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ANALYSIS

Managing the Risks of Sea Lice Transmission Between Salmon Aquaculture and Wild Pink Salmon Fishery

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ABSTRACT

A common external effect of aquaculture is the transmission of infectious diseases to wild fish stocks. A frequently cited example of this is the infection of wild salmon by sea lice from salmon farms. Management of the disease risk to wild salmon populations requires an understanding both of the disease transmission mechanisms and the control incentives faced by fish farmers. In this paper we develop a bioeconomic model that integrates sea lice population dynamics, fish population dynamics, aquaculture, and wild capture salmon fisheries. Using an optimal control framework, we investigate options for managing the sea lice infection externality. We pay particular attention to the role of sea lice management on the stability of wild stocks, and the sensitivity of sea lice effects on wild fisheries. We find that the stability of wild stocks is related to sea-lice-induced mortality (inversely) and the value of wild fishery.

1. Introduction

Aquaculture is a rapidly growing industry that has become a major supplier of fish and shellfish to the global market (FAO, 2014). Concern about the environmental effects of aquaculture is also growing. The production of shrimp and salmon, two of the most lucrative and widely traded aquaculture products, is responsible for a range of environmental impacts due to the off-site effects of disease transmission, waste discharge, escapees, the use of chemicals and drugs, and the consumption of fishmeal and fish oil (Naylor et al., 1998). The most important of the environmental externalities of salmon farming is the transmission of sea lice to wild fish stocks (Asche et al., 2009; Taranger et al., 2015; Lafferty et al., 2015).

In this paper we focus on a particular disease externality of coastal salmon farms— the effect of sea lice on wild fish stocks. This effect has been debated extensively. Researchers agree that sea lice are one of many factors that affect wild stock levels. However, there is disagreement about the size of the effect. Some argue that lice are not instrumental in wild stock population decline (Marty et al., 2010). Others claim that where salmon net-pens provide ideal conditions for sea lice, they are the primary threat to vulnerable migrating wild juveniles (Krkošek et al., 2006, 2007). In both Norway and Canada, sea lice are argued to be a major threat to the sustainability of marine aquaculture and the viability of wild fisheries, and are subject to strict regulations (Torrissen et al., 2013).

The generic problem in the management of wildlife disease externalities of aquaculture is the regulation of transmission risks due to contact between infected farmed stocks and susceptible wild stocks (Conrad and Rondeau, 2015; Fischer et al., 2015, 2016). The mitigation of disease risk requires reduction in either the infection rate of farmed stocks or contact between farmed and wild stocks. In the case of marine salmon aquaculture, the infection rate of farmed fish may be reduced by chemical controls. Since farmed fish stocks have a reservoir-host effect on disease transmission, this also affects disease transmission to wild fish stocks.

From a social perspective, salmon farmers should ideally take account of the costs incurred by wild capture fisheries when deciding how much in-farm disease control to apply. Nor is the disease of wild salmon the only off-site effect to consider. It may, for instance, change the structure and distribution of other species within the system (Burge et al., 2014). Since disease is an external cost of salmon production, however, it will not be considered in the absence of regulatory, property-rights, or tax-based initiatives by a fishery authority.

This study focuses on the optimal management of sea lice externalities between salmon aquaculture and wild salmon fisheries that run in both directions. Sea lice are native ectoparasite copepods, common on wild adult salmon. The salmon louse (*L. salmonis*) has a free-living phase and a parasitic phase in its approximately 2-month life cycle (Frazer, 2009). Once attached to salmon, lice feed on mucous, blood, and skin which causes both morbidity and mortality of salmon (Costello, 2006). When wild stocks migrate to a fresh water environment in the fall for spawning, lice from wild stocks disperse into fish farms located on the migration route of wild stocks and infest the

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farmed fish. If not treated in the farms, the lice grow rapidly and re-infest wild juveniles when they emigrate into marine environment in the early summer. Although the disease problem associated with fish farms is widely recognized, there are few estimates of the ecological and economic impacts on both farmed and wild fisheries. One estimate is that sea lice may cost the salmon industry US$480 million a year or 6% of product value (Costello, 2009). Currently, salmon farms control lice with in-food chemical such as emamectin benzoate (SLICE) with high efficacy to control all stages of sea lice (Stone et al., 2000), and with cleaner fish such as wrasse or lumpfish. These controls have different cost effectiveness (Liu and Bjelland, 2014), also sea lice may develop resistance to SLICE (McEwan et al., 2015).

To analyze this problem we develop a bioeconomic model that incorporates epidemiological, ecological, and economic elements. As in prior studies of wildlife disease management that employ an optimal control framework (Gramig et al., 2009; Horan et al., 2010), we treat the level of disease control as endogenous. Specifically, we integrate sea lice population dynamics in an economic model of salmon production to determine the optimal control policy—first from the perspective of salmon aquaculture producer, and then from the perspective of a joint fisheries manager. By taking account of the complex relationship between sea lice populations in farmed and wild fisheries, we are able to assess the economic impact of salmon aquaculture on the wild fishery due to sea lice transmission. While our model is calibrated on the pink salmon fishery in Pacific Canada, our approach can readily be applied to the management of the disease effects of aquaculture on wild fisheries more generally.

The structure of the paper is as follows. Section 2 describes various components of sea lice-salmon interactions in aquaculture. Section 3 presents a bioeconomic model of farmed and wild fisheries. The main results and the outcome of numerical simulations are presented in Section 4. This is followed by sensitivity analysis provided in Section 5. Finally, Section 6 discusses the results and draws conclusions.

2. A Model of Sea Lice-salmon Interactions in Aquaculture

2.1. Sea Lice Dynamics

We consider a coastal area in which an Atlantic salmon (*Salmo salar*) farm (or a coordinated aquaculture industry consisting of many farms) is connected by the free-living stage of sea lice transmission with wild pink salmon stocks when they migrate into or out of spawning rivers. The farm manager releases salmon smolts ($F_{f,0}$) into fish farms just before wild adults head home for spawning. Fish farmers either employ batch harvesting at fixed intervals to target specific markets, or employ graded harvesting during the whole grow-out season. Aquaculture salmon production has a production cycle between 1.5 and 2.5 years (Asche et al., 2009). In this study we assume that production involves fixed interval batch harvesting-all fish are harvested 24 months after being released.

We divide sea lice growth into a free-living copepodite phase and an adult lice phase. Sea lice cannot survive in a fresh water environment. Due to the relatively brief spawning migration (August and September) of wild pink salmon from marine environment to fresh water environment, gravid lice from homecoming wild adult stocks would infest farmed stocks by spreading copepodite produced by gravid lice ($L_{w,t}$). Copepodites have a probability of ρ to attach to farmed ($F_{f,t}$) or wild ($F_{w,t}$) hosts if present in coastal waters. They then survive to adult lice stage with probability ψ_t depending on environmental factors, such as salinity and water temperature (Tucker et al., 2000). Settlement success ψ_t is assumed to be periodically forced, and takes the form,

$$\psi_t = \varepsilon_1 + \varepsilon_2 \sin\left(\frac{2\pi}{12}t\right) \tag{1}$$

This simple sinusoidal function generates a 12 month periodicity to infections, $t = 1, 2\ldots12$, and has a seasonal force impact coefficient of ε_2 and a base settlement success of ε_1.

When migrating wild juveniles pass by fish farms close to wild migratory routes from May to July they are subject to lice infestation. Wild juveniles are vulnerable because of their small size, and also because that they are subject to the environmental stress caused by the transition from fresh water to marine environment. We assume that the chemical treatment u_t, if applied, kills both adult sea lice and copepodites on farmed fish. The mortality rate associated with chemical treatment for copepodites and adult sea lice is denoted by k and z, respectively.

2.2. A Well-mixed Coastal Environment

The hydrodynamic environment is one of the main factors affecting the dynamics of sea lice transmission (Adams et al., 2012). Two different environments are considered here. First, we consider a coastal environment in which copepodites are well-mixed (Ashander et al., 2012), implying that copepodite density is the same across the whole area including the farm system. In what follows, subscript f denotes farmed stock, subscript w denotes wild stock, and subscript t denotes time (measured in months). If X_t denotes total copepodite abundance in the coastal area at time t, and $L_{f,t}$ denotes lice abundance in the farm, then a discrete model for sea lice dynamics in farm is,

$$X_{t+1} = \lambda\left(L_{f,t} + L_{w,t}\right) + X_t\left(1 - \rho\left(F_{f,t} + F_{w,t}\right)\right)(1 - \xi) f_c(u_{t-2}, u_{t-1}, u_t) \tag{2}$$

$$L_{f,t+1} = \rho\psi_t X_t F_{f,t} + L_{f,t}(1 - \nu)\left(F_{f,t+1}/F_{f,t}\right) f_l(u_{t-2}, u_{t-1}, u_t) \tag{3}$$

The dynamics of copepodite and lice populations are described by Eqs. (2) and (3). They are similar to a discrete-time version of the canonical Anderson-May host parasite model (Anderson and May, 1978). Eq. (2) describes the dynamics of copepodites in the coastal area. The first term on the right hand side (RHS) is the number of copepodites produced by lice on farmed $L_{f,t}$ and gravid lice $L_{w,t}$ which is equal to zero when there are no adult wild stocks in the coastal area. Copepodite production is taken to be at the constant rate, λ. $F_{w,t}$ denotes the abundance of wild juveniles at the end of month t. The second term has three components. The first component, $X_t(1 - \rho(F_{f,t} + F_{w,t}))$, is total copepodite abundance after dispersal and attachment to fish host. Copepodites are assumed to attach to hosts at the rate ρ. The second component is the surviving proportion after natural mortality of ξ and the third component is copepodite mortality due to chemical treatment, $f_c(u_{t-2}, u_{t-1}, u_t)$, the control being included in feed. Copepodite transmission between farmed and wild fish only happens during the spawning migration of wild adults and the emigration of juvenile wild stocks. Because sea lice cannot survive in a fresh water environment we assume that in this well-mixed system copepodites do not attach to wild spawning adults. However, wild juveniles will be infested when they migrate into the ocean.

Eq. (3) gives the total lice abundance in the farm at the beginning of each time unit (month) as the sum of the newly mature adults and the lice remaining from last period after natural mortality and the effects of chemical control. The first term on the RHS of Eq. (3) is the number of copepodites attached to hosts that become adult, the survival rate being ψ_t. The second term on the RHS is the number of lice remaining from last period. There are four components in this term. The first component is the total lice number at the beginning of the period, the second component $(1 - \nu)$ is the proportion surviving after natural mortality ν. The third one is the proportional change in the lice due to mortality between $F_{f,t+1}$ and $F_{f,t}$. We assume that if 10% of fish are killed, 10% of adult lice will also be killed. If all fish are harvested, then all lice will be killed in the process. The last component, $f_l(u_{t-2}, u_{t-1}, u_t)$, is the lice kill function due to chemical treatment.