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Risk aversion in renewable resource harvesting[☆]

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ABSTRACT

We study optimal harvesting of a renewable resource with stochastic dynamics. To focus on the effect of risk aversion, we consider a resource user who is indifferent with respect to intertemporal variability. In this setting, a constant escapement strategy is optimal, i.e. the stock after optimal harvesting is constant. We find that under common specifications of risk aversion, increasing risk and risk aversion increase current resource use. We show that this is due to an investment effect, i.e. the resource user invests in risk free alternatives, rather than the risky resource stock. A quantitative application of the model for the Eastern Baltic cod fishery shows that risk and risk aversion can have a much larger effect on optimal harvesting than found in the previous literature.

1. Introduction

Renewable natural resources are inherently volatile assets, exemplified by forests affected by fires and pest outbreaks (Patto and Rosa, 2022), freshwater reservoirs subject to fluctuating rainfall (Dettinger et al., 2011), and the growth of fish stocks depending on environmental conditions (Möllmann et al., 2021).[1] In many cases, climate change amplifies volatility (Sguotti et al., 2019). Thus the riskiness of incomes derived from natural resource use is of high and increasing concern both for risk-averse individual resource users and for policies regulating resource use. A key problem is to characterize optimal management of a dynamic renewable natural resource if the resource users are risk averse. The question of how risk and risk aversion affect the optimal use of natural assets is relevant beyond the management of renewable natural resources. Arguably, risk and uncertainty are of prime concern for climate change (Weitzman, 2009; IPCC, 2021) and biodiversity decline (IPBES, 2019), and insights from an analysis of optimal resource harvesting may contribute to the understanding how risk and risk aversion affect optimal policies for tackling risk in climate and biodiversity change. Indeed, Dasgupta (2021, chapters 4 and 4*) proposes to model key aspects of the global biosphere in a way that closely resembles renewable resource dynamics as we consider here.

Analyzing the optimal use of natural resources inherently requires a dynamic analysis: not only risk aversion, but also time preferences matter – in particular the preference for intertemporal smoothing of consumption. Various ways for disentangling risk and time preferences have been proposed in the literature (Kreps and Porteus, 1978; Epstein and Zin, 1989; Traeger, 2009; Bommier and Grand, 2018), and empirical studies show that these aspects of preferences are distinct (Epstein and Zin, 1991; Knapp and Olson, 1996; Epaulard and Pommeret, 2003). In the Epstein–Zin (1989) framework, (relative) risk aversion and the preference for

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[1] The seminal early work on stochastic resource models includes Reed (1974), Beddington and May (1977), Reed (1978, 1979), Pindyck (1984) and Clark and Kirkwood (1986).

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intertemporal smoothing are described by one parameter each. These parameters can be meaningfully compared, and typically the risk aversion parameter is much larger than the parameter capturing the preference for intertemporal smoothing (Vissing-Jørgensen and Attanasio, 2003; Epstein et al., 2014; Bai and Zhang, 2022).

In this paper, we focus on the effect of risk aversion and adopt the strong assumption that the decision-maker, albeit risk-averse, is indifferent with respect to intertemporal variability.[2] In a market setting, this assumption is valid if the resource user has access to perfect capital markets, but insurance is not available. We acknowledge this setting is a stark abstraction from reality, but we believe that it helps understanding the impact of risk aversion by analytically isolating its effect.

The previous literature on optimal harvesting of renewable resources with stochastic dynamics has mostly considered a setting where the resource users are neutral with respect to both, intertemporal variability and risk. Reed (1979) shows that optimal resource use then is characterized by a 'constant escapement' strategy: It is optimal to harvest all of the resource stock that goes beyond some constant quantity that should optimally be left in stock (i.e. 'escape' harvesting). This is because the statistical distribution of the future stock can be fully controlled by the user by adjusting current escapement. Costello and Polasky (2008) and Costello et al. (2015) apply this type of model to a spatial setting; Costello et al. (2019) consider both volatility of resource growth and the possibility of a regime shift, and always find the constant escapement strategy to be optimal.[3]

Another strand of literature considers risk aversion, but without disentangling risk aversion from the preference for intertemporal consumption smoothing. The implicit assumption is that the parameter capturing (relative) risk aversion is the same as the one capturing the preference for intertemporal consumption smoothing. McGough et al. (2009) linearize the problem around the optimal steady state to study under which conditions a constant escapement strategy is optimal. They show that for a decision maker who is both risk averse and averse against intertemporal variability, constant escapement is not optimal. Roughgarden and Smith (1996), Weitzman (2002), and Sethi et al. (2005) consider, on top of volatility of resource growth, additional uncertainties in form of measurement error and policy implementation error. A typical result is that risk and risk aversion, compared to a hypothetical situation without risk, have only a small effect on optimal harvesting (Kapaun and Quaas, 2013; Tahvonen et al., 2018).

Recent studies considered both risk aversion and a preference for intertemporal consumption smoothing, using an Epstein and Zin (1989) setting to disentangle these two aspects of risk- and time preferences. Quaas et al. (2019) use this framework to characterize the insurance value of natural capital, but do not analyze how resource use depends on risk or risk aversion. Augeraud-Véron et al. (2019) and Augeraud-Véron et al. (2021) consider a similar model to study the insurance value of biodiversity. However, these studies rely on very specific assumptions on the biological model to enable analytical insights. Augeraud-Véron et al. (2019) and Augeraud-Véron et al. (2021) study the effect of land conversion for agriculture versus conserving biodiversity. As biodiversity conservation can act as natural insurance, they postulate that converting land is increasing agricultural volatility. Accordingly, they find that land conversion is decreasing in risk aversion both in the social optimum and in a non-cooperative setting.

The model set up in this paper allows for a general resource growth function, and risk aversion, while assuming neutrality with respect to intertemporal variability of income. We show that under these assumptions optimal harvesting is still characterized by a constant escapement strategy. This reveals that the essential assumption to obtain this result is neutrality with respect to intertemporal variability, but not the assumption of risk neutrality. We exploit this result to derive analytical insights into optimal resource use under risk and risk aversion. We decompose the optimality condition for the constant escapement size into three different effects, namely wealth, investment, and gambling effects. We show how the wealth effect is linked to prudence (Kimball, 1990): if the resource may be diminished in the future, this will lead to lower rate of return from harvesting, and subsequently lower wealth. A prudent manager will want to for-arm herself against risk by investing in the resource (by increasing escapement), in order to increase future wealth and ensure a higher rate of return in the future. The investment effect represents the manager's dislike of risk and acts in the opposite direction to the wealth effect. Analogous to the investment effect in Ren and Polasky (2014), when the manager is risk averse an investment in a risky asset must be compensated by a higher expected return. Due to the concavity of the recruitment function, decreasing escapement increases the expected growth rate of the resource and thus leads to a higher expected future return. The gambling effect is concerned with the curvature of the cost function, as discussed by Kapaun and Quaas (2013). The user has a propensity to increase escapement and bet on good environmental conditions as this may reduce the cost of harvesting in the future.

Finally, we quantify the effect of risk and risk aversion on optimal harvesting in an application to the Baltic Sea cod fishery. This case study shows a strong effect of risk and risk aversion: Optimal management strongly decreases with risk aversion. This finding is in contrast to previous contributions that have not disentangled risk and time preferences (Kapaun and Quaas, 2013; Tahvonen et al., 2018). This result also differs from that of a risk-neutral user (who increases escapement under increased risk) and also contradicts a common intuition of many in the environmental community that risk aversion should give rise to more conservative management.

Our analysis suggests that the common assumption that the decision-makers are not only risk averse, but also have a preference for intertemporal smoothing, conceals the effect of risk aversion on optimal resource use. We find that under risk and risk aversion the certainty equivalent of future income from resource harvesting is (much) smaller than in a deterministic benchmark. In the setting considered here, this reduces the return of investing into the resource stock and thus reduces optimal escapement. A strong preference for intertemporal smoothing offsets this effect: The resource user will decrease current harvest in order to increase the

[2] As mentioned above, consistent with the existing related literature, we still focus on what is likely the most important dimension of the problem.

[3] Costello et al. (2001) show that constant escapement strategy is not optimal when managers are able to make predictions about the development of the stock, though.

certainty equivalent of future income. Depending on the degree of risk aversion and magnitude of risk, we show that the optimal escapement policy may differ considerably and this in turn may have significant implications for management: moving from risk neutral to risk averse managers might entail a significant decrease in welfare, which may give rise to insurance as a potential policy tool.

The paper is structured as follows: Section 2 outlines the model. Section 3 characterizes the optimal escapement policy for a user facing constant unit costs and Section 4 derives the optimal escapement policy for a user facing convex costs.[4] Both Sections 3 and 4 discuss comparative statics and use an example with constant absolute risk aversion (CARA) preferences to illustrate the theoretical findings. Section 5 then applies the model to the Baltic Sea cod fishery. Section 6 provides a discussion of the results and concludes.

2. The model

We consider the stock of a renewable resource in discrete time (index t). x_t is the resource stock at the beginning of period t, pre-harvest. Throughout period t resource harvest h_t diminishes the stock down to the 'escapement' $s_t = x_t - h_t$. Between periods the stock grows and growth dynamics of resource stock are described by the following stochastic Markovian transition equation

$$x_{t+1} = z_{t+1}\, g(x_t - h_t) = z_{t+1}\, g(s_t), \tag{1}$$

where z_{t+1} is a series of independently and identically distributed random shocks with unit expectation. Shocks are distributed on a finite interval $[\underline{z}, \overline{z}]$, where $0 < \underline{z} \le 1 \le \overline{z} < \infty$, with some given probability density function. We will also consider the deterministic benchmark case where $\underline{z} = \overline{z} = 1$, such that $z_t = 1$ for all t.

The expected resource stock at the beginning of the next period, $g(s_t)$, is an increasing, strictly concave, and twice differentiable function of escapement, $g'(s_t) > 0$ and $g''(s_t) < 0$. We also assume that $g'(s_t) > 1$ for sufficiently small s_t, whereas $g'(s_t) < 1$ for sufficiently large s_t. Thus, the expected growth of the resource, which is $g(s_t) - s_t$, is positive for sufficiently small s_t. There is, however, some value of $s_{\max}$ such that $s_{\max} = g(s_{\max})$, i.e., $s_{\max}$ is the expected carrying capacity of the resource. Given stochasticity, the next period's stock is a random variable, and so is the carrying capacity. Finally, we assume $\underline{z}\, g'(0) > 1$ such that (as the support of the shock z_{t+1} is finite) there is an interval of sufficiently small escapement levels where the stock will grow for sure, i.e., where $z_{t+1}\, g(s_t) \ge \underline{z}\, g(s_t) > s_t$ with certainty.

There is a single resource user with risk averse preferences. The resource we consider is small relative to the overall size of the market, and thus for the resource user the market price p of resource harvest is given. To focus on the effect of stochastic resource dynamics we keep p constant over time.

We assume that total harvesting costs can be written as $C(x_t) - C(s_t) = C(x_t) - C(x_t - h_t)$. They are increasing and convex in h_t and decreasing in x_t. Unit harvesting costs, $c(y) = C'(y)$, are (weakly) decreasing and (weakly) convex in the current stock size y, $c'(y) \le 0$ and $c''(y) \ge 0$. For some resources (e.g., fish) search costs decrease with the resource abundance, $c'(y) < 0$. For other resources, such as a forest, such a stock dependence of cost may be negligible, $c'(y) = 0$. Net revenues of resource harvesting in period t are obtained by integrating the flow of profit over the harvesting season,

$$\pi(x_t, s_t) = \int_{s_t}^{x_t} (p - c(y))dy = p\, x_t - C(x_t) - (p\, s_t - C(s_t)). \tag{2}$$

In the analysis, we consider two cases. First, we consider a resource where unit harvesting costs are independent of stock size, i.e. $C(y) = c\, y$, and then we consider the case where unit costs are strictly decreasing and strictly convex in current stock size, $c'(y) < 0$ and $c''(y) > 0$.

In a deterministic setting without shocks (i.e. in Eq. (1) we have $z_t = 1$ for all t), the resource manager would maximize the present value of net revenues with a discount factor β,

$$\bar{U}(x_0) = \max_{\{s_t\}} \sum_{t=0}^{\infty} \beta^t \pi(x_t, s_t) \tag{3}$$

subject to (1), with initial stock size x_0. The maximization in (3) is over the entire plan of future escapement levels, $\{s_t\}$. Using $U(x_t)$ to denote the corresponding present value of net revenues starting from period t, with x_t as the corresponding initial stock size, the problem to maximize (3) can also be written in recursive form (i.e. as the Bellman equation):

$$\bar{U}(x_t) = \max_{s_t} \left\{ \pi(x_t, s_t) + \beta\, \bar{U}(x_{t+1}) \right\} \overset{(1)}{=} \max_{s_t} \left\{ \pi(x_t, s_t) + \beta\, \bar{U}(g(s_t)) \right\}. \tag{4}$$

The present value of net revenues from resource harvesting is the sum of net revenues from the current period plus the present value of net revenues starting from the next period, discounted to the current period.

In the stochastic setting the future net revenues are uncertain. For a risk neutral resource manager it would be appropriate to replace the second term simply by the *expected* present value of net revenues starting from the next period. For a risk-averse resource manager, however, the value of the resource in the next period is less than the expected present value of net revenues. To capture this effect, we use the *certainty equivalent* of the present value of net revenues starting from the next period, i.e. the certain payment that the risk-averse resource manager finds just as good as the stochastic stream of net revenues of resource harvesting. Formally, we use v_{t+1} to denote the present value of net revenues of harvesting the stochastic resource in the future. The resource

[4] We also provide the characterization of optimal resource harvesting under changes in risk over time (in Appendix G).

manager evaluates this with the expected utility function $\mathbb{E}\left[f(v_{t+1})\right]$, where $\mathbb{E}[\cdot]$ is the expectation over future stochastic shocks. The concavity of the function $f(v_{t+1})$ captures risk aversion in the Arrow–Pratt sense: $\rho = -f''(v)/f'(v)$ is interpreted as absolute risk aversion, and $\eta = -v\, f''(v)/f'v(v)$ is relative risk aversion. Based on this, the certainty equivalent of v_{t+1} is $\mu(v_{t+1}) = f^{-1}\mathbb{E}[f(v_{t+1})]$.

Analogously to the deterministic case, the resource manager's preferences can be modeled by the following Bellman equation (Traeger, 2009):

$$V(x_t) = \max_{s_t} \left\{ \pi(x_t, s_t) + \beta\, \mu \left(V\left(z_{t+1}\, g(s_t)\right) \right) \right\}. \tag{5}$$

where $V(x_t)$ represents the value function. The certainty equivalent of future use of the stochastic resource replaces the deterministic present value of net revenues starting from the next period in Eq. (4).

That the current net revenues of resource harvesting enter linearly in Eq. (5) reflects the assumption of indifference with respect to intertemporal variability. By contrast, a common way of modeling a preference for intertemporal smoothing would be to apply, in the Bellman equation (5), a concave function to both the current net revenues and the certainty equivalent of future net revenues (Epstein and Zin, 1989; Traeger, 2009).

As stock growth and net revenues are strictly concave functions of x_t and s_t, and as the certainty equivalent operator $\mu(\cdot)$ is sub-additive, the Bellman equation (5) has a unique solution (Stokey et al., 1989, Theorem 9.6). The solution to (5) is interior in the first period of time, $0 < s_0 < x_0$, if the initial resource stock x_0 is large enough. This is always the case if the initial stock is at the expected carrying capacity, $x_0 = s_{\max}$, which we assume to be the case.

In the stochastic dynamic setting, it is usually not possible to simultaneously satisfy the common rationality requirements for decision-making over time (such as time consistency, Koopmans, 1960) and for decision-making under risk (such as independence of irrelevant alternatives, von Neumann and Morgenstern, 1944). Here, we use a framework that preserves time consistency: With preferences described by (5) the resource manager will always find it optimal to follow the resource harvesting plan that was optimal in the beginning. However, the value $V(x_t)$ that a resource manager with these preferences attaches to the stochastic resource is not the same as the certainty equivalent of the present value of net revenues of resource harvesting, $V(x_0) \neq \mu\left(\sum_{t=0}^{\infty} \beta^t\, \pi(x_t, s_t)\right)$ – the preferences described by (5) do not satisfy the von Neumann–Morgenstern axioms with respect to the entire stream of net revenues of resource harvesting. Thus, whereas the recursive preferences considered here are time consistent, ordinal dominance (or preference monotonicity) is usually not satisfied (Bommier and Grand, 2018). This means that in order to derive unambiguous results for comparative static analysis, further assumptions must be made. These are discussed in detail in Sections 3 and 4.

Whereas we focus on general risk preferences for the most part of the analysis, i.e. we allow for an arbitrary concave function $f(v)$, we will also consider the two examples of constant absolute risk aversion (CARA) and constant relative risk aversion (CRRA). The assumption of a constant absolute risk aversion $\rho = -f''(v)/f'(v) > 0$ implies the following functional forms for $f(\cdot)$ and certainty equivalence operator:

$$CARA: \quad f(v) = -e^{-\rho\, v}; \quad \mu(v) = -\frac{1}{\rho}\, \ln\left(\mathbb{E}\left[e^{-\rho\, v}\right]\right). \tag{6}$$

The assumption of a constant relative risk aversion $\eta = -v\, f''(v)/f'(v) > 0$ implies

$$CRRA: \quad f(v) = \frac{1}{1-\eta}\, v^{1-\eta}; \quad \mu(v) = \left(\mathbb{E}\left[v^{1-\eta}\right]\right)^{\frac{1}{1-\eta}}. \tag{7}$$

The next section solves the model for the case of constant unit costs, $c(y) = c$, whereas Section 4 considers the case of convex costs, $c'(y) < 0$ and $c''(y) > 0$.

3. The case of constant marginal costs

In the case of constant marginal costs, $c(y) = c < p$, marginal net benefit is constant. Without loss of generality we normalize the marginal net benefit to one, $p - c = 1$. The Bellman equation (5) simplifies to

$$V(x_t) = \max_{s_t} \left\{ x_t - s_t + \beta\, \mu \left(V\left(z_{t+1}\, g(s_t)\right) \right) \right\}. \tag{8}$$

We show in Appendix A that the value function is linear in the stock size, and can be written as

$$V(x) = x + b, \tag{9}$$

with some constant $b \in \mathbb{R}$. The following proposition, proven in Appendix A, characterizes this optimal escapement strategy.

Proposition 1. *For $x_0 > s^* > 0$ and $z\, g'(s^*) > 1$, the solution is interior and a constant escapement policy is optimal such that optimal escapement is $s_t = s^*$, with s^* implicitly determined by the two conditions*

$$1 = \beta\, g'(s^*)\, \frac{\mathbb{E}[z_{t+1}\, f'(z_{t+1}\, g(s^*) + b)]}{f'(\mu(z_{t+1}\, g(s^*) + b))} \tag{10}$$

$$b = -s^* + \beta \mu(z_{t+1}\, g(s^*) + b). \tag{11}$$

As condition (10) and condition (11) are independent of the current stock, optimal resource harvesting is characterized by a most rapid approach path to a 'constant escapement' strategy, i.e. it is optimal to always let a constant stock size s^* remain. Therefore the functional form of Reed's model is maintained when allowing for risk-averse preferences.

The optimality condition (10) states that at the optimum, the user chooses escapement to balance their current marginal returns with discounted future marginal returns. This means current period marginal profits of the last unit harvested (the left-hand side of the condition) must equal the discounted expected marginal returns resulting from leaving an additional unit of stock unharvested for the next period. Condition (11) specifies the constant b as the expected present value of the net benefit of conserving a quantity s^* of the resource for future use.

Note that both the optimal escapement level s^* and the constant term b in the value function (9) appear in both conditions, (10) and (11). If the user is risk averse, i.e. if $f(\cdot)$ is concave, neither for s^* nor for b an explicit expression can be derived.

To study the optimality condition in more depth we consider, independently, how an increase in the degree of risk aversion and magnitude of risk impact the optimal escapement decision. Defining an increase in risk as a mean preserving spread (Rothschild and Stiglitz, 1970), we find conditions for the optimal escapement to be decreasing in both the degree of risk aversion and the magnitude of risk. In order to do this, we first look at how a risk neutral user would optimally use the resource.

3.1. The case of a risk neutral user

For a risk neutral user, the function $f(\cdot)$ characterizing risk preferences is the identity function. The Bellman equation (8) simplifies to

$$V(x_t) = \max_{s_t}\left\{ x_t - s_t + \beta\,\mathbb{E}[z_{t+1}\,g(s_t)]\right\} = \max_{s_t}\left\{ x_t - s_t + \beta\, g(s_t)\right\} \tag{12}$$

Using s^*_{RN} to denote the optimal escapement policy for a risk neutral user, the constant optimal escapement policy is characterized by

$$1 = \beta g'(s^*_{RN}) \quad \Leftrightarrow \quad r = g'(s^*_{RN}) - 1 \tag{13}$$

Eq. (13) is independent of the random variable z_{t+1} meaning an increase in the magnitude of risk has no impact on the optimal escapement decision. This is the same optimality condition for a user facing zero risk, s^*_{DET} such that $s^*_{DET} = s^*_{RN}$, where DET stands for the deterministic case $z_{t+1} \equiv \mathbb{E}[z_{t+1}] = 1$ for all t. The return resulting from a marginal reduction in current escapement, r, must equal the discounted return from keeping that marginal unit of current escapement in the sea for the next period $g'(s^*_{RN}) - 1$.

3.2. The case of a risk-averse user

For a risk-averse user with constant marginal costs, the optimality condition in (10) shows that the optimal escapement policy depends on the random variable, and hence the magnitude of risk.

Given that the left-hand sides of Eqs. (10) and (13) are the same, risk aversion decreases the optimal escapement relative to the risk-neutral case if and only if the right-hand side of (10) is less than the right-hand side of (13). The same holds if we consider a risk-averse user and compare the optimal escapement levels under stochastic resource dynamics with random shocks to the deterministic problem where $z_{t+1} \equiv \mathbb{E}[z_{t+1}] = 1$ for all t.

Thus, the optimal escapement under risk aversion is greater (less) than the optimal escapement under risk neutrality (and the deterministic case) if and only if the following condition holds:

$$s^* \gtreqless s^*_{RN} = s^*_{DET} \quad \Leftrightarrow \quad \frac{\mathbb{E}[z_{t+1}\, f'(z_{t+1}\, g(s^*) + b)]}{f'(\mu(z_{t+1}\, g(s^*) + b))} \gtreqless 1 \tag{14}$$

In order to explain the user's escapement decision in more detail, we rewrite (10) using the joint expectation formula.

$$1 = \beta g'(s^*)\left\{ \frac{\mathbb{E}[f'(z_{t+1}\, g(s^*) + b)]}{f'(\mu(z_{t+1}\, g(s^*) + b))} + \frac{\mathrm{cov}(z_{t+1}, f'(z_{t+1}\, g(s^*) + b))}{f'(\mu(z_{t+1}\, g(s^*) + b))} \right\} \tag{15}$$

This allows the optimal escapement decision to be decomposed into two different effects influencing escapement, a wealth effect and an investment effect. The wealth effect corresponds to the first term in the brackets of Eq. (15). If this term is greater than one, the wealth effect works to increase escapement under uncertainty. The investment effect corresponds to the second term in the brackets. If this term is positive, the investment effect works to increase escapement under uncertainty. The following propositions 2 and 3 state conditions for the wealth effect to increase or decrease escapement under uncertainty and state the result that the investment effect is always negative for a risk-averse user.

The following proposition is proven in Appendix B.

Proposition 2. *Assume that a decreasing function $\varphi(\cdot)$ exists such that $f'(\cdot) = \varphi(f(\cdot))$. The wealth effect is positive, i.e. it tends to increase optimal escapement under risk, if and only if $\varphi(\cdot)$ is convex.*

Proposition 2 provides conditions for the wealth effect to increase optimal escapement relative to the deterministic and risk neutral cases. We call this the wealth effect, because a risk-averse user increases escapement under uncertainty to protect against low levels of future wealth. The wealth effect here resembles the income effect known from the optimal savings literature (Sandmo, 1970).

The condition $\phi(\cdot)$ is convex means that $f'(\cdot)$ is convex relative to $f(\cdot)$. Given that $f''(\cdot) < 0$, if $f'(\cdot)$ is convex, then we can say that $f(\cdot)$ exhibits *prudence* in the sense of Kimball (1990). Therefore, one can also understand Proposition 2 in the way that positive absolute prudence $-f'''(\cdot)/f''(\cdot)$ is a necessary condition for a positive wealth effect, i.e. that it tends to increase optimal escapement under risk.

However, even a positive wealth effect is not sufficient for the result that optimal escapement is higher under risk than in the deterministic case. The reason is that optimality condition (15) also includes the investment effect, captured by the covariance term. The investment effect is always negative:

Proposition 3. *The investment effect tends to decrease optimal escapement under risk,*

$$\frac{\mathrm{cov}(z_{t+1}, f'(z_{t+1}\, g(s^*) + b))}{f'(\mu(z_{t+1}\, g(s^*) + b))} < 0 \tag{16}$$

Proof. See Appendix C. □

This effect represents the manager's dislike of risk and decreases optimal escapement relative to the deterministic and risk neutral case. We call this the investment effect. Intuitively, risk makes investing in the resource a poor investment for the risk averse manager. In order to compensate for this, the manager increases current harvest (decreasing escapement) and invests in risk-free alternatives yielding a high rate of return.

Proposition 3 shows that prudence in the sense of Kimball (1990) is not sufficient for the result that optimal escapement would increase with risk. The reason is that the investment effect counteracts the wealth effect that comes about due to prudence. The following proposition states that if prudence is low enough, risk will always decrease optimal escapement:

Proposition 4. *Optimal escapement is lower in the risky setting than in the deterministic case if the following condition on (relative) prudence holds*

$$-\frac{z_{t+1}\, g(s^*)\, f'''(z_{t+1}\, g(s^*) + b)}{f''(z_{t+1}\, g(s^*) + b)} \leq 2. \tag{17}$$

Proof. See Appendix D. □

The case of preferences with constant absolute risk aversion (CARA, Eq. (6)) provides a benchmark of particular interest. With CARA preferences, the first-order condition for optimal escapement, condition (10), becomes independent of the constant b from Eq. (11). It reads

$$1 = \beta\, g'(s^*)\, \frac{\mathbb{E}\left[z_{t+1}\, e^{-\rho\, z_{t+1}\, g(s^*)}\right]}{\mathbb{E}\left[e^{-\rho z_{t+1}\, g(s^*)}\right]} \tag{18}$$

Moreover, due to the fact that risk aversion is independent of wealth with CARA preferences, the wealth effect does not change optimal escapement compared to the deterministic case. That is, as risk increases there is no propensity to increase escapement to ensure a certain level of future wealth. On the other hand, the investment effect (the negative co-variance term) still remains (Proposition 3). For constant absolute risk aversion $\rho > 0$, we overall find

$$1 = \beta g'(s^*) \left(1 + \frac{\mathrm{cov}\left(z_{t+1}, e^{-\rho\, z_{t+1}\, g(s^*)}\right)}{\mathbb{E}\left[e^{-\rho\, z_{t+1}\, g(s^*)}\right]}\right) < \beta\, g'(s^*). \tag{19}$$

In conclusion, optimal escapement decreases under both risk and risk aversion with CARA preferences, but not necessarily if absolute risk aversion is decreasing with wealth.

4. Optimal escapement policy with convex costs

In the case of convex marginal costs, marginal benefit $p - c(y)$ is increasing in the current stock size y. We show in Appendix E that the value function is linear in the profit,

$$V(x_t) = p\, x_t - C(x_t) + b. \tag{20}$$

with a constant $b \in \mathbb{R}$.

Also in the case of variable marginal costs, optimal resource harvesting is characterized by a constant escapement strategy. The following proposition, proven in Appendix E, characterizes this strategy.

Proposition 5. *For $x_0 > s^* > 0$ and $z\,g'(s^*) > 1$, the solution is interior and a constant escapement policy is optimal such that the optimal escapement is $s_t = s^*$, with s^* implicitly determined by*

$$p - c(s^*) = \beta g'(s^*) \frac{\mathbb{E}[z_{t+1}\, f'(p\, z_{t+1}\, g(s^*) - C(z_{t+1}\, g(s^*)) + b)(p - c(z_{t+1}\, g(s^*)))]}{f'(\mu(p\, z_{t+1}\, g(s^*) - C(z_{t+1}\, g(s^*)) + b))} \tag{21}$$

$$b = -(p\, s^* - C(s^*)) + \beta\, \mu(p\, z_{t+1}\, g(s^*) - C(z_{t+1}\, g(s^*)) + b). \tag{22}$$

This optimality condition includes a couple of extra terms compared to the case of constant marginal costs. The convexity of costs creates an additional stock effect which interacts with the user's risk preference. In a similar manner to Section 3, we first look at the deterministic case, and the case of a risk neutral user. These cases are then compared with that of a risk-averse user to provide a discussion on how an increase in the magnitude of risk and degree of risk aversion impact s^*.

4.1. Baseline cases of zero risk and risk neutral user

With convex costs, the optimality condition for a user facing zero risk becomes

$$p - c(s^*_{DET}) = \beta\, g'(s^*_{DET})(p - c(g(s^*_{DET}))) \tag{23}$$

such that at the optimum, the escapement decision of the user depends on the curvature of their marginal cost function. In case of zero risk, $\mu(\cdot)$ is the identity. We thus can directly solve (22) to obtain the constant b. This, in turn, gives the next period's value function as

$$V_{DET}(g(s^*)) = \frac{p\, g(s^*) - C(g(s^*)) - (p\, s^* - C(s^*))}{1 - \beta}, \tag{24}$$

which is simply the present value of the constant stream of net benefits from resource harvesting.

With convex costs, the optimality condition for a risk neutral user is

$$p - c(s^*_{RN}) = \beta\, g'(s^*_{RN})\mathbb{E}[z_{t+1}\ \ (p - c(z_{t+1}\, g(s^*_{RN})))] \tag{25}$$

such that at the optimum, the user's current marginal profits (LHS) must equal their expected discounted future marginal profits. Kapaun and Quaas (2013) show that by assuming $y\,c(y)$ is concave in the random variable y (coinciding with empirical estimates) such that marginal net future returns are convex in the random variable, an increase in the magnitude of risk increases the optimal escapement policy. They refer to this effect (as reflected in the right-hand side of Eq. (25)) as the 'gambling effect'. This is because there is a propensity for the manager to bet on good environmental conditions and increase escapement under uncertainty. The intuition for this is as follows. A positive shock to the future stock leads to higher future marginal returns and a higher harvest. On the other hand, a negative shock to the future stock leads to lower future marginal returns, but this effect is reduced because harvest is lower. We consider this case in the subsequent analysis, i.e. we assume that $y\,c(y)$ is concave in y.[5]

Due to the convexity of marginal costs, the optimal escapement for a risk neutral user is no longer independent of the random variable z_{t+1}, and hence comparative static analysis of an increase in the magnitude of risk is no longer the same as the analysis for an increase in the degree of risk aversion.

4.2. The case of a risk-averse user

In the convex marginal cost case, the optimality condition now depends on the risk preferences of the user, as well as on the curvature of the cost function. Using the joint expectation formula we can rewrite Eq. (21) as

$$\begin{aligned} p - c(s^*) \ &= \beta g'(s^*)\Bigg(\mathbb{E}[z_{t+1}\,(p - c(z_{t+1}\, g(s^*)))]\, \frac{\mathbb{E}[f'(p\, z_{t+1}\, g(s^*) - C(z_{t+1}\, g(s^*)) + b)]}{f'(\mu(p\, z_{t+1}\, g(s^*) - C(z_{t+1}\, g(s^*)) + b))} \\ &\quad + \frac{\mathrm{cov}\Big(z_{t+1}\,(p - c(z_{t+1}\, g(s^*))), f'(p\, z_{t+1}\, g(s^*) - C(z_{t+1}\, g(s^*)) + b)\Big)}{f'(\mu(p\, z_{t+1}\, g(s^*) - C(z_{t+1}\, g(s^*)) + b))}\Bigg). \end{aligned} \tag{26}$$

Comparing the optimality condition with the constant marginal cost case, the two terms in brackets in (26) can again be interpreted as wealth and investment effects. Both effects are now modulated by the 'gambling effect'. The wealth effect term is multiplied by the additional term $\mathbb{E}[z_{t+1}\,(p - c(z_{t+1}\, g(s^*)))]$, which is exactly similar to the positive gambling effect highlighted in Eq. (25).

Similarly, the investment effect term contains the covariance of $f'(\cdot)$ not only with the shock z_{t+1}, as in the constant marginal cost case, but with the term $z_{t+1}\,(p - c(z_{t+1}\, g(s^*)))$, which again captures a 'gambling effect' as the expression $z_{t+1}\, c(z_{t+1}\, g(s^*))$ is concave in z_{t+1}. Thus, unlike the constant marginal cost case, risk aversion is no longer sufficient for the investment effect to be negative. The gambling effect counteracts the risk averse user's propensity to divest away from the risky stock. The sign of the investment effect now depends on the trade off between the effect driven by risk aversion and that driven by the curvature of harvesting costs.

The curvature of marginal costs also implies that the comparative statics results on an increase in the degree of risk aversion and magnitude of risk may no longer be the same. The impact on escapement of an increase in the degree of risk aversion only depends on the net wealth and investment effect, whereas the impact on escapement of an increase in the magnitude of risk is more complex and also depends on the gambling effect. We quantify these effects in the numerical example in the next section.

[5] Note that this effect resembles the standard result from the literature that risk increases investments if and only if the third derivative of the utility function is positive (Eeckhoudt et al., 1995).

5. Numerical example: Eastern Baltic Sea cod fishery

An empirical example of the Baltic Sea cod fishery is used to quantitatively illustrate the theoretical findings. The cod fishery is one of the economically most important fisheries in the Baltic Sea. The stock reproduction strongly depends on environmental conditions (temperature, oxygen content, salinity), which are highly variable. This is due to the brackish nature of the Baltic Sea, where especially oxygen content and salinity change depending on irregular inflow events from the North Sea (Roeckmann et al., 2005; Kapaun and Quaas, 2013; Tahvonen et al., 2018; Voss and Quaas, 2022).

The fishery has been extensively studied in fish biology and fisheries economics, such that biological and economic parameters are readily available from the literature. For the biological growth function we use estimates from Froese and Proelß (2010). Reproduction is modeled using the logistic function

$$x_{t+1} = z_{t+1}\left(s_t + r\, s_t\left(1 - \frac{s_t}{K}\right)\right), \tag{27}$$

with an intrinsic growth rate $r = 0.48$/year, and a carrying capacity $K = 2283$ thousand tons. As Kapaun and Quaas (2013), we assume the stochastic shocks to be log-normally distributed with unit mean, such that the magnitude of risk is fully determined by the variance σ^2 of the shocks. We use the value $\sigma^2 = 0.083$ estimated by Kapaun and Quaas (2013) for the Eastern Baltic cod fishery.

Tahvonen et al. (2018) specify a marginal harvesting cost function

$$c(y) = c\, y^{-\chi}, \tag{28}$$

with parameters $c = 6.604$ and $\chi = 0.426$. Thus, the function $y\,c(y)$ is concave. In line with the discussion in Section 4.1, we thus expect a gambling effect that would tend to increase optimal escapement under uncertainty. For the price we use the average of the years 2015–2020, which was 2 Euros/kg of fish (BLE, 2016–2021). We use a discount rate of 5% per year, i.e. we set $\beta = 0.952$.

Estimates for the coefficient of relative risk aversion, $\eta = -v\, f''(v)/f'(v)$ are available from the financial economics literature. Whereas it is far from clear which is the exact number to use, the literature mostly considers values between $\eta = 5$ and $\eta = 10$ to be realistic (Vissing-Jørgensen and Attanasio, 2003; Epstein et al., 2014; Bai and Zhang, 2022). In line with this evidence, the literature in climate economics has used similar specifications, ranging from $\eta = 4.3$ (den Bremer and der Ploeg, 2021) to $\eta = 7.5$ or $\eta = 10$ (Ackerman et al., 2013). To explore how the optimal policy and values depend on risk aversion, we vary this parameter from risk neutrality ($\eta = 0$) to the value $\eta = 10$ as a relatively high estimate in the range considered realistic in the financial economics literature. We use $\eta = 7.5$, the lower of the values considered in Epstein et al. (2014) as the benchmark case.

In the following analysis we consider risk preferences characterized by constant relative risk aversion (CRRA) or characterized by constant absolute risk aversion (CARA). For the case of CARA preferences, we vary the coefficient of absolute risk aversion, but for comparison convert the coefficient of absolute risk aversion, $\rho = -f''(v)/f'(v)$ into a coefficient of relative risk aversion by multiplying with the current level of wealth, v, to obtain $\eta = v\,\rho$.

Eq. (20) states that the value function is of the form $V(x_t) = p\,x_t - C(x_t) + b$. Here, b is a constant, independent of the current stock. It is obtained from the Bellman equation (5). To illustrate the optimization problem, we define $\tilde{V}(x_t, s_t) = p\,x_t - C(x_t) + V_0(s_t)$, where $V_0(s_t)$ is determined by the recursive equation

$$p\,x_t - C(x_t) + V_0(s_t) = p\,x_t - C(x_t) - \left(p\,s_t - C(s_t)\right) + \beta\,\mu\left[p\,z_{t+1}\,g(s_t) - C\left(z_{t+1}\,g(s_t)\right)\right] \tag{29}$$

In the following we call $V_0(s_t)$ the 'expected net present value of escapement'. Comparing (29) with the Bellman equation (5) for the present specification of the model shows that $b = \max_{s_t} V_0(s_t)$.

Fig. 1 shows the expected net present value of escapement for the numerical example. Given the same coefficient of relative risk aversion at the optimum, it is no surprise that the curves for CRRA and CARA preferences are quite similar around the optimum. Also, whereas the optimal escapement levels are similar, the optimal escapement level for CARA preferences is smaller than for CRRA preferences, as there is no wealth effect for CARA preferences. The difference between optimal escapement in the cases with and without risk is substantial, though. Also the expected net present value of escapement with risk and risk aversion is everywhere below the one without risk, reflecting that the certainty equivalent is smaller than the expected value. Correspondingly, using the escapement level that would be optimal in the riskless case would lead to a substantial welfare loss in the situation of uncertainty.

Fig. 2 shows more comprehensively how the optimal escapement level and the expected present value of escapement depend on risk aversion.

In Fig. 2, Panel A shows that the optimal escapement levels are similar for CARA and CRRA preferences, when the coefficients of relative risk aversion at the optimum are the same. Due to the absence of the wealth effect, the optimal escapement for CARA preferences is consistently smaller than the optimal escapement level for CRRA preferences.

If risk aversion is very low, i.e. close to risk-neutrality, optimal escapement is slightly higher under uncertainty than in the case without risk. This is due to the convex marginal cost (Kapaun and Quaas, 2013). For risk aversion in line with empirical evidence from the financial economics literature, however, the optimal escapement level is substantially below the optimal escapement without risk, going down to just over half the deterministic optimal escapement level for a coefficient of relative risk aversion of $\eta = 10$.

Considering the effect on the value of the natural resource in Fig. 2, Panel B, this is also reflected in the expected net present value of escapement, which, for $\eta = 10$, is less than half of the value without risk. The type of risk preferences plays almost no role. Again, the case of very small risk aversion is special: the expected net present value of the resource then is higher in the setting with uncertainty than without, because the expected future harvesting costs are lower than the future harvesting costs at the expected stock size: $C(z_{T+1}\,g(s)) = c/(1-\chi)\,\left(z_{t+1}\,g(s)\right)^{1-\chi}$ is concave in z_{t+1}.

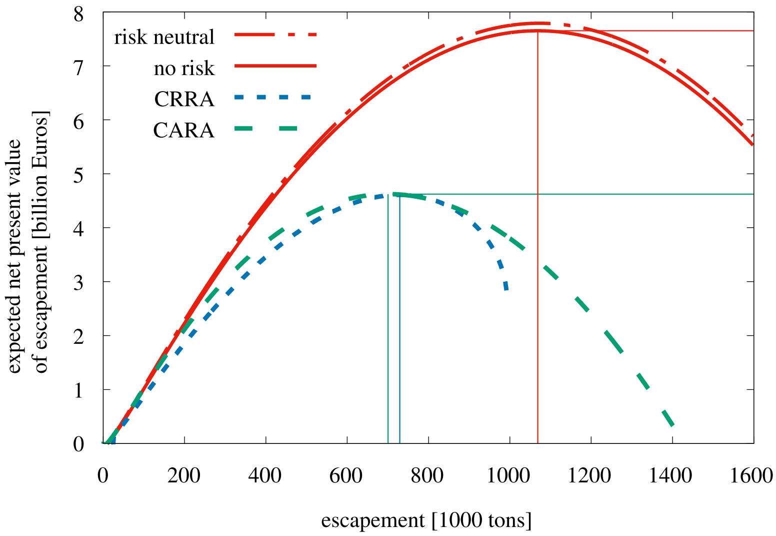

Fig. 1. The expected net present value of escapement, $V_0(s_t)$, as a function of escapement for the case of no risk (red solid line) and for two types of risk preferences: constant relative risk aversion (CRRA) with coefficient of risk aversion $\rho = 7.5$ (dashed green line), and constant absolute risk aversion (CARA) corresponding to a constant relative risk aversion coefficient of $\eta = 7.5$ at the optimal wealth level (thus $\rho = 1.27$/billion Euros; small-dashed blue line). The vertical lines indicate optimal escapement levels, the horizontal lines the maximized expected net present value of escapement for the cases of no risk and CARA preferences.

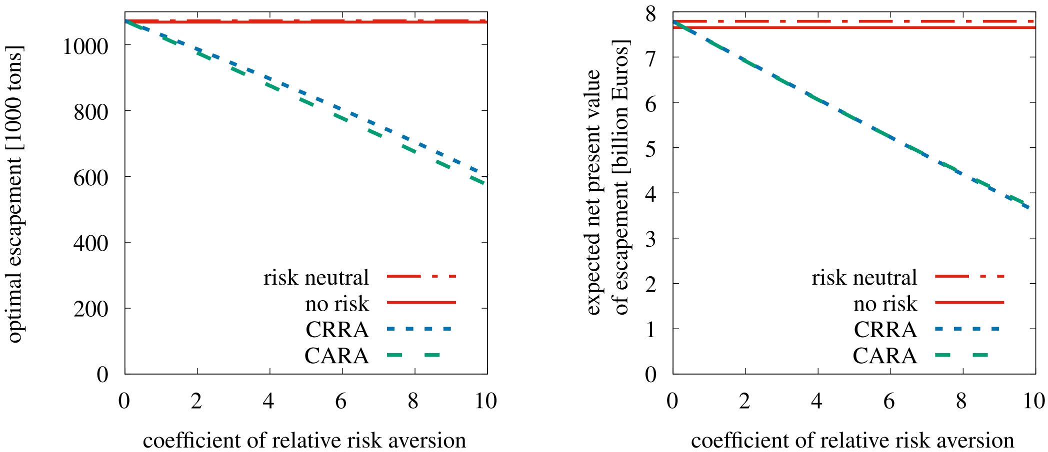

Fig. 2. Sensitivity analysis with respect to risk aversion for the cases of no risk, and under uncertainty with risk-neutral decision-maker, and decision-makers with constant relative risk aversion (CRRA) and constant absolute risk aversion (CARA), translated into the corresponding coefficient of relative risk aversion for the wealth level at the optimal escapement. Panel A shows the optimal escapement levels; panel B the expected net present value of escapement.

6. Discussion and conclusion

In the course of climate change, the magnitude of existing environmental risks are expected to increase (IPCC, 2021). This is an important and increasing issue for renewable resource users, where formal insurance is typically not available. Here, we have addressed the question how optimal resource harvesting depends on risk and the resource user's risk-aversion.

We have presented a theoretical model of harvesting a renewable resource with stochastic dynamics, focusing on the effect of risk aversion on optimal harvesting decisions. We have shown that optimal harvesting is characterized by a constant escapement strategy even for a risk-averse user, provided that the per-period payoff is linear in harvest and that the user is indifferent with respect to intertemporal variability.[6]

Three effects determine how risk affects the optimal escapement level: the wealth, investment, and gambling effects. The gambling effect depends on the curvature of harvesting costs only and tends to increase optimal escapement under risk. It vanishes if marginal harvesting costs are linear, otherwise it is present independent of risk aversion.

[6] We highlight how the model can be extended to a decentralized setting in Appendix F.

The two other effects depend on the type of risk preferences. With constant marginal harvesting costs (a common assumption for natural resources such as forests) and with risk preferences characterized by constant absolute risk aversion, only the investment effect is present. It always tends to decrease optimal escapement with risk, due to the propensity to divest away from the risky stock and avoid risk.

The wealth effect is present if absolute risk aversion is non-constant, and then typically tends to increase optimal escapement with risk. This effect depends on the degree of prudence. We show that if prudence is low enough, the net result of the investment effect and the wealth effect, is that optimal escapement decreases with risk.

To quantify our theoretical results we apply our model to the Eastern Baltic Sea cod fishery and highlight that risk aversion can have a sizeable impact on the user's management decision. The more risk-averse the user, the lower the optimal escapement level, supporting our theoretical results. This result differs from that of a risk-neutral user, who increases escapement under increased risk and also contradicts a common intuition of many in the environmental community that risk aversion should give rise to more conservative management. In our model this intuition is only captured by the wealth effect. Previous empirical work focusing on risk neutral agents (Sethi et al., 2005; Kapaun and Quaas, 2013; Tahvonen et al., 2018) find that biological uncertainty only has a small effect on the escapement level, suggesting that using models with deterministic recruitment may not be detrimental to policy-making. Our paper shows this may not be the case when the user is risk-averse. Depending on the degree of risk aversion, and magnitude of risk, the optimal escapement policy may differ considerably and this in turn may have significant implications for management.

We here assume that a regulator manages the resource stock such that she chooses optimal escapement according to the preferences of a representative fisherman. There are several pieces of evidence suggesting that fishermen are risk averse. In the Baltic Sea cod fishery, there is a management plan that has been co-developed by policymakers and fishers. This management plan includes a rule that limits changes in the total allowable catch. We interpret this as evidence for risk aversion. There is also evidence for German commercial fishermen, a majority of them operating in the Baltic sea (Drupp et al., 2019). Appendix H presents the evidence from an incentivized (Holt and Laury, 2002) task on the choice of lotteries that the fishermen did as part of the survey. Although there is substantial heterogeneity between the implied degree of risk aversion among fishermen, there is a clear indication that most fishers were risk averse. Even though there is little evidence that the Baltic Sea cod fishery is managed optimally, we study the optimal management policy under risk averse preferences to highlight the welfare loss when moving from risk neutral to risk averse managers: This decrease in welfare gives rise to insurance as a potential policy tool.

The previous literature also has found that the effect of risk on optimal harvesting is relatively small if the preference for intertemporal smoothing is the same as risk aversion (Kapaun and Quaas, 2013). Our analysis provides an explanation for why this is the case. With risk and risk aversion, the expected present value of escapement is (much) smaller than in the deterministic or risk neutral case (cf. Fig. 2, Panel B). For this reason, the resource manager who is indifferent with respect to intertemporal variability will chose an escapement level that is (much) smaller than in the deterministic or risk neutral case (cf. Fig. 2, Panel A). A resource manager who has a strong preference for intertemporal smoothing, however, would adjust harvest under risk such as to increase the expected present value of escapement, relative to the current net revenues of harvesting. This means reducing current harvest and increasing escapement to compensate for the effect of risk and risk aversion.

Whilst these results are insightful and provide an important contribution to the literature on renewable resource management, the stylized nature of tractable models and the assumptions on which they are based must be acknowledged. As said initially, to focus on the effect of risk aversion, we considered a user who is indifferent with respect to intertemporal variability. In practice, credit markets will also be imperfect, such that decision makers may actually exhibit a preference for intertemporal smoothing for income from resource use. Furthermore, we focus on a resource stock described by a single stock variable. For some interesting cases it seems appropriate to consider a more differentiated description of resource dynamics, taking into account the size structure of populations (Patto and Rosa, 2022; Tahvonen et al., 2018), or interactions with other resource stocks (Costello and Polasky, 2008). Developing this analysis in such settings constitutes an interesting avenue for further research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Proof of Proposition 1

We conjecture the value function is of the form $V(x) = a\,x + b$ with some constants $a > 0$ and b, and show that this solves the Bellman equation (8) when $a = 1$ and b is determined by (10) and (11). Substituting the guess $V(x) = a\,x + b$ into Eq. (8) gives

$$a\,x + b = x - s + \beta f^{-1}(E[f(a\,(z_{t+1}\,g(s)) + b)]) \tag{30}$$

As this equality must hold for any stock size x, it follows that $a = 1$. With $a = 1$, Eq. (30) becomes (11), where $s = s^*$. The first-order condition for optimal escapement, using the guess $V(x) = x + b$, is

$$1 = \beta\, g'(s)\,(f^{-1})'(E[f(z_{t+1}\,g(s) + b)])\; E[z_{t+1}\, f'(z_{t+1}\,g(s) + b)]. \tag{31}$$

As the optimality condition is independent of the current stock, the condition characterizes a stock-independent, constant optimal escapement level $s = s^*$. Applying the inverse function theorem, condition (31) becomes (10).

Appendix B. Proof of Proposition 2

Recall that $f'(\cdot)$ is positive and decreasing, capturing risk aversion. Thus, its inverse function ${f'}^{-1}(\cdot)$ exists and must be a decreasing function as well. Hence,

$$\frac{\mathbb{E}[f'(z_{t+1}\, g(s^*)+b)]}{f'(\mu(z_{t+1}\, g(s^*)+b))} \gtreqless 1 \tag{32}$$

$$\Leftrightarrow \quad {f'}^{-1}\left(\mathbb{E}[f'(z_{t+1}\, g(s^*)+b)]\right) \lesseqgtr \mu(z_{t+1}\, g(s^*)+b) \tag{33}$$

$$\Leftrightarrow \quad \varphi\left(f\left({f'}^{-1}\left(\mathbb{E}[f'(z_{t+1}\, g(s^*)+b)]\right)\right)\right) \gtreqless \varphi(\mathbb{E}[f(z_{t+1}\, g(s^*)+b)]) \tag{34}$$

$$\Leftrightarrow \quad \mathbb{E}[\varphi(f(z_{t+1}\, g(s^*)+b))] \gtreqless \varphi(\mathbb{E}[f(z_{t+1}\, g(s^*)+b)]) \tag{35}$$

Applying Jensen's inequality, the last inequality holds with $>$ if $\varphi(\cdot)$ is convex, with equality if $\varphi(\cdot)$ is linear, and with $<$ if $\varphi(\cdot)$ is concave.

Appendix C. Proof of Proposition 3

As $f''(\cdot)<0$, we have $(z_{t+1}-1)\left(f'(z_{t+1}\, g(s^*)+b)-f'(g(s^*)+b)\right)\leq 0$ for all z_{t+1} with strict inequality for all $z_{t+1}\neq 1$. Taking the expectation, we thus get

$$0 > \mathbb{E}\left[(z_{t+1}-1)\left(f'(z_{t+1}\, g(s^*)+b)-f'(g(s^*)+b)\right)\right] \tag{36}$$

$$= \mathbb{E}\left[z_{t+1}\, f'(z_{t+1}\, g(s^*)+b)\right]-\mathbb{E}\left[f'(z_{t+1}\, g(s^*)+b)\right] \tag{37}$$

Rearranging, we find

$$\mathbb{E}\left[f'(z_{t+1}\, g(s^*)+b)\right] > \mathbb{E}\left[z_{t+1}\, f'(z_{t+1}\, g(s^*)+b)\right] \tag{38}$$

$$= \mathbb{E}\left[f'(z_{t+1}\, g(s^*)+b)\right] + \operatorname{cov}\left[z_{t+1}, f'(z_{t+1}\, g(s^*)+b)\right], \tag{39}$$

thus $\operatorname{cov}\left[z_{t+1}, f'(z_{t+1}\, g(s^*)+b)\right]<0$.

Appendix D. Proof of Proposition 4

As $\mu(z_{t+1}\, g(s^*)+b) < g(s^*)+b$, and $f'(\cdot)$ is decreasing, it follows that $f'(\mu(z_{t+1}\, g(s^*)+b)) > f'(g(s^*)+b)$. Thus, the numerator on the left-hand side of (14) is smaller than the denominator, if the expression in the expectation operator is weakly concave in z_{t+1}, as then

$$\mathbb{E}[z_{t+1} f'(z_{t+1}\, g(s^*)+b)] \leq f'(g(s^*)+b) < f'(\mu(z_{t+1}\, g(s^*)+b)). \tag{40}$$

The curvature of this expression in the expectation operator is

$$\begin{aligned}
&\frac{d^2}{d z_{t+1}^2}\left(z_{t+1}\, f'(z_{t+1}\, g(s^*)+b)\right)\\
&= \frac{d}{d z_{t+1}}\left(f'(z_{t+1}\, g(s^*)+b) + z_{t+1}\, g(s^*)\, f''(z_{t+1}\, g(s^*)+b)\right)\\
&= z_{t+1}\left(g(s^*)\right)^2 f'''(z_{t+1}\, g(s^*)+b) + 2\, g(s^*)\, f''(z_{t+1}\, g(s^*)+b),
\end{aligned} \tag{41}$$

which is weakly negative if and only if (17) holds.

Appendix E. Proof of Proposition 5

We conjecture the value function is of the form $V(x)=a(px-C(x))+b$. with some constants $a>0$ and b, and show that this solves the Bellman equation (5) when $a=1$ and b is determined by (21) and (22). Substituting the guess into Eq. (5) gives

$$a\,(p\,x-C(x))+b = p(x-s)-C(x)+C(s)+\beta f^{-1}(E[f(a(p\,z_{t+1}\, g(s)-C(z_{t+1}\, g(s)))+b)]) \tag{42}$$

As this equality must hold for any stock size x, it follows that $a=1$. With $a=1$, Eq. (42) becomes (22), where $s=s^*$. The first-order condition for optimal escapement, using the guess for the value function, is

$$p-c(s)=\beta\, g'(s)\,(f^{-1})'(E[f(z_{t+1}\, g(s)+b)])\, E[(p\, z_{t+1}-z_{t+1}\, c(z_{t+1}\, g(s)))\, f'(z_{t+1}\, g(s)+b)]. \tag{43}$$

As the optimality condition is independent of the current stock, the condition characterizes a stock-independent, constant optimal escapement level $s=s^*$. Applying the inverse function theorem, condition (43) becomes (21).

Appendix F. Non-cooperative harvesting by risk-averse resource users

We consider two resource users $i \in \{1,2\}$ harvesting the same stock in a non-cooperative fashion. Stock dynamics are similar to (1), but escapement is the stock left after harvesting by both users, $s_t = x_t - \sum_i h_t^i$. To be specific, we assume that the two users harvest sequentially within a given period, i.e. first user 1 harvests, and then user 2. Both resource users operate on the same market, i.e. both face the price p, and have the same harvesting technology, i.e. unit harvesting costs are $c(y)$ for both. We allow for heterogeneous risk aversion, i.e. the certainty equivalent operator $\mu^i(v)$ may be different for the two resource users.

The Markov-perfect Nash equilibrium harvesting strategies are found by solving the system of Bellman equations

$$V^1(x_t) = \max_{h_t^1} \left\{ p\, h_t^1 - \int_{x_t - h_t^1}^{x_t} c(y)\, dy + \beta\, \mu^1 \left(V^1 \left(z_{t+1}\, g\left(x_t - h_t^1 - h_t^2 \right) \right) \right) \right\} \tag{44a}$$

$$V^2(x_t) = \max_{h_t^2} \left\{ p\, h_t^2 - \int_{x_t - h_t^1 - h_t^2}^{x_t - h_t^1} c(y)\, dy + \beta\, \mu^2 \left(V^2 \left(z_{t+1}\, g\left(x_t - h_t^1 - h_t^2 \right) \right) \right) \right\}. \tag{44b}$$

As shown by Clark (1991, chapter 5.4), the solution of the corresponding problem for a deterministic resource (and in a continuous-time setting) is that the resource is harvested down to the level where unit harvesting costs are equal to the price. We find that the same is true for the stochastic resource harvested by risk-averse users:

Proposition 6. *A constant escapement s^{NE} characterized by the condition that unit harvesting cost are equal to the price, $c\left(s^{NE}\right) = p$, is a Markov-perfect Nash equilibrium. Harvesting strategies are independent of risk aversion.*

Proof. We use the guess that escapement is equal to s^{NE} in the system of Bellman Eqs. (44). We obtain

$$V^1(x_t) = \max_{h_t^1} \left\{ p\, h_t^1 - \int_{x_t - h_t^1}^{x_t} c(y)\, dy + \beta\, \mu^1 \left(V^1 \left(z_{t+1}\, g\left(s^{NE} \right) \right) \right) \right\} \tag{45a}$$

$$V^2(x_t) = \max_{h_t^2} \left\{ p\, h_t^2 - \int_{x_t - h_t^1 - h_t^2}^{x_t - h_t^1} c(y)\, dy + \beta\, \mu^2 \left(V^2 \left(z_{t+1}\, g\left(s^{NE} \right) \right) \right) \right\}. \tag{45b}$$

The corresponding first-order conditions are

$$p - c(x_t - h_t^1) = 0 \tag{46a}$$

$$p - c(x_t - h_t^1 - h_t^2) = 0 \tag{46b}$$

This shows that resource user 1 will choose $h_t^1 = x_t - s^{NE}$. The reason is that otherwise resource user 2 would choose harvest such that $p = c(x_t - h_t^1 - h_t^2)$, and escapement would be at the same level as if $h_t^1 = x_t - s^{NE}$, and thus for resource user 1 there is no future benefit of conserving any unit of the stock that could be profitably harvested. □

Appendix G. Optimal escapement with trend in risk

We consider model (1), but instead of i.i.d. random shocks z_{t+1} we consider the stochastic process proposed by McGough et al. (2009)

$$z_{t+1} = v_{t+1}\, z_t^{\zeta}, \tag{47}$$

where v_{t+1} is i.i.d. with mean one, and $\zeta > 0$ measures the persistence of the shock.

We conjecture the value function is of the form $V(x,z) = x + b(z)$, and show that this solves the Bellman equation. Substituting the guess $V(x,z) = x + b(z)$ into Eq. (8) gives

$$x + b(z) = x - s + \beta f^{-1}(E[f(a(v\, z^{\zeta}\, g(s)) + b(z))]) \tag{48}$$

The first-order condition for optimal escapement, using the guess $V(x,z) = x + b(z)$, is

$$1 = \beta\, g'(s)\, (f^{-1})'(E[f(v\, z^{\zeta}\, g(s) + b(z))])\, E[v\, z^{\zeta}, f' \left(v\, z^{\zeta}\, g(s) + b(z) \right)]. \tag{49}$$

As the optimality condition is independent of the current resource stock, the condition characterizes an optimal escapement that is independent of the current resource stock, but depends on the state of the environment z that determines the next period's shock on resource productivity.

Appendix H. Risk aversion of German fishermen

Here we provide evidence from a survey among German commercial fishermen in winter 2015/2016. The survey was sent to all 896 commercial fishermen in Germany that were registered at the German Federal Office for Agriculture and Food, which is necessary to obtain a fishing quota. The surveys were sent out on Friday, December 4, 2015, and the closing date was January 31, 2016. A total of 136 fishermen responded to the survey, amounting to an overall response rate of 15%. The survey included an incentivized (Holt and Laury, 2002) risk task. More details on the survey can be found in Drupp et al. (2019).

Table 1
Risk task in the survey with German commercial fishermen..

Choice #	Payoff A if lottery number on 2016/2/6 is 0,1,2,3, or 4	Payoff A if lottery number on 2016/2/6 is 5,6,7,8, or 9	% of fishers choosing	Implied CRRA coefficient η
1	7,00€	7,00€	17	$\eta > 3.46$
2	6,00€	9,00€	6	$3.46 < \eta < 1.16$
3	5,00€	11,00€	28	$1.16 < \eta < 0.71$
4	4,00€	13,00€	16	$0.71 < \eta < 0.50$
5	3,00€	15,00€	12	$0.50 < \eta < 0$
6	2,00€	16,00€	21	$\eta < 0$

Of the 136 responding fishermen, 121 completed the risk task presented in Table 1. All of them were paid out. A decision-maker with preferences characterized by constant relative risk aversion (CRRA) is indifferent between choices 1 and 2 for a CRRA coefficient $\eta = 3.46$; indifferent between 2 and 3 for $\eta = 1.16$; indifferent between 3 and 4 for $\eta = 0.71$; indifferent between 4 and 5 for $\eta = 0.50$; and indifferent between 5 and 6 if he is risk neutral, $\eta = 0$. The results from Table 1 shows that there is a substantial degree of heterogeneity in risk aversion, but most fishers are clearly risk-averse. The risk elicitation task was done in an abstract and static setting. Whereas we take it as evidence that fishermen in the Baltic sea are generally risk averse, the results from the task cannot be taken directly to quantify the coefficient of relative risk aversion in the dynamic setting of fishery management.

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