Allocation of Research Resources for invasive species with a commercial value: The case of the Red King Crab

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Abstract

This paper models the optimal allocation of research resources for an invading species. Resources may be allocated ex-ante (ahead of the invasion frontier) or ex-post (within the invaded area). Ex-ante research helps define external damages by establishing the baseline ecosystem services and values; ex-post research determines restoration needs and costs. Furthermore ex-post research may include research that improves management of any commercial aspect of the invading species. In other words benefits of research may accrue either from improved information regarding the potential or actual damages of the invasion or from improved information for solving the dynamic common property management challenges of a commercial species. In such a case, simple application of the precautionary approach to the invasion has direct quantifiable costs in foregone commercial benefits. For the purposes of the analysis we are using the Red King Crab (*Paralithodes camtschaticus*) as a case study. The Red King Crab is a well-established invader in the Barents Sea that conveys both harvesting benefits and ecosystem damages, which may be spatially differentiated. The damages can be alleviated by harvest. We distinguish the research in different types based on their potential to reveal successfully these marginal external benefits from commercial harvesting. We illustrate how misallocation of research resources can be avoided when decision-makers are faced with the allocation dilemma and there is a significant amount of uncertainty on the ecosystem impacts. The model highlights the importance of the prioritizing criterion in research resource allocation for invasive species with a commercial value, as a means of identifying the underlying bioeconomic trade-off.

Keywords: *Commercial Invasive species, Research Resources Allocation, Bioeconomic Trade-Offs*

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1. Introduction

The allocation of resources between establishing a baseline and understanding the dynamics of an invasion is indisputably an ubiquitous challenge - a real problem at the frontier of every invasion. Invasive Species often hold a commercial value in the market, therefore entering human preferences in both positive and negative ways (Schlaepfer et al., 2011; Courtois et al., 2012). In cases where the control of such invasions relies on commercial harvesting, management decisions need research input regarding both the invasion externalities and the size of the (commercial) stock. Yet, very little literature has studied the resource-allocation problem for invasive species that hold a commercial value. Instead, resources have often been allocated based on ad hoc decision-making processes and other political considerations while economic analysis has generally been absent from designing and evaluating programs that fit the needs of the invasion (Epanchin-Niell, 2017). With this paper we contribute to the literature by examining the trade-off that arises for a species with a dual role, as a nuisance and as a commercial resource, via the allocation of research resources.

Despite a burgeoning scientific literature on the management of invasive species (Finnoff et al., 2005; Epanchin-Niell and Wilen, 2012; Leung et al., 2005; Kaiser and Burnett, 2010; Costello et al., 2017) significantly fewer scholarly works look at the allocation of resources for efficient research into fighting invasions in their expansion phase. The problem of allocating resources optimally in invasive species management is not new however and management strategies on how to maximize returns on expenditures across stages of invasions have been studied in various different contexts (Epanchin-Niell, 2017; Kaiser and Burnett, 2010). One strand of that limited literature focuses on the spatiotemporal dimension of the problem for identifying optimal management strategies (Baker, 2016; Cacho and Hester, 2011). Another strand of the literature looks at the optimal search effort levels for detection, accounting for the invasive species' biological characteristics and impacts (Cacho et al., 2007; Mehta et al., 2007). Other studies have sought to answer how resources should be allocated between quarantine and surveillance (Moore et al., 2010) or between prevention, surveillance and eradication (Rout et al., 2011).

Our applied focus on the research prioritization criterion for the management of the species differentiates this study from previous economic analyses of commercial invasive species (Zivin et al., 2000; Horan and Bulte, 2004; Falk-Petersen and Armstrong, 2013). The management of invasive species that hold a value in the market garners considerable attention among local stakeholders and can often be expected to be contentious and divisive, since they are viewed as an asset by some and as a liability by others. The benefits from research on such species with a dual role may accrue either from providing precise estimates on the commercial stock, and thereby enabling improved solutions to the commons problems, or from identifying the negative externalities from the invasion, and thereby alleviating the imperfect information problem. Optimal harvesting of the species, either for commercial purposes or for control of the external damages, requires information on both problems. The invasion externalities can be either studied ex-ante by identifying baseline ecosystem services and values in areas of similar habitat that have not been invaded yet or ex-post by identifying the needs for restoration as well as the costs of the invasion in the already heavily invaded area.

In this paper we are using the Red King Crab invasion in Norway as a case study, in order to illustrate how misallocation of resources can be avoided when decision-makers are faced with the allocation dilemma and there is a significant amount of uncertainty on the ecosystem impacts that makes impact studies notoriously difficult to perform. The modelling approach in this paper is relevant for several pertinent real-world cases of commercial invasive species and can inform on invasive species priorities more broadly.

The Red King Crab *(Paralithodes camtschaticus)*, hereafter RKC, is a well-established sub-Arctic invasion in the Barents Sea, which conveys both potential harvesting benefits and ecosystem damages. The management of the RKC has in recent years generated heated public debate, particularly in Norway, given the commercial interest as well as the underlying ecosystem damages that occur with the increase in its stock and spread (Kourantidou et al., 2015). The species originally introduced in Russia in the 1960s (Orlov and Ivanov, 1978), nowadays covers both Russian and Norwegian waters, with its main distribution covering the southern part of the Barents Sea, between 25^o E and 57^o E (Pechora Sea)(Zakharov, 2015).

The current paper focuses on the Norwegian management of the stock which is being decided upon advice provided by the Institute of Marine Research (IMR). We distinguish research performed by IMR into different types and discuss the way in which resources are being allocated to each one of them, taking into account the spatial dimension of the invasion and its management. The analysis that follows from our reduced-dimension model for resource allocation in the RKC case, suggests that the budget-constrained social optimum depends upon the probability of "success" reflected via the difficulty involved in each type of research. The application of our model, through real-world data on monies that have been invested so far, challenges regulators' preferences for allocating limited resources to research objectives that seem less productive or less likely to improve our understanding of the social optimum due to large uncertainties and difficulties entailed. Our approach is based on the assumption of asymmetric productivity of the different research types and suggests that misallocation of research resources on the invasive crab can be suboptimal or even generate negative welfare impacts in the long-run. This is because harvest restrictions meant to preserve the valuable crab, so as to ensure a long-term fishery, are likely to impose high ecosystem externalities.

The sketch of the paper is organized as follows. In section 2 we discuss the different types of research and the challenges that come along with allocation of resources among those. We contextualise this basic framework of distinct research types in the RKC invasion case for purposes of illustrating the allocation dilemma under the existence of uncertainties and spatial heterogeneity. We proceed in Section 3 with a simple stylized model that illustrates the need to prioritize allocation of research resources following the probability of "success" of ex-ante (frontier) and ex-post (invaded area) research types in revealing the marginal external benefits from harvesting. In section 4 we discuss the management along with allocation of research resources for the RKC in Norway over the last years. In Section 5 we discuss the role of economies of scope among different research types as well as the way in which those types interact with each other for the case of the RKC. Section 6 concludes on the importance of the prioritizing criterion in research resource allocation for invasive species with a commercial value, as a means of identifying the underlying bioeconomic trade-off.

2. Background

The management of any lucrative invader clearly requires a multi-faceted approach that comprises of a coherent policy on both the commercial harvesting and the transitory dynamics of the invasion, since it pits potential economic gains against uncertain ecosystem changes. In what follows, we attempt to evaluate the economic rationale behind the allocation of research resources for acquiring the different types of information needed to address this interplay of ecology and economic behavior. First we distinguish the resources allocated for research on the profitable invasive crab into the following 3 categories of research types: Commercial (C) type of research, Baseline (B) research and Restoration (R) research.

Research type C (Commercial) focuses on the commercial fishery and ideally aims at identifying the Maximum Economic Yield (MEY), though perhaps without internalizing external damages of

the invasion. Type C research includes stock assessments and costs of the fishing fleet that help provide the necessary information for estimating the optimal stock level that maximizes fishery profits. Better understanding of the stock enables managers to reduce dynamic losses from either overharvesting or underharvesting the commercial population. That is, it improves information needed to solve the common property management challenge of the fishery. In the case of the RKC this type of research is currently being conducted east of 26^o E (eastern patch), where the fishery is quota-regulated, for determining the annual quotas, but not west of 26^o E (western patch) where the fishery is open-access (Hjelset et al., 2009) (JH Sundet, Institute of Marine Research, Norway, personal communication, 2016). The spatially differentiated regulatory regime for the RKC targets a long-term profitable fishery in the east while at the same time limiting the spread of the species in the west.
Research type R (Restoration) focuses on identifying the ecosystem losses and providing information on the cost of the ongoing invasion externalities. There is limited amount of such research for the RKC to date and the studies available are not easily grouped to yield a reliable estimate of those costs. Most of the Norwegian impact studies available have taken place in fjords located in the eastern patch (Mikkelsen and Pedersen, 2012; Mikkelsen, 2013; Jørgensen et al., 2016; Jørgensen and Spiridonov, 2013; Oug et al., 2011) where the fishery is being regulated by quotas. The main goal of Research type R is to reveal the external benefits of harvest to the ecosystem, that is the Marginal External Benefits (MEB) of control of the invasion. These benefits are the damages avoided by removal of the crabs from the ecosystem. The information provided by R type research improves managers' ability to reduce dynamic losses to ecosystem services. That is, if there exist damages from the invasion, research identifying those damages can guide managers to increase control of the invasion, through increasing the harvest and even if necessary subsidizing it. This would counter the stock conservation efforts that research expenditures of type C may promote, creating potential conflict amongst different stakeholder groups.
Research type B (Baseline) refers to ecosystem baseline research, which takes place west of 26^o E for the case of the RKC. Up until now it has been conducted primarily for purposes other than the crab invasion. Its results therefore, have not directly been related to impacts of the crab. This type of research identifies the baseline ecosystem assets which are at risk from expansion of the invasion. Like research type R, the results of type B research can potentially be used for combating the externalities of the invasion.

Figure (1) shows the interactions among the different types of research. Type C and R occur in the same space (the heavily invaded area east of 26^o E), though their outputs are likely to lead to contrasting policy recommendations. Types B and R represent the ex-post and ex-ante efforts to determine the external costs of the invasion, with B providing a goal-post for conservation and restoration. Types C and B are needed to delineate the direct opportunity costs of management decisions of further spread of the invasion or its prevention; preventing the spread has opportunity costs that research type B identifies.

The socially optimal harvest can be achieved with a combination of B, C and R. A combination of all 3, includes allocation of research resources to the commercial fishery, to the external benefits of harvest in the "fully" invaded area as well as to monitoring in the recently (and only partly) invaded frontier area that establishes a baseline and provides opportunities for EDRR (Early Detection and Rapid Response). With limited budgets, decisions must be made regarding how to allocate resources across the different research types. We identify appropriate margins for analysis in the research decision amongst research types. In this paper, we focus on the spatial allocation of resources, because R and C types of research can be jointly produced while B type research must be conducted separately. We do not attempt to separate C and R, leaving direct assessment of the margin between commercial stock information improvement and improved information about external damages for future research.

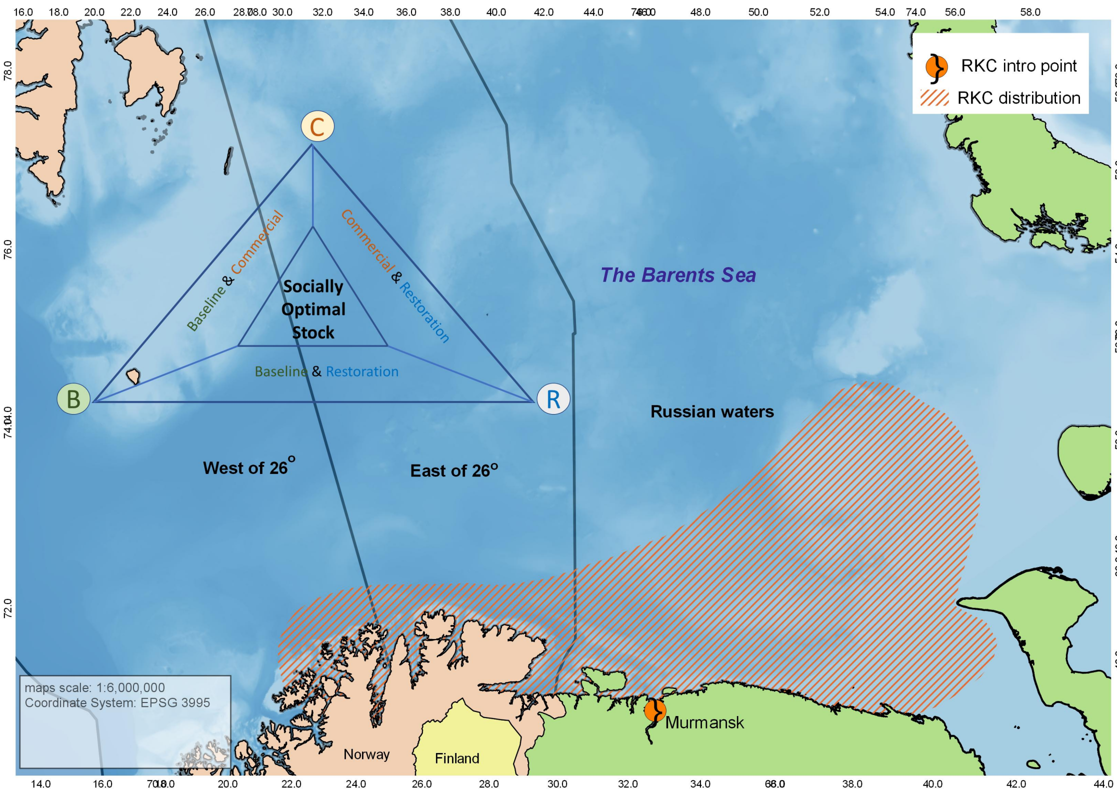


Figure 1. **RKC study area & Types of Research**
C: Commercial, B: Baseline, R: Restoration

The importance of this analysis lies in answering the question of where the marginal resource unit available for research is better spent. Baseline research on the frontier is anticipated to have more diffuse chances of proving directly applicable to management decisions than research within the existing invaded area. Furthermore, research in the invaded area has two direct avenues for improving social welfare - through reducing the missing information about the commons problem and through the external damages, while research at the frontier focuses on only improving the information over the external damages. Thus we expect a priori that research in the invaded area is more productive than research at the frontier.

3. The Model

We take a cost minimization approach to the question of resource allocation across space. We cannot strictly quantify the profit from investment across research types, but instead consider the production of successful research as a general output whose costs we seek to minimize. We distinguish the resources/research dollars invested in each type of research in R_B, R_C and R_R for Baseline, Commercial and Restoration research respectively. Since R_C and R_R take place in the invaded area and are frequently jointly produced, we collapse these two types of research of the invaded area into one, R_I. For the case of the RKC this assumption of stock assessments (reflected via C) and impact assessments (reflected via R) carried out in tandem by research vessels, east of 26^o E, is an assumption with empirical merit (JH Sundet, Institute of Marine Research, Norway, personal communication, 2016).

We further assume the existence of a "hit or miss" effect for the results of the types of research performed in the western (B) and the eastern patch ($R\&C$ or I) respectively. By "hit or miss" we define the probability of success for each research area; this can be interpreted as the probability that research will yield information that reduces the uncertainty and changes the social planner's optimum or that it will yield an increase in the well-being from better management. These probabilities are given in our set-up by P_B, P_C and P_R respectively; with P_I being a function of P_C and P_R. A research "hit" is essentially buying information that makes management move away from the current path because social welfare outcomes can be increased by doing so, or reaffirms the existing path through decreased variance, and is therefore a convenient framing tool in this setting where we are agnostic about the payoff functions of the different research types. The concept of a "hit or miss" is not new in the conservation biology literature, especially in cases of studies which include large uncertainties (Sivasithamparam et al., 2007). Tait and Williams (1999) point out the "hit and miss" nature of research and breakthroughs, which underlie big part of the knowledge generation in science. We use that concept in our modelling framework in order to account for significant scientific developments, stemming from either research area, that improve our understanding of the invasion and alter its management in ways that correct for the social optimum.

We begin with the assumption that Research type I has a higher potential for "success" compared to type B, which is justified by the fact that the results from the area east of 26^o E, where R type of research takes place, reflect the interaction of the invasive crab with the ecosystem as opposed to type B research which demonstrates ecosystem identifications in the absence of the crab [3].

Studies in the invasive species economic literature have typically sought to identify optimal management strategies in terms of control and prevention as well as design mechanisms and policy instruments to achieve optimal stock levels. Although the optimal allocation of resources to prevention versus control of invasions is not new in the literature (e.g. see Leung et al. (2002)), there has been scant coverage of information costs of research that account for pre and post-invasion stages. We therefore seek to deepen our understanding of such resource allocation problems for invasions through the R& D literature, which provides useful intuition on ways to allocate resources among heterogeneous projects. Applying the framework suggested by Choi and Gerlach (2014), we demonstrate, using a set of assumptions pertinent to the invasion problem, that in a socially optimal context, the probability of achieving research "hits" matters in how we allocate research resources. We associate a high probability of a research "hit" to an increase in the effectiveness of the research in revealing information, either about the external benefits or about the stock. Choi and Gerlach (2014), in the static part of their model, set up a framework that explains how firms engaging in innovation projects / R&D behave and what is the socially optimal division of projects among those firms. They find that it is optimal to allocate more resources to the more "challenging" project from the ones available, as opposed to the fact that the firms show a preference for engaging into the less "challenging" ones. We extend this result to spatially differentiated invasive species management on either side of the invasion frontier. Further, we clarify their theory in the context of cost minimization and input substitution in order to understand the limits of this recommendation.

We assume that research is needed in both areas, and that P_B, for reasons suggested above, is less likely, ceteris paribus, to generate a "hit" than P_I. That is:

[3] Arguably, a (possibly weaker) case can also be made for higher probabilities of success of B instead of I, or even for equal probabilities of success between the two; the implications of those on the allocation of resources will be discussed at the end of our analysis

$$0 < P_B < P_I \leq 1. \tag{1}$$

The probability that research type B fails to produce new knowledge useful for optimal crab management, within a certain period of time, is given by $(1 - P_B)^{R_B}$. The respective probability of failure in research type I is given by $(1 - P_I)^{R_I}$. The probability of the research dollar being efficiently/successfully invested will then be

$$P(R_B) = 1 - (1 - P_B)^{R_B} \tag{2}$$

$$P(R_I) = 1 - (1 - P_I)^{R_I} \tag{3}$$

Ideally, the social planner would maximize the expected payoffs from the different types of research, but since those are not known, it is not beneficial to weight those probabilities with random or assumed payoffs. One of our key simplifying assumptions is that research types B and I are independent so that an increase in the probabilities of success of one type of research due to exogenous factors, does not reinforce the probability of "success" of the other type [4].

The regulator who is managing the invasive crab within the resource constraints handed to him, is maximizing the probability that both types of research turn out "hits", which is measured in terms of yielding information useful on the invasion that will prevent social welfare losses in the future. The objective function is

$$\max_{R_B, R_I} W = P(R_B)P(R_I) = [1 - (1 - P_B)^{R_B}][1 - (1 - P_I)^{R_I}], \tag{4}$$

s.t

$$R_B + R_I = R_T, \tag{5}$$

where R_T is the total budget available for RKC-related research. In order to make the analysis more tractable, we consider the research resources (R_B, R_I, R_T) to be continuous variables.

The First-Order Conditions (FOCs) imply that the research resources should be allocated in such a way so that the marginal benefits, from success across the two types of research are equal,

$$\frac{\partial P(R_B)}{\partial R_B} P(R_I) = \frac{\partial P(R_I)}{\partial R_I} P(R_B). \tag{6}$$

The intuition for the equalized marginal benefits is obvious and has been discussed thoroughly in the environmental economics literature (see for example Tietenberg and Lewis (2016)).

The equality in (6) determines the optimal research dollar allocation, R_B^o and R_I^o. The analysis that follows shows that as long as (1) holds, then $R_I^o < R_B^o$ also holds, which implies that the optimal allocation of research resources favors, at the margin, the most "challenging" type of research or the type with the higher chances for a "miss". The marginal contribution of each type of research in succeeding to provide more information on the RKC impacts needs to be equal, which would require $R_I^o = R_B^o$ if the level of difficulty of succeeding in getting the information from the two types of

[4] Had there been some "complementary" relationship between types B and I, we would have to consider the joint probability of success as well. Economies of scope would potentially arise if an increase in the probability of success of type B (I) resulted in increased probability of success for type I (B). Potential effects of mutual or one-direction reinforcement are being ignored in this reduced-dimension model for the sake of simplicity and clarity of exposition

research was the same. Given though the limited resources available, reflected in our model through the budget constraint R_T, we will be showing that it is optimal to invest more heavily in the more "challenging" type of research, which we consider here to be the baseline one, type B.

Solving for R_B from the constraint (5), we have

$$R_B = R_T - R_I. \tag{7}$$

Substituting (7) into the maximization problem (4), that simplifies to

$$\begin{aligned}\max_{R_I} W &= P(R_B)P(R_I) \\ &= 1 - (1-P_B)^{R_T - R_I} - (1-P_I)^{R_I} + (1-P_I)^{R_I}(1-P_B)^{R_T-R_I}. \end{aligned}\tag{8}$$

The FOC, after rearranging, becomes

$$\begin{aligned}\frac{\partial W}{\partial R_I} &= \ln(1-P_I)(1-P_I)^{R_I}[(1-P_B)^{R_T-R_I} - 1] \\ &\quad + \ln(1-P_B)(1-P_B)^{R_T-R_I}[1-(1-P_I)^{R_I}] = 0. \end{aligned}\tag{9}$$

From what follows, it will be shown that the unique solution implies more research units to research type B, or $R_I^o < R_B^o$, which can also be expressed as $R_I^o < R_T/2$.

The negative sign of the Second-Order Condition (see Appendix), implies the existence of a unique maximum. Note that at $R_I = 0$, it holds that $\frac{\partial W}{\partial R_I} = -[1-(1-P_B^{R_T})]\ln(1-P_I) > 0$.

In order to show that the FOC (9) (for ease of notation F hereafter) when evaluated at R_T is negative, which will confirm our initial assumption that the optimal allocation of research resources to the less "challenging" or more prone to a research "hit" type, should be less than half of the budget $R_I^o < R_{T/2}$, we need to find the sign of $\frac{\partial F(\frac{R_T}{2})}{\partial P_I}$. We find the sign of the derivative to be negative (see Appendix). In order to verify the negative sign we also check the sign of the cross partial, which is also negative (see Appendix)

$$\frac{\partial^2 F(\frac{R_T}{2})}{\partial P_I \partial P_B} < 0 \tag{10}$$

More specifically this implies that the derivative takes its highest value at $P_B = 0$ where

$$\left.\frac{\partial F(\frac{R_T}{2})}{\partial P_I}\right|_{P_B=0} = 0. \tag{11}$$

It follows that $\frac{\partial F(\frac{R_T}{2})}{\partial P_I} < 0$ for all $P_B > 0$. This implies that $F(\frac{R_T}{2}) < 0$ for all $P_I > P_B$, while also that $R_I^o < \frac{R_T}{2}$. The implications of this result indicate that the resources allocated to the type of research with the higher probability of "success" should not exceed half of the available budget. In this simplified context we have used a division into only 2 different types of research, which implies that more than half of the research budget should be allocated to the more "challenging" type of research with the lower probabilities of "success" or the higher chances for a research "miss", which is the Baseline Research on the western frontier in our case study. We further consider comparative statics with respect to the probabilities of "success" of each research type, at the optimal allocation of research resources (R_I^o). First we consider the case where some exogenous factor increases the success probability of research type I:

$$\left.\frac{\partial F}{\partial P_I}\right|_{P_I^o} = \ln(1-P_I)^{R_I}[((1+R_I)(1-(1-P_B)^{-R_I+R_T} + \frac{R_I(1-P_B)^{1-R_I+R_T}}{1-P_I}] < 0. \tag{12}$$

Conversely, with an increase in the success probability of research type B we have

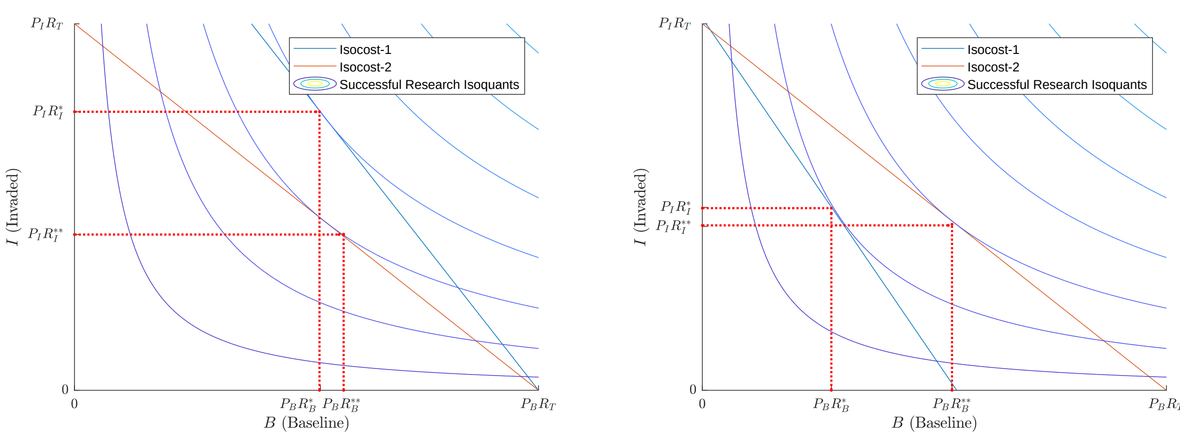
$$\begin{aligned}\left.\frac{\partial F}{\partial P_B}\right|_{P_I^o} &= (-1-P_B)^{1-R_I+R_T}[(R_I-R_T)(1-P_I)^{R_I}\ln(1-P_I) \\ &\quad -(-1+(1-P_I)^{R_I})(-1+(R_I-R_T)\ln(1-P_B))] > 0. \end{aligned} \tag{13}$$

The sign of (12) reflects the sign of $\frac{\partial R_I^o}{\partial P_I}$ and the sign of (13) reflects the sign of $\frac{\partial R_I^o}{\partial P_B}$ or

$$\left.\frac{\partial F}{\partial P_I}\right|_{P_I^o} \stackrel{s}{=} \frac{\partial R_I^o}{\partial P_I} \qquad \text{and} \qquad \left.\frac{\partial F}{\partial P_B}\right|_{P_I^o} \stackrel{s}{=} \frac{\partial R_I^o}{\partial P_B}, \tag{14}$$

implying that at the optimal state of resource allocation, an increase (decrease) in the probability of success of the restoration type of research will lead to a decrease (increase) in the resources allocated to it, while conversely an increase (decrease) in the probability of success of the baseline research while at the optimal state, will lead to an increase (decrease) in the restoration's research budget.

In Figure (2), we illustrate the trade-off in a cost-minimization framework. Generally speaking, research aims to generate "hits" that improve management capabilities through better information. A field of isoquants illustrates bundles of combined research at the frontier and in the invaded area that produce equal quantities of successful research, or else "research hits". Thus the slope of the isoquants is the Marginal Rate of Technical Substitution between research success at the frontier and research success in the invaded area, where the MRTS is the ratio of marginal productivities of the research in I and B.



(a) (b)

FIGURE 2. **Trade-offs between Baseline (B) Research at the Frontier and the Invaded (I) area**

This MRTS, which has the standard convexity, monotonicity and transitivity properties reflecting that more research input will generate more research output, and that there are increasing opportunity costs of switching from one research type to another as one increases the use of the new input and reflects the welfare function in the model.

While we consider the input price of research to be equivalent in the two areas, the price of successful research is not. Thus the isocost lines reflect the research expenditures weighted by their probabilities of success. In other words, if all resources are devoted to one type of research, say B, then the amount of successful research generated is $P_B R_T$, and vice versa.

For initial conditions $P(B)$, $P(I)$, and R_T the $P_B R_B^*$ and $P_I R_I^*$ show the expected bundles of successful research from R_B^* and R_I^*, as reflected in (6).

An external upward shift to the "success" probability of I, which essentially translates into a decrease in the cost of performing I, will lead to a decrease in the resources allocated to that research type and therefore more allocated to type B (R_I^{**}, R_B^{**}). Conversely an external inwards shift to the probability of "success" of type B which translates into a increase in its costs of performance, leads to a decrease in resources allocated to type I and therefore an increase in resources for research type B.

This appears counter-intuitive from the perspective of most cost-minimization problems, where the additional dollar should be allocated to its most productive use. The logic, however, is made clear when one considers the output and substitution effects present in this case. Generally if both inputs are normal factors of production, the output and substitution effects operate in the same direction. In other words, an increase in the cost of one factor (or reduction in its effectiveness in generating hits) should lead to a reduction in the allocation of resources to that factor in favor of the more productive one. In this case, however, putting the additional dollar into the lower productivity resource increases the probability that the dollar funds success more at the margin than it would do for the higher productivity resource. It is worth noting at this point that although we consider the assumption in (1) to hold since we expect the I type research in the fully invaded area east of 26^o E to be more informative than the baseline research in the newly and partly invaded area west of 26^o E, technically we are agnostic about this relationship. Had the probability of "success" of the baseline type of research been higher, our results would be reversed in the sense that an optimal allocation would indicate more resources to the research in the invaded area. In the special case where the probabilities of "success" between the two types of research are equal so that the difficulty level in yielding information useful that advances the short and long-term management of the invasion is the same, then the optimal allocation of resources would suggest that monies are divided equally among the two types of research. Furthermore, in the special case where research in only one area can yield positive social welfare, this analysis will not apply.

4. Application in the RKC case

The Norwegian Parliament, operating under guidelines adopted from a White Paper since 2008 (Fiskeri-og Kystdepartement Der kongelige, 2007), has decided that in Norwegian waters east of 26^oE and south of 71^o $30'$ N RKC fishing will be quota regulated and to the west of this point open-access. The IMR annually estimates RKC stocks and delivers those estimates to the Directorate of Fisheries, which in turn provides management advice to the Ministry of Fisheries and Coastal Affairs for setting the annual Total Allowable Catch (TAC).

The amount of resources available to the IMR for research on various aspects of the RKC invasion/fishery has varied since the beginning of research fisheries in 1994. Starting from 2004, we have classified the resources allocated to the different projects based on our definitions of C, R and B types of Research. In C we have included stock assessments, population surveys, research fisheries in Tana and Laksefjørd, development of methodologies for stock evaluation east of 26^o E and development of stock models. B includes population surveys in the non-commercial area as well as studies of spread of the RKC west of 26^o E. R includes bycatch studies and ecosystem impact studies. We have excluded 2006-2010 projects with a focus on proliferation and spread, reproduction and recruitment, tags and recaptures (approx. 3.7 mil.NOK) as well as the collection of historical data (approx. 0.5 mil.NOK). We regard those projects as directly jointly useful research for all 3 research type categories and therefore the numerical estimates we have accounted for can be considered as lower bound estimates.

The commercial fishery in Norway started for the first time in 2002. The Norwegian government handed out quotas to the fishermen as a compensation for bycatch losses from the crab (mostly in cod and lumpsucker fisheries). Bycatches declined significantly within approximately a decade, due to improvements in gear technology after a series of experiments on the overlapping fisheries (Furevik et al., 2007, 2008; Furevik and Ulvestad, 2012). As the RKC fishery started becoming profitable and bycatches were less of a problem, the allocation of quotas started increasing significantly (Table 1), with the primary focus of the management being a long-term stock in the eastern patch adjacent to the Russian border.

Year	**Stock Estimates (legal males)**	**TAC**	**% Fished Crab Stock**
2002	779 000	100 000	13%
2003	1 307 000	200 000	15%
2004	1 325 000	280 000	21%
2005	750 000	280 000	37%
2006	901 000	300 000	33%
2007	975 000	300 000	31%
2008	795 000	569 000	72%
2009	468 000	539 000	115%
2010	371 000	409 000	110%
2011	672 000	520 000	77%
2012	766 000	950	51%
2013	933 000	1 050	41%
2014	577 000	1 080	72%
2015	677 000	1 300	68%
2016	440 000	2 050	165%

Table 1. **RKC Stock Estimates (in individuals), Total Allowable Catch (TAC) (2002-2016) (in individual crabs up until 2011 and in tons after 2012) * Norwegian Environmental Agency (2017); Hjelset (2014); Fiskeridirektoratet (n.d.)**

* The TAC for 2012-2016 was converted from tons into individuals using the average weight per crab (e.g see Sundet (2009)).

Figure (3) shows the ratio of Quota to Stock over time on the left hand-side axis (in columns) [5]. We see that the average ratio is approximately 0.1 and that this mainly increased from 2002 to 2011 and

[5]For the late 1990's- early 2000's accurate information on crab abundance is generally missing(Hjelset, 2014), JH Sundet, Institute of Marine Research, Norway, personal communication, (2017)

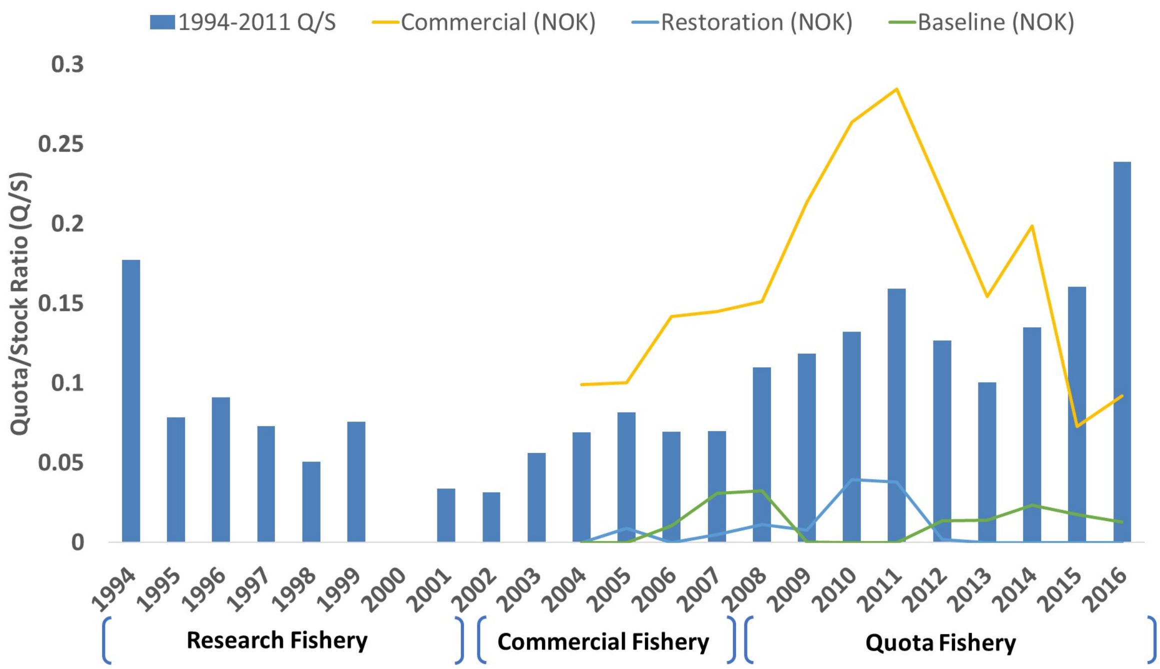


Figure 3. **Estimates of Annual Quota to Stock (Q/S) relationship 1993-2016 (measured in individual crabs) & Research Resources spent in Commercial, Restoration and Baseline Research (2004-2016), during the 3 phases of the crab Fishery (Research, Commercial and Quota Fishery) a,b**

Sources: Petryashov et al. (2002); Norwegian Environmental Agency (2017); Hjelset (2014)

[a] Differs from the harvest rate reported in Hjelset (2014) which accounts for stock estimates of legal males only. The Quota to Stock relationship here accounts for the total stock of RKC.

[b] The regulation on the TAC in Norway has switched measurement units from individual crabs to tons and therefore for the years 2012-2016 we have converted the tons of crabs into individuals using the average yearly crab weights

again from 2013 to 2016. This increasing ratio shows a growing intensity of harvest that supports greater concern for external benefits of harvesting. The drop in the years following 2011 however, indicates a rebalancing towards commercial conservation resulting in too few crabs harvested in these years. We seek further evidence to identify the connection between the trends illustrated in Figure (3) and the balance of research dollars. To that end, Figure (3) also shows expenditures (in mil. NOK) for the 3 types of research since 2004. The commercial expenditures outweigh significantly expenditure on both Restoration and Baseline research, throughout the entire period of research on the RKC.

During the period of the research fisheries from 1994-2001, both quotas and exploitation rates were low (Hjelset, 2014), given that knowledge about the population was limited. At the urging of Russian fishing managers, the newly introduced species was treated as a potential fishery rather than an invasion and was therefore harvested conservatively. In the years that followed, the "invasion" was recognised for its bycatch damages. Those were alleviated by having those fishermen affected by the bycatches receiving the benefits of the limited RKC harvest starting from 2002. In the period between 2002-2007 more refined knowledge on the growing RKC population became available. In 2007, with the newly introduced regulation, we can see action taken for the first time on research hits other than type C (Fiskeri-og Kystdepartement Der kongelige, 2007) (see Figure (3)), suggesting an awareness that there was more at stake than bycatch losses. In response the quotas were pushed upwards, with the increasing exploitation rate following the path of expenditures in C type research.

Figure (4) shows the cumulative spending in Baseline and Restoration research over time and exemplifies how the two have interacted over time. We see Baseline Research leading until 2010 and continuing to increase after 2011, when additional investments in Restoration Research stop. The annual rate of change in the exploited stock is likely to have ramped up expenditures and pressure for a higher fishing mortality until 2008 when then first official management plan came into force. This is followed by declining exploitation rates, which pick up from Baseline expenditures and result in a more intense exploitation after 2013 and 2015.

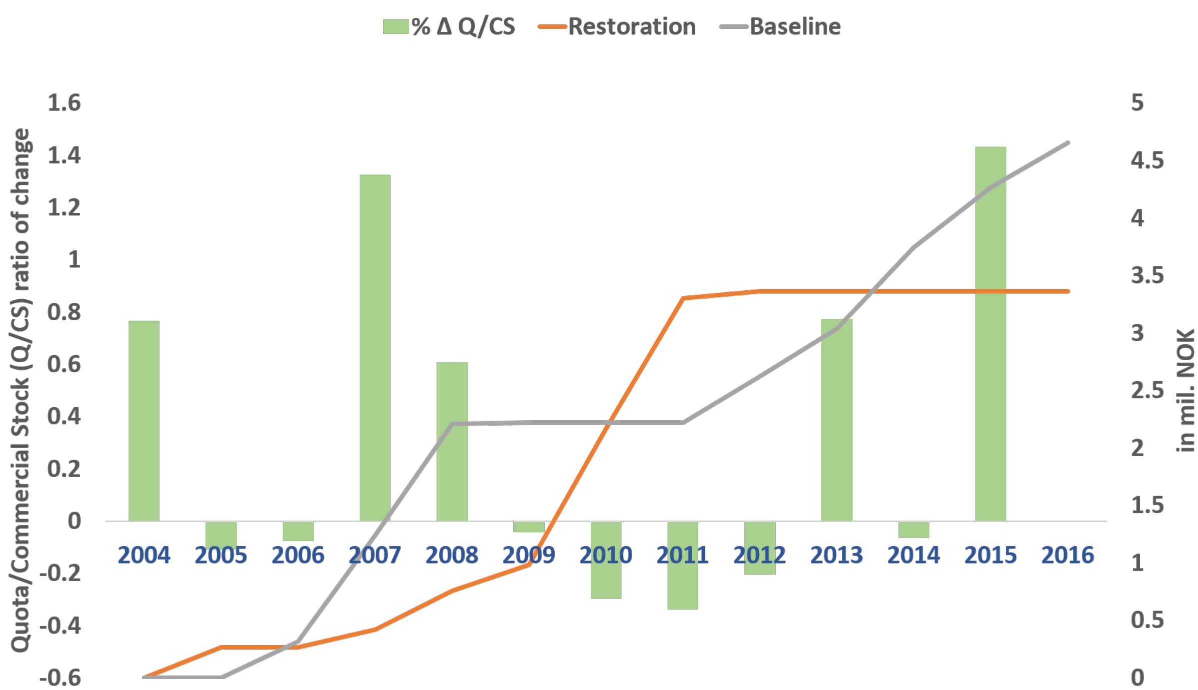


Figure 4. **Quota to (Commercial) Stock (Q/CS) Annual Ratio of Change & Cumulative Annual Expenditures in Research types *R* and *B* (in mil. NOK) (2004-2016)**

The expenditure data do not allow us to establish a clear connection between research "hits" and resources. However the rise in B type expenditures up to 2008 is likely to have informed the increase in fishing pressure while it might also have driven the establishment of the line at 26^oE. This led to the designation of the area west of that point as open-access, in an effort to delay the invasion. It is interesting to see that once the line was drawn, the allocation shifted back to more resources allocated to type R. We attribute the overall fewer expenditures in B and R, after 2011, to the diminishing interest in research for ecosystem impacts from the invasion, a trend confirmed by the biology and ecology literature across time (Kourantidou and Kaiser, 2017).

Table (2) shows the allocation of resources (as graphed in Figure (3)), from 2004 to 2017 along with the Total Annual Landings and the Annual First-Hand Value from 2002 til 2015, from the most

Year	Budget (in 1000 NOK)	Total landings (in round weight tons)	First Hand Value (in 1000 NOK)
2002	-	414	31 227
2003	-	823	58 278
2004	2 969	1 294	80 385
2005	3 269	1 223	68 958
2006	4 767	1 041	50 936
2007	6 184	1 267	59 200
2008	7 276	5 199	135 134
2009	6 989	5 613	127 585
2010	10 246	1 905	87 560
2011	9 695	1 782	151 777
2012	7 088	1 437	116 961
2013	5 046	1 321	80 444
2014	6 658	1 695	132 168
2015	3 186	2 175	184 169
2016	3 150	-	-
2017	5 357	-	-

TABLE 2. Annual Resources allocated for RKC research (2012-2017), Total Landings (2002-2015), First-Hand Value (2002-2015)
Source: Fiskeridirektoratet (2017), JH Sundet, Institute of Marine Research, Norway, personal communication, (2017)

recently available Profitability survey on the Norwegian fishing fleet (Fiskeridirektoratet, 2017). The total landings along with the first-hand value (see Table 2) might be a poor indicator of efficiency in decision-making as far as the research budget allocation is concerned, but it does provide a one-dimensional view of the "success" for the local economy of Northern Finnmark, which is reflected through the C type of research in our model. According to the project leader for the RKC in IMR, since 2011 approximately 25% of the available resources have been used to monitor the spread of the crab west of 26^oE. The remaining 75% has mainly been used for stock assessments with a small percentage of it (approximately 10%) having been used for exploration of ecosystem impacts of the invasion such as impact studies on benthic species, tag and recapture studies, fecundity studies etc. In addition to that, approximately 1.5 mil. NOK were used annually in a project to investigate behavior of the crab when entering traps, developing gillnets to reduce bycatch of crabs and other fish technology issues; a project that lasted for about 10 years [6].

The Research related to determining stocks and quotas (type C research in our set-up) clearly dominates over the entire series of years and reflects how research budgets have been allocated primarily to suit the interests of commercial development of the stock. More specifically we see an increasing trend in money allocated to Type C after 2007, when the regulation for management of the stock came into place for the first time. Resources allocated to Restoration and Baseline types have been significantly lower over the years. The implementation of open-access after 2007 coincides with an increase in resources allocated to Restoration and a decrease in Baseline Research.

[6] In addition to IMR's repetitive stock assessment investigations, Master and PhD projects have also been financed by the University of Tromsø. More specifically 4 PhDs and 10 Master Theses focusing on the biology, the impacts and the management of the RKC, were conducted from 2004 til 2016, the costs of which has been estimated to be approximately 18 mil. NOK

On top of that, after 2012 there have been hardly any resources available for studies on ecosystem impacts or bycatches (R) and the resources allocated for studying the spread over to the west have been kept at a minimum. The diminishing resources allocated to R and B Research, along with the fewer negative ecosystem impacts documented in the literature over time (Kourantidou and Kaiser, 2017), signal declining concerns for the negative impacts of the invasion in Norway, with the interest in the commercial fishery taking over.

In Figure 5 we depict the NOK spent in C type of research per crab and per commercial crab, for which we have used the total annual stock estimates for RKC and the annual stock estimates for male harvestable RKC (crabs of significant size that are of commercial interest) (Norwegian Environmental Agency, 2017). The differences in the two paths over time illustrate that while research expenditures per crab have been fairly constant, expenditures per commercial crab had a large increase from 2008 to 2012. This is partly attributable to a drop in the numbers of commercial crabs available (see Table (1)), but also an increase in spending (Table(2), Figure (3)).

The fishing mortality for the RKC has increased steadily from the start of the fishery in 1994 and has been kept after 2008 and on, at or above fishing mortality rate that maintains the MSY. Both this and the MSY indicator are important parameters, on which IMR researchers base their advice for the annual TACs. The high fishing pressure on the RKC is justified by the decision to limit the spread in the western patch (JH Sundet, Institute of Marine Research, Norway, personal communication, 2016), which we view as a response to type B and R research.

In Figure (6) we use the percentile range (90th - 10th percentile) and the median for the RKC biomass index the relative population size of male crabs with carapace length greater than $130mm$ (Sundet et al., 2016) [7], as a proxy for the Coefficient of Variance (CV) for the past 40 years. The policy relevance of the limited variation of CV in the years after 2001 is that the uncertainties on the stock estimates have started shrinking. We view this as a sign that the investments in C type of research have resulted in very efficient models and more accurate stock estimates. Note that the difference in the trend that shows up in the post 2007 period between the NOK per crab and NOK per commercial crab (Figure (5)), does not create any effect on the CV (Figure (6)). One would expect such an effect if the fluctuations in the commercial crab stock relative to the total stock were a surprise to researchers.

Although it is not straightforward to disentangle the reasoning behind the allocation of research resources over the past years, Figures (5) and (6) indicate that the population of the invasion as a whole needs to be viewed differently than the commercial stock.

Without evaluating the economic rationale behind the management objectives, the C type of research in the RKC fishery appears to exhibit overall research success, or a high level of' 'hits"; it has been informing decision-makers accurately enough for setting the annual TACs that will serve their long-term goals for a dynamically profitable stock in the eastern patch. The stability of this indicator over the last 15 years reinforces the argument that additional investments in type C research may not yield many further improvements in our understanding of the invasion or the fishery and are therefore not expected to make any significant difference in identifying the social optimum. Although we caution against drawing strong inferences, given possible future changes in the dynamics of the populations, the payoffs from additional investments into C type of research

[7] The Biomass limit is set empirically; values below that limit imply an increased risk of recruitment failure and a sharp decline in future harvests. At lower levels, the recruitment of the stock is hard to be predicted due to the low spawning biomass. A commonly used value for the Biomass limit in most fishery assessments is 0.3 of the Maximum Sustainable Yield biomass and is being seen as an "alert" sign for fishery managers. Although it is hard to get accurate scientific estimates for Biomass limit, the empirical formula of 0.3 works as a practical tool in assessments and management (JH Sundet, Institute of Marine Research, Norway, personal communication, 2016)

are relatively small and therefore the allocation of resources shall be restricted to annual stock estimates, in order to allow space for allocation to overlooked baseline research at the western frontier.

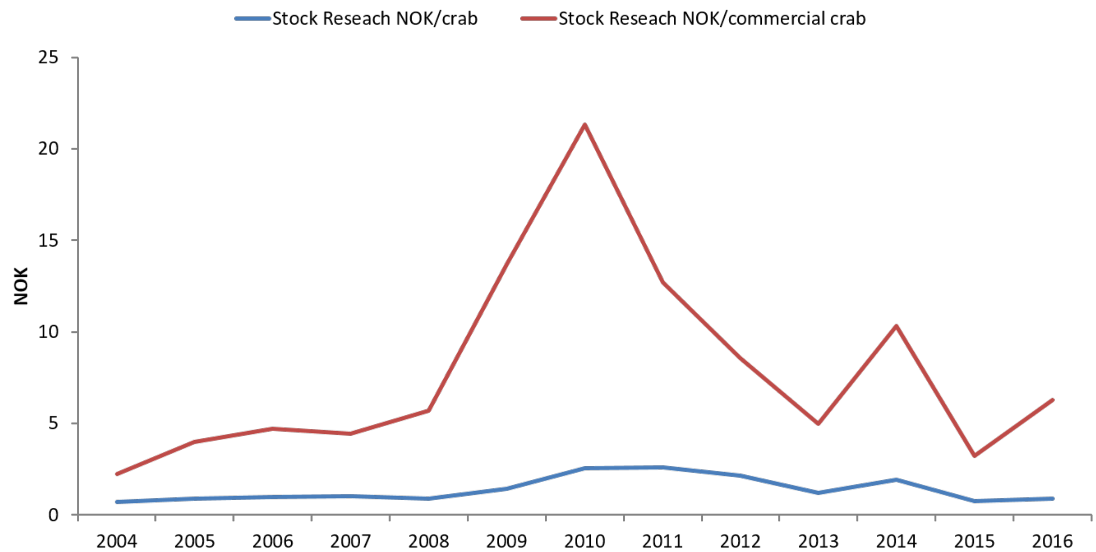


FIGURE 5. **Type C research per crab and per commercial crab**

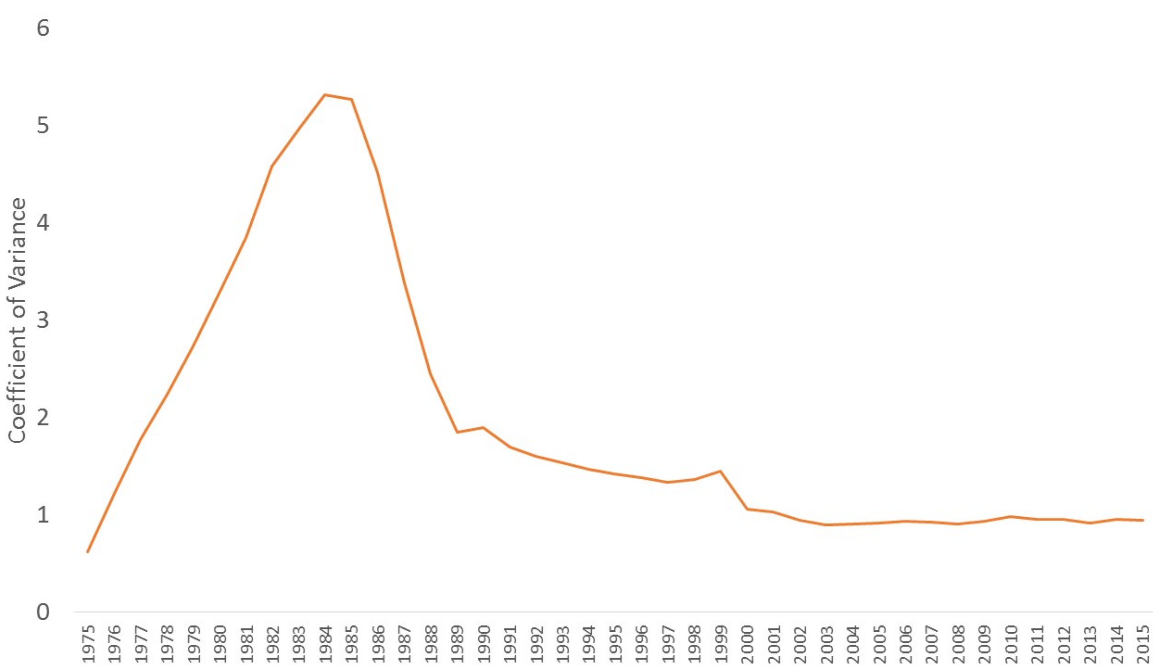


FIGURE 6. **Coefficient of Variance of the RKC biomass Index, 1975 - 2015**

5. Discussion

The role of economies of scope is critical for prioritizing and allocating research resources, although not explicitly modelled here. In many cases, even when more than one invasion is considered, monies available are expected to come from the same resource pools (Burnett et al., 2006) and this is also the case for studying different aspects of the same species. Research type B and type I are spatially divided and thus restrict the potential for "direct" economies of scope. Yet, as long as the areas west and east of 26^oE share similar biological characteristics, it is reasonable to assume that 1$ spent in B type of research increases the Marginal Benefits from the I type of research (through R), since B identifies the ecosystem values that have already been lost in the heavily invaded area where R takes place. This begs the question of how much reinforcement is needed for this feedback effect in type B. Results from different (diversified) ecosystems are generally preferred in biological research since they provide a more holistic view of the invasive species' impacts. However increased similarity among the two ecosystems (west and east of 26^o E) is likely to increase the strength of the feedback effect due to economies of scope.

Economies of scope are also likely to exist between type C and type R; which we have modelled as one here, type I, in order to reflect on the allocation of resources across space. The two-dimension model here can be extended to accommodate economies of scope by 1) Weighting the role of type R and type C in I, 2) Choosing a functional form that explicitly accounts for the 3 inputs and their interaction, 3) Accounting for external inputs to B type research (that alter the management dynamics in the West). The results from type C are a critical input for type R research since they contribute to building an understanding of the benefits society is giving up (gaining) by shrinking (augmenting) the stock in lieu of the negative (positive) externalities. However a greater interest in type C is likely to impede communication of results from type R research, since interests might be at odds. This can be reflected in the literature which displays a conflict of opinions in the perception of the crab's impacts. This conflict is particularly noticeable among researchers looking at impacts in Russian waters who generally find no significant damages (Anisimova et al., 2005; Dvoretsky and Dvoretsky, 2015) and researchers focusing on the western Norwegian part of the crab distribution who do (Oug et al., 2011; Michelsen, 2011) (see also Kourantidou and Kaiser (2017)). Furthermore the lack of documentation of negative ecosystem impacts from the RKC invasion on the Russian side could possibly be attributed to the fact that there is no longer space for a B type research (in some area where the invasion is still limited) which would allow them to build up a baseline for understanding future impacts. Norway has had the advantage of being able to establish a baseline for monitoring in the west due to the gradual expansion of the species westwards and prior interest of benthic values in that area. A large part of the crab distribution area was monitored before the arrival of the crab for different reasons - such as its overlap with oil and cold-water coral fields. In the distribution area west of 26^o E , there is available information from other (and past) research programs that could be utilized for studying the impacts of the invasive crab. However no such research efforts are currently taking place with the exception of few recent benthic megafauna studies (Jørgensen et al., 2015). MAREANO is an ongoing program in Norway which collects a large series of data across the coast of Norway, amongst others, on seabed characteristics, biotopes, distribution of benthic fauna communities and biodiversity. It is a large program led by the Norwegian Environment Agency, with more than 168 mil. NOK allocated to it in the first phase (2006-2010) and almost 500 mil. NOK in the second phase up until 2015 (MAREANO, n.d.). Given the interaction of the invasive crab with the soft-bottom benthic habitat, such data can serve as benchmark information for type B research. With MAREANO results informing Baseline research in the west about the values at stake from the crab's spread, the dynamics of the resource management problem alter, so that types I and C are weighted differently in relation to B. An additional reason for linking the existing results of research type

B in the west (such as from programs like MAREANO) with the crab invasion is that it is not necessarily accurate to use results from the east. The invasion damages might differ across space, which practically means that results from benthic bottom studies in the east might be misleading when invasion externalities are considered for the west. Furthermore there are a series of other different parameters to be taken into account in each area such as the overlap of RKC with other species' spawning grounds etc.

The existing body of research on the RKC, provides mixed signals with respect to the optimal stock of the invasion. The great bulk of the research that has been done on the RKC so far has been focusing on the crab bycatches in other fisheries, the predation upon commercial and non-commercial species (benthos) as well as the spread of disease vectors. These studies attempt to quantify the effects of the invasion in the ecosystem and offer qualitative guidance on the risks that the introduced crab is posing. The diverging viewpoints among researchers in Norway and Russia are an important harbinger in determining policies on harvest control rules (Kourantidou and Kaiser, 2017). Policy-makers are urged to infer results from those studies and identify the magnitude of fishery profits needed to outweigh the costs of invasion. The ambiguous net impacts of the invasion, as reflected in the ecological and biological literature over time, make the task of deciding how much weight to put in each type of research, particularly tedious. The recent rise of the RKC's industry economic activity in Norway (processing plants, exports etc) is putting additional pressure for more weight on Commercial Research. In this context, we fear that the Restoration and Baseline types of Research might be undermined given the existing contrariness in the literature and the lack of cooperation between Norway and Russia. Despite the existence of shared data for the crab between the two countries (Jørgensen and Spiridonov, 2013; Eriksen, 2012; Korneev et al., 2015) very little of it is publicly available, which is one of the main drivers of the adversarial positions among stakeholders regarding the management of the species.

6. Conclusions

The limited biological knowledge on the impacts of the invasive crab is clearly what jeopardizes its management and allows space for conflict between different stakeholder groups. Examples of conflict include on the one hand accusations towards the Norwegian Government by environmental organizations for violating the UN Convention on Biological Diversity with the management it applies on the invasive crab (Miljøvernforbund, 2010; WWF-Norge, 2002) and on the other hand disappointment on behalf of the RKC industry when new regulations targeting at a lower stock come into force (Sved, 2010; Norum and Sandmo, 2010). There is no doubt that more biological research can elucidate critical unknowns and provide suggestions for the optimal management of the RKC fishery. However research on intact ecosystems, particularly targeting prey species that do not have a market-value (such as the benthic species which are at stake from the crab's predation) comes at a cost which can be significant.

The paper's principal output has been to establish a reasoning that supports the need to prioritize allocation of resources among research types with different objectives. When it comes to invasive species with a commercial value, decision-makers are often poised between investing more resources in understanding the harvesting potential of the species or in exploring the potential ecosystem impacts from the invasion. In this paper's reduced dimension model we have distinguished the research for the invasive crab in different types and we have allowed asymmetry among those types. The asymmetry is being reflected via the probability of "success" or the chances of a "research hit" that causes changes in the social planner's perception of the social optimum. The probability for success of each research type essentially refers to the difficulty that each one of them entails in the process of revealing the marginal external benefits from harvesting. The marginal external benefits reflect the ecosystem losses prevented due to harvesting and identify the bioeconomic trade-off which is the net revenue foregone for reducing the stock and the growth of the crab. The model, albeit at the cost of some simplifications, helps articulate the implications of choosing to allocate more research resources to the more "challenging" type of research in a socially optimal context. The underlying intuition for this model set-up comes down to the dilemma of how the available resources for research on the invasive crab should be allocated optimally, given the spatial division of the invaded area, the differences in the status of the invasion and the different management applied in each one of those areas. Whether the costs of poor stock estimates are higher or lower than a poor understanding of the ecosystem damages from the invasion, remains unclear given that the the exact payoffs are uncertain. In this model though we show that the different research types can be treated as regular inputs to production of "research hits" and should be therefore funded accordingly. Our results also hint that, especially under the existence of biological uncertainties, the allocation of the available research resources to the heterogeneous invaded patches can be as important as the total research budget available.

The model, coupled with the data on actual resources spent on research for the RKC invasion provide the first systematic evidence that more resources need to be allocated on the western frontier of the invasion which is currently overlooked due to the low crab abundances and the limited commercial interest in the fishery. In Norway, the allocation of research resources has been significantly larger in the area of commercial interest East of 26^oE compared to the frontier are West of 26^oE. We view the imbalanced resource allocation as a management choice driven mostly by a static and ad-hoc administrative border on the line of the 26^oE rather than a result of weighting bioeconomic trade-offs of the invasion/fishery. Yet, one of the main drivers for the contentious policy of the Norwegian government to maintain a long-term sustainable fishery in the eastern patch and invest in it instead of eradicating, is the political willingness to support local communities, including the Sami indigenous peoples of Norway. Sundet and Hoel (2016) suggest that the growing RKC fishery as well as the crab processing sector support small coastal communities in Northern Finnmark and in some cases there is significant economic dependence on the crab fishery as well. Given the existing knowledge gaps on ecosystem losses from the invasion, we caution against drawing any inferences between policy making and benefit for the local communities.

Appendix A.

The Second-Order Condition is

$$\frac{\partial^2 W}{\partial R_I^2} = -(1-(1-P_I)^{R_I})\ln^2(1-P_B)(1-P_B)^{R_T-R_I} - (1-P_I)^{R_I}\ln^2(1-P_I)(1-(1-P_B)^{R_T-R_I}) - 2(1-P_I)^{R_I}\ln(1-P_B)(1-P_B)^{R_T-R_I},$$

which can be rearranged as following, for ease of identifying the sign

$$\frac{\partial^2 W}{\partial R_I^2} = \frac{(1-P_I)^{R_I}}{(1-P_B)^{R_I}}\ln(1-P_I)^2[(1-P_B)^{R_T} - (1-P_B)^{R_I}] - (1-P_B)^{R_T-R_I}\ln(1-P_B)[2(1-P_I)\ln(1-P_I) + \ln(1-P_B)P_I^{R_I}] < 0.$$

The expression $\frac{\partial F(\frac{R_T}{2})}{\partial P_I} < 0$ is negative since the following holds

$$\frac{\partial F(\frac{R_T}{2})}{\partial P_I} = (1-P_I)^{(\frac{R_T}{2}-1)}[(1-(1-P_B)^{\frac{R_T}{2}})(1+\frac{R_T}{2}\ln(1-P_I)) + \frac{R_T}{2}(1-P_B)^{\frac{R_T}{2}}\ln(1-P_B)] < 0$$

on the condition that $R_T\ln(1-P_I) < -2$, which we consider likely to hold.

The sign of the cross partial in (10) is

$$\frac{\partial^2 F(\frac{R_T}{2})}{\partial P_I \partial P_B} = -\frac{1}{2}\ln R_T(1-P_I)^{1+\frac{R_T}{2}}(1-P_B)^{-1+\frac{R_T}{2}} - \ln(1+\frac{R_T}{2})(1-(1-P_I^{\frac{R_T}{2}}))(1-P_B)^{\frac{R_T}{2}} < 0$$

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