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Allocation of research resources for commercially valuable invasions: Norway's red king crab fishery

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ABSTRACT

This paper models the optimal allocation of research resources aimed at understanding the consequences of a marine invasion. The model assumes returns to research are uncertain. Furthermore there are joint returns to research ahead of the invasion frontier and within the already invaded area. Research ahead of the frontier helps define external damages by establishing the baseline ecosystem services and values; research in the invaded area determines restoration needs and costs associated with controlling the invaded area's population. Additionally, research in the invaded area may improve management of any commercial aspect of the invading species, which may warrant accommodation. In such a case, simple application of the precautionary approach to the invasion has direct quantifiable costs in foregone commercial benefits. Benefits of research thus may accrue either from improved information regarding the potential or actual damages of the invasion, or from improved information for solving the common property management challenges of a commercial species. In the latter case, improved management heightens expectations of foregone benefits ahead of the frontier. We use the Red King Crab (*Paralithodes camtschaticus*) invasion in Norway as a case study. The crab is a valuable global commodity whose invasive presence in the Barents Sea is impacting the benthos. Harvesting or controlling the crab reduces these impacts, but the net benefits of doing so are uncertain and require both baseline research and restoration research to ascertain. We distinguish the research for Red King Crab in different types based on the potential to reveal marginal external benefits from commercial harvesting. We illustrate how misallocation of research resources can be reduced when the uncertainties create incentives that promote research into tangible commercial benefits over less certain ecosystem benefits. Our analysis suggests that there is currently greater marginal benefit from directing more research resources toward baseline research at the frontier of the invasion instead of making additional investments in research that focuses on the commercial potential of the invasive yet valuable crab.

1. Introduction

As invasive species spread, research resources may be expended ahead of the invasion frontier or within already-affected ecosystems. The general goal of research expenditures is to improve management decisions regarding the invasion by reducing uncertainties. Ahead of the frontier, research expenditures can identify baseline conditions and values for existing ecosystem resources. This in effect identifies the benefits of stopping the spread of the invasion. Research expenditures within invaded areas may have multiple roles; they may identify control and restoration costs if or when the invader is removed from the system, or they may identify commercial benefits of accommodating the species' presence, through for example a long-term sustainable harvest. These benefits are foregone in viable habitat areas ahead of the frontier. Understanding trade-offs between research expenditures ahead of the invasion frontier and within invaded areas facilitates improved management of the invasion across its time horizon (Epanchin-Niell, 2017; Burnett et al., 2006, 2008; Kaiser, 2014) and reduces ad hoc decision-making lacking in economic analysis (Epanchin-Niell, 2017).

This paper expands the standard timeline of management options for an invasive species to formally include research ahead of the invasion frontier, and it integrates this expansion across the invasion timeline by investigating trade-offs in research ahead of the frontier and within an already invaded area. It demonstrates that failure to consider in tandem

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the benefits of research both ahead of the frontier and in already invaded areas may result in difficulties in optimally prioritizing the allocation of resources to research types with different objectives. The paper develops a research and development (R&D) model adapted from Choi and Gerlach (2014) to analyze the choice of how to allocate research resources across the two regions, given uncertain and unequal research returns, when both types of research are needed. The model illustrates trade-offs between baseline research at the frontier (B) and research in the invaded area (I). Exploiting the duality of production and cost, we express the allocation problem as one of cost-minimization in order to determine where the marginal resource unit is better spent.

Baseline research at the frontier is considered more challenging because it can be anticipated to have lower or more diffuse chances of proving directly applicable to management decisions than research within the invaded area. At the same time, drawing from the Choi and Gerlach (2014) framework we find that under some conditions it will be optimal to allocate more resources to the more challenging research project. In short this is because success benefits from joint production of actionable knowledge in both types of research. An additional resource unit invested in the riskier type does not directly buy greater success, but it can improve the odds of success. At the margin, the success rate across the two research types needs to be equal for an optimal allocation. Thus, research ahead of the frontier should often constitute the greater portion of the research portfolio, despite its lower expected productivity.

Using different methodology, this sets up a corollary finding for research investment decisions to the theoretical conclusions of Finnoff et al. (2007) that risk-averse managers may choose control of an invasive species after its arrival in order to reap smaller certain gains over potentially larger but more uncertain gains from prevention.

We apply the model to research efforts of the Institute of Marine Research (IMR) in Norway over the last decades pertaining to the ongoing Red King Crab (*Paralithodes camtschaticus*) invasion in the Barents Sea. This application fosters insights into a second important consideration in the allocation of research resources. That is, when the invasive species has significant commercial potential, research into commercial benefits rather than ecological damages may induce accommodation, and acceptance of further spread, over control of the invaded area and prevention of spread to new areas. This extends our understanding of how invasive species management decisions may inefficiently favor certain economic benefits from a commercially valuable invasive species over uncertain or diffuse ecosystem benefits from controlling the invasion. Our results support policy makers tasked with allocating limited resources across disparate interests by providing a framework for weighing the marginal gains of additional research in relation to each other and the total gains from research productivity.

Further still, the challenge of determining research priorities in resource conservation is a widely applicable one. Given economic constraints on resources, there is a risk for disproportional investments in different types of research, where e.g. more emphasis may be placed on ecological rather than social types of research, or vice-versa (Davis et al., 2019) so that optimal management outcomes are not achieved.

2. Background and model

2.1. Background

Despite a large 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 controlling invasions in their expansion phase. 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; Burnett et al., 2007; Burnett and Kaiser, 2007). Another strand of the literature looks at the optimal search effort levels for detection, accounting for the invasive species' biological characteristics and ecological impacts (Cacho et al., 2007; Mehta et al., 2007; Kaiser and Burnett, 2010). 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). Invasive species sometimes 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). 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 the species may be viewed as an asset by some and as a liability by others. Optimal harvesting of the species, either for commercial purposes or for control of damages, requires information on both the over-exploitation of the commons that may arise with a newly viable commercial species (Christiansen et al., 2014; Bailey, 2011; Rosen, 2020) and the externalities of the invasive species (Kourantidou, 2018).

2.2. Model

Productivity in research is uncertain. We instead exploit the duality of production and cost to take a cost minimization approach to the question of resource allocation across space. We cannot strictly quantify the gain from investment across research types, nor do we wish to limit the definition of the anticipated gains to the research organization by formalizing the benefit side of this research in the objective function. Thus we consider the production of successful research as an output whose costs we seek to minimize. We distinguish the resources or research funding invested into Baseline research at the frontier of the invasion (R_B) or into research investments in the Invaded area (R_I). Research in I consists of two types of investment, Commercial research (R_C) and Restoration research (R_R), which are frequently co-produced.

We assume the existence of a "hit or miss" effect for the results of the types of research performed in the frontier and in the invaded area respectively. By "hit or miss" we define the probability of success for research in each area as the probability that research will yield information that reduces the uncertainty regarding current harvest impact on the invader or its externality. Successful research will yield an increase in societal well-being from better management. These probabilities of success are represented in our model by P_B for baseline research in the frontier area and P_I for research in the invaded area.

A research "hit" in our model occurs when the research results in information that causes management to either move away from the current path because social welfare outcomes can be increased by doing so, or when it reaffirms the existing path through decreased variance. The research hit 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 a big part of the knowledge generation in science. We use this concept in our modeling 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 in the invaded area I, which consists of Restoration (R) and Commercial (C) research, has a higher potential for "success" compared to the Baseline (B) type of research. In terms of Restoration research, the assumption reflects the fact that Restoration research has fewer uncertain dimensions than Baseline research. This is because the invasion impacts in the Baseline research area are more hypothetical, particularly as ecosystem conditions and/or usage may differ in the two areas so that research findings may be more difficult to interpret correctly. Commercial research interests reinforce the higher potential of research type I because commercial research can identify direct economic returns compared to the more indirect returns from ecosystem conservation uncovered with Baseline research. Research in both areas, however, is needed, as the two types (B and I) complement each other in defining the net external benefits of controlling and/or containing the invasion. We 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. We apply the framework suggested by Choi and Gerlach (2014), using a set of assumptions pertinent to the invasion problem. We demonstrate that in a socially optimal context, the probability of achieving research "hits" matters alongside the monetary amounts in how we allocate research resources, and that the way in which it matters may be counter-intuitive.

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 two potential innovation projects/R&D behave, and compare this to 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, because success benefits from joint production of innovations in both projects. Private incentives fail to realize this joint benefit and underinvest in the riskier project. We extend this result to spatially differentiated invasive species management by a public agency on either side of the invasion frontier. In this case, the socially optimal outcome should be attainable, but incentive structures within the agency may prevent its realization. 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:

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

The probability that research type B fails to produce new knowledge useful for optimal invasion 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 unit of research funding 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 (research agency) 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. Thus an increase in the probabilities of success of one type of research due to exogenous factors does not directly change the probability of "success" of the other type.[1]

We further assume that the total budget for research is exogenous, an assumption with empirical merit for most invasive species management problems. The decision maker's responsibility over the budget is to advise management of ecosystem resources efficiently enough so that both the commercial harvest and the externality are in their purview.[2]

The regulator who is managing the invasive species within the resource constraints handed to him, is maximizing the probability that both types of research turn out "hits". This is measured in terms of yielding information on the invasion that is useful for preventing social welfare losses in the future. Thus the regulator is choosing the resource allocation in order to maximize the effectiveness of the research funding invested in each area. Considering the efficiency of the agency in this way allows some insights into the "power relations" that may favor commercial research C over baseline B and restoration R research. A decision system focused on overall efficiency would meet this optimum condition.

The objective function is therefore

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

s.t

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

where R_T is the total budget available for invasive species-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.

The equality in (6) determines the optimal research funding 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 invasion 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 research was the same. Given though the limited resources available, reflected in our model through the budget constraint R_T, we will show that it is optimal to invest more heavily in the more "challenging" type of research, here, type B.

Solving for R_B from the constraint (5), we have $R_B = R_T - R_I$.

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

$$\underset{R_I}{max} W = P\left(R_B\right)P\left(R_I\right) \\ =1-(1-P_B)^{R_T-R_I}-(1-P_I)^{R_I}+(1-P_I)^{R_I}(1-P_B)^{R_T-R_I}. \tag{7}$$

The FOC, after rearranging, becomes

$$\begin{aligned}\frac{\partial W}{\partial R_I} &= ln(1-P_I)(1-P_I)^{R_I}[(1-P_B)^{R_T-R_I}-1] \\ &+ ln(1-P_B)(1-P_B)^{R_T-R_I}[1-(1-P_I)^{R_I}] = 0.\end{aligned} \tag{8}$$

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 A), implies the existence of a unique maximum. Note that at $R_I = 0$, it holds

[1] With feedback effects 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 unidirectional reinforcement are ignored in this reduced-dimension model for the sake of simplicity and clarity of exposition.

[2] We recognize that different interests within research institutes or decision-making bodies might have different power over budget negotiation. This can result in making this more strategic question of bureaucratic budget maximization but in this context we assume cooperation amongst interests for the common good.

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 (8) (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 A). In order to verify the negative sign we also check the sign of the cross partial, which is also negative (see Appendix A)

$$\frac{\partial^2 F(\frac{R_T}{2})}{\partial P_I \partial P_B} < 0. \tag{9}$$

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

$$\frac{\partial F(\frac{R_T}{2})}{\partial P_I}|_{P_B=0} = 0. \tag{10}$$

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 B at the invasion frontier. 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:

$$\frac{\partial F}{\partial P_I}|_{P_I^o} = ln(1-P_I)^{R_I}[(1+R_I)(1-(1-P_B)^{-R_I+R_T}) + \frac{R_I(1-P_B)^{1-R_I+R_T}}{1-P_I}] < 0. \tag{11}$$

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

$$\begin{aligned}\frac{\partial F}{\partial P_B}|_{P_I^o} &= (-1-P_B)^{1-R_I+R_T}[(R_I-R_T)(1-P_I)^{R_I}ln(1-P_I) \\ &\quad -(-1+(1-P_I)^{R_I})(-1+(R_I-R_T)ln(1-P_B))] > 0.\end{aligned} \tag{12}$$

The sign of (11) reflects the sign of $\frac{\partial R_I^o}{\partial P_I}$ and the sign of (12) reflects the sign of $\frac{\partial R_I^o}{\partial P_B}$ or

$$\frac{\partial F}{\partial P_I}|_{P_I^o} \overset{s}{=} \frac{\partial R_I^o}{\partial P_I} \quad \text{and} \quad \frac{\partial F}{\partial P_B}|_{P_I^o} \overset{s}{=} \frac{\partial R_I^o}{\partial P_B}, \tag{13}$$

implying that at the optimal state of resource allocation, an increase (decrease) in the probability of research success in the invaded area will lead to a decrease (increase) in the resources allocated there, while conversely an increase (decrease) in the probability of research success in the frontier area while at the optimal state, will lead to an increase (decrease) in the research budget for the invaded area.

In Fig. 1, 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 (MRTS) 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 types I and B in the invaded and baseline areas respectively.

This MRTS, which has the standard convexity, monotonicity and transitivity properties reflects that: (a) more research input will generate more research output and (b) there are increasing opportunity costs of switching from one research type to another as one increases the use of the new input.

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 (see Fig. 1) we get $P_B R_B^*$ and $P_I R_I^*$ at the optimum, which 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 inward shift to the probability of "success" of type B, which translates into an increase in its costs of performance, leads to a decrease in resources allocated to 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 unit of research funding 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 unit of research funding into the lower productivity resource increases the probability that this monetary unit will be funding success more at the margin than it would do for the higher productivity resource.[3]

2.3. Case study in the Barents Sea

We contextualize the theory with the case of the Red King Crab invasion in the Barents Sea. The crab, hereafter RKC, is a well-established Arctic invasion, 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. This debate stems from the commercial interests in conflict with the underlying ecosystem damages that occur with the increase in its stock and spread (Kourantidou, 2018). The RKC, originally introduced in Russia in the 1960s (Orlov and Ivanov, 1978), now covers both Russian and Norwegian waters, with its main distribution covering the southern part of the Barents Sea, between 25° E and 57° E (Pechora Sea) (Zakharov, 2015) (see Fig. 2 for introduction point and spread/ distribution area).

The Norwegian Parliament has established that in Norwegian waters

[3] It is worth noting that although we consider the assumption in (1) to hold since we expect the I type research in the fully invaded area to be more informative than the baseline research in the newly and partly invaded area, 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 should go 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.

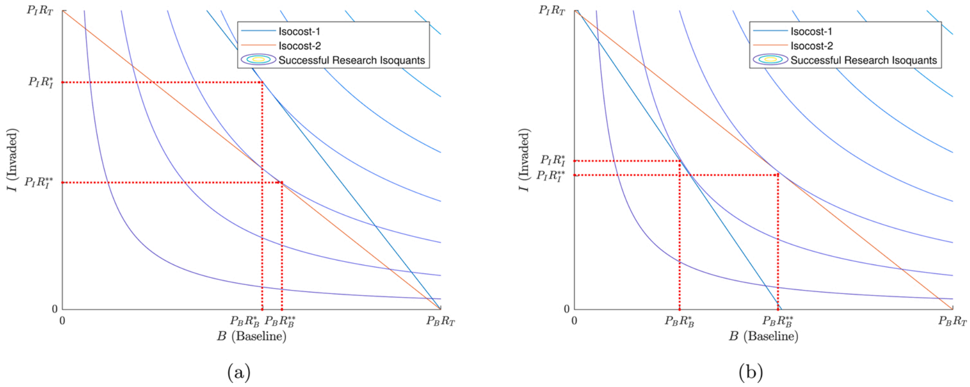

Fig. 1. Trade-offs between baseline (B) research at the frontier and the invaded (I) area.

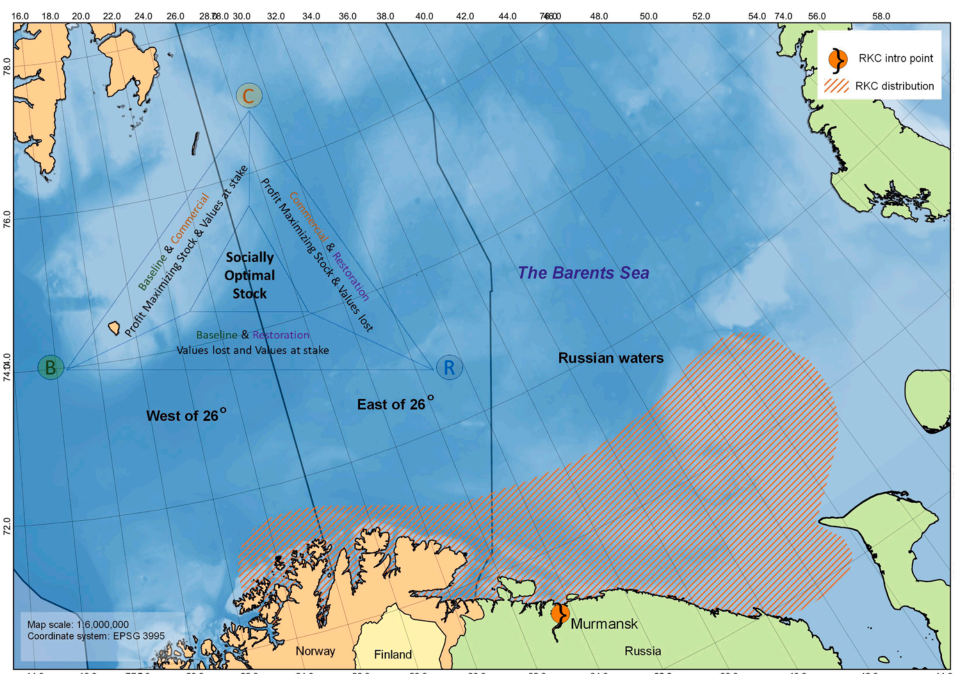

Fig. 2. RKC study area & types of research. C: Commercial, B: baseline, R: restoration.

east of 26˚ E and south of 71˚30′ N, RKC fishing will be quota regulated, while to the west and north of these boundaries fishing will be open-access. The western boundary at the 26˚ E line was initially agreed in 2005 with the Russian counterparts so that Norway could apply its own management while maintaining joint interests in the east. The current management regime became operational in 2008 under guidelines adopted from a 2007 White Paper reported to the Parliament (Fiskeri-og Kystdepartement, 2007).

This spatial division has sharpened the public debate at the invasion frontier: residents in the quota area have become invested in protecting the future of the profitable stocks, while residents just to the west of the 26˚ E line want more inclusion in this windfall. Consistent pressures from both sides have resulted in several changes in who should qualify to participate in the quota regulated fishery. These changes have included requirements for minimum revenues from other species catches and proof of residency in the region, to ensure that only local professional fishers affected by the invasion benefit from the crab fishery. Under the Ministry of Food and Fisheries, the Directorate of Fisheries proposes how the regulation and participation conditions should be adjusted each year, after taking into account stakeholders' views on quota requirements, gear restrictions (number of pots), closures for research vessels, and reporting.[4] Consultations with stakeholders on both sides of the 26˚ E quota line have gathered input over the years, specific to the question of whether vessels from western Finnmark should be included in the quota-regulated area east of 26˚ E (see e.g. Fiskeridirektoratet, 2016). This has recently brought a significant expansion to the fishery via the Norwegian Parliament. Effective from 2021, vessels registered in western Finnmark will be able to participate in the quota fishery on the

[4] Those include the Norwegian Fishermen's Association (Norges Fiskarlag), the Norwegian Seafood Federation (Sjømat Norge), Norway's Coastal Fisheries (Norges Kystfiskarlag), the Fisheries Buyers Association (Fiskekjøpernes Forening), Finnmark's County Municipality and Innovation Norway (Finnmark Fylkeskommune og Innovasjon Norge) (Fiskeridirektoratet, 2015). Other stakeholders with a say in the decision-making process and the spatial configuration of the management include the Norwegian Seafood Enterprise Association (Norske Sjømatbedrifters Landsforening), the communities of Sør-Varanger, Nesseby, Vadsø, Vardø, Båtsfjord, Berlevåg, Tana, Lebesby, Porsanger, the West-Finnmark Regional Council (Vest-Finnmark Regionråd), the Sami Fisheries Organization (Sjøsamisk Fangst- og fiskeriorganisasjon), the Sami Parliament (Sametinget) the Norwegian Environment Agency (Miljødirektoratet) and the Fjørd Fisheries Council (Fiskeridirektoratet, 2016).

same terms as vessels in eastern Finnmark (Stortinget, 2020).

The Institute of Marine Research (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). We focus on the research decisions of the IMR, which provides advice for the Norwegian management of the stock. We distinguish research performed by IMR into the 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.

IMR is a public research institution whose primary responsibility is to provide advice to national authorities such as the Ministry that sets the annual TACs, the RKC industry (fishers and processing plants), and society more broadly (IMR, n.d.). The IMR has traditionally had a fisheries rather than an invasive species focus, as opposed to other research institutes in Norway whose primary focus has been on ecological and broader environmental research. However, IMR's research group on "Benthic Resources and Processes" has taken the lead on RKC research; the group's interests range from optimal and sustainable management of shellfish to the way ecosystems are being impacted from introduced benthic species. IMR's findings have been informing ongoing policy decision making for the management of the crab (Fiskeri-og Kystdepartement, 2007; Nærings og Fiskeridepartementet, 2015), which is why we focus our analysis on the budget allocation therein.

IMR is also part of the executive group for the long term MAREANO program, which has been mapping the oil-rich western Norwegian continental shelf and its biodiversity (MAREANO, n.d.). This area overlaps with the invasion frontier, and could provide relevant information for understanding the baseline. The well funded, 15 year program, however, stems from an effort to improve the knowledge base in resource management for primarily oil and gas exploration, but also fisheries exploitation, in the western Barents and Norwegian Sea. As part of our discussion, we address the consequences of the existing disconnect between the MAREANO program and RKC research in spite of IMR's responsibilities to both. The challenge posed here by needing to combine information across programs in meaningful ways provides additional insight into the more general difficulty in invasive species management arising from multiple jurisdictions with differing goals and gaps in communication (Ameden, 2008; Paini et al., 2010).

The application of our model to this case, through real-world data on monies that have been invested so far at IMR, challenges regulators' preferences for allocating limited resources to research objectives that, on the surface, may seem less productive or less likely to improve our understanding of the social optimum due to large uncertainties and difficulties entailed. The data allow us to investigate the expected marginal net benefits of reallocations of research funding between the frontier and the invaded area.

3. Application

The management of any invader requires a multi-faceted approach that generates a coherent policy on both the harvesting – potentially commercial – and the transitory dynamics of the invasion. When the invader has commercial benefits, it pits potential economic gains against uncertain ecosystem changes. In what follows, we attempt to illustrate how 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 may advise research resources be allocated. We find that increases in research resource allocation to seemingly more risky research endeavors could benefit social welfare. We distinguish the resources allocated for research on the profitable invasive crab into two spatial categories, in line with the model's definitions. The resources are thus allocated to: a) Baseline research in the frontier (B) and research in the invaded area (I). Because the data allow for greater specificity, in this application we are able to further consider allocation to two different research sub-types: commercial (C) research and restoration (R) research, within the invaded area (I). The three types are described in greater detail below.

Research type C (commercial) focuses on the commercial fishery and aims at identifying the maximum economic yield (MEY). Without internalizing external damages of the invasion, this MEY will be lower than optimal. 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. In this context, it is viewed as the least risky research endeavor, given that there is well-established knowledge on performing stock assessments and estimating costs of the fishing fleet.[5] 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°E (eastern patch), where the fishery is quota-regulated, for determining the annual quotas, but not west of 26°E (western patch) where the fishery is open-access (Hjelset et al., 2009). The spatially differentiated regulatory regime for the RKC aims to allow a long-term profitable fishery in the east while at the same time to limit the spread of the species in the west.[6]

Research type R (restoration) focuses on identifying the ecosystem losses and providing information on the cost of the ongoing invasion externalities in the already invaded area. 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 benefits from 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) takes place on the benthos west of 26°E for the case of the RKC. Up until now it has been conducted primarily for purposes other than the crab invasion, serving the goals of the MAREANO program rather than those of IMR's "Benthic Resources and Processes" research group, which leads RKC research. There is little recognition that the MAREANO program's output could inform baseline RKC research at IMR (BA Kaiser, personal inquiry, 2019).[7] Its results, therefore, have not directly been related to potential impacts of the crab. Like research type R, the results of type B research can potentially be used for improving management of the invasion externalities.

Fig. 2 shows the interactions among the different types of research.

[5] Input is often used from the Alaskan RKC fishery and the models for stock assessments used there.

[6] Harvesting has been criticized in the ecology literature for its ineffectiveness in decreasing the spread of invasions, while it has even been suggested that it may bring unintended outcomes resulting in increased abundance in response to harvest (see e.g. Zipkin et al., 2009). Examining the effectiveness of harvest as a management tool goes beyond the scope of this paper and we therefore accept the assertion of the Norwegian regulatory authorities that open-access does limit the spread further west.

[7] 2019 Shellfish Symposium, Tromsø, Norway, 5–7 November

Type *C* and *R* occur in the same space (the heavily invaded area east of 26° E),[8] though their outputs may lead to contrasting policy recommendations. Types *B* and *R* represent the 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 only be achieved with a combination that jointly includes positive expenditures of R_B on *B* and of R_I, on *I*, so that risks and uncertainties about both the invasion externalities and fisheries dynamics can be properly measured and acted upon. With research resource constraints, perfect information is not expected to be achievable; the application of the model identifies appropriate margins for divisions of the resources, with uncertainties remaining.

We focus on the spatial allocation of resources, because *R* and *C* types of research can be jointly produced through research *I* in the invaded area while *B* type research must be conducted separately. Formal consideration of trade-offs between research types in the invaded area (i.e. assessment of the margin between commercial stock information improvement and improved information about restoration activities) is left for future research, though we are able to provide some insights on the relative relationship between the two types.

In applying the model, we anticipate that, as with the general case, baseline research has lower or more diffuse chances of proving directly applicable to management decisions than research within the invaded area. That is because research in the invaded area has two direct avenues for improving social welfare – through reducing the missing information about the commons problem and through clarifying 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 in the sense that a unit of research funding spent is more effective at informing policy options than the unit of funds spent for research at the frontier.

In 1997, IMR started in cooperation with the Directorate of Fisheries Regional Office in Vadsø, to record crab bycatches. In 2003, IMR launched the first research program with a focus on the effects of the king crab on the ecosystem.

Given the high commercial interest for the crab fishery, however, IMR's main focus over the past decade has been to build up a long-term stock in the eastern fjords. We view the interests in commercial exploitation from stakeholders in the RKC industry as a strong influencing mechanism in IMR's decision-making processes on where to put the research foci. The social pressure upon decision-making is implicitly reflected in the demand for more accurate stock estimates that can help yield a sustainable crab stock in the long run. In this context, in order to provide an understanding of how the decision-making framework addresses the way in which research is prioritized within IMR, we look at the expenditure in different research projects over the past decade. We further examine the cost-effectiveness of research resources allocation across different research types. Our model captures essential features of the research resource allocation challenge for the RKC. In this section we extrapolate, using real-world data in order to mesh the manager's behavior with the optimal allocation of resources across space, where we see human incentives changing, depending on the interests of the different stakeholders.

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 *I* and *B* types of Research, differentiating *C* and *R* research where possible.

[8] Stock assessments (reflected in *C*) and impact assessments (reflected in *R*) are carried out in tandem by research vessels, east of 26° E (JH Sundet, Institute of Marine Research, Norway, personal communication, 2016).

In *C* we have included stock assessments, population surveys, research fisheries in Tana and Laksefjørd, development of methodologies for stock evaluation east of 26° 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° 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 fishers 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.

Table 1
RKC male stock, total allowable catch (TAC) (2002–2016) in individual crabs (2002–2009/2010) and tons (2010/2011–2016), and estimated exploitation rates[a,b] (Norwegian Environmental Agency, 2017; Fiskeridirektoratet, 2011, 2017a).

Year	Harvestable male RKC	Fishing season	TAC	% estimated RKC exploitation
2002	779 000	2002	100 000	13
2003	1 307 000	2003	200 000	15
2004	1 325 000	2004	280 000	21
2005	750 000	2005	280 000	37
2006	901 000	2006/2007	300 000	33
2007	975 000	2007/2008	304 000	31
2008	795 000	2008/2009	679 000/ 2375[c]	85
2009	468 000	2009/2010	474 000/ 1185[c]	(101)
2010	371 000	2010/2011	900[c]	96
2011	672 000	2011/2012	1200[c]	75
2012	766 000	2012/2013	900[c]	45
2013	933 000	2013/2014	1000[c]	40
2014	577 000	2014/2015	1100[c]	70
2015	677 000	2015	1040[c]	54
2016	440 000	2016	2000[c]	(161)

[a] The stock estimates include "legal" male crabs (see e.g. Hjelset, 2014). The TACs are for males only but include injured crabs as well. Separate TACs for female and injured crabs were only introduced after the 2008/2009 fishing season.
[b] The TAC numbers in this Table include crab quantities for the commercial, research as well as leisure/tourism fishing.
[c] In order to estimate the % of RKC exploitation, the TACs for the fishing seasons following 2010/2011 were converted from tons into individuals using the annual estimates for the average weight per crab (see e.g. Sundet, 2009).

Fig. 3 shows the ratio of quota to stock (Q/S) over time on the left hand-side axis (in columns).[9] The average ratio is approximately 0.1 and this mainly increased from 2002 to 2011 and again significantly in

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

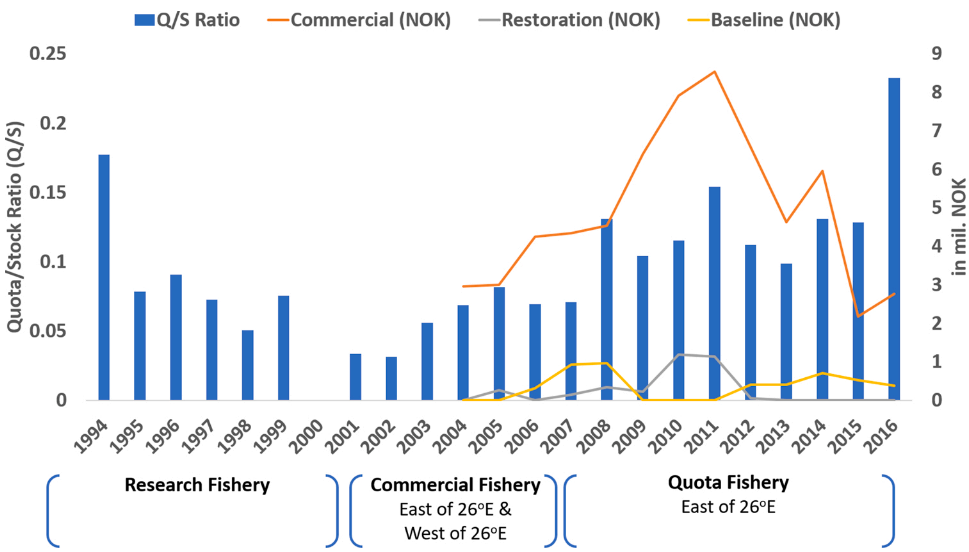

Fig. 3. Estimates of annual quota to stock (Q/S) relationship 1994–2016 (measured in individual crabs) & research resources spent in commercial, restoration and baseline research (2004–2016), during the 3 phases of the crab fishery (research, commercial and quota fishery). Differs from the harvest rate 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. The regulation on the TAC in Norway has switched measurement units from individual crabs to tons and therefore for the years 2010–2016 we have converted the tons of crabs into estimated individuals using the average yearly crab weights. Sources: Petryashov et al. (2002), Norwegian Environmental Agency (2017), Hjelset (2014), and Fiskeridirektoratet (2011, 2017a).

2016.[10] 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 toward commercial conservation resulting in likely too few crabs harvested in these years compared to the optimal case including external damages. We seek further evidence to identify the connection between the trends illustrated in Fig. 3 and the balance of research funding. To that end, Fig. 3 also shows expenditures (in mil. NOK) for the 3 types of research since 2004. The data on the research expenditure provided by IMR, cover the period 2004–2016. The costs budgeted for the different projects on an annual basis were classified according to the scope and aims of research (e.g. stock assessments east of 26˚E were classified under Commercial research, bycatch and ecosystem impact studies under Restoration research, population surveys in non-commercial areas and spread east of 26˚E under Baseline research). 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). This is expected since 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 (Kourantidou, 2018; Petryashov et al., 2002). In the years that followed, the "invasion" was recognized for its bycatch damages. Those were alleviated by having the fishers 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, 2007) (see Fig. 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.

Fig. 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 the 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.

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 also can be understood to have played a role in the establishment of the line at 26˚E. 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*. Elsewhere, we have found that the published ecology literature has shown diminishing interest in research for ecosystem impacts from the invasion over time (Kourantidou and Kaiser, 2019). This re-allocation pairs with the overall lower expenditures in *B* and *R* shown here after 2011, and reinforces the connections between research investments and findings.

Table 2 shows the allocation of resources (as graphed in Fig. 3), from 2004 to 2017 along with the total annual landings and the annual first-hand value from 2002 tile 2015, from the profitability survey on the Norwegian fishing fleet (Fiskeridirektoratet, 2017b).[11] The total landings along with the first-hand value (Table 2) might be poor indicators of efficiency in decision-making as far as the research budget allocation is concerned, but together they 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 lead scientist 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˚E. 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

[10] Some small portion of the fluctuation in the Q/S ratio (especially for the years following 2010) can possibly be attributed to the conversion of tons into individual crabs. The Norwegian authorities have started, after the 2008/2009 season, announcing the TACs in tons instead of individuals as they used to do before. For those fishing seasons that cover two consecutive years, we have made the conversion from tons into individuals using the average RKC weight from the two respective years.

[11] The annual profitability surveys present the main economic results on the Norwegian fishing fleet and provide broad information on total catch and values for the fleet as well as more specific information on landings and first-hand values per species. The published profitability surveys can be found here https://www.fiskeridir.no/fiskeridir/Statistikk/Publikasjoner/Loennsomhetsundersoekelse-for-fiskefartoey

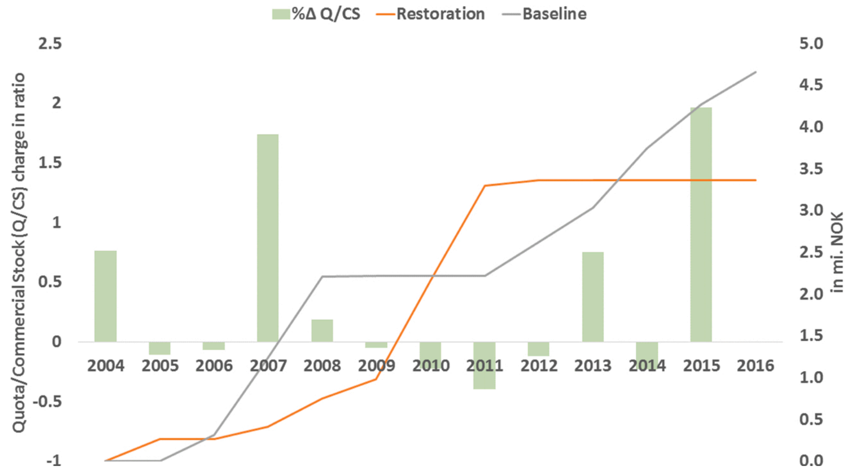

Fig. 4. Quota to (commercial) stock (Q/CS) annual change in ratio & cumulative annual expenditures in research types *R* and *B* (in mil. NOK) (2004–2016).

Table 2
Annual resources allocated for RKC research (2012–2017), total landings (2002–2015), first-hand value (2002–2015).

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	2969	1294	80 385
2005	3269	1223	68 958
2006	4767	1041	50 936
2007	6184	1267	59 200
2008	7276	5199	135 134
2009	6989	5613	127 585
2010	10 246	1905	87 560
2011	9695	1782	151 777
2012	7088	1437	116 961
2013	5046	1321	80 444
2014	6658	1695	132 168
2015	3186	2175	184 169
2016	3150	–	–
2017	5357	–	–

Source: Fiskeridirektoratet (2017b) and JH Sundet, Institute of Marine Research, Norway, personal communication (2017).

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.[12] For such a split to reflect the optimal research resource allocation, the assumed success probability of *B* needs to be significantly higher than *R* (see Appendix B for a simple numerical illustration). For such an allocation to be reasonable, the gap between the relative probabilities should be large; If for example both probabilities are low such a resource split would not make sense.

The research related to determining stocks and quotas (type *C* research in our set-up) clearly dominates over the entire period examined 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 in the west after 2007 coincides with an increase in resources allocated to Restoration and a decrease in Baseline research. 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 low. 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, 2019), signal declining concerns for the negative impacts of the invasion in Norway, with the interest in the commercial fishery taking over.

In Fig. 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, Fig. 3).

The fishing mortality for the RKC has increased steadily from the start of the fishery in 1994 and has been kept, at or above the fishing mortality rate that maintains the MSY, since 2008. 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 types *B* and *R* research.

In Fig. 6 we use the percentile range (10^{th}–90^{th} percentile) and the median of the RKC biomass index for the relative male crab population size (carapace length greater than 130 mm) (Sundet et al., 2016),[13] in order to estimate the relative interdecile range (RIDR) for the past 40 years. The policy relevance of the limited variation of RIDR in the years

[12] 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 tile 2016, the costs of which has been estimated to be approximately 18 mil. NOK.

[13] 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 predict 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. This is seen as an "alert" sign for fishery managers. Although it is hard to get accurate scientific estimates for the 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).

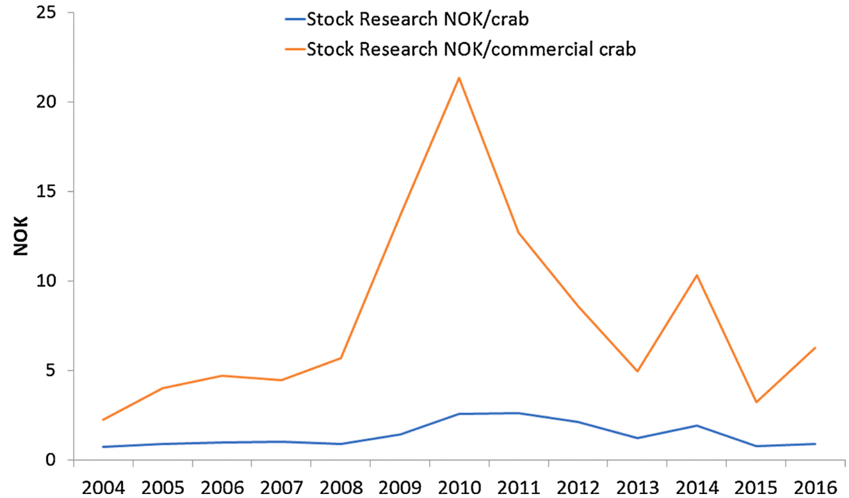

Fig. 5. Type C research per crab and per commercial crab.

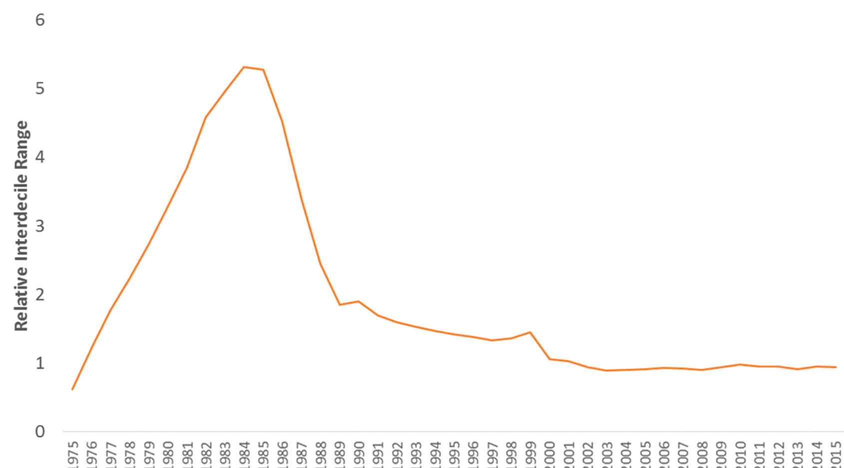

Fig. 6. Relative interdecile range of the RKC biomass index, 1975–2015. The calculations were made based on information in Sundet et al. (2016).

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 efficient models and more accurate stock estimates. Note that the difference in the trend in the post 2007 period between the NOK per crab and NOK per commercial crab (Fig. 5), does not create any effect on the RIDR (Fig. 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, on behalf of IMR, behind the allocation of research resources over the past years, Figs. 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 (see Fig. 6) 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 may now be small compared to payoffs from investments in the other types of research. Therefore a policy recommendation based on this analysis would be to restrict the allocation of resources in *C* type research to annual stock estimates, in order to allow space for allocation to overlooked baseline research at the western frontier.

4. Discussion

The role of economies of scope is critical for prioritizing and allocating research resources, although not explicitly modeled 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° E share similar ecological characteristics, it is reasonable to assume that $1 spent in *B* type of research increases the marginal benefits from the *I* type of research (particularly 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 ecological 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° 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 modeled as one here, in 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 (Kourantidou and Kaiser, 2019). 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). Furthermore the lack of documentation of negative ecosystem impacts from the RKC invasion on the Russian side could 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.

In addition to that, we see budget decisions within IMR getting intertwined with the fisheries focus for commercial conservation of the stock. This results in invasive species research falling through the cracks. 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 overlapping with the conflict between oil and cold-water coral fields.

As discussed, in the area west of 26˚E, the ongoing MAREANO program led by the Norwegian Environment Agency, and other past research programs, have relevant information and resources for studying the impacts of the invasive crab. However no such research coordination or other efforts are currently taking place, with the exception of few recent benthic megafauna studies (Jørgensen et al., 2015). The budget allocated to MAREANO was more than 196 million NOK in the first phase (2006–2010) and over 882 million NOK in the second phase up until 2019 (MAREANO, n.d.). MAREANO collects a large series of data across the coast of Norway on seabed characteristics, biotopes, distribution of benthic fauna communities and biodiversity. Given the interaction of the invasive crab with the soft-bottom benthic habitat, such data can serve as benchmark information for type *B* research. MAREANO results can thus almost directly inform Baseline research in the west about the values at stake from the crab's spread. This appears to be a significant missed opportunity. We expect that a more informed understanding of the changes in the west, that MAREANO could provide, could alter the dynamics of the resource management; research types *R* and *C* will be weighted differently in relation to *B*. Adapting the MAREANO results for the western frontier of the crab invasion would provide obvious opportunities for economies of scope and is in the best interest of resource managers concerned with identifying baseline ecosystem values. For that to happen, the scope of the decision-makers' objective function needs to be broadened via better intra- and inter-agency communication channels.

An additional reason for linking the existing results of research type *B* in the west (from programs like MAREANO) with the crab invasion is that the ecosystem values at stake in the frontier may differ than those in the invaded area, where the benthic habitat has already been altered by the invasion. The potential invasion damages might have differed across space even before the arrival of the crab, which in practice means that results from benthic bottom studies in the east might be misleading when invasion externalities are considered for the west. 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, geomorphological and oceanographic characteristics that may affect species aggregations, reproduction, diversity, effects of climate change on the RKC stock, etc. (Dvoretsky and Dvoretsky, 2020, 2016).

If the ecological research comparing Russian Barents and Norwegian Barents impacts from the crab are to be taken at least partially at face value, in which Russian benthic impacts have been portrayed as lower than those in Norway, then this may well be the case (Kourantidou and Kaiser, 2019). In practice, this body of ecological research also provides mixed signals with respect to the optimal stock of the invasion. A large portion of the research that has been done on the RKC so far has focused on the crab bycatches in other fisheries, the predation upon commercial and non-commercial species (benthos), and the spread of disease vectors (Kourantidou and Kaiser, 2019). These studies attempt to quantify the effects of the invasion in the ecosystem and offer qualitative guidance on the risks that the introduced crab poses. The initially divergent viewpoints among researchers in Norway and Russia, which have slowly been converging over the years, are an important harbinger in determining policies on harvest control rules (Kourantidou and Kaiser, 2019). 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 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.) has put additional pressure for more weight on commercial research. In this context, we fear that restoration and baseline types of research might be undermined given the existing contradictions in the literature and the lack of cooperation between Norway and Russia. Note that 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.

The lack of cooperation between Russia and Norway in managing the crab stock exacerbates the problem. The split management stems from the different ecological concerns and management objectives across the two countries. The problem of inadequate cooperation when it comes to management of an established population is wider though. Policy responses to the introduction and spread of invasions across the world have put significant effort in tackling the transboundary risk. Management mandates across countries/jurisdictions are well known to differ; here we show they may also differ across and even within research institutes in the same country/jurisdiction. The management challenge is therefore twofold and it comes down to the lack of regular institutional mechanisms for invasive species management. The differences in the management mandates often vary in the objectives for which they were created, the purposes they are meant to serve, the management means available to them, and also the degree to which they allow for the involvement of third-party stakeholders.

One way to rectify these problems when it comes to resource allocation, is to build an adequate understanding of how species invasions cross budgeting lines, which in turn calls for inter-agency collaborations. That requires first identifying who those agencies really are; for example in the case of the RKC, that would include institutes with a broader focus on invasive species management and ecological research, and go beyond fisheries management. This can foster increased scientific cooperation and move decision-making up a level by broadening the scope of the research. As the failure to integrate results from the MAREANO program into RKC Baseline research exemplifies, the mechanisms are often available but not activated as they should.

5. Conclusions

The limited knowledge on the impacts of the invasive crab jeopardizes its management and allows space for conflict between different stakeholder groups. Examples of conflict include on the one hand accusations toward the Norwegian government 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 ecological research can elucidate critical unknowns and provide suggestions for improved management of the RKC fishery. However research on intact ecosystems, particularly targeting prey species that do not have a direct market-value (such as the benthic species which are at stake from the crab's predation) comes at a cost.

The paper's principal output has been to establish a model and application that illustrate the consequences of failing to consider the benefits of invasive species research both ahead of the frontier and in already invaded areas as a jointly necessary effort for prioritizing the allocation of resources among research types with different objectives. This expands and integrates the management options across an invasion timeline to include research resource allocations that can reduce uncertainties in multiple dimensions. In the particular case of an invasive species with a commercial value, decision-makers are often asked implicitly to choose between investing more resources in understanding the harvesting potential of the species or in exploring the potential ecosystem impacts from the invasion. Our application illustrates more explicitly how the choice can result in unbalanced investments that favor commercial benefits, even within a research institute charged with acting in the public's best long run interests. In this paper's reduced dimension model we have categorized the research for the invasive crab into different types and we have assumed 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 entails in the process of revealing the marginal external benefits from harvesting. These benefits reflect the ecosystem losses prevented due to harvesting and identify the bioeconomic tradeoff 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 area. Whether the costs of poor stock estimates are higher or lower than those that stem from a poor understanding of the invasion losses, remains unclear given that the exact payoffs remain 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.

The analysis of the data on research resources spent on the RKC invasion in the context of our model provides the first systematic evidence that more resources should be allocated on the western frontier of the invasion. The frontier is currently overlooked due to the perceived low crab abundances and the limited commercial interest in the open-access 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 area West of 26^oE. We view the imbalanced resource allocation as a management choice driven mostly by stakeholder interests rather than a result of weighing the bioeconomic tradeoffs of the invasion/fishery. Yet, one of the main drivers for the contentious policy of the Norwegian government to maintain a longterm sustainable fishery in the eastern patch is to support local communities.[14] 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 growing, 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.

Author contributions

Melina Kourantidou: Conceptualization, data collection, methodology, visualization, analysis, writing – original draft preparation, writing – reviewing and editing. Brooks Kaiser: Methodology, analysis, supervision, writing – reviewing and editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fishres.2020.105871.

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[14] This includes the Sami Indigenous peoples of the region, who have coadapted to the ecological changes wrought by the invasion by diversifying small-scale fjord fishing and gaining governmental support for access to the crab (Broderstad and Eythorsson, 2014).

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