Economic Impacts of Biological Invasion:

Escaped Farmed *vs*. Native Species

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ABSTRACT

Escaped farmed species is one type of biological invasions that have various potential ecological and economic effects on native species. The paper develops a general invasive species impact model explicitly capturing both ecological and economic effects of invasive species, especially farmed escapees, on native stock and harvesting. First, possible effects of escaped farmed species on the growth and stock of the native species are examined. Next, a bioeconomic model to analyze changes in yield, benefit distribution and overall profitability is constructed. Different harvesting cases such as commercial, recreational and joint commercial and recreational fishing are explored. The model is illustrated by a case study of the interaction between wild and farmed Atlantic salmon in Norway. The results suggest that the harvest and profitability of the native species decline after an invasion, but the total profit from the harvest of both the native and farmed stock may increase or decrease depending on the strength of the ecological and economic forces.

Keywords: biological invasion, escaped farmed species, native species, profitability

1. INTRODUCTION

During the last few decades, there have been increasing concerns about the effects of invasive species within various ecosystems. Invasive species are in some instances intentionally introduced to a new environment in order to obtain recreational and/or commercial gains for the human interests (Williams *et al.* 1995). In other cases, human activities have indirectly allowed intruders to establish themselves in a new environment. For example, at the large scale, global warming may push organisms to the high latitudes (Carlton 2000), and transportation and shipping may carry organisms cross the oceans (Enserink 1999). Small scale events such as waste-water discharges and farming activities may release organisms to the surrounding environment. Regardless of their origins, invasive species potentially generates diverse risks and effects on native species, local communities and ecosystems (Mooney and Hobbs 2000). The potential economic effects of invasive species consist of damages on economic enterprises, food safety and human health, market and international trade (Lovell, Stone and Fernandez 2006). These economic impacts can be severe. For example, Pimentel *et al.* (2002) and Pimentel, Zuniga and Morrison (2005) estimated that annual damage costs associated with invasive species ranged from millions to billions of dollars in the US. In addition to economic impacts, invasive species also generate ecological impacts, including losses in biodiversity, and changes in the structures and functions of populations and ecosystems (Mooney and Hobbs 2000). Holmes (1998) argued that invasive species are the second most important cause of biodiversity losses worldwide, just after habitat degradation.

In this paper, we analyze another potential concern associated with invasive species, namely the ecological and economic impacts of an invasive species from farming facilities on the natural habitants when there are interactions (e.g., competition and hybridization) between them. Farmed species in general are reared in confined facilities and located in specific areas that provide suitable environment for species growth and are accessible to markets. Due to natural disaster, accident and human errors, farmed animals can escape from their reared facilities to the surrounding environment, potentially generating both ecological and economic impacts on the native species.

The farmed escapees interact with the native species in various ways. Ecologically, they may interact through competition, predation, hybridization, colonization and spreading diseases and parasites. These ecological interactions may have both positive and negative effects on native species. In the case of escaped farmed salmon, for instance, once survived and established in the natural surroundings, escaped farmed salmon likely compete with the native salmon for food, natural habitat, even mates, which may alter the stock level and structure of native salmon (Naylor *et al.* 2005). It is reported that successful inbreeding between escaped farmed and native salmon reduces the fitness and productivity (McGinnity *et al.* 2003), dilutes the genetic gene pools (McGinnity *et al.* 2004; Roberge *et al.* 2008), and threatens the survival of the offspring of native salmon (Hindar *et al*. 2006). Also, escaped farmed salmon may spread diseases and parasites leading to augmented mortality of native salmon (Bjørn and Finstad 2002; Gargan, Tully and Poole 2002; Krkošek *et al.* 2006). If the number of escapees is low, the effects may be negligible; the effects become severe as the number of escapees gets larger. Particularly, some vulnerable native stocks may potentially go extinct with repeated invasion.

Escaped farmed species can also generate economic impacts through market. If invasive species has economic value as native species, escaped farmed species may increase the total stock level for harvesting. Additionally, in many respects, it may be impossible for the harvesters to separate native and escaped species if they belong to the same species or are closely related. Hence, this effect may result in increasing supply, and can be seen as an *economic quantity effect* (Olaussen and Skonhoft 2008a). Furthermore, harvesters may be concerned about the quality of their catch due to the share of escaped farmed species in the catch and interbreeding between farmed and native species. This could be directly related to the existence value of the genetically native species or to the loss of biodiversity due to gene flow from farmed to native species. Another interpretation is that harvesters simply prefer to harvest "clean" or "pure" native species. This can be seen as an *economic quality effect* (Olaussen and Skonhoft 2008a).

In this paper we aim to develop a general bioeconomic model to capture both ecological and economic effects of invasive species on native species. More specifically, we examine the ecological and economic effects of escaped farmed aquatic species on native aquatic stocks and harvest. However, the model framework and various mechanisms discussed here can be transferable to other situations where escaped farmed species mix with their native counterparts, or where an ecosystem, for any reason, faces a yearly influx of invasive species. For example, there is an apparent analogue to agricultural invaders that are grown commercially but escape to interbreed with native species. The increasing aquaculture production of both salmon and other species such as cod and halibut worldwide highlights the importance of addressing this specific issue.

The rest of the paper is organized as follows. The next section provides a general literature review on the economics of invasive species with an emphasis on aquatic species invasion. In sections three and four we derive the ecological and economic impact mechanisms of invasive species in general and escaped farmed species in particular on native species. We first introduce the ecological model of invasive species. Then in section four, the cost and benefit of the ecological system is considered where the flow of the services it provides is taken into account. No stock values, like existence value is included. The exploitation of the system is analyzed in section five where we consider a unified planner solution in equilibrium fishery situations; that is, there is zero growth in the fish stocks. In section six we apply the methodological framework to Atlantic salmon in Norway to explore the ecological and economic effects of escaped farmed salmon on native salmon stock and fishery under different scenarios. Section seven concludes the paper.

2. 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 and Jin 2006). Due to the reliable data availability, the latter case such as the economics of pest management and disease control have been extensively studied in agriculture, forestry and fisheries, but the former case are much less addressed (Perrings, Zuniga, and Morrison 2000). More especially, there is a very limited bioeconomic literature on measuring the damage costs associated with invasion. This limitation is probably due to lack of good data as well as uncertainties and measurement problems when facing the many components that are difficult to quantify accurately (Perrings, Zuniga, and Morrison 2000). This literature review focuses on the bioeconomic models estimating economic effects of invasive species on native organisms with a special interest in aquatic species.

A general conceptual bioeconomic model of the economic impact of the invasion is first developed by Knowler and Barbier (2000) and Barbier (2001). They specify two principles that should be followed when modeling the economic effects of an invasion on a native species. First, the exact interaction between the invader and native habitant should be examined, and second, they stress that the correct measure of the economic impacts of invasion is to compare the economic values (i.e., profits) of the *ex post* and *ex ante* invasion scenarios. The first principle is the essential step for an appropriate economic evaluation of an invasion. The conceptual model includes both diffusion and interspecies competition effects. The authors consider the invader as a pest without commercial value, and the native species is commercially harvested for economic values. Knowler and Barbier (2000) illustrate a special case of this bioeconomic model by only capturing interspecies competition. They model a predator-prey relationship between native anchovy species and invading comb-jellyfish in the Black Sea. The anchovy species is the prey for the comb-jelly fish, whose invasion leads to the decline in the productivity of anchovy species. The study indicates that the introduction of comb-jelly fish would have been destructive for local fishing communities dependent on the fishery for sustaining their livelihood.

Later, Knowler, Barbier and Strand (2002) and Knowler and Barbier (2005) apply this predator-prey bioeconomic model to further examine the interactions among nutrient enrichment, invasive comb-jellyfish and native anchovy in the Black Sea under different management strategies. The anchovy benefits from the nutrient abatement, and suffers from the competition and predation by comb-jellyfish. They show that the outbreak of comb-jellyfish resulting from nutrient enrichment can dilute the benefits raised by the pollution abatement. Similarly, Settle and Shogren (2002) examine the introduction of exotic lake trout into Yellowstone Lake based on the predation-prey relationships among lake trout, cutthroat trout, bear, bird and human beings. The authors find that if the invasive lake trout keeps unchecked, the native cutthroat trout population would dramatically decline, even go extinct, which further affects the grizzly bear population depending on cutthroat trout as the essential food source. The bioeconomic models in these studies are founded on the predation-prey-relationship between invasive and native species.

If invasion is viewed as a form of biological pollution, it, like other types of pollution, generates externalities on the 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 both demand and supply of commercial fish products under both open access and when fish stocks are efficiently allocated. They theoretically show that water quality affects the fish growth through fish reproduction and carrying capacity, and also changes the 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 generative positive net benefits if two species have different population growth. But, the introduction of signal crayfish will wipe out native noble crayfish because the two species cannot coexist.

However, in the case of fisheries and aquaculture, the literature on dealing with the economic impacts of farmed fish on native fish species is even smaller. Olaussen and Skonhoft (2008a) study 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 invasion, namely, *ecological level effect, ecological growth effect, economic quantity effect* and *economic quality effect*. Ecologically, escaped farmed salmon has negative impact on the growth of native salmon, and positive effect on the stock of native salmon; economically, it has a positive effect on supply (quantity) and negative effect on demand (quality) of native salmon.

In addition, a few 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 wild fish products. The results suggest that commercial fish stock declines since 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 in this paper differs from previous studies in several ways. First, we explicitly model the effects of an invasive species on the growth and stock of a native species by using a logistic growth model. We presume that both growth and stock effects on a native species are negative, and treat native and farmed species as separate stocks with a separate growth function for the escaped farmed salmon contrasting Olaussen and Skonhoft (2008b) who regard farmed salmon as a single exogenous flow into the system. Second, different from Knowler, Barbier, and Strand (2002) and Knowler and Barbier (2005) we consider the escaped farmed species as a potentially commercially valuable species. Additionally farmed species coexist with native species, not utterly replacing native species like in the crayfish case (Kataria 2007). A nonselective harvesting strategy is applied for both escaped and native species. Third, instead of using cultured area or aquaculture production as dependent variable to alter the carrying capacity (Hoagland, Jin, and Kite-Powell 2003), we hold the carrying capacity unchanged, and use the biomass of escapees as a *deterministic* variable to translate the ecological risks and effects into growth and stock variables of a native stock. Fourth, we assume that the growth of the invasive species is independent on the native species but dependent on its own biomass.

3. BIOLOGICAL MODEL

In absence of invasive species, the natural growth of the 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:

$$F(X) = rX(1 - X/K), \tag{1}$$

where r is the intrinsic growth rate and K 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 represents competition since carrying capacity can be interpreted as the maximum number of fish the environment can support.

Once farmed escapees survive and strive in the environment where native individuals reside, they become a part of the ecosystem, and directly and indirectly interact with native individuals. For instance, farmed salmon can escape to the rivers where they compete with native salmon, while farmed cod and halibut run off to the open ocean in which they interact with native habitants including their native counterparts. In brief, farmed escapees directly compete with native individuals over the natural habitat and food sources as well as mates in some cases. This competition results in changes in the structure and productivity of the native stock. Hence, incorporating the escaped farmed species, the growth function changes to $F(X,Y)$, where Y is the size of the escaped farmed species, or invasive species stock in general, also measured in number of fish (or in biomass). Typically, more escapees mean lower natural growth of the wild population, i.e. $\partial F(X,Y)/\partial Y = F_Y < 0$.

This negative growth effect may work through different channels. Based on the logistic 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 a competition mechanism is adopted by adding the term βY, with β as the competition coefficient. Modifying Eq. (1), we then obtain:

$$F(X,Y) = \tilde{r}X[1-(X+\beta Y)/K] \ . \tag{2}$$

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

As mentioned above, escaped organisms may inbreed with the 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, and name it as *growth effect*. The intrinsic growth rate can be then redefined as $\tilde{r} = \tilde{r}(X,Y) = r(1-e^{-\gamma X/Y})$, where $\gamma > 0$ is a scaling parameter. This formula indicates that the intrinsic growth rate declines with increasing biomass of escapees 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 $0 < Y < \infty$.

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

$$F(X,Y) = r(1-e^{-\gamma X/Y})X[1-(X+\beta Y)/K] \ . \tag{3}$$

Figure 1 demonstrates both the stock and growth effect on the native species 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.

In addition to the size of the parameters β and γ, the natural growth depends on the biomass of escaped farmed species Y, and where a higher Y yields a stronger negative effect.

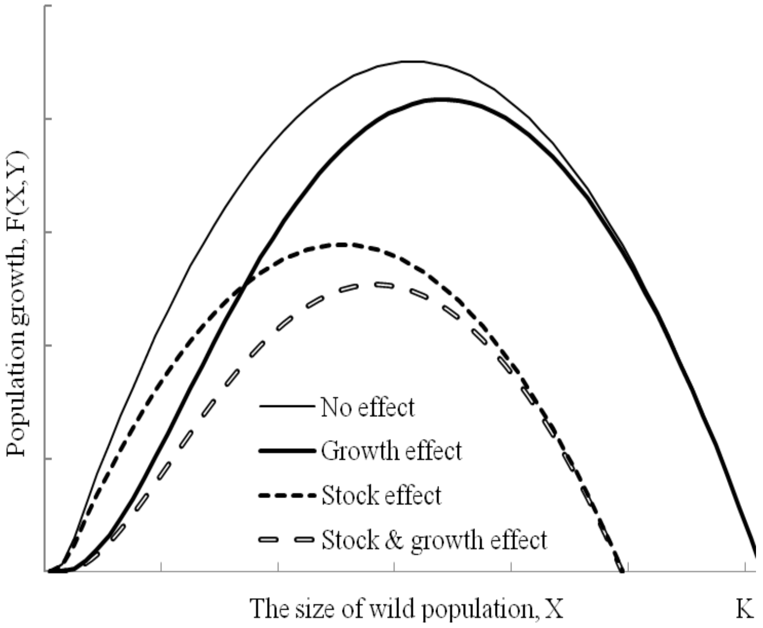

Figure 1. The growth and stock effects of escapees on the native stock growth.

Legend: light solid curve represents the growth without any effects; dark solid curve represents growth effect; dotted curve represents stock effect and dashed curve represents both stock and growth effects.

So far, we have assumed that invasive species in general, and escaped farmed species in particular, have negative ecological effects on native species. However, in some instances the effects may be positive. Japanese Seaweed, *Sargassum muticum*, for example, an invasive 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, and Arrontes 2005). Another example is invasive zebra mussels which have positive effects on water quality and the richness of macro-invertebrates in lakes. These positive effects, however, may counterbalance the negative effects on fouling of underwater structures and devices (Ricciardi 2003). Nevertheless, most marine species selected for aquaculture are generally highly-valuable 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 farmed species are also harvested, and since the escapees increase the stock available for harvest *ceteris paribus*, they may also have a positive ecological level effect. Salmon enhancement in Norway, Canada, Japan and the U.S is a good example of this *ceteris paribus* positive level effect (see also section two above).

Additionally, the growth of escaped farmed species as a part of the ecosystem has to be considered as well. All the time, the escaped farmed species growth is assumed to be governed by a density dependent growth. It should be noted that there may also be a feedback effect from native species on escaped farmed species similar to the effect of farmed species on native species. However, we have not been able to find empirical evidence in the literature on this aspect. It is assumed that this effect is weak or even negligible, and we do not take this effect into account in the growth of escaped farmed stock. Therefore, the natural growth of escaped farmed species is assumed to be density dependent by its own biomass only, and where the logistic growth function is adopted:

$$G(Y) = sY(1 - Y / K). \tag{4}$$

s is the intrinsic growth rate of farmed species while the carrying capacity is assumed to be the same as for the native species since they share the same habitat. We therefore consider a relatively simple growth model with an equal carrying capacity and an opposite structure of a unidirectional two species trophic-level model (see, e.g., Wilen and Brown 1986).

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

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

and

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

respectively. In an ecological equilibrium, the natural growth of the native species stock must exactly be balanced by the harvest, while the natural growth plus the flow of new escapees should be equal to the harvest of the invasive species. Thus, in equilibrium, we have $F(X,Y) = h$ and $G(Y) + m = q$. Equilibrium exploitation only will be studied below.

4. COST AND BENEFITS

Native species provides various values, including direct and indirect use values, option values and non-use values such as existence value or intrinsic value. Here we only consider the values directly related to the harvesting of native species and/or farmed species, which are evaluated based on market prices. Thus, within our unified planner framework, the objective of the planner is to maximize the net surplus of harvesting both native and escaped farmed species. As already indicated, two types of harvesting activities are considered: one is the harvest by commercial fishermen, and the other is the harvest by recreational anglers. The net benefit for commercial harvest is determined by the meat value harvested together with 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. We start to look at the commercial fishery.

4.1 Commercial fishing

The harvest functions are assumed to be of the standard Schaefer type where $h_t = \theta E_t X_t$ and $q_t = \theta E_t Y_t$ are the harvest of native and escaped farmed species, respectively, with θ as the catchability coefficient and E_t as the effort measured in, say, net fishing days (fishing days times number of nets). Note that these specifications imply non-selectivity in harvest with identical catchability coefficient for both native and escaped species. Therefore, the harvest only differs due to the abundance of native and escaped species. As a consequence, the harvest ratio is always equal to the stock ratio; that is, $h_t / q_t = X_t / Y_t$.

With $p > 0$ and $v \geq 0$ as the harvest prices of the native and invasive species, 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 writes:

$$\pi_t = p\theta E_t X_t + v\theta E_t Y_t - cE_t \,. \qquad (7)$$

The profit is increasing in the effort as long as $(p\theta X_t + v\theta Y_t - c) > 0$ which certainly will hold in an optimal program when the harvesting value only, as here, matters for the management. As indicated by (7), the invasive species may also be harvested for its economic value. However, in some instances 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 species is merely a pest, like the jelly-fish case in Knowler, Barbier an Strand (2002) and Knowler and Barbier (2005). Fishing is then for pest control, but takes place as a byproduct of the native species fishing through the non-selectivity in harvest. Section 5 will more fully explain these different cases.

4.2 Recreational fishing

Besides the commercial fishing, there may also be recreational fishing. Indeed, in some instances, the recreational fishery is the most important. Such a fishery is the Norwegian Atlantic Salmon fishery explored further in this paper (Section 6 below). While commercial fishing of the salmon takes place in the fjords and inlets, the salmon is also harvested in the rivers during their upstream spawning migration in the summer and autumn. The fishing activity in Norwegian rivers is almost always recreational in nature. In contrast to the net fishing in the fjords, this harvest is dominated by recreational anglers with fishing rods. Each angler pays a time restricted fishing permit to a landowner/river manager who is authorized the right by the state to sell fishing licenses. The license may be issued for some few hours and up to a seasonal permit. However, the most common is day permits issued on a 24 hour basis (Olaussen and Skonhoft 2008b).

Most of these rivers are managed by a single landowner, or a cooperation of landowners, acting as a single agent. The willingness to pay for a recreational fishery typically declines with the charged price (Anderson 1993). When assuming that the fishing permit price b_t also depends on the stock size X_t and/or Y_t, the inverse demand function may be written as $b_t = b(D_t, X_t, Y_t)$ and where D_t is the number of fishing permits, or number of fishing days. The overall surplus from recreational fishing in the rivers is made up of the landowner profit by selling fishing permits, plus angler surplus and is hence defined as:

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

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

In addition to being decreasing in the number of fishing permits, $b_D < 0$, the permit price is assumed to increase in the size of the native stock, $b_X > 0$, as a higher fish stock indicates a higher quality of the river (see, e.g., Olaussen and Skonhoft 2008b). The permit price may, however, both increase and decrease in the abundance of escaped farmed fish. It is increasing, $b_Y > 0$, 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 either preferences, or simply to difficulties to separate between escaped farmed and native species. On the other hand, the license 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. See also section 6.1 below.

4.3 Economic effects of invasion

The key goal of this paper is to examine the economic impacts of escaped farmed species on native species. Just as in Knowler and Barbier (2000) and Barbier (2001), the economic net effect of an invasion is determined by comparing the pre- and post-invasion scenarios. That is, the economic effect is the difference of the net benefits yielded from harvesting both native and farmed species *before* and *after* invasion. The net benefit discussed above reflects the post-invasion scenarios. If $\pi_{0,t}$ is the net current benefit of pre-invasion fishing for the commercial fishery, and $U_{0,t}$ for the recreational fishing, the current invasive economic impact B_t may be expressed as:

$$B_{C,t} = \pi_t - \pi_{0,t} = [(pX_t + vY_t)\theta - c]E_t - [(pX_{0,t})\theta - c]E_{0,t} \qquad (9)$$

and

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

respectively.

5. EXPLOITATION

As mentioned, the management of the considered ecological system is analyzed as an *equilibrium* fishery problem[1]. The unified planner then aims to maximize the overall net benefit in ecological equilibrium; that is, there is a zero growth rate in the native species stock as well as in the invasive species stock. We first consider commercial harvest alone. When using the general natural growth functional forms and omitting the time subscript, the Lagrangian of this problem writes:

$$L = (p\theta EX + v\theta EY - cE) - \lambda[\theta EX - F(X,Y)] - \mu[\theta EY - (G(Y) + m)] \quad (11),$$

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

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[1] Analyzing dynamic problems where the present value net benefit is maximized are hence left out in the present exposition. However, it is well known that the steady state of such problems coincide with the solution of the parallel equilibrium fishery problems except for the discount rate; that is, for zero discount rate these solutions are similar.

In this problem, harvesting effort E is the single control variable while there are two stock variables. The first order conditions with $X > 0$, $Y > 0$ and $E > 0$ are[2]:

$$\partial L / \partial E = p\theta X + v\theta Y - c - (\lambda \theta X + \mu \theta Y) = 0 \ , \tag{12}$$

$$\partial L / \partial X = p\theta E - \lambda\left[\theta E - F_X(X,Y)\right] = 0 \, , \tag{13}$$

and

$$\partial L / \partial Y = v\theta E + \lambda F_Y(X,Y) - \mu\left[\theta E - G'(Y)\right] = 0 \, . \tag{14}$$

Control condition (12) indicates that fishing effort should be used up to the point where the marginal revenue is equal to the marginal costs, which are made up of the effort cost plus the costs of reduced stocks evaluated at their shadow prices. The native species stock condition (13) states that the number of native species should be maintained so that the value of one more species on the margin should equalize its marginal cost, evaluated at its shadow price. Condition (14) has the same interpretation for the invasive species.

Rewriting (13) as $\lambda = p\theta E / (\theta E - F_X)$ it is seen that $\lambda > 0$ because the harvest function θEX has to intersect with the native species natural growth function F from below to secure an interior maximum solution (cf. also footnote 2). Moreover, rewriting equation (14) as $\mu = (v\theta E + \lambda F_Y)/(\theta E - G')$, it is first observed that $(\theta E - G') > 0$ also must hold for the same reason. When next inserting for λ and rearranging, we find that $\mu \geq 0$ if $v(\theta E - F_X) \geq -pF_Y$. Therefore, the invasive species shadow price is positive suggested that its harvesting price v is 'high' together with a 'small' negative effect on the native species growth; that is, F_Y is small in value. This may be considered as the 'value' case of the invasive species. In the opposite case, we have the 'pest', or 'nuisance' situation with a negative shadow price, $\mu < 0$[3]. However, whether the invasive species is to be considered as a pest or not it will always be optimal to harvest it, even if $v = 0$ and the invasive species is for sure a pest. This is due to the non-selective nature of this fishery.

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[2] As indicated by Figure 1, we may have a potentially non-convexity problem in our optimization as the native species growth function $F(X,Y)$ is not concave for 'small' values of X. This is confirmed by the numerical solution of the model (section 6) where we obtain an interior minimum point in addition to an interior (global) maximum point. At this maximum point, $F(X,Y)$ is concave in X.

[3] For a similar classification, see Schulz and Skonhoft (1996), Zivin, Hueth and Zilberman (2000) and Horan and Bulte (2004).

When the control condition (12) is rewritten as $(p-\lambda)\theta X+(v-\mu)\theta Y=c$, it is seen that $(p-\lambda)<0$ holds when the difference between the market price and the shadow price of the invasive species is 'large'. In this case, equation (13) written as $(p-\lambda)\theta E=-F_X\lambda$ indicates that F_X is strictly positive in an optimal program. Therefore, for a given optimal number of invasive species, the optimal native stock size will then be located to the left hand side of the peak value of the natural growth function, or X^{msy} (cf. also Figure 1). If the invasive harvesting price is 'low' and $\mu<0$, and the fishing cost c is 'low', we have $F_X>0$ for sure. As demonstrated below (section 6.2) this will be the baseline result in the numerical simulations, and hence contrasts the standard one species Gordon-Schaefer equilibrium harvesting model (Clark 1990). On the other hand, with 'high' c, but also 'low' value of the catchability coefficient θ, we typically end up with an 'large' optimal native stock and a solution to the right hand side of X^{msy}.

We then consider the recreational fishery. Harvest is still defined through the Schaefer functions $h=\varphi DX$ and $q=\varphi DY$ where effort is given in number of fishing days, or equivalently, number of licences (see above), with φ as the recreational catchability coefficient. Therefore, just as in the commercial case, non-selectivity with equal catchability coefficients indicates that the harvest ratio is proportional to the fish abundance ratio. The Lagrangian function now reads:

$$L=\int_0^D b(\xi,X,Y)d\xi-zD-\lambda[\varphi DX-F(X,Y)]-\mu[\varphi DY-(G(Y)+m)]. \tag{15}$$

The first-order conditions with $X>0$, $Y>0$ and $D>0$ are:

$$\partial L/\partial D=b(D,X,Y)-z-(\lambda\varphi X+\mu\varphi Y)=0, \tag{16}$$

$$\partial L/\partial X=\int_0^D b_X(\xi,X,Y)d\xi+\lambda[F_x(X,Y)-\varphi D]=0 \tag{17}$$

and

$$\partial L/\partial Y=\int_0^D b_Y(\xi,X,Y)d\xi+\lambda F_y(X,Y)+\mu[G'(Y)-\varphi D]=0. \tag{18}$$

The interpretations of these conditions are analogue to the commercial case equations (12), (13), and (14) above and should require no further comments. The important difference is that the willingness to pay for fishing permits, and hence the fish price, depends on the stocks of native and invasive species and the number of permits. Thus, while being exogenous in the commercial fishery, this price is endogenous in the recreational case. The cost structure is also different as there is no direct harvesting costs included in this recreational case. The landowner has a fixed unit cost of providing permits, but even in the presence of this fixed cost structure, condition (16) indicates that the landowner's profit generally is positive; at least when both shadow prices are positive. However, it should also be noted that if there are no stock effects in the demand function and $\int_0^D b_X(\xi, X, Y)d\xi$ and $\int_0^D b_Y(\xi, X, Y)d\xi$ equalize zero, conditions (17) and (18) indicate a zero shadow price for the wild as well as the invasive stock. As a consequence, condition (16) then yields zero landowner profit. Just as in the commercial model, we can 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 may happen when the native demand stock value effect is substantial while the other outcome may happen if, say, the harvesting catchability coefficient is 'high' or the willingness to pay for permits is 'high'.

The first order conditions (16) – (18) together with the equilibrium conditions $F(X,Y) = \varphi DX$ and $G(Y) + m = \varphi DY$ yield five equations determining the size of the two fish stocks, the effort and the two shadow prices. In addition, the native species harvest follows as $h = \varphi DX = F(X,Y)$ and the invasive harvest as $q = \varphi DY = G(Y) + m$. Combining these two equilibrium conditions yields $F(X,Y)/(G(Y) + m) = X/Y$. Therefore, the effects of the yearly inflow of escapees m on the fish abundance are channeled directly through this composite equilibrium condition. Differentiation now yields $(1/X)(F_X - F/X)dX - (1/Y)\{[G' - (G+m)/Y] - (1/X)F_Y\}dY = (1/Y)dm$. $F(X,Y)$ is concave in X at the optimum (footnote 2), $(F_X - F/X) < 0$, and the invasive stock function is concave as well, $[G' - (G+m)/Y] < 0$. Therefore, suggested that the optimal size of the invasive stock increases with a higher inflow (see Section 6), we find that the native stock may either increase or decrease if the negative ecological effect from the invasive 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. As discussed above, the size of the ecological effect is contingent upon a growth effect and a stock effect and is steered by two separate parameters in the specific functional form (section 3 above). In the numerical section it will be demonstrated that these parameters, and hence the magnitude of F_Y, have strong effects on the economics of this fishery. Note also that we have the same composite equilibrium condition in the commercial fishery.

As mentioned, combined commercial and recreational fishery management may also be an option. The net benefit of both fisheries together $(\pi + U) = (p\theta EX + v\theta EY - cE) + [\int_0^D b(\xi, X, Y)d\xi - zD]$ is then to be maximized subject to the ecological constraints. The first order control conditions of this problem are:

$$\partial L / \partial E = p\theta X + v\theta Y - c - (\lambda\theta X + \mu\theta Y) \leq 0; \;\; E \geq 0 \qquad (19)$$

and

$$\partial L / \partial D = b(D, X, Y) - z - (\lambda\varphi X + \mu\varphi Y) \leq 0; \;\; D \geq 0 \qquad (20)$$

while the stock conditions $\partial L / \partial X = 0$ and $\partial L / \partial Y = 0$ simply add up from the previous two separate harvest situations.

If the willingness to pay for recreational fishing is ‘high’ relatively 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 (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 sequentially fishing (cf. the Norwegian Atlantic Salmon fishery mentioned above and considered further in the numerical section). Such scheme complicates the analysis further as the biological constraints have to be adjusted accordingly. However, a sequential fishery is not pursued further in this paper (but see Olaussen and Skonhoft 2008b).

6. AN EMPIRICAL APPLICATION TO SALMON

6.1 Data and specific functional forms

The methodological framework discussed above will be illustrated empirically using the case of Atlantic salmon (*Salma salar*) in Norway. Atlantic salmon has become one of the most successfully farmed species for industrialized aquaculture, and salmon aquaculture is one of the fastest growing food producing sectors in the world. Just over three decades, farmed salmon production has increased from 500 tons in 1970 to over 1.3 million tons in 2006 (FAO 2007). Farmed salmon production has exceeded wild production worldwide since 1998. In contrast, native salmon stocks have declined in most areas, particularly in the North Atlantic. Some believe that salmon aquaculture has contributed to this decline because it triggers reduction in the survival of wild salmon (e.g., Ford and Myers 2008), spread of diseases and parasites (Bjørn and Finstad 2002; Gargan, Tully, and Poole 2002; Krkošek *et al.* 2006), and inbreeding (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 salmon aquaculture industry and wild salmon stocks (e.g., Esmark, Stensland, and Lilleeng 2005).

Atlantic salmon is an anadromous fish species. Its spawning and juvenile development take place in freshwater, while they feed and grow in the sea before returning to their natal rivers. Wild salmon is commonly harvested by two sectors: commercial fishing and recreational fishing. As already indicated (section 3), commercial fishermen harvest salmon in the fjords and inlets when salmon migrate toward their spawning ground, and recreational anglers target it in the rivers. Commercial harvest is specially destined for the meat value while recreational fishing is conducted by individuals for sport and leisure with possible addition for personal consumption. In addition, escaped farmed salmon in fjords and rivers are also caught by commercial fishermen and recreational anglers. As mentioned earlier, in the case of Norwegian salmon, the commercial and recreational fishery mainly takes place in a sequential pattern where the commercial fishermen harvest before the recreational fishing takes place.

In addition to the logistic natural growth functions (section 3) and the Schaefer harvest functions specified for the commercial and recreational fisheries (section 4), the inverse demand function in the recreational fishery has to be specified. It is given as $b = b(D, X, Y) = \alpha + \eta(1 - e^{-\kappa\varphi(X+Y)}) - \phi D$ where $\alpha > 0$ and $\phi > 0$ are the standard choke and slope parameters of the inverse demand function, respectively, while $\eta > 0$ and $\kappa > 0$ are parameters describing 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., $(h + q)/D = (\varphi DX + \varphi DY)/D = \varphi(X + Y)$, and where we hence assume the same quality effect of both wild and escaped salmon (see also section 4 above). This demand specification implies that when the fish abundance is 'small', the license choke price approaches α while it approaches its maximum value $(\alpha + \eta)$ when the fish abundance is 'high'. The baseline values for ecological and economic parameters are shown in Table 1. As seen from this table, some of the parameter values are based on qualified guess work and calibrations only, but sensitivity analyses are presented for the most important parameters.

Table 1. Baseline values ecological and economic parameters

Parameter	Description	Value	Reference
K	Carrying capacity	25,000 (salmon)	Assumed
r	Intrinsic growth rate, native salmon	0.26	Fishbase
s	Intrinsic growth rate, farmed salmon	0.26	Calibrated
β	Habitat competition coefficient	0.10	Calibrated
γ	Scaling factor growth effect	5	Calibrated
m	Yearly influx escaped farmed salmon	500 (salmon)	Calibrated
θ	Catchability coefficient, commercial	0.003 (1/day)	NOU
φ	Catchability coefficient, recreational fishery	0.000015(1/day)	OS
α	Reservation price (stock size equal 1)	500 (NOK/day)	OS
$\o$	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 fishery	50 (NOK/day)	OS
c	Unit cost of fishing, commercial	100 (NOK/day)	NOU
η	Demand translation parameter	500 (NOK/day)	Calibrated
κ	Quality effect parameter	3.33 (1/salmon)	Calibrated

Sources: Fishbase= www.fishbase.org., OS= Olaussen and Skonhoft (2008a) and NOU= NOU (1999).

6.2 Results

We first consider the commercial fishery separately and where the same price is assumed for escaped and wild salmon (Table 1). The results are shown in Table 2 which also reports the pre-invasion results. For the given parameter values and the optimal size of the invasive stock, the stock value representing the peak of the native stock growth function is about $X^{msy} = 12{,}100$. Hence, the size of the native stock is located to the left hand side of this peak. As discussed above (section 5) this outcome typically implies a rather large gap between the harvesting price of the invasive species and its shadow value. We find $\mu = 26$ (NOK/salmon) and therefore $(p - \mu) = 24$. The wild salmon shadow value $\lambda = 83$ (NOK/salmon) is substantial higher. On the other hand, as expected, we find the optimal stock size to be above $X^{msy} = K/2 = 12,500$ in the pre-invasive case (see also Table 1). While the native stock intrinsic growth rate is 0.26 in the pre-invasive situation it reduces slightly to $\tilde{r} = \tilde{r}(X,Y) = 0.26(1 - e^{-5*9,933/15,133}) = 0.25$ in the post invasive case (section 3 and Table 1). On the other hand, the stock effect given by the term, $\beta Y = 0.1*15,133 = 1,533$, which is about 15% of the optimal native salmon stock (1,533/9,933), is more profound. Altogether these two effects combined give a rather strong effect meaning that the optimal wild stock becomes significant lower than in the pre-invasion case. As a consequence, the native salmon fishery profit declines due to the invasive escaped farmed salmon, dropping from NOK 77 (thousand) pre-invasion to 63 (not reported in the table). Nevertheless, the profit becomes NOK 89 higher (115%) than the pre-invasion profit. Therefore, this native salmon profit loss is more than compensated by the profit attained from harvesting escaped farmed salmon. In fact, the profit of farmed salmon is higher than the profit of wild salmon because the harvest of farmed salmon is higher than that of the wild salmon. In addition, the optimal fishing effort is somewhat higher post-invasion than pre-invasion.

Table 2. Commercial fishing. Baseline parameter values

	Pre-invasion	Post-invasion	Difference
Stock size wild salmon, *X*	12,830	9,933	-2,897 (-23%)
Stock size farmed salmon, *Y*	-	15,133	
Harvest of wild salmon, *h*	1,623	1,348	-275 (-17%)
Harvest of farmed salmon, *q*	-	2,053	
Fishing effort, *E*	42.2	45.2	-3 (-7%)
Profit, π ('000 NOK)	77	166	+89 (+115%)

We have also looked at the situation where the escaped salmon harvesting price is zero , $v = 0$. With all the other parameter values unchanged, escaped farmed salmon then has a negative shadow price ($\mu = -6$) and is harvested just as a pest by-product due to the non selective nature of the fishery and for the benefit of the native salmon stock (section 5 above). The profit now declines significantly from 166 (NOK thousand) to 65 in this post-invasion pest case. We also find that the harvest and profit of the wild stock declines only slightly. Therefore, the escaped harvest price gives small quantum effects and the profit reduction is basically related to the missing invasive harvesting value.

We then turn to the recreational fishing situation. For the baseline parameter values the native stock as well as the invasive stock becomes higher than in the commercial case. In contrast to the commercial baseline case, the optimal native stock size is now is located to the right hand side of X^{msy} also in the post invasion case. As discussed above (section 5), this may typically indicate a rather 'low' permit demand, and/or a 'low' recreational fishery catchability coefficient. The results reported in Table 3 show that the size of the wild stock also decreases after invasion while the total surplus is higher after invasion. The angler surplus increases by 37% and the landowner profit increases by 18%. It is also seen that the harvest of wild salmon slightly decreases compared to that of pre-invasion while the total harvest dramatically increases by 119%. Further, note that the number of fishing days increases by 17% while the permit price increases only slightly after invasion. The shift in the demand function due to higher fish abundance translates therefore simply to more fishing days.

Table 3. Recreational fishing. Baseline parameter values

	Pre-invasion	Post-invasion	Difference
Stock size wild salmon, X	17,136	13,734	-3,402 (-20%)
Stock size farmed salmon, Y	-	18,413	
Harvest of wild salmon, h	1,401	1,314	-87 (-6%)
Harvest of farmed salmon, q	-	1,761	
Total harvest of salmon, $h+q$	1,401	3,075	+1,674 (+119%)
Fishing days, D	5,452	6,378	+926 (+17%)
Permit price, b (NOK/day)	133	134	+1 (+1%)
Angler surplus ('000 NOK)	1,784	2,440	+656 (+37%)
Landowner profit ('000 NOK)	455	539	+84 (+18%)
Total surplus, U ('000 NOK),	2,239	2,979	+740 (+33%)

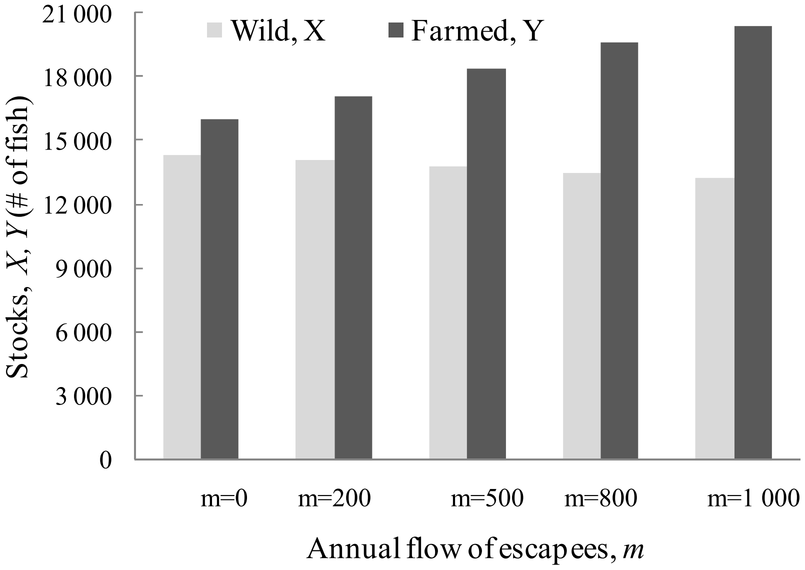
For the given ecological parameter values, the above results suggest that the ecolocial and economic effects of escaped farmed salmon on native salmon are substantial, i.e., F_Y is 'large' in value. The results also reveal that the harvest and profit of native salmon decrease after escaped farmed salmon enter the environment. However, farmed escapees yield supplementary harvests and profit and surplus to fishermen and anglers. These compensate the losses suffering from harvesting native salmon, and the total harvest and surplus become even higher than pre-invasion. This highlights an important feature of escaped farmed salmon.

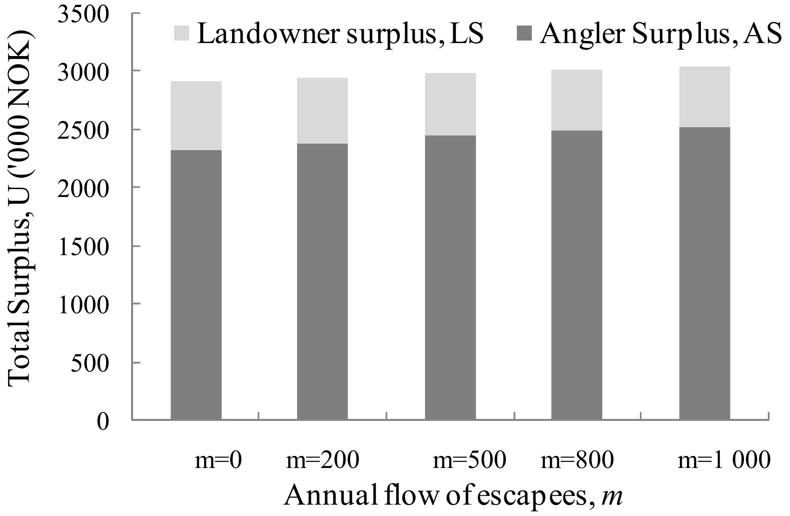
Since it contributes to the stock available for harvest, the incentives among fishermen, anglers and landowners to require that farmed fish do not escape are weak. For these reasons, the potential long term negative impacts through ecological mechanisms may hence be neglected by the various stakeholders.

As mentioned, salmon is typically harvested by both a commercial and recreational fishing sector in Norway. However, due to the high total surplus generated by the recreational fishery, our results typically 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) (Section 5). Thus, the mixed fishing is not considered here.

6.3 Sensitivity analysis

We have also tested the robustness of the results to changes in some key ecological and economic parameters. Since recreational fishing generates higher economic surplus to the society, we use this fishery to demonstrate these effects. We start to look at changes in the annual inflow of escapees, m, where we used 500 salmon in the baseline scenario, see Figure 2. Such changes may be related to the number of farmed salmon facilities in the given fjord- and river system, the regulation of the farmed salmon industry, and/or new technologies. We find that the equilibrium wild stock and harvest only slightly decline with an increasing annual flow of escapees (upper panel), cf. also section 5 where this effect is explained. On the contrary, the harvest and stock of farmed salmon increase significantly. The angler surplus rises gradually while the total profit increases slightly with an increasing inflow (middle panel). These effects are related to the reduced permit price and the increase in the number of fishing days (lower panel).


Wild, X
Farmed, Y
Stocks, X, Y (# of fish)
21 000
18 000
15 000
12 000
9 000
6 000
3 000
0
m=0
m=200
m=500
m=800
m=1 000
Annual flow of escapees, m


Landowner surplus, LS
Angler Surplus, AS
Total Surplus, U ('000 NOK)
3500
3000
2500
2000
1500
1000
500
0
m=0
m=200
m=500
m=800
m=1 000
Annual flow of escapees, m

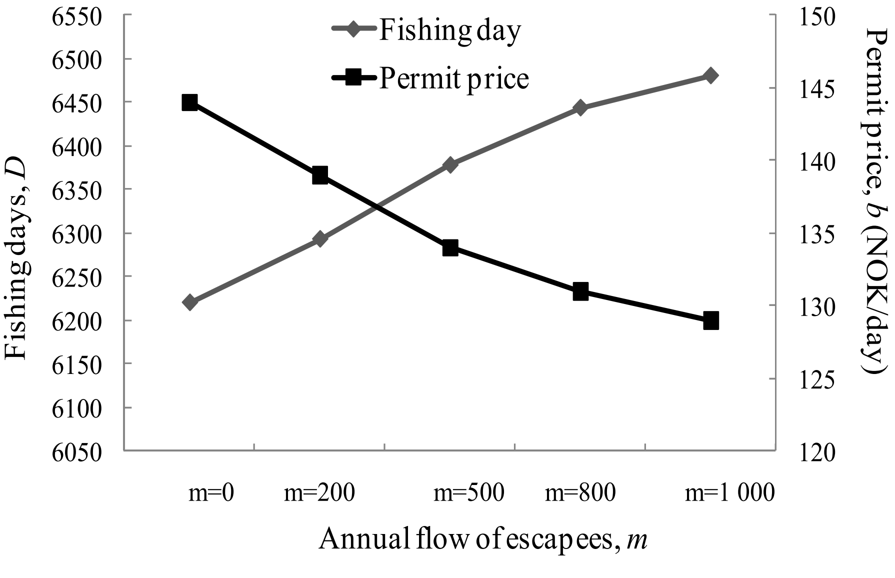

Fishing day
Permit price
Fishing days, D
6550
6500
6450
6400
6350
6300
6250
6200
6150
6100
6050
Permit price, b (NOK/day)
150
145
140
135
130
125
120
m=0
m=200
m=500
m=800
m=1 000
Annual flow of escapees, m

Figure 2. Recreational fishing. Effects of different yearly influx of farmed escapees m . Upper panel: stocks of wild and farmed salmon. Middle panel: landowner's profit and angler surplus. Lower panel: fishing day and permit price.

We next study changes in the parameter β which steers the intensity of the habitat competition between the wild and escaped farmed salmon. A higher β indicates that escaped farmed salmon has a stronger negative stock effect on wild salmon, i.e. F_Y increases in value (see Section 3). The results in Table 4 show that the optimal wild salmon stock declines rapidly with increasing stock competition and the location of the optimal stock shifts from the right hand side of X^{msy} to the left hand side. On the other hand, the farmed escaped stock increases. The number of fishing days and the permit price are strongly influenced as well, and the price increases and the fishing days decline with a higher value of β . As a consequence, the total surplus and benefit distribution change. For example, when changing β from the baseline value of 0.1 to 0.5, the total surplus declines from 2,979 to 2,507 while the landowner profit increases from 539 to 1,156. Therefore, fewer permits sold by the landowner is more than compensated by the higher permit price.

Table 4. Recreational fishing. Effects of increased habitat competition coefficient β . Baseline values in italics ($\beta = 0.1$).

	β=0.05	*β=0.1*	β=0.3	β=0.5
Stock size wild salmon, *X*	14,641	*13,734*	9,852	5,404
Stock size farmed salmon, *Y*	18,353	*18,413*	18,723	20,501
Permit price, *b* (NOK/day)	133	*134*	144	294
Fishing days, *D*	6,425	*6,378*	6,132	4,745
Harvest of wild salmon, *h*	1,411	*1,314*	906	385
Harvest of farmed salmon, *q*	1,769	*1,716*	1,722	1,459
Angler surplus ('000 NOK)	2,477	*2,440*	2,256	1,351
Landowner profit ('000 NOK)	533	*539*	578	1,156
Total surplus, *U* ('000 NOK)	3,010	*2,979*	2,835	2,507

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 wild 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. The optimal native stock also now shifts its location from the right hand side of X^{msy} when the permit demand is low, i.e., α is 'small', to the left hand side of X^{msy} when the permit demand shifts up. For instance, we find $X^{msy} = 12{,}190$ when $\alpha = 800$ while the optimal stock is slightly above 11,000.

Table 5. Recreational fishing. Effects of changed choke price α. Baseline values in italics (α =500 NOK/day).

	α =400	*α =500*	α =600	α =800
Stock size wild salmon, X	14,617	*13,734*	12,867	11,138
Stock size farmed salmon, Y	19,229	*18,413*	17,626	16,120
Permit price, b (NOK/day)	120	*134*	151	185
Fishing days, D	5,735	*6,378*	7,003	8,225
Harvest of wild, h	1,257	*1,314*	1,352	1,374
Harvest of farmed, q	1,654	*1,761*	1,851	1,989
Angler surplus ('000 NOK)	1,973	*2,440*	2,943	4,059
Landowner profit ('000 NOK)	400	*539*	706	1,111
Total surplus U ('000 NOK)	2,373	*2,979*	3,648	5,170

Finally we studied the effects of shifts in the catchability coefficient φ. Such shifts may be related to changes in gear restrictions and gear use (fly fishing, fishing lure, spinning bait). When the catchability coefficient increases from its baseline value of 0.000015 to a higher value, we find, not surprisingly, lower stock sizes both of the escapees and the wild 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 higher fishing price. As a consequence, we find increased landowner profit while angler surplus almost remains unchanged. The more or less unchanged value of the angler surplus is due to a two sided effect (section 5 and 6.1 above). 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, neutralized through the catch per effort stock effect.

Table 6. Recreational fishing. Effects of changes catchability coefficient φ. Baseline values in italics ($\varphi = 0.000015$).

	φ=0.00001	$\varphi = 0.000015$	$\varphi = 0.00002$
Stock size of wild salmon, X	16,700	*13,734*	11,036
Stock size of farmed, Y	21,208	*18,413*	16,034
Permit price, b (NOK/day)	103	*134*	171
Fishing days, D	6,301	*6,378*	6,222
Harvest of wild, h	1,052	*1,314*	1,373
Harvest of farmed, q	1,336	*1,761*	1,995
Angler surplus (‘000 NOK)	2,382	*2,440*	2,323
Landowner profit (‘000 NOK)	331	*539*	754
Total surplus, U ('000NOK)	2,713	*2,979*	3,076

7. CONCLUDING REMARKS

We develop a general invasion impact model capturing both ecological and economic effects of invasive species on native species. More specially, we model the effects of escaped farmed species on native species. Ecologically, two effects, namely growth and stock, are specified and incorporated into the logistic growth function of native species. Both have negative effects on the natural growth of native species. Economically, the benefit associated with native and escaped farmed species are explored. Native species is exploited for commercial values, while escaped farmed species is harvested either for commercial value or just as a pest byproduct due to the non selectivity nature of the fishery. 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 a nonselective harvesting technology and are analyzed in ecological equilibrium only. The nonselective harvesting assumption generates results that to some extent contrast the conventional perfect fishing selectivity case which makes our finding more interesting. Atlantic salmon in Norway is used as a case study to illustrate the interaction between wild and escaped farmed salmon. Sensitivity analysis is conducted to test the robustness of the results to changes in some key parameters used in the model such as yearly influx of escapees, habitat competition coefficient, chock price and catchability coefficient.

As expected, the ecological results are quite dramatic with respect to the stock, growth and harvest of native species, while the economic effects are not that profound. Clearly, ecological effects are substantial, even devastating, if the number of escaped farmed species is so large or the effect is so severe that native species may go extinct. At equilibrium, both species can coexist with farmed escaped species dominating the habitat given the values of parameters used in the model. However, economically, it turns out that the total net benefits received by fishermen and/or anglers and landowners are not declining, in some case they are even better off from harvesting both native and farmed species than solely catching native species. This is because the economic benefit lost from harvesting native species is compensated by the gain from harvesting escaped farmed species. This indicates that from a social welfare perspective, the benefit is transferred from farmers to fishermen, anglers and landowners in the case of salmon aquaculture. On the other hand, as the present partial analysis exposes, the potentially very severe negative ecological externalities escaped farmed salmon may incur on the native stocks through e.g. genetic pollution may not be taken into account by fishermen, anglers and landowners.

The model developed and the findings revealed here have the potential to provide many insights for fishermen/anglers and policy-makers. This ‘cheery’ picture may prevent fishermen/anglers, the society and policy-makers from recognizing the potential danger of losing a native salmon stock, even species, and taking appropriate actions. Moreover, it is clear that the cost of mitigating or eliminating escaped farmed species is likely very high once the escaped farmed species is established in the wild. Therefore, the society may bear a huge cost of removing the escapees. In sum, this study provides salmon farming and native salmon fishing sectors, and policy makers a broader understanding of the escape problems; and also sheds some light for them in order to develop appropriate management responses to reduce the escapees through investment on safer infrastructure and effective policies.

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