R&D in natural resource based industries: Governments should prioritize innovation which reduces environmental hazards

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Abstract

Sustainable yield from a natural resource fluctuates in response to both natural conditions and harvesting practices. On the one hand, research and development (R&D) may reduce the fluctuations through more knowledge of ecosystem functioning. On the other hand, R&D may also increase the fluctuations if it results in more efficient harvesting operations with increased impact on the environment.

We analyze the incentives for innovation in a natural resource based industry. The direction of technical change can either be towards *profitability enhancing* innovations or *environmental hazard reducing* innovations. We then pose the following research questions: Is the market's ranking of *profitability enhancing* and *environmental hazard reducing* innovation projects in line with the ranking of the social planner?

In order to investigate our research question, we develop a theoretical model of innovation in a natural resource based industry, which we also calibrate to the Norwegian aquaculture industry. Two key results emerge; first, the government should subsidize the adoption of environmental hazard reducing technology. Second, the private incentive for *profitability enhancing* innovation is likely to outperform the private incentives for *environmental hazard reducing* innovation. In fact, the optimal R&D subsidy to to the former type of R&D is negative, while the optimal R&D subsidy to the latter type of R&D is positive and larger the more serious the environmental hazard.

Keywords: Renewable natural resources, innovation, environmental policy, aquaculture

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1 Introduction

Utilization of a provisioning ecosystem service by one agent regularly reduce the availability of the same provisioning service to other agents. Obvious examples are wild fisheries and fresh water reservoirs. It also holds for less obvious provisioning ecosystem services such as fish farming in open pens in which the health condition in one seafarm affects the productivity of all other neighboring seafarms.

Heavy utilization of provisioning ecosystem services may also reduce the availability of other ecosystem services such as recreation and biodiversity, categorized as a cultural and supporting ecosystem services, respectively. Again fish farming can be used as an example; fish farms utilize natural aquatic environments to provide the domesticated fish species with fresh water and oxygen. However, in many instances the activity reduces biodiversity in the surroundings and the opportunities for recreation such as hobby fishing.

The producer to producer externality in natural resource harvesting, may lead to overexploiting if entry is not regulated. Natural resource management therefore implies some form of regulation restricting the number of economic actors having the right to harvest the resource. In principle, entry restrictions can also be used to limit the environmental consequences of harvesting. While many papers have looked at various ways to restrict entry in natural resource management, no paper has to our knowledge looked at the interplay between natural resource management and innovation. We therefore develop a theoretical model of environmental innovations in a natural resource based industry, which we also calibrate to the Norwegian aquaculture industry.

We divide innovations into *profitability enhancing* and *environmental hazard reducing* innovations. *Profitability enhancing* innovations enables more efficient harvesting of the resource or improves the value of the harvest. *Environmental hazard reducing* innovations, on the other hand, reduces both the negative producer to producer externality and the environmental externality of harvesting. Thus, there is a positive externality in *adoption of environmental hazard reducing* innovations.

Our overarching research question is whether the market's ranking of private innovation projects is in line with the ranking of the social planner. In order to answer this question, we also inquire into closely related issues such as; what drives R&D investments and new technology adoption in natural resource based industries? How can the government obtain the first best levels of *profitability enhancing* and *environmental hazard reducing* innovation and adoption?

Our main result suggests that *environmental hazard reducing* innovations should be prioritized: The government should give an adoption subsidy to environmental innovations, and in addition, the government should also offer a directed R&D subsidy in case the environmental externalities of harvesting are large. As far as we know these results are new to the literature.

The adoption subsidy should be given since the private incentive to adopt an *environmental hazard reducing* innovation drops in the number of other users having adopted the innovation, while this is not the case for *profitability enhancing* innovations. Moreover, the R&D subsidy might be necessary since the innovator cannot capture all the benefits to society of an environmental innovation even if entry to the natural resource is regulated.

Theoretical environmental economics has for a long time been concerned with innovation in pollution abatement technology. Earlier contributions, such as Downing and White (1986), compare different environmental policy instruments with respect to how they affect environmental R&D. However, traditional environmental policy instruments, such as emission taxes, are rarely used in natural resource management. The earlier literature assumed that polluting firms could innovate, and did not include patents and licensing of innovations. However, according to Requate (2005) most pollution abatement innovations happen outside the polluting industry. Therefore, Laffont and Tirole (1996), Requate (2005) and Fischer and Newell (2008) separate the innovator from the polluting sector, as we also do in our model of innovation in a natural resource based industry.

In the environmental economics literature this gives rise to a potential commitment problem; when setting environmental policy, the government might try to influence the license fee set by the innovator for the new technology. In particular, the government would like the license fee to be low in order to increase adoption of the new technology. However, because this may hamper the profit of the innovator, the incentives to invest in R&D are undermined. Interestingly, in the case of a natural resource based industry, we find that the effect of not being able to commit to future policies goes in the opposite direction. When innovating for a natural resource based industry, the innovator strategically seeks to influence the regulator to issue more harvesting licenses. This increases the incentives to do innovation, and thus, even if appropriabillity is less than 100 percent and there is no public support to R&D, the amount of innovation in a natural resource based industry may be sufficient. In fact, the optimal subsidy to *profitability enhancing* R&D could turn out to be negative due to this effect.

So far the literature of innovation in natural resource based industries is mainly empirical. Moreover, innovations in natural resource based industries have been about reducing harvesting costs, see e.g. Bjørndal and Gordon (2000) on wild fisheries and Asche, Guttormsen and Nielsen (2013) on fish farming. However, according to the literature, innovation in natural resource based industries can also reduce negative environmental externalities, see e.g. Asche, Roll and Tveterås (2008) for a study on fish farming. Furthermore, Thavonen (2016) argues that in many instances replacing clear cut forestry with modern continuous cover forestry could significantly increase the supply of other types of ecosystem services without hampering the profits of the forestry operation. Finally, the introduction marine reserves in wild fisheries does not necessarily affect long run fish catches, while safeguarding other important marine ecosystem services (Dayton et al.,1995). However, as far as we know, no contributions has yet studied theoretically the incentives for innovations reducing environmental hazards.

The point of departure for our theoretical model is fish farming. In 2012 fish farming overtook capture fisheries with respect to metric tons produced (World Bank, 2016). Many countries are involved in fish farming e.g. China, the US, Canada, Chile, Scotland and Norway, and they all have ambitious plans to expand production as profitability is very good. However, many types of fish farming are riddled with environmental problems (see e.g. Edwards, 2015).The distinction between *profitability enhancing* and *environmental hazard reducing* innovations thus seems particularly suitable for the current research and development (R&D) efforts in fish farming (Asche 2017; Greaker et al. 2020). Inspired by the numerical calibration of innovation in energy markets in Fischer and Newell (2008), we also calibrate our theoretical model to Norwegian fish farming.

Separating knowledge into different types has some resemblance to the directed technical change literature, which lately has been extended into treating environmental innovations versus innovations in polluting technologies, see Acemoglu et al. (2012), and more lately Greaker, Heggedahl and Rosendahl (2017). One of the findings from this literature is that R&D subsidies should be directed away from technologies that are polluting towards environmental innovations even when emission taxes perfectly reflect the social cost of pollution. This result is however based on the existence of inter-temporal knowledge spill-overs, which we do not include in our model.

The lay out of the rest of the paper is as follows. In Section 2 we introduce our game theoretical model. Then in Section 3 we solve for the sub game perfect equilibrium and compare the market outcome with socially optimal outcome. In Section 4 we calibrate the model to Norwegian data for fish farming. In Section 5 we introduce a best available technology standard for *environmental hazard reducing* innovations. Then in Section 6 we discuss the relevance of our model for other natural resource based industries. Finally, in Section 7 we conclude.

2 The model

2.1 Preliminaries

In many types of fish farming juvenile fish are taken from hatcheries and placed in open cages in which they are fed until they reach maturity and harvested. The open cage provides the growing fish with a continuous supply of oxygen rich water, and does not require the farmer to collect and process waste from the farm. On the other hand, the open cage also allows for various negative externalities as already mentioned. Hence. in most countries you need a license from a regulator to place a fish cage in the commons. Since entry is restricted, a license owner will on the average earn a supra-normal profit.[1]

We let n denote the number of identical license owners having the right to place a fish cage in the commons. Each license has a value $(1-\varphi(\cdot))r(\cdot)$ equal to the expected supra-normal profit (henceforth; just profit). The function $r(\cdot)$ is the potential profit from the farm, while the function $\varphi(\cdot)$ should be interpreted as an environmental hazard rate depending on among others the number of other license owners in the area.

Both the hazard rate and the potential profit also depends on the available levels of knowledge. There are two representative innovation firms each specialized in one type of knowledge; either *profitability enhancing* knowledge K_t or *environmental hazard reducing* knowledge K_b (henceforth; technological and biological knowledge, respectively). The innovators offer the latest knowledge K_t (K_b) to the license owners at a price ω_t (ω_b). The license owners decide themselves whether they want to utilize the latest knowledge, or whether they will stay with the established knowledge.

[1] See for instance Greaker et al. (2017).

2.2 The effect of new knowledge

We let the potential profit from a license be denoted by the function $r(K_t)$. We assume $r_1 > 0$, $r_{11} < 0$, that is, profit per license increases in the level of technological knowledge. In fish farming, new technological knowledge could be higher valued marketing channels, more efficient feeding and faster growth variants of the fish specie in question.

At any point in time an unexpected environmental accident may hit a license owner. The accident could be loss of oxygen in the water due to pollution, infectious disease spreading, or, in particular for salmon farming; outburst of sea lice or simply escapes[2]. Moreover, environmental hazards may also imply environmental costs in addition to the loss in profits for the license owners; one example from fish farming is reduced wild salmon stocks.

We let the environmental hazard rate $\varphi(\cdot) \in \langle 0, 1 \rangle$ depend on the number of licenses n, the stock of biological knowledge K_b and the number of license owners who has adopted the latest biological knowledge m ($m \leq n$). In particular, we assume that the environmental hazard rate faced by an individual license owner can be described by:

$$\varphi(n, m, K_b) = \begin{array}{cc} \rho(n) - \frac{m}{n}\lambda(K_b) - \frac{n-m}{n}\gamma(K_b) & \text{if adoption of the latest technology} \\ \rho(n) - \frac{m}{n}\lambda(K_b) & \text{if free-riding} \end{array} \tag{1}$$

where $\rho', \lambda', \gamma' > 0$, $\rho'' \geq 0$ and $\lambda'', \gamma'' < 0$.

By the first term in (1) we incorporate a *tragedy of the commons* effect present in virtually all renewable resource industries (both rows). For instance, closely located farms increases the risk of spreading of infectious diseases and sea lice, see e.g. Asche et al. (2009).

The *tragedy of the commons* effect can be reduced by license owners adopting the latest level of biological knowledge. For instance, in fish farming innovators are currently doing research along a number of alternative routes to reduce the sea lice pressure; better treatments of infected salmon, closed pen designs, develop natural resistance to sea lice by selective breeding etc.[3] Any license owner that adopts the new technology, not only benefits herself, but also all other license owners e.g. the occurrence of sea lice in the area is reduced. The positive externality of technology adoption is given by the second term in (1) (both rows). We assume that the external effect of adoption is larger the higher the investment in biological knowledge K_b, and larger, the greater fraction of license owners m/n having adopted the latest level of knowledge.

There may also be a private benefit of knowledge adoption given by the third term in (1) (only the top row). The private benefit is also increasing in the investment in biological knowledge K_b, but decreasing, in the fraction of license owners having adopted the latest level of knowledge. As the general level of protection increases, the risk of others hampering your operation is lower, and, consequently, the private benefit of adopting the latest technology is diminishing.[4]

[2] Escapes often happen during treatment of deseases such as sea lice, and hence the probability of escapes also increases in the density of fish farms.

[3] See for instance Greaker et al. (2020).

[4] For instance, if more licence owners have switched to sea lice resistant salmon, you have less to gain since the sea lice pressure anyhow is reduced.

Finally, we make two assumptions about (1):

Assumption 1

$$0 < \rho(n) - \frac{m}{n}\lambda(K_b) - \frac{n-m}{n}\gamma(K_b) < 1, \forall K_b, n, m \text{ and } m \leq n$$

Assumption 1 implies that the environmental hazard rate cannot be removed completely.

Assumption 2

$$\arg\min_{m} \left\{ \rho(n) - \frac{m}{n}\lambda(K_b) - \frac{n-m}{n}\gamma(K_b) \right\} = n$$

That is, the environmental hazard rate is minimized with $m = n$. This requires $\lambda(K_b) - \gamma(K_b) > 0, \forall K_b$. Thus, given that adoption is costless at once the new technology is developed, it is socially efficient that all farms adopt.

2.3 Social welfare

Social welfare consists of the expected profits from all the licenses $(1-\varphi(\cdot))r(\cdot)n$ subtracted the expected environmental costs of the licenses, which are given by an environmental damage function $d(\bar{\varphi}(n, m, K_b)n)$ where $\bar{\varphi}(n, m, K_b)$ is the average environmental hazard rate, and $d\prime > 0$, $d'' \geq 0$.

The government sets the number of licenses. Furthermore, the government supports investment in new knowledge by directed research subsidies denoted by the rates σ_t and σ_b, respectively. The government may also support adoption of new knowledge by a subsidy s_t (s_b) to the innovator per adopting license owner. When considering these subsidies, the government takes into account the cost of developing new knowledge and, potentially also, increased harvesting costs when using new biological knowledge.

3 Solving the model

The model is solved as a three stage game. In the first stage, the government set research subsidy rates, and the two innovators invests in the two types of knowledge. Then the government issues a certain number of licenses and sets adoption subsidies given the new levels of knowledge. In the last stage, the innovator set prices ω_b and ω_t for utilizing the latest levels of knowledge, and the license owners decide whether to adopt the new knowledge. We solve the game by backwards induction.

3.1 Adoption of the latest level of biological knowledge

Assume that $m-1$ license owners have adopted the latest level of biological knowledge. It is profitable for the next license owner also to adopt if:

$$\left[\rho(n) - \frac{m}{n}\lambda(K_b) - \frac{n-m}{n}\gamma(K_b)\right] r(\cdot) - \omega_b - \left[\rho(n) - \frac{m-1}{n}\lambda(K_b)\right] r(\cdot) \geq 0$$

$$\Leftrightarrow$$

$$\left[\frac{\lambda(K_b)}{n} + \frac{\gamma(K_b)(n-m)}{n}\right] r(\cdot) - \omega_b \geq 0,$$

that is, the increase in expected profit caused by a decrease in the hazard rate, must be equal or larger than the price of the new biological knowledge. We assume that n is large such that $\lambda(K_b)/n \approx 0$. Thus, the maximum price the innovator can charge is $\gamma(K_b)(n-m)r(\cdot)/n$. Note that the this price is declining in m, and thus, the innovator faces a traditional downward sloping demand curve. [5]

The R&D cost of developing the new biological knowledge is sunk cost, however, providing the new knowledge to a license owner may still involve a positive marginal cost per adopting license owner. We set this cost to $b \geq 0$. Thus, the biological knowledge innovator set price ω_b maximizing revenues:

$$\left(\frac{\gamma(K_b)(n-m)r(\cdot)}{n} - b + s_b\right) m$$

where s_b is the adoption subsidy.

By differentiating this expression with respect to m, we can find the revenue maximizing m:

$$m^0 = \frac{n}{2}\left(1 - \frac{b - s_b}{\gamma(K_b) r(\cdot)}\right) \tag{2}$$

Hence, without a subsidy s_b, at most only half of the license owners will adopt the latest biological knowledge. The adoption price is $\omega_b = \gamma(K_b)r(\cdot)/2 + (b - s_b)/2$, and the biological innovator will obtain revenue:

$$\frac{n\left(\gamma(K_b)r(\cdot) - b + s_b\right)^2}{4\gamma(K_b)r(\cdot)} \tag{3}$$

We can now turn to the technological innovator.

3.2 Adoption of the latest level of technological knowledge

Denote the potential profit from a license when utilizing the established technology by $\bar{r}$. A license owner will adopt the latest level of technological knowledge if:

$$\begin{array}{lr} (1-\rho(n) + \frac{\lambda(K_b)m^0}{n} + \frac{\gamma(K_b)(n-m^0))}{n} \left[r(K_t) - \bar{r}\right] - \omega_t \geq 0 & \text{when latest level of } K_b \\ (1-\rho(n) + \frac{\lambda(K_b)m^0}{n})) \left[r(K_t) - \bar{r}\right] - \omega_t \geq 0 & \text{when established level of } K_b \end{array}$$

where ω_t is the price for utilizing the new knowledge K_t. The technological innovator has two options: Either she can set a high price, and only those who has the latest level of biological knowledge will adopt, or she can set a low

[5] Note also that in order to sell the latest level of biological knowledge, there must be a private benefit of adoption $\gamma(\cdot) > 0$. If $\gamma(K_b) = 0 \forall K_b$, a private market for new biological knowledge will not work. The government then need to set a mandatory standard. We analyze this case in Section 5.

price, and all license owners will adopt.[6] With $m^0 \leq n$ license owners having adopted the latest level of biological knowledge, and comparing the two profit expressions, we get that it is optimal to let all license owner adopt if:

$$\begin{aligned} & (1-\rho(n)+\frac{\lambda(K_b)m^0}{n}+\frac{\gamma(K_b)(n-m^0))}{n}\left[r(K_t)-\bar{r}\right]m^0 \\ \leq & \quad (1-\rho(n)+\frac{\lambda(K_b)m^0}{n}))\left[r(K_t)-\bar{r}\right]n \end{aligned}$$

Rearranging we obtain:

$$1-\rho(n)+\frac{m^0}{n}\left[\lambda(K_b)-\gamma(K_b)\right]\geq 0$$

which must hold by Assumption 1 and 2. Hence, we can conclude that the innovator will set the low price $\omega_t = (1-\rho(n)+\lambda(K_b)(m^0/n)))\left[r(K_t)-\bar{r}\right]$, and that all license owners will adopt the latest level of technological knowledge in equilibrium. Hence, there is no need for an adoption subsidy to technological knowledge. In the case in which there is no adoption subsidy to biological knowledge, we thus have:

Proposition 1 *While all license owners will adopt the latest level of technological knowledge, only a fraction of the licence owners will adopt the latest level of biological knowledge.*

As we will soon see, the rate of adoption for the latest level of biological knowledge is not necessarily socially optimal.

3.3 The number of licenses and the adoption subsidy

We start by assuming that the regulator can decide both the number of licenses n and the number of firms adopting the latest level of biological knowledge m. With m license owners having adopted the latest level of biological knowledge, the average accident risk $\bar{\varphi}(n, m, K_b)$ is given by:

$$\begin{aligned} & \left(\rho(n)-\frac{\lambda(K_b)m}{n}\right)\frac{n-m}{n}+\left(\rho(n)-\frac{\lambda(K_b)m}{n}-\frac{\gamma(K_b)(n-m)}{n}\right)\frac{m}{n} \\ = & \quad \rho(n)-\frac{\lambda(K_b)m}{n}-\frac{\gamma(K_b)(n-m)m}{n^2} \end{aligned}$$

From the assumptions already made about the ρ, λ and γ functions we have: $\bar{\varphi}_n > 0$, $\bar{\varphi}_m < 0$, $\bar{\varphi}_K < 0$ and $\bar{\varphi}_{nn}, \bar{\varphi}_{KK} > 0$. We can then write the maximization problem of the government:

$$\max_{n,m}\left[(1-\bar{\varphi}(n,m,K_b))r(K_t)n-d(\bar{\varphi}(n,m,K_b)n)-bm\right] \tag{4}$$

The first-order condition for the optimal number of licenses is given by:

$$\frac{\partial W}{\partial n}=(1-\bar{\varphi}(n,m,K_b))r(K_t)-r(K_t)\bar{\varphi}_n n-d'\left(\bar{\varphi}(n,m,K_b)+\bar{\varphi}_n n\right)=0 \tag{5}$$

[6] We assume that third degree price discrimination between license owners is not possible.

Since the welfare function is concave in n, the socially optimal number of n^* is given as the solution to (5) The first term (in brackets) are the average profit earned on a license. The second term $r(K_t)\varphi_n n > 0$ is the expected loss to all producers of increasing n which is not internalized by the individual license owner when deciding to enter. The third term is marginal environmental damage. We note that this is affected by (from left to right): i) there are more licenses which involves a given risk $\bar{\varphi}(n, K_b) > 0$, and ii) all licenses become more risky $\bar{\varphi}_n n > 0$.

For the optimal number of license owners adopting the new knowledge we have:

$$\frac{\partial W}{\partial m} = -r(K_t)\bar{\varphi}_m n - d'\bar{\varphi}_m n - b = 0$$

By inserting for $\bar{\varphi}_m n$, we see that the optimal number of adopting firms can be written:

$$m^* = n\left(\frac{\lambda(K_b)}{2\gamma(K_b)} + \frac{1}{2} - \frac{b}{2\gamma(K_b)\left(r(K_t) + d'\right)}\right)$$

By Assumption 2 we have $\lambda(K_b) > \gamma(K_b)$. For $b = 0$, it is then straight forward; the optimal m is a corner solution with $m^* = n$. For small additional costs of more sustainable harvesting practices b, you still get a corner solution. The condition is:

$$[\lambda(K_b) - \gamma(K_b)]\,[r(K_t) + d'] \geq b \tag{6}$$

that is, the social gain from lower accident risk caused by the last license owner to switch to the new technology, must be higher than the additional harvesting cost. Throughout the paper we will assume that this is the case, and hence, that $m^* = n$ even if $b > 0$.[7].

In order to obtain $m^* = n$, the government must set the following subsidy:

$$s_b = \gamma(K_b)r(\cdot) + b \tag{7}$$

The optimal subsidy can easily be derived from (2) setting $m^0 = n$. Note that the subsidy is higher than the additional costs of more sustainable harvesting practices. The government actually has to pay the innovator a premium equal to the private gain received by the first license owner who adopts the new technology. Moreover, with $s_b = \gamma(K_b)r(\cdot) + b$, the innovator will set $\omega_b = 0$. Since the government wants every license owner to adopt the new technology, the license owners must get the new technology for free.

When $m = n$, we have for the average accident probability $\bar{\varphi} = \rho(n) - \lambda(K_b)$. Moreover, all license owners adopt the latest technological knowledge to the price $(1 - \rho(n) + \lambda(K_b))r(K_t)$. Thus, with the adoption subsidy to biological knowledge, we have full adoption of both biological and technological knowledge in the first stage of the game.

Proposition 2 *In order to obtain the socially optimal rate of adoption, the government needs to subsidize adoption of new biological knowledge, but not new technological knowledge.*

[7] The assumption will not affect our main results as long as $m^* > m^0$, which must hold for $s_b = 0$.

The result should not come as a surprise, since there are both positive producer to producer and positive environmental externalities when new biological knowledge is adopted by an additional firm. Still it may be worth emphasizing that even if the environmental externality can be controlled by the entry regulation, it provides insufficient incentives for adopting environmental hazard reducing technology.

3.4 Optimal response to new innovations

It is of interest to see how the regulator responds to investments in new knowledge. By differentiating wrt. K_b (5) we obtain:

$$\frac{dn}{dK_b} = \frac{(r(K_t) + d')\,\bar{\varphi}_K + d''\,(\bar{\varphi}(n, K_b) + \bar{\varphi}_n n)\,\bar{\varphi}_K n}{\partial^2 W/\partial n^2} > 0$$

since $\partial^2 W/\partial n^2 < 0$, $\bar{\varphi}_K < 0$ and $\bar{\varphi}_n, d', d'' \geq 0$.

Further, by differentiating wrt. K_t (5), we also have:

$$\frac{dn}{dK_t} = \frac{r'\,[\bar{\varphi}_n n - (1 - \bar{\varphi}(n, K_b))]}{\partial^2 W/\partial n^2} > 0$$

since $\partial^2 W/\partial n^2 < 0$ and $\bar{\varphi}_1 n - (1 - \bar{\varphi}(n, m, K_e)) < 0$ for the optimal n.

Proposition 3 *New biological and/or technological knowledge induces the government to issue more licenses.*

The mechanisms are partly different: New biological knowledge both increases the average expected profit of the license owners, and reduces the risk of environmental hazards, while more technological knowledge only increases the expected profit of the license owners making the regulator willing to take more environmental risks. Thus, we also have the following result:

Corollary 4 *New technological knowledge will increase the frequency of environmental accidents.*

The corollary follows directly from Proposition 1; a higher number of licenses increases the environmental hazard rate. Note, however, that if the harvesting operation do not involve environmental costs $d(\cdot)$, we have $\bar{\varphi}_n n - (1 - \bar{\varphi}(n, m, K_e)) = 0$ from (5). Thus, with $d(\cdot) \approx 0$ more technological knowledge will not lead to more licenses.

3.5 Privately optimal R&D

We assume that there are two representative innovators setting R&D levels simultaneously. Inserting the optimal subsidy from (7) into the revenue function (3), we have that the biological innovator maximizes profits V_b given by:

$$V_b = \gamma(K_b) r(K_t) n - (1 - \sigma_b) K_b$$

where the first term is the revenue from the adoption subsidy when providing the license owners with the new biological knowledge, and the second term is the private cost of R&D taking into account the R&D subsidy rate for biological knowledge σ_b.

The technological innovator maximizes V_t given by:

$$V_t = (1 - \rho(n) + \lambda(K_b))r(K_t)n - (1 - \sigma_t)K_t$$

where the first term is the revenue from sales of new technological knowledge to the license owners, and σ_t is the R&D subsidy rate for technological knowledge. The first order conditions are given by:

$$\frac{\partial V}{\partial K_b} = r(K_t)n\gamma' + \gamma(K_b)r(K_t)\frac{dn}{dK_b} + \sigma_b - 1 = 0 \tag{8}$$

$$\frac{\partial V}{\partial K_t} = n(1 - \rho(n) + \lambda(K_b))r' + [1 - \rho(n) + \lambda(K_b) - \rho' n]\, r(K_t)\frac{dn}{dK_t} + \sigma_t - 1 = 0 \tag{9}$$

We assume that the profit functions of the representative innovators are concave, and hence that the optimal K_b and K_t are given as solutions to (8) and (9). The first term in (8) is the marginal increase in the income from the adoption subsidy, which is equal to the increase in the private benefit of new biological knowledge times the number of license owners.

The first term in (9) is the marginal increase in the potential value of all licenses given the accident risk. Note that both representative innovators act strategically e.g. they foresee that more knowledge of either type will increase the number of licenses, and that they will be able to sell their new knowledge to more license owners (second term in both (8) and (9)). Remember that the strategic effect for new technological knowledge is only positive as long as there is a negative environmental externality. This finding is highlighted in the proposition below:

Proposition 5 *The negative external environmental effects of natural resource harvesting increases the incentives to do profit enhancing innovation through a positive strategic effect.*

3.6 Socially optimal R&D

We have already looked at the optimal number of license owners adopting the latest level of biological knowledge. With $m^* = n^*$, the average biological hazard rate $\bar{\varphi}(n, m, K_b)$ is given by $\rho(n) - \lambda(K_b)$. The optimal levels of new knowledge is then found from solving:

$$\max_{n, K_b, K_t} W = (1 - \rho(n) + \lambda(K_b))r(K_t)n - d((\rho(n) - 2\lambda(K_b))n) - K_b - K_t$$

The first order condition for the optimal n is given by (5) (with $\bar{\varphi}(n, m, K_b) = \rho(n) - \lambda(K_b)$ and $\bar{\varphi}_n = \rho'$). The solution for n^* may be different to the extent that the privately optimal levels of K_b and K_t are different from the socially optimal levels.

Moreover, we have for K_b and K_t:

$$\frac{\partial W}{\partial K_b} = n(r(K_t) + d')\left(\lambda'\right) - 1 = 0 \tag{10}$$

$$\frac{\partial W}{\partial K_t} = n(1 - \rho(n) + \lambda(K_b))r' - 1 = 0 \tag{11}$$

The first term in (10) is the marginal gain from new biological knowledge, that is, the revenue and environmental value of a lower biological hazard rate. This marginal value should be set equal to the marginal cost of R&D funds(which is equal to unity). Likewise, the first term in (11) is the marginal gain in expected total revenue from new market knowledge, which also should be set to unity.

We immediately note that (10) and (11) differs from (8) and (9), thus, in order to induce the socially optimal levels of R&D the government needs to set $\sigma_b, \sigma_t \neq 0$. Using (10) and (11) together with (8) and (9), we have for the optimal R&D subsidy in the biological knowledge case:

$$\sigma_b = n\lambda' d' + nr(K_t)\left(\lambda' - \gamma'\right) - \gamma(K_b)r(K_t)\frac{dn}{dK_b} \tag{12}$$

Remember that the adoption subsidy to the biological innovator depends only on the private benefit of biological R&D e.g. $\gamma(K_b)r(K_t)$. However, a lower accident probability also decreases the expected environmental costs. The first term in (12) expresses this positive external value of new biological knowledge.

Moreover, again since the adoption subsidy only reflects the private benefit of biological R&D, incentives for biological R&D may be too small if the increase in the public benefit from adoption of new biological R&D is much larger than the increase in the private benefit from adoption of new biological R&D e.g. $\lambda' - \gamma' >> 0$. This is off course hard to have a general opinion on, and we may well have that the second term in (12) is close to zero.

Finally, the third term in (12) is the strategic effect of new biological knowledge. Note that this effect reduces the need for R&D subsidies, but only if the private benefit of environmental hazard reducing innovations $\gamma(\cdot)$ is significant.

For the optimal R&D subsidy in the technological knowledge case we have:

$$\sigma_t = -\left[1 - \rho(n) + \lambda(K_b) - \rho' n\right] r(K_t)\frac{dn}{dK_t} < 0 \tag{13}$$

Due to the adoption subsidy s_b, all license owners adopt the latest level of biological knowledge. The technological innovator can thus appropriate all profit gains from the new technological knowledge. The strategic effect then makes the incentives for technological innovation excessive e.g. we have $\sigma_t < 0$.

In the following proposition we try to summarize our findings:

Proposition 6 *With a subsidy to adoption of the latest biological knowledge such that all license owners adopt, the optimal R&D subsidy to technological R&D is negative, while the optimal R&D subsidy to biological R&D may be positive if the environmental externality is large and/or if the private benefit of environmental hazard reducing innovations $\gamma(\cdot)$ is likely to be small.*

Our results indicates that R&D subsidies should be directed towards biological knowledge creation. Our numerical simulations below also show that private biological R&D may fall far short of the socially optimal levels of such R&D.

Moreover, we may off course have a situation in which the government does not subsidize adoption of new biological R&D. In the Appendix we solve the model for this case as well. The result for the R&D subsidy does not differ very much from the results in this section: We find that R&D subsidies should be directed towards biological knowledge creation both when such innovation has the properties of a public good, that is $\lambda(\cdot)$ is large compared to $\gamma(\cdot)$, and/or when the environmental externality is large.

4 An application to the Norwegian fish farming industry

Fish farming in Norway is focused on salmon and sea trout which are bred in open pens in protected coastal areas like the Norwegian fjords and archipelagos. The coastal landscape provides Norway with a comparative advantage in fish farming, and Norway is by far the worlds largest producer of salmon and sea trout. The profit per license is currently very high, and the government recently conducted two auctions for new licenses; one in 2018 and one in 2020. The price of a license increased by 13% from 2018 to 2020, while the loss rate measured by the Norwegian Fishery Directorate stayed constant at 21% even if the number of licenses increased.[8]

Every second year since 2001 the NIFU Step group has collected R&D data on fish farming from universities, research institutes and private businesses. The R&D data is grouped under the following categories:production effectiveness, feeding, breeding and genetics, technical equipment, slaughtering and distribution, market development, environmental and cultural effects, and health and deceases. We have grouped the six first categories under "technical R&D", and the two last under "biological R&D". For the latest year of reporting; 2017, we have that € 71 million was spent on biological R&D and € 197 million was spent on technical R&D.

We use these figures to calibrate our model in order to illustrate the potential scale of misallocation of R&D investments. In the Appendix we explain how we use the data to calibrate our model. In short, we use simple square root formulas for the functions $r(K_t)$, $\lambda(K_b)$ and $\gamma(K_b)$, while for the effect on the hazard rate $\varphi(\cdot)$ of more licenses $\rho(n)$ we use a simple quadratic form. Moreover, for the environmental damage function we use the simple linear form $\delta * n * \varphi$. The parameter δ is calibrated by assuming that the observed number of licenses is socially optimal. We also assume that the observed levels of R&D is privately optimal given equal subsidy rates between environmental and technological R&D. Finally, we assume that a certain share of the changes we observe from 2018 to 2020 is due to random shocks. All the parameters can then be calibrated.

Remember that the value of a license increased by 13% from 2018 to 2020. We only ascribe 10% of this increase in value to technological R&D in 2017. The value of a license is very sensitive to the market price of salmon which historically has fluctuated a lot.[9] Furthermore, as mentioned the loss rate stayed constant from 2018 to 2020 even if the number of licenses increased. In Figure 1 we present results for the case in which the biological R&D in 2017 can explain

[8] The loss rate is the average loss in biomass from the pens over all the licenses.

[9] Assuming that technological R&D is more potent e.g. gives rise to a higher share of the change in value of a license, yields the absurd result that private technological R&D is taxed - remember that the observed levels of R&D should be privatly optimal.

50% of the reduction in the loss rate that needs to have taken place from 2018 to 2020:

Figure 1 "Optimal levels of R&D with full adoption"

Figure 1 to be placed here

On the x-axis we have the marginal environmental costs of accidents e.g. the parameter δ. The start value is calibrated from the first order condition for the optimal number of licenses, however, there are reasons to believe that the Norwegian government has put a too low value on the environmental costs e.g. wild salmon stocks have been drastically reduced because of fish farming.[10] On the y-axis we have million € in R&D spending. Then there are four graphs; the solid lines depict the optimal levels of R&D for different levels of the environmental costs, while the stippled lines depict the private levels of R&D e.g. the outcome of profit maximization by the representative innovators. Our model simulation yields stark results ; there is too much technological R&D and way too little biological R&D, that is, the grey stippled line is placed above the solid grey line, while the solid black line is far above the stippled black line.

As mentioned in the former section, we have also solved the model for the case without an adoption subsidy. We can use the same data to calibrate the model for this case as well. However, since we assume that the levels of R&D we observe are privately optimal, the values of some of the parameters will come out of the calibration differently. Below we present results for the case in which 70% of the reduction in the loss rate from an increase in the number of licenses from 2018 to 2020 is due to biological R&D in 2017, while only 15% of the increase in value from a license from 2018 to 2020 can be explained by technological R&D in 2017.[11]

Figure 2 "Optimal levels of R&D with no adoption subsidy to biological R&D"

Figure 2 to be placed here

Like in Figure 1, on the x-axis, we have the marginal environmental costs of accidents e.g. the parameter δ., and on the y-axis we have million € in R&D spending. Again, there are four graphs; the solid lines depict the optimal levels of R&D for different levels of the environmental costs, while the stippled lines depict the private levels of R&D e.g. the outcome of profit maximization by the representative innovators. Comparing Figure 2 to Figure 1, we note that we obtain the same results as in Figure 1; there is too much technological R&D and way too little biological R&D, that is, the grey stippled line is placed above the solid grey line, while the solid black line is far above the stippled black line.

[10] See for instance: https://www.vitenskapsradet.no/Nyheter/Nyhetsartikkel/ArticleId/4559/Status-of-wild-Atlantic-salmon-in-Norway-2018

[11] This yields an R&D subsidy rate of 0.5, and a value of $\gamma(\cdot)$ of about half the value on $\lambda(\cdot)$.

Finally, we have checked the robustness of our results. We assume that an optimal adoption subsidy is in place, but we vary the extent to which biological R&D in 2017 has caused the change in the loss rate from an increase in the number of licenses from 2018 to 2020.

Figure 3 "Sensitivity to the effectiveness of biological R&D"

Figure 3 to be placed here

The legend on the axis is the same as above. Then there are three solid lines each showing the optimal level of biological R&D for different values of the effectiveness of biological R&D. Note that we vary the effectiveness of biological R&D by adjusting the extent to which changes in the loss rate is caused by a random shock and not the biological R&D we observe. For instance, the lower solid line shows a case in which random shocks cause 80% of the changes in the loss rate. Since biological R&D then is correspondingly less effective, optimal investment levels are lower. Still we observe that investment levels are too low if the level of environmental damage is increased.[12]

5 Mandated biological technology adoption

Since subsidizing adoption of new biological knowledge may be costly, governments may prefer just to mandate the new technology avoiding any expenditures on an adoption subsidy. With mandated biological technology adoption the government requires all license owners to use the latest technology for environmental accident prevention. Thus, we have full adoption of both biological and technological knowledge in the last stage of the game. In the second stage of the game the government set the number of licenses as before. There is no qualitative changes to this stage of the game.

In the first stage of the game the innovators set their levels of R&D. For the technological innovator the situation is the same as with an adoption subsidy; all license owners adopt the new biological knowledge. Hence, the technological innovator can appropriate all profit gains from the new technological knowledge. The strategic effect then makes the incentives for technological innovation excessive, see (13).

With mandated technology adoption, it is hard to know what price ω_b the biological innovator can charge for new biological knowledge. Therefore, we simply assume that the biological innovator receives a share $\theta \in [0,1]$ of the increase in total industry profit.[13] Let total profits before R&D be given by Π^0. The biological innovator then maximizes:

$$V_b = \theta \left[(1 - \rho(n) + \lambda(K_b)) r(K_t) n - \Pi^0 \right] - nb - (1 - \sigma_b) K_b$$

where nb is the cost of providing the new technology to all license owners.

The first order condition writes:

[12] Note that is is not possible to increase the randomenss of the observed loss rate any further without coming into conflict with the assumption: $\lambda(K_b) - \gamma(K_b) > 0, \forall K_b$.

[13] See e.g. Fischer and Newell (2008) for this way of modelling the income of the innovator.

$$\frac{\partial V_b}{\partial K_b} = \theta\lambda' r(K_t)n + \theta\left[1-\rho(n)+\lambda(K_b)-\rho' n\right] r(K_t)\frac{dn}{dK_b} - b\frac{dn}{dK_b} - (1-\sigma_b) = 0$$

The socially optimal level of R&D is given by (10), and thus, we have for the optimal subsidy to environmental hazard reducing innovation:

$$\sigma_b = \lambda'(1-\theta)r(K_t)n + \lambda' d' n - \left[\theta\left(1-\rho(n)+\lambda(K_b)-\rho' n\right) r(K_t) - b\right]\frac{dn}{dK_b} \quad (14)$$

Despite the mandate, which ensures full adoption, the incentives for biological innovation may be inadequate. First, since $\theta < 1$, the biological innovator does not appropriate all gains in the license owners profit from an increase in K_b (first term in 14) Second, the expected environmental costs are reduced for which the innovator does not get paid (second term in 14). On the other hand, the strategic effect reduces the need for R&D subsidies (third term in 14). Note that since adoption is not subsidized, the strategic effect is weakened by the cost of the new technology b.

Proposition 7 *With a mandate ensuring full adoption of new biological knowledge, we have $\sigma_t < 0$, and $\sigma_b > 0$ if:*

$$\lambda'(1-\theta)r(K_t) + \lambda' d' n > \left[\theta\left(1-\rho(n)+\lambda(K_b)-\rho' n\right) r(K_t) - b\right]\frac{dn}{dK_b}$$

Thus, if the strategic effect is weak e.g. dn/dK_b close to zero and/or b is large or if the environmental costs of accidents are high, a technology mandate seems to provide an argument in favor of directing R&D subsidies towards biological knowledge creation. This holds even if appropriabillity is perfect e.g. $\theta = 1$.

6 The relevance of our model for other natural resource based industries

Salmon farming in open pens is one example of a natural resource based industry. The question is whether our results carry over to other natural resource based industries. Shrimp farming may be another example. According to Barbier and Fox (2004) shrimp farming also involves both a negative producer to producer externality and a negative environmental externality; in the form of diseases and loss of mangrove forest, respectively. Moreover, according to Barbier and Fox (2004) there exist farming technologies making it possible to reduce the negative externalities, however, in many cases their costs are prohibitive for small scale shrimp farmers.

The model may also provide insights for capture fisheries. A reoccurring problem in capture fisheries is bycatch of juvenile fish and other non-targeted species, see e.g. WWF (2009). With point of departure in the North Sea Trawl fishery, Catchpole et al. (2007) study the effects of different gear types on bycatch and on the sustainability of targeted fish stocks, and find that innovations in fishing gear can improve sustainability. If governments rely on markets to allocate R&D funds, and support all R&D projects by the same rate, development of more sustainable fishing gear may be cash strapped. This is especially so as the private value of more sustainable fishing gear $\gamma(\cdot)$ is likely to be small compared to the public value of more sustainable fishing gear $\lambda(\cdot)$.

The modern method of conducting forestry, so called *clear cut forestry*, also has its environmental problems e.g. reduced biodiversity, increased water run off and soil damage, release of forest carbon and loss in amenity value. Moreover, clear cut forestry implies that the forest is even aged making it more susceptible to diseases which entails a potential producer to producer externality. Tahvonen and Rämö (2016) analyses *continuous cover* forestry as an alternative to *clear cut* forestry, and find that many of the externalities connected with clear cut forestry might be reduced, while not hurting profitability significantly. On the other hand, few private forest owners seems to be interested in converting their operations to continuous cover forestry. We can only speculate to what extent this is caused by lack of R&D funds going into developing continuos cover forestry schemes and equipment.

7 Discussion and conclusion

We have analyzed innovation policy in the context of a natural resource with special focus on fish farming. One novelty of the paper is that we divide innovations into *profit enhancing* and *environmental hazard reducing* innovations. Given that innovation can take two directions, we have posed the following research question: Is the market's ranking of *profit enhancing* and *environmental hazard reducing* innovation projects in line with the ranking of the social planner?

We analyze the research questions within a theoretical model of innovation and by calibrating the model to the Norwegian salmon farming industry. Our main result suggests that *environmental hazard reducing* innovations should be prioritized: The government should give an adoption subsidy to environmental innovations, and in addition, the government should also offer a directed R&D subsidy in case the environmental externalities of harvesting are large. As far as we know these results are new to the literature.

The paper also includes additional theoretical results; for instance, when innovating for a natural resource based industry, there is a strategic effect which increases the incentives to do innovation. Thus, even if appropriabillity is less than 100 percent, the amount of innovation in a natural resource based industry may be sufficient even without public support. In fact, the Norwegian government has on two occasions promised additional licenses as a reward to innovation. In 2013 a number of new licenses were promised to those who came up with a method of reducing the environmental impact of a fish farm, indicating that $dn/dK_b > 0$. In 2017 more new licenses were to be given away in order to test of all kinds of innovations in fish farm technology indicating both $dn/dK_b > 0$ and $dn/dK_t > 0$.

In order to derive our results we have been forced to simplify our model in several ways. First, we assume that all license owners are identical. This is very much the case for the single salmon farm as they use standardized technology and the same breed of salmon. On the other hand, the natural conditions in one area may differ from another area. We thus like to think of our model as an "area model", and not a "country model". Moreover, there will of course be differences in the size of the firms owning the salmon farms. If one firm owns many firms in an area, the firm may internalize the tragedy of the commons effects. In particular, this may lead to higher adoption of new biological knowledge than in our model, and less need for an adoption subsidy to new biological knowledge. Still, the results regarding the incentives to do the two types of R&D are likely to hold. That is, with a dominating firm owning the majority of licenses in an area, the situation is more like the case in Section 5 with a mandatory standard and a low appropriabillity parameter θ.

Second, we have introduced a strict boundary between profitability enhancing and environmental hazard reducing innovations. There may of course be innovations that both reduce environmental hazards and improve profitability directly through $r(\cdot)$. The incentive for adoption of such innovations will, as far as we can see, tend to be the same as the incentive for adoption of pure profitability enhancing innovations. However, as the adoption of such innovations entails a positive external effect, the optimal R&D subsidy to profitability enhancing innovations may no longer be negative. Still, in our opinion, the misallocation of R&D funds will be more serious when innovations only are likely to reduce environmental hazards and the private benefit of adoption is small. Regulators cannot know *a priori* to what extent ideas for such innovations exist, but they can commit to support such innovations more than profitability enhancing innovations. As far as we know, this is not happening in Norway today.

Third, our model includes no population dynamics of the biological resource. Our interpretation of the model is that the bioeconomic system is in a steady state situation in which both the level of harvesting, the harvesting effort and the population size is optimal. Innovations will change the optimal solution, and this will trigger a transition period in which we move from one optimal solution to another optimal solution changing the harvest level, the harvesting gear and possibly the steady state stock of the biological resource. We do not model the transition, but in our opinion, including transition dynamics would not change the main result of the paper. The transition period could of course give rise to transition costs, but it should be possible to include those in the cost of biological knowledge adoption b or implicitly in the function $r(\cdot)$.

Finally, we assume that innovation is carried out in separate firms, and we do not model innovation by the license owners. As mentioned in the introduction, this is in line with much of the later literature on environmental innovation. If innovation happens in the firms that own licenses, the crucial question is whether a firm that innovates will patent its idea, and start to sell the new knowledge to other license operators. If yes, our model should still be a reasonable description of actual matters. If not, we conjecture that the incentives to environmental hazard reducing innovations is even smaller as the profit maximizing level of adoption of new biological knowledge is unlikely to be only one firm.

Summing up, we conclude that for natural resource based industries the private incentive for *profitability enhancing* innovation is likely to outperform the private incentives for *environmental hazard reducing* innovation. Governments should consider responding to this by prioritizing environmental hazard reducing innovation in public R&D spending.

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Appendix

A The case with no adoption subsidy

In order to simplify the analysis we set $b = 0$. Without an adoption subsidy, the regulator takes into account that the adoption rate for new environmental knowledge will be $m^0 = n/2$, see (2). The average accident risk $\bar{\varphi}(n, m, K_b)$ is thus given by:

$$\begin{aligned} & \frac{1}{2}\left[\rho(n) - \frac{\lambda(K_b)\frac{n}{2}}{n} - \frac{\gamma(K_b)(n-\frac{n}{2})}{n}\right] + \frac{1}{2}\left[\rho(n) - \frac{\lambda(K_b)\frac{n}{2}}{n}\right] \\ = \; & \rho(n) - \frac{\lambda(K_b)}{2} - \frac{\gamma(K_b)}{4} \end{aligned}$$

As before, the regulator maximizes welfare W with respect to the number of licenses n. This leads again to the equation (5), but since $m = n/2$, the optimal number of licenses will be different from the case when $m = n$. Inserting $b = s_b = 0$ into (3), we have that the biological innovator maximizes profits V_b given by:

$$V_b = \frac{\gamma(K_b)r(K_t)n}{4} - (1 - \sigma_b)K_b$$

where the first term is the revenue from sales of new biological knowledge to the license owners, and the second term is the private cost of R&D taking into account the R&D subsidy rate for biological knowledge σ_b.

Since not all license owners adopt the new biological knowledge, the technological innovator can only charge $\omega_t = 1 - \rho(n) + \lambda(K_b)/2$. The technological innovator thus maximizes V_t given by:

$$V_t = (1 - \rho(n) + \frac{\lambda(K_b)}{2})r(K_t)n - (1 - \sigma_t)K_t$$

where the first term is the revenue from sales of new technological knowledge, and σ_t is the R&D subsidy rate for technological knowledge. The first order conditions are given by:

$$\frac{\partial V}{\partial K_b} = \frac{r(K_t)n}{4}\gamma' + \frac{\gamma(K_b)r(K_t)}{4}\frac{dn}{dK_b} + \sigma_b - 1 = 0 \tag{15}$$

$$\frac{\partial V}{\partial K_t} = n(1 - \rho(n) + \frac{\lambda(K_b)}{2})r' + (1 - \rho(n) + \frac{\lambda(K_b)}{2} - \rho' n)r(K_t)\frac{dn}{dK_t} + \sigma_t - 1 = 0 \tag{16}$$

The interpretation of these equations is the same as for (8) and (9). In first best, the regulator sets n, K_b and K_t knowing that $m = n/2$, to maximize:

$$W = \left[1 - \rho(n) + \frac{\lambda(K_b)}{2} + \frac{\gamma(K_b)}{4}\right] r(K_t)n - d\left(\left[\rho(n) - \frac{\lambda(K_b)}{2} - \frac{\gamma(K_b)}{4}\right] n\right) - K_b - K_t$$

where the first order condition for the optimal n is essentially the same as before, although the solution for the optimal n will differ due to a lower adoption rate. Moreover, we have for K_b and K_t:

$$n(r(K_t) + d')\left(\frac{\lambda'}{2} + \frac{\gamma'}{4}\right) - 1 = 0 \tag{17}$$

$$n(1 - \rho(n) + \frac{\lambda(K_b)}{2} + \frac{\gamma(K_b)}{4})r' - 1 = 0 \tag{18}$$

The interpretation of these equations is the same as for (10) and (11). Using (17) and (18) together with (15) and (16), we have for the optimal R&D subsidy in the biological knowledge case:

$$\sigma_b^w = nr(K_t)\frac{\lambda'}{2} + n\left(\frac{\lambda'}{2} + \frac{\gamma'}{4}\right)d' - \frac{\gamma(K_b)r(K_t)}{4}\frac{dn}{dK_b} \tag{19}$$

where the superscript w denotes *without adoption subsidies*.

The biological innovator is only able to charge for the private benefit of her R&D, however, for every license owner that adopts the new technology, all other license owners experience a lower accident probability. The first term in (19) expresses this external value of new biological knowledge.

A generally lower accident probability also decreases the expected environmental costs. Moreover, for the individual license owner, adoption of the latest biological knowledge reduces the accident probability more than if she just free rode on the others adoption. This is good both for the license owner and for the environment. However, the license owner does not factor in the environmental effect, and consequently the innovator does not get paid for this. The second term in (19) expresses this external value of new biological knowledge, which is larger the higher is the environmental costs of the harvesting operation. Thus, a high d' will tend to make σ_b^w positive.

Finally, the third term in (19) is the strategic effect of new biological knowledge. Note that this effect reduces the need for R&D subsidies.

For the optimal R&D subsidy in the technological knowledge case without subsidies to adoption of new biological knowledge we have:

$$\sigma_t^w = \frac{\gamma(K_b)n}{4}r' - (1 - \rho(n) + \frac{\lambda(K_b)}{2} - \rho' n)r(K_t)\frac{dn}{dK_t} \tag{20}$$

Again, we see by the second term in (20), that the strategic effect reduces the need for subsidies. The subsidy to technological knowledge may still be positive if the first term in (20) is large. A license owner that has adopted the latest biological knowledge, has a higher benefit from new technological knowledge. The technological innovator cannot charge for that without loosing half of the market, and hence, the incentives for doing technological R&D may be too small.

Note that in both (19) and (20) the term $\gamma(K_b)$ plays a key role. A low $\gamma(K_b)$ implies that it is more tempting to free ride on other license owners' adoption of new technological knowledge. Further, a low $\gamma(K_b)$ also implies that the extra benefit an adopter of new biological knowledge gains from adopting the latest technological knowledge is small, which *ceteris paribus*, reduces the need for subsidizing new technological knowledge.

B The numerical model

Below we summarize that data presented in the main text:

Table 1 "Norwegian fish-farming"

	φ	n	K_b	K_t	$(1-\varphi)r(K_t)$
2018	0.21	1113	0	0	15
2020	0.21	1162	71	197	17

We calibrate the model for two cases; with full adoption and with partial adoption, that is, with no adoption subsidy.

B.1 With full adoption

When calibrating the model we normalize the levels of R&D before 2017 to zero, and we assume that levels of R&D in 2017 took effect in 2020. Moreover, we assume that levels of R&D only explains a part of the changes we observe in the variables. For the increase in expected profit from a license we therefore set $\Delta(1-\varphi)r(K_t) = (1-\varphi)\alpha\sqrt{K_t} + \xi\Delta(1-\varphi)r(K_t)$. The parameter α can then easily be calibrated from:

$$\alpha = \frac{(1-\xi)\Delta(1-\varphi)r(K_t)}{(1-\varphi)\sqrt{K_t}}$$

where ξ is the fraction of the increase in profits explained by exogenous shocks.

For the average hazard rate we have:

$$\varphi = \frac{n^2}{\bar{n}} - \frac{m}{n}\bar{\lambda}\sqrt{K_b} - \frac{(n-m)m}{n^2}\bar{\gamma}\sqrt{K_b}$$

where $\bar{n}$, $\bar{\lambda}$ and $\bar{\gamma}$ are parameters to be calibrated. First, since we have normalized K_b before 2017 to zero, $\bar{n}$ can then easily be calibrated from:

$$\bar{n} = \frac{(n_{2018})^2}{\varphi_{2018}}$$

where the subscripts refer to the year of measure.

Then we assume $m = n$ in 2020, and the last term in the hazard rate equation disappears. Furthermore, as above we assume that the change in the hazard rate caused by the change in N only partly can be explained by the level of biological R&D. We may then calibrate $\bar{\lambda}$ from:

$$\bar{\lambda} = \frac{(1-\zeta)\left(\frac{(n_{2020})^2}{\bar{n}} - \varphi_{2020}\right)}{\sqrt{K_b}}$$

where ζ is the fraction of the change in hazard rate explained by exogenous shocks.

Moreover, for the environmental damage function we use $\delta * n * \varphi$. The parameter δ is calibrated from the first order condition for the optimal number of licenses. We use 2018 as our point of departure:

$$\delta = \frac{r(K_t)}{\left(\varphi + \frac{2n^2}{\bar{n}}\right)} - r(K_t)$$

Finally, the levels of R&D should be privately optimal. This implies that the following must hold for technological innovation:

$$\frac{\partial V}{\partial K_t} = n(1-\varphi)\frac{\alpha}{2\sqrt{\Delta K_t^1}} + \left[1-\varphi-\frac{2n^2}{\bar{n}}\right] r(K_t)\frac{dn}{dK_t} + \sigma_t - 1 = 0$$

From this we can calibrate σ_t:

$$\sigma_t = 1 - n(1-\varphi)\frac{\alpha}{2\sqrt{\Delta K_t^1}} - \left[1-\varphi-\frac{2n^2}{\bar{n}}\right] r(K_t)\frac{dn}{dK_t}$$

where

$$\frac{dn}{dK_t} = \frac{\alpha\left[\frac{2n^2}{\bar{n}} - (1-\varphi)\right]\bar{n}}{-12n(r(K_t)+\delta)\sqrt{\Delta K_t^1}} > 0$$

For biological innovation we must have:

$$\frac{\partial V}{\partial K_b} = r(K_t)n\frac{\bar{\gamma}}{2\sqrt{K_b}} + \bar{\gamma}\sqrt{K_b}r(K_t)\frac{dn}{dK_b} + \sigma_b - 1 = 0$$

We set $\sigma_t = \sigma_b$. From this we can calibrate $\bar{\gamma}$:

$$\bar{\gamma} = \frac{1-\sigma_t}{\frac{r(K_t)n}{2\sqrt{K_b}} + \sqrt{K_b}r(K_t)\frac{dn}{dK_b}}$$

where

$$\frac{dn}{dK_b} = \frac{\bar{\lambda}\bar{n}}{12n\sqrt{K_b}} > 0$$

B.2 With partial adoption

The calibration of the parameters α, $\bar{n}$ and δ is the same. Then, we set $m = n/2$ in 2020 and $\bar{\gamma} = \mu\bar{\lambda}$. The average hazard rate is then given:

$$\varphi = \frac{n^2}{\bar{n}} - \frac{(2+\mu)\bar{\lambda}}{4}\sqrt{K_b}$$

Furthermore, as above we assume that the change in the hazard rate caused by the change in n only partly can be explained by the level of biological R&D. We may then calibrate $\bar{\lambda}$ from:

$$\bar{\lambda} = \frac{4(1-\zeta)\left(\frac{(n_{2020})^2}{\bar{n}} - \varphi_{2020}\right)}{(2+\mu)\sqrt{K_b}}$$

where ζ is the fraction of the change in hazard rate explained by exogenous shocks. However, we still do not know μ.

As assumed above, the levels of R&D should be privately optimal. This implies that the following must hold for technological innovation:

$$\frac{\partial V}{\partial K_t} = \frac{\alpha n(1-\varphi)}{4\sqrt{\Delta K_t^1}} + \left[1-\varphi-\frac{2n^2}{\bar{n}}\right] r(K_t)\frac{dn}{dK_t} + \sigma_t - 1 = 0$$

From this we can calibrate σ_t:

$$\sigma_t = 1 - \frac{\alpha n(1-\varphi)}{4\sqrt{\Delta K_t^1}} - \left[1 - \varphi - \frac{2n^2}{\bar{n}}\right] r(K_t)\frac{dn}{dK_t}$$

where, as above, we have:

$$\frac{dn}{dK_t} = \frac{\alpha\left[\frac{2n^2}{\bar{n}} - (1-\varphi)\right]\bar{n}}{-12n(r(K_t)+\delta)\sqrt{\Delta K_t^1}}$$

We set $\sigma_t = \sigma_b$. For biological innovation we must have:

$$\frac{\partial V}{\partial K_b} = \frac{n\mu\bar{\lambda}r(K_t)}{8\sqrt{K_b}} + \frac{\mu\bar{\lambda}\sqrt{K_b}r(K_t)}{4}\frac{dn}{dK_b} + \sigma_b - 1 = 0$$

where

$$\frac{dn}{dK_b} = \frac{(2+\mu)\bar{\lambda}\bar{n}}{48n\sqrt{K_b}}$$

We use this to calibrate μ.

Figures “R&D in natural resource based industries: Governments should prioritize innovation which reduces environmental hazards”

Figure 1

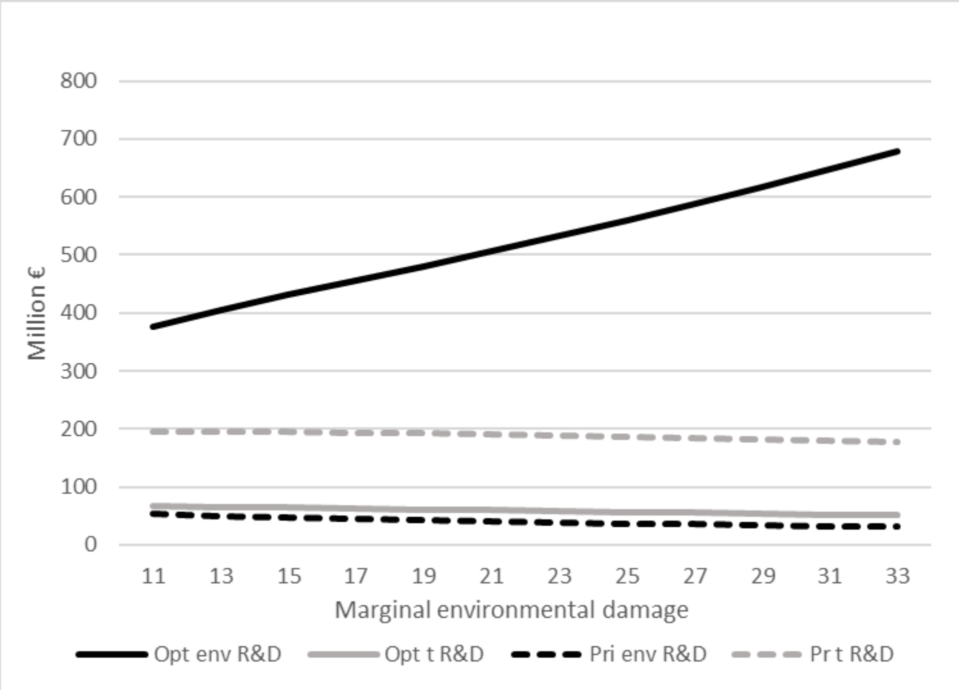


Figure 2

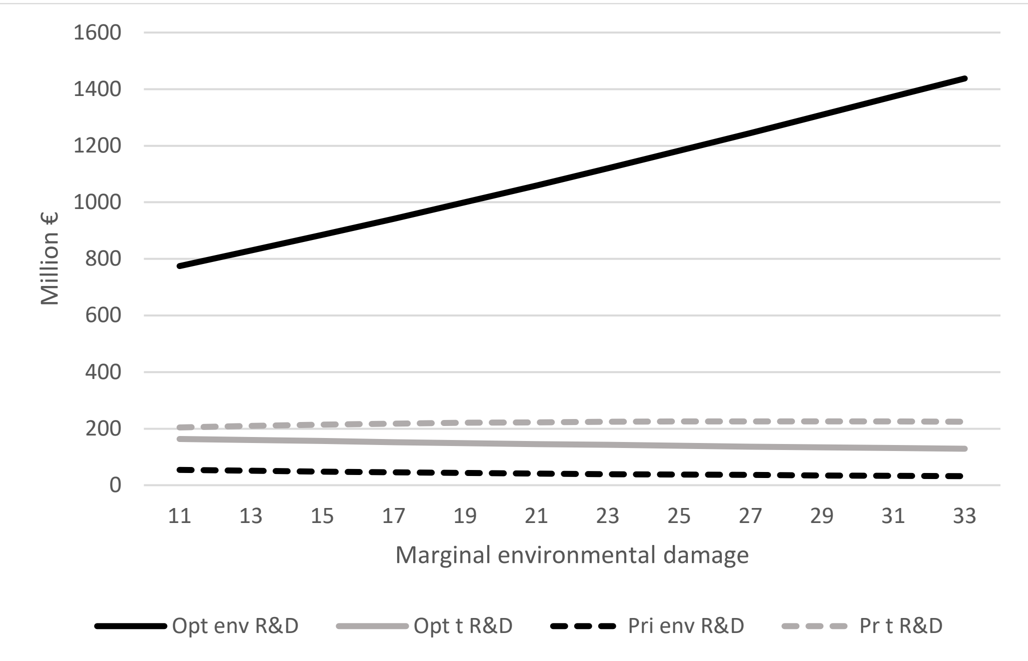
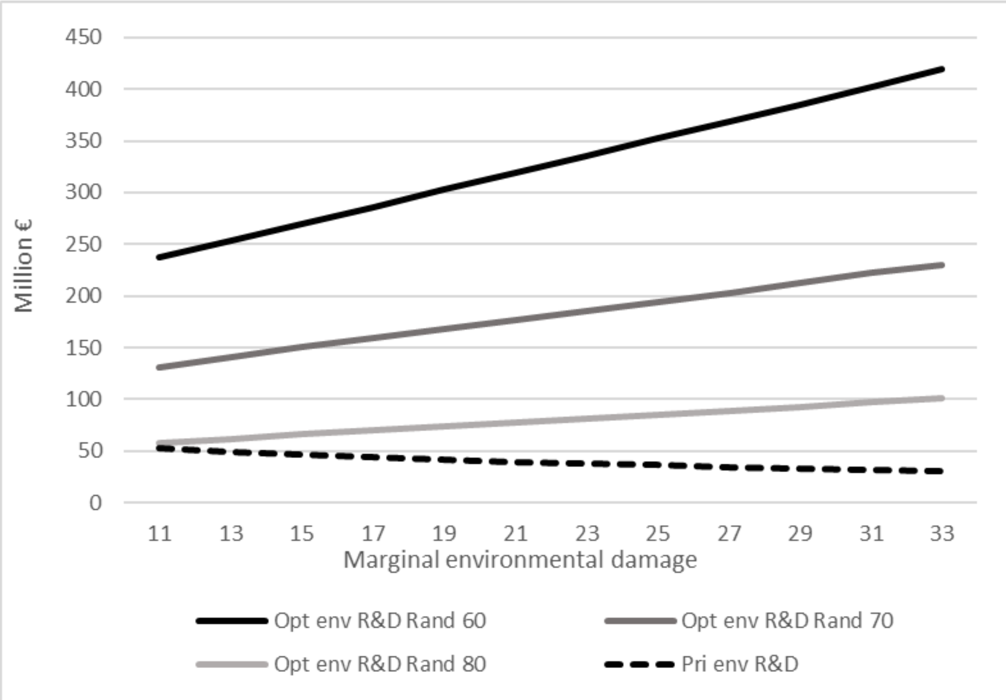


Figure 3



450
400
350
300
250
200
150
100
50
0
Million €
11
13
15
17
19
21
23
25
27
29
31
33
Marginal environmental damage
Opt env R&D Rand 60
Opt env R&D Rand 70
Opt env R&D Rand 80
Pri env R&D