population increases linearly with the size of the invasive stock. This is seen by rewriting the growth function (2) as $F(X,Y) = \tilde{r}X\left(1-\frac{X}{K_X}\right)-\left(\frac{\tilde{r}\beta}{K_X}\right)XY$. The invasive fish natural growth, Equation (4), has similar structure (see main text).

3. The inclusion of m_t hence means that we have an ecological system with (unintended) species introduction. Contrary to this, for example, Rondeau (2001) considers a situation with intended species introduction, but where the population growth equation (a deer population is analyzed) is of the similar type as Equation (6).
4. The implicit assumption here is that the recreational fishers know the current year's stocks. Due to stock assessments before the fishing season starts (which usually is in mid June) this assumption may not be far too unrealistic.
5. For a similar classification, see Schulz and Skonhoft (1996), Zivin, Hueth and Zilberman (2000) and Horan and Bulte (2004).

REFERENCES

Anderson, J.L. (1985a) Private aquaculture and commercial fisheries: bioeconomics of salmon ranching. *Journal of Environmental Economics and Management*, **12**, 353–370.

Anderson, J.L. (1985b) Market interactions between aquaculture and the common-property commercial fishery. *Marine Resource Economics*, **2**, 1–24.

Anderson, L.G. (1993) Toward a complete economic theory of the utilization and management of recreational fisheries. *Journal of Environmental Economics and Management*, **24**, 272–295.

Barbier, E.B. (2001) A note on the economics of biological invasions. *Ecological Economics*, **39**, 197–202.

Bjorn, P.A. & B. Finstad (2002) Salmon lice, *Lepeophtheirus salmonis (*Kroyer), infestation in sympatric populations of arctic char, *Salvelinus alpinus* (L.), and sea trout, *Salmo trutta* (L.), in areas near and distant from salmon farms. *ICES Journal of Marine Science*, **59**, 131–139.

Carlton, J.T. (2000) Global change and biological invasions in the oceans. In H.A. Mooney & R.J. Hobbs (Eds.), *Invasive Species in a Changing World* (pp. 31–54). Island Press, Washington, DC, USA.

Clark, C.W. (1990) *Mathematical Bioeconomics: Optimal Management of Renewable Resources*, 1st ed. John Wiley & Sons, Hoboken, New Jersey, USA.

Enserink, M. (1999) Predicting invasions: Biological invaders sweep in. *Science*, **285**(5435), 1834–1836.

Esmark, M., S. Stensland, & M.S. Lilleeng (2005) *On the Run—Escaped Farmed Fish in Norwegian Waters.* World Wildlife Fund (WWF), Oslo, Norway.

Flaaten, O. (1991) Bioeconomic of sustainable harvest of competing species. *Journal of Environmental and Resource Economics*, **20**, 163–180.

Fleming, I.A., K. Hindar, I.B. Mjolnerod, B. Jonsson, T. Balstad, & A. Lamberg (2000) Lifetime success and interactions of farm salmon invading a native population. *The Royal Society Proceedings, Biological Sciences*, **267**(1452), 1517–1523.

Fleming, I.A., B. Jonsson, M.R. Gross, & A. Lamberg (1996) An experimental study of the reproductive behaviour and success of farmed and wild Atlantic Salmon (*Salmo salar*). *The Journal of Applied Ecology*, **33**(4), 893–905.

Food and Agriculture Organization of the United Nations (FAO) (2010) *The State of World Fisheries and Aquaculture 2010.* Fisheries and Aquaculture Department, FAO, Rome, Italy.

Ford, J.S. & R.A. Myers (2008) A global assessment of salmon aquaculture impacts on native salmonids. *PLoS Biology*, **6**(2), 411–417.

Gargan, P.G., O. Tully, & W.R. Poole (2002) The relationship between sea lice infestation, sea lice production and sea trout survival in Ireland, 1992–2001. In D. Mills (Ed.), *Salmon on the Edge* (pp. 119–135). Blackwell Science Ltd, Oxford, UK.

Hannesson, R. (1983) Optimal harvesting of ecologically interdependent fish species. *Journal of Environmental Economics and Management*, **10**, 329–345.

Hindar, K., I.A. Fleming, P. McGinnity, & O. Diserud (2006) Genetic and ecological effects of salmon farming on native salmon: Modeling from experimental results. *ICES Journal of Marine Science*, **63**, 1234–1247.

Hoagland, P. & D. Jin (2006) Science and sconomics in the management of an invasive species. *BioScience*, **56**(11), 931–935.

Hoagland, P., D. Jin, & H. Kite-Powell (2003) The optimal allocation of ocean space: Aquaculture and native-harvest fisheries. *Marine Resource Economics*, **18**, 129–147.

Holmes, B. (1998) Day of the sparrow. *New Scientist*, **2140**, 32–35.

Horan, R.D. & E.H. Bulte (2004) Optimal and open access harvesting of multi-use species in a second-best world. *Environmental and Resource Economics*, **28**, 251–272.

Kataria, M. (2007) A cost-benefit analysis of introducing a non-native species: The case of signal crayfish in Sweden. *Marine Resource Economics*, **22**, 15–28.

Knowler, D. & E.B. Barbier (2000) The economics of an invading species: A theoretical model and case study application. In M. Perrings, M. Williamson, & S. Dalmazzone (Eds.), *The Economics of Biological Invasions* (pp. 70–93). Edward Elgar, Cheltenham, UK.

Knowler, D. & E.B. Barbier (2005) Managing the Black Sea Anchovy Fishery with nutrient enrichment and a biological invader. *Marine Resource Economics*, **20**, 263–285.

Knowler, D., E.B. Barbier, & I. Strand (2002) An open-access model of fisheries and nutrient enrichment in the Black Sea. *Marine Resource Economics*, **16**, 195–217.

Krkošek, M., M.A. Lewis, A. Morton, L.N. Frazer, & J.P. Volpe (2006) Epizootics of native fish induced by farm fish. *Proceedings of the National Academy of Sciences of the USA*, **103**(42), 15506–15510.

Liu, Y., O.H. Diserud, K. Hindar, & A. Skonhoft (2012) An ecological-economic model on the effects of interactions between escaped farmed and wild salmon. *Fish and Fisheries*, **14**(2), 158–173.

Lovell, S.J., S.F. Stone, & L. Fernandez (2006) The economic impacts of Aquatic invasive species: a review of the literature. *Agricultural and Resource Economics Review*, **35**(1), 195–208.

Maynard Smith, J. (1974) *Models in Ecology*. Cambridge University Press, Cambridge, UK.

McConnell, K.E. & I.E. Strand (1989) Benefits from commercial fisheries when demand and supply depend on water quality. *Journal of Environmental Economics and Management*, **17**, 284–292.

McGinnity, P., P. Prodöhl, A. Ferguson, R. Hynes, N. Ó Maoiléidigh, N. Baker, D. Cotter, B. O'Hea, D. Cooke, G. Rogan, J. Taggart, & T. Cross (2003) Fitness reduction and potential extinction of native populations of Atlantic salmon *Salmo salar* as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society of London B*, **270**, 2443–2450.

McGinnity, P., P. Prodöhl, N. Ó Maoiléidigh, R. Hynes, D. Cotter, N. Baker, B. O'Hea, & A. Ferguson (2004) Differential lifetime success and performance of native and non-native Atlantic salmon examined under communal natural conditions. *Journal of Fish Biology*, **65**(1), 173–187.

Mesterton-Gibbons, M. (1996) A technique for finding optimal two-species harvesting policies. *Ecological Modeling*, **92**, 235–244.

Mooney, H.A. & R.J. Hobbs (eds.) (2000) *Invasive Species in a Changing World*. Island Press, Washington, DC, USA.

Naylor, R., K. Hindar, I.A. Fleming, R. Goldburg, S. Williams, J.P. Volpe, F. Whoriskey, J. Eagle, D. Kelso, & M. Mangel (2005) Fugitive salmon: Assessing the risks of escaped fish from net-pen aquaculture. *Bioscience*, **55**(5), 427–437.

Norges offentlige utredninger (1999) Til Laks°at Alle kan Ingen Gjera? *NOU*, **9**, 1–394.

Olaussen, J.O. & A. Skonhoft (2008a) On the economics of biological invasion: An application to recreational fishing. *Natural Resource Modeling*, **21**(4), 625–653.

Olaussen, J.O. & Y. Liu (2011) On the willingness-to-pay for recreational fishing—Escaped farmed versus wild Atlantic Salmon. *Aquaculture Economics & Management*, **15**(5), 245–261.

Olaussen, J.O. & A. Skonhoft (2008b) A bioeconomic analysis of a Native Atlantic Salmon (*salmo salar*) recreational fishery. *Marine Resource Economics*, **23**(3), 273–293.

Olsen, L.J. (2006) The economics of terrestrial invasive species: A review of the literature. *Agricultural and Resource Economics Review*, **35**(1), 178–194.

Perrings, C., M. Williamson, & S. Dalmazzone (Eds.) (2000) *The Economics of Biological Invasions*. Edward Elgar, Cheltenham, UK.

Ricciardi, A. (2003) Predicting the impacts of an introduced species from its invasion history: An empirical approach applied to Zebra Mussel invasions. *Freshwater Biology*, **48**, 972–981.

Roberge, C., É. Normandeau, S. Einum, H. Guderley, & L. Bernatchez (2008) Genetic consequences of interbreeding between farmed and native Atlantic Salmon: Insights from the transcriptome. *Molecular Ecology*, **17**(1), 314–324.

Rondeau, D. (2001) Along the way back from the brink. *Journal of Environmental Economics and Management*, **42**(2), 156–182.

Sánchez, Í., C. Fernández, & J. Arrontes (2005) Long-term changes in the Structure of Intertidal assemblages after invasion by Sargassum Muticum (Phaeophyta). *Journal of Phycology*, **41**(5), 942–949.

Schulz, C.E. & A. Skonhoft (1996) Wildlife management, land-use and conflicts. *Environment and Development Economics*, **1**, 265–280.

Settle, C. & J.F. Shogren (2002) Modelling native-exotic Species within Yellowstone Lake. *American Journal of Agricultural Economics*, **84**(5), 1323–1328.

Strobele, W.J. & H. Wacker (1991) The concept of sustainable yield in multi-species fisheries. *Ecological Modelling*, **53**, 61–74.

Tschirhart, J. (2009) Integrated ecological-economic models. *Annual Review of Resource Economics*, **1**, 381–407.

Williams, C.K., I. Parer, B.J. Coman, J. Burley, & M.L. Braysher (1995) *Managing Vertebrate Pests: Rabbits, Bureau of Resource Science*. Australian Government Publishing Service, Canberra, Australia.

Zivin, J., B. Hueth, & D. Zilberman (2000) Managing a multiple-use resource: The case of feral pig management in California rangeland. *Journal of Environmental Economics and Management*, **39**, 189–204.