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FACULTY OF BIOSCIENCES, FISHERIES AND ECONOMICS
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Management of the alien invasive red king crab

Integrating natural and social science perspectives

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A dissertation for the degree of Philosophiae Doctor

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Summary

Application of interdisciplinary research and decision tools is believed to be important to ensure effective environmental policy making. Recognition of the ecosystem as a whole is the basis of ecosystem based management frameworks that emphasise the need to maintain the integrity of ecosystems in order to secure their functions and thereby the flows of ecosystem services to humans. Ecosystem service frameworks can be used to integrate information on human benefits from and concerns regarding ecosystem services into a common platform for communication and evaluation of the trade-offs involved in management.

The red king crab (*Paralithodes camtschaticus*) is a highly valuable resource that also represents a potential threat since it is an alien invasive species in the Barents Sea ecosystem. This thesis explores the use of different interdisciplinary frameworks to analyse how ecological, social and economic concerns could be accounted for in deciding on how the king crab should be managed in the Norwegian part of the Barents Sea. Clarification of terminology used in invasion biology and systematisation of ecological information in order to establish the ecological knowledge base for management forms the basis for further analysis. Bio-economic modelling and discourse analysis are used to explore how uncertainty and the range of services the ecosystem provides can be incorporated in management. Finally the use of ecosystem service frameworks to integrate ecosystem and social science research in ecosystem based management is discussed.

The ecological review revealed numerous knowledge gaps in our understanding of how the king crab interacts with native biota. It also identified negative impacts on benthic ecosystems that provide supporting services, and on provisioning services through predation on eggs of commercial fish. Bio-economic analysis illustrated the need to identify the correct relationship between crab stock size and ecosystem damage. It also showed that optimal harvest of king crab cannot be reconciled with the Barents Sea management goal of securing the ecosystem structure. The discourse analysis showed that people recognise both positive and negative impacts of the crab on supporting, provisioning and cultural services. In addition the impacts on ecosystem services we do not have the knowledge to value today, or option values, were important in forming people's perception on how the crab should be managed.

This thesis demonstrates that while the natural sciences have a clear role to play in establishing the ecological knowledge base, uncertainty and the need to account for stakeholder concerns calls for integration of social science research in the management process. Ecosystem service frameworks can be useful tools for identification, integration and evaluation of such information.

List of papers

Paper 1 Falk-Petersen, J, Bøhn, T. and Sandlund, O.T. 2006. ”On the numerous concepts in invasion biology”. Biological Invasions, 8: 1409-1424.

Paper 2 Armstrong, C.W. and Falk-Petersen, J. 2008. “Habitat-fisheries interactions. A missing link?” ICES Journal of Marine Science, 65: 817-821.

Paper 3 Falk-Petersen, J., Renaud, P. and Anisimova, N. 2011. “Establishment and ecosystem effects of the alien invasive red king crab in the Barents Sea”. ICES Journal of Marine Science, 68 (3): 479-488.

Paper 4 Falk-Petersen, J. and Armstrong, C. “To have one’s cake and eat it – managing the alien invasive red king crab stock” (submitted).

Paper 5 Falk-Petersen, J. Option lost or opportunity gained? Perceptions on the Barents Sea red king crab invasion (submitted).

Introduction

The use of interdisciplinary research and analytic frameworks accounting for both social and ecological factors has been identified as the key to effective environmental policy making (Anton, Young, Harrison et al. 2010; Christie 2011). Research and education programs have responded to this challenge by combining disciplinary approaches in order to create tools that can be used to communicate between and create a common understanding across different disciplines (Pickett, Kolasa and Jones 2007; Miller, Baird, Littlefield et al. 2008). Interdisciplinary research and management can operate at different scales. Ecology includes disciplines within the natural sciences. It is the study of the relationship between organisms and their environment, and each other (Henderson and Lawrence 2000). Such information can be used to summarize what is known about a specific ecosystem, explore the mechanisms operating within these and identify important knowledge gaps in our understanding of their functioning (Dollar, James, Rogers et al. 2007; Falk-Petersen, Renaud and Anisimova 2011). Information at an ecosystem, as oppose to species, level is increasingly being used to guide environmental policy. It is also the foundation of ecosystem based management frameworks that also aim to integrate social sciences.

Ecosystem based management[1] is an interdisciplinary concept where sustainable development is sought through securing the well-being of both humans and ecosystems (Garcia and Cochrane 2005; Curtin and Prellezo 2010). Within this framework there is a strong emphasis on understanding how ecosystems function, thus integrating ecological research, but also on identification and valuation of the range of ecosystem services humans benefit from. The latter is important in order to translate ecological processes into a language more easily understood by policy makers and non-scientists, and to evaluate trade-offs between different uses, non-uses, and user groups (FAO 2003; Beaumont, Austen, Atkins et al. 2007; Christie 2011). While such valuation exercises may identify ecosystem services and knowledge gaps to be filled in order to give a more complete picture of the services provided, a lack of data makes it challenging, or even impossible, to quantify these (Beaumont, Austen, Atkins et al. 2007). As a result there has been a call for a better understanding of ecosystem functions, including the role of biodiversity, and how different stressors affect the ability of ecosystems to produce the range of services humans benefit from (Anonymous 2006; Beaumont, Austen,

[1] The large literature on various approaches to ecosystem management will not be addressed in this thesis. Rather, “ecosystem based management frameworks” will be used as a more general term.

Atkins et al. 2007; Anton, Young, Harrison et al. 2010; Christie 2011). An important issue within this area of research is identification of threshold points beyond which the ability of ecosystems to deliver services changes dramatically or irreversibly (Anton, Young, Harrison et al. 2010). In their bio-economic analysis of ecological threshold points, however, Perrings and Pearce (1994) argue that as a consequence of the uncertainty regarding ecological threshold values, bio-economic analysis should be accompanied by ethical judgements on the socially acceptable level of impact. The precautionary principle also emphasises the importance of involving stakeholders in management in order to capture the wider social and economic impacts of both action and inaction (UNESCO 2005).

To what degree attempts to fill knowledge gaps identified within the natural sciences reduces the uncertainty involved in managing natural systems has been questioned. Furthermore, the strong focus on understanding ecological processes has resulted in socio-economic aspects being ignored in management processes (Knol 2010; Christie 2011). Incorporation of stakeholders into the decision making process has been identified as an important part of managing under uncertainty, both to make the management process more legitimate and to help focus scientific questions (van den Hove 2000; Anonymous 2004). The importance of incorporating uncertainty and risk is also stressed within ecosystem based management frameworks (FAO 2003). The degree to which tools developed to identify ecosystem services account for this aspect vary. Some argue that uncertainty should be treated separately within concepts related to the precautionary principle, while others believe these values should be explicitly emphasised within ecosystem service frameworks (Defra 2007; Balmford, Walpole, ten Brink et al. 2008).

I will argue that applying ecosystem service frameworks can be useful for capturing and integrating natural and social science aspects in management. The interdisciplinary case study chosen for this thesis, the main results and the papers will be introduced first. This will be followed by a synthesis and finally I will present a framework for integrating social science research in ecosystem based management in order to better account for uncertainty and the range of benefits obtained from ecosystems. At the start of my PhD I was not very familiar with ecosystem service frameworks, but as my work progressed I found that it could be a useful tool for organizing, integrating and discussing the knowledge gained through my work on the red king crab. The concept will therefore play a central role in the introduction to the papers in this thesis, as well as in the synthesis and discussion.

Research questions and objectives

This thesis applies different interdisciplinary frameworks and models to the case of the red king crab invasion in the Norwegian part of the Barents Sea. The red king crab (*Paralithodes camtschaticus*) was introduced from the north Pacific to the Kola fjord in North-West Russia by Russian scientists in the 1960s in order to establish a new commercial fishery (Orlov and Ivanov 1978). The crab established and spread into the Norwegian part of the Barents Sea. Due to its high commercial value, Norwegian and Russian policy initially focused on building up a commercially viable crab population and in 1978 all harvesting of crabs was banned. In 2002 the fishery was opened for commercial harvest regulated by quotas. In Norway these quotas were allocated to small-scale fishers as a compensation for economic losses related to bycatch of crabs in traditional fisheries. The crab became an important economic resource for this part of the fleet and associated small fishing communities (Anonymous 2007). However, the crab is not only an important resource, but also represents a threat as it is an alien species to the Barents Sea. Alien species, through direct and indirect interactions, can have severe impacts on native ecosystems. While alien species can contribute to species diversity, they are also a major driving force behind species extinction and a global trend towards homogenisation of ecosystems (Mack, Simberloff, Lonsdale et al. 2000; McNeely 2006). Concerns about ecological impacts contributed to Norwegian authorities implementing a western limit of 26º E for king crab expansion in 2004, beyond which growth and spread of the crab is to be controlled mainly through an open access fishery (Anonymous 2007). Figure 1 shows the native and Barents Sea distribution of the crab, as well as the line dividing the Norwegian quota-regulated and open-access management zone.

Thus, the king crab represents a contribution as well as a potential threat to the economic, social and ecological system. This thesis looks at how these aspects can be analysed within interdisciplinary research frameworks and discusses how this type of research can be integrated in management. This issue is addressed through looking at the following:

2. What information is needed in order to provide the ecological foundation for an ecosystem service approach to management? (Paper 2 and 3).
3. How should the impact of the king crab on the ecosystem be accounted for in order to determine the socially optimal management strategy? (Paper 3, 4 and 5).

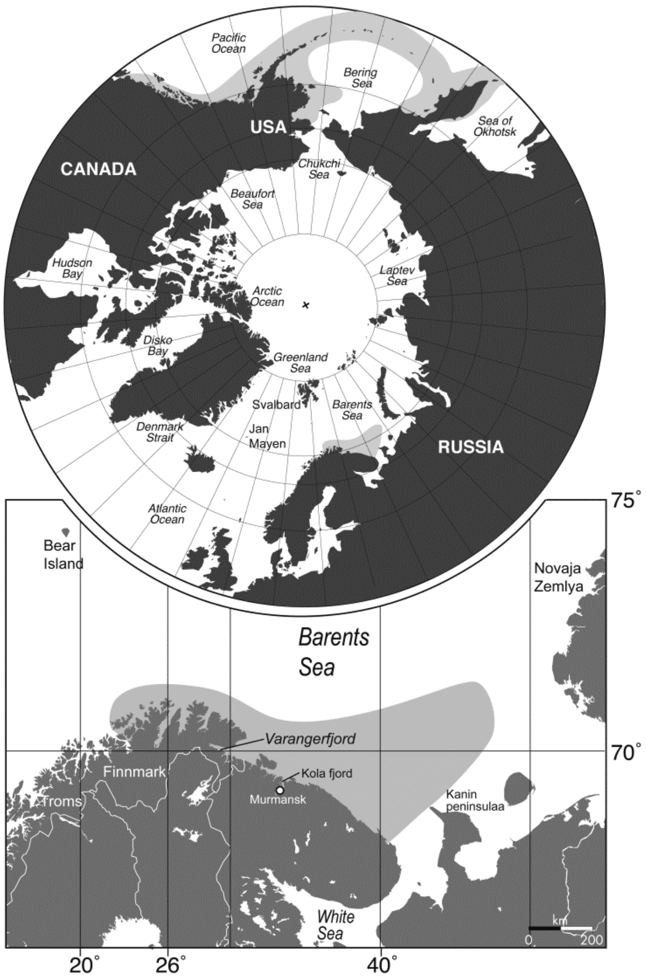

Figure 1: Map showing the native distribution of the red king crab in the Pacific, current distribution in the Barents Sea and the 26º E line dividing the Norwegian quota regulated (east) and open access management zone.

Methods

Focusing on a common problem and goal is identified as important for development of interdisciplinary research (Pickett, Burch and Grove 1999; Morse, Nielsen-Pincus, Force et al. 2007). Thus, while the use of case-study research to make generalizations has been debated (Flyvbjerg 2006), it is regarded as a key to successful interdisciplinary studies. In this thesis reviews of the literature are used to establish current level of knowledge of ecological processes and how different stressors will affect these. Review papers accumulate information and results from research on a topic to present a coherent representation of the state of the art within that field. The reviews are a starting point for exploring how conceptual frameworks can be used to integrate ecological and social issues in management. Conceptual frameworks are tools for organizing information, which again can reveal patterns that can guide further research. This can lay the foundation for creating models that describe how things work, and theories that explain phenomena. It can also be used to examine whether supply of scientific information matches social goals and demands (Rapport 1985; Pickett, Kolasa and Jones 2007; Hart and Calhoun 2010). In order to integrate different disciplinary understandings within a shared framework and to secure good communication, the terms to be used have to be clearly defined in order to secure a common understanding and use of concepts. Paper 1 is a contribution to the effort of clarifying terms and concepts related to alien species, but the issue is also addressed in paper 3, 4 and 5 with respect to how the terms “carrying capacity/ sustainability” are used and understood within king crab management.

A central document in this thesis is the white paper on management of the red king crab adopted by the Norwegian government in 2007 (Anonymous 2007). The report discusses Norway’s obligations and rights with respect to the king crab as an alien species according to international law. It concludes that at the time no serious damages to the ecosystem had been documented as a result of the king crab invasion. This statement carries a judgement on what level of damage and type of knowledge is needed to conclude on the impacts of the crab. Paper 3 is a response to the lack of scientific documentation on the impact of the crab on the Barents Sea ecosystem. Being a commercially important species in the north Pacific the crab has been a subject of research in this area, particularly to understand its population dynamics. Some of this literature discusses trophic interactions. Together with impact studies conducted in the Barents Sea, this information is a useful starting point for understanding how it may interact with native biota. A literature review was therefore conducted in order to integrate studies from the Pacific and the Barents Sea. While quantitative ecosystem models can be useful tools to integrate information on trophic interactions, see for example Falk-Petersen (2004), their validity depends on sufficient data input. Furthermore, trophic models account for feeding interactions, but do not look at the structural role of organisms. King crabs feed on benthic organisms that are believed to play an important role in the Barents Sea ecosystem, in particular some species that form or maintain habitat for other organisms. A lack of long-term studies on benthic structure and dynamics, including quantitative trophic information (Wassmann, Reigstad, Haug et al. ; Gerasimova 1997), resulted in quantitative frameworks being disregarded as tools for organizing information from the literature review. A thorough literature review did provide sufficient information to make conclusions regarding the role the crab is expected to play in the Barents Sea ecosystem. It also revealed important areas of further research to fill important knowledge gaps in our understanding of how the king crab may alter current ecosystem functions. A similar case identifying knowledge gaps that need to be filled in order to better account for the services benthic ecosystems potentially provides is presented in Paper 2. The paper focuses on the structural importance of benthic ecosystems in securing commercial fish production.

Papers 2 and 3 introduce the concept of ecosystem functions and services and points to lack of knowledge as a limitation to management. Papers 4 and 5 explore how uncertainty and the range of services the ecosystem provides can be accounted for in management. Paper 4 uses a bio-economic model to demonstrate the key mechanisms determining the optimal harvesting strategy of a species that has a commercial value, but also inflicts a cost on the traditional fisheries and negatively affects ecosystem services. While integrating biological and economic information, a limitation to this approach for finding the optimal crab stock size is that the costs are underestimated because of a lack of quantitative information on what impacts the king crab invasion will have on ecosystem services. It does, however, demonstrate the mechanisms determining the optimal management strategy when this information is lacking. Furthermore, it explores how biodiversity loss, treated as a cost, affects optimal crab stock size when the damage is non-linear in crab stock size. The latter reflects the recognition that that ecosystem changes may not always be gradual, and instead may be characterised by thresholds. Ecosystem based management perspectives focus on the need to maintain the integrity of ecosystems in order to secure their functions (Guerry 2005). While being an important focus of research, the contribution of biological diversity to ecosystem functioning and the ability of the ecosystem to withstand stress is not fully understood (Holling 1973; Dayton, Tegner, Edwards et al. 1998; Jackson 2001; Nunes and van den Bergh 2001; Curtin and Prellezo 2010). However, biological diversity contributes to human welfare in numerous ways (Mace, Norris and Fitter 2012), so treating biodiversity loss as a cost can be justified despite limited ecological understanding. Furthermore, as argued in Paper 4, management goals set by society can be used to establish threshold points. The ecosystem based management plan for the Barents Sea provides such a reference point through stating that the structure, functioning and productivity of the ecosystems are to be maintained (Anonymous 2006).

Evaluation of the risk the king crab represents is central when assessing Norway's obligations with respect to alien species according to international law (Anonymous 2007). However, conventional risk assessment is only applicable when there is a good basis for predicting the likelihood of harm and the extent of the consequences (Anonymous 2004), which is not the case when it comes to the red king crab invasion. Paper 5 is a response to the challenge of Perrings and Pearce (1994) on including ethical judgement into the analysis of the acceptable level of impact when facing uncertainty. Inclusion of stakeholders in the management process to account for social and economic impacts is also stressed in the precautionary principle (UNESCO 2005), another central guideline referred to in the white paper on how the king crab should be managed. A valuation study to capture the degree to which people were willing to pay for reducing the risk the king crab represents was considered in order to provide a better cost estimate for the bio-economic model. Stated preference techniques have been used to measure environmental concerns in monetary terms when the attributes to be assessed are non-tangible or do not yet exist (Spash 2006). While it is not possible to eradicate the king crab from the Barents Sea, previous studies have found willingness to pay even just to delay an inevitable invasion (McIntosh, Shogren and Finnoff 2010). However, these authors could provide respondents with expected impact scenarios, many of which were impacts that would directly affect people's welfare. Such translation of ecosystem functions into ecosystem services that people benefit from has been identified as the key to capture environmental concern among the public (Barkmann, Glenk, Keil et al. 2008). Because of the lack of knowledge of how the king crab may affect native ecosystems and associated services humans benefit from, and that long-term consequences of invasions are hard to predict from the current short-time data series available (Strayer, Eviner, Jeschke et al. 2006), creating scenarios in terms of services that people could relate to was not seen as a sound option. To explore how stakeholders' opinions could be included in management, a discourse analysis was performed in order to capture people's perceptions on what services the king crab affected and how they believed the king crab should be managed. Q-methodology is used to identify different social perspectives. The starting point of the analysis is the public debate on the topic of interest (Webler, Danielson and Tuler 2009). Thus rather than asking people about their perceptions based on a theoretical concept such as ecosystem services, it aims to secure that respondents are familiar with and can relate to the issues in the survey. After conducting the survey, the information on ecosystem services identified in the debate on the king crab was organized using the Millennium Ecosystem Assessment (MEA) framework (Millenium Ecosystem Assessment 2005).

Ecosystem function refers to how biotic and abiotic elements of an ecosystem combine to produce ecosystem services (Millenium Ecosystem Assessment 2005; Curtin and Prellezo 2010). The lack of valuation of these services is claimed to be an important underlying factor behind the degradation of ecosystems and biodiversity loss seen today (TEEB 2008). Through identification of ecosystem services and valuation of these, ecological and social aspects can be integrated into a common framework and translated into a currency that can be used to evaluate trade-offs. MEA is the most widely used framework for identifying the range of benefits obtained from ecosystem services (Millenium Ecosystem Assessment 2005). MEA divides ecosystem services into four categories. Provisioning services are products such as food, fuel, fibre and biochemical that humans obtain from ecosystems. Regulating services are benefits obtained from the regulation of ecosystem processes such as climate and water regulation, erosion control, storm protection and water purification. Cultural services are non-material benefits obtained through for example spiritual enrichment and cognitive development, including social relations, cultural heritage and recreation. Supporting services are those necessary for the production of all other ecosystem services such as nutrient cycling, primary production, production of oxygen and habitat (Defra 2007).

The Total Economic Value (TEV) framework can be used to value provisioning, regulating and cultural services, with supporting services being valued through these categories (Defra 2007). TEV divides economic values into use values and non-use values (Pearce 1994). The latter is the value put on knowing that something exists and that others may benefit from a resource in the future. Use values are values arising from the use of a resource either directly or indirectly through ecosystem functions. This group of values also includes option values, which are the values ecosystems represent to future welfare in terms of processes we do not have the knowledge to value, and benefits not predicted today (for example marine prospecting). Some authors have pointed out that option values are not a part of the MEA framework (Balmford, Walpole, ten Brink et al. 2008), while others argue that these values are implicitly accounted for within the MEA through TEV (Defra 2007). While the ways nature contributes to current and future human welfare may be difficult or impossible to measure, the benefits may be substantial. This recognition has resulted in inclusion of option values within ecosystem service frameworks building on MEA (Beaumont, Austen, Atkins et al. 2007; Balmford, Walpole, ten Brink et al. 2008), rather than accounting for these values using the TEV framework in a step to follow after ecosystem services have been identified as illustrated in Hein, van Koppen, de Groot et al. (2006). Uncertainty is a key element in management of the king crab invasion. Option values were also identified in Paper 5 as important for forming people's perceptions on the king crab invasion. The MEA framework was therefore adapted according to Beaumont, Austen, Atkins et al. (2007) (Figure 2) and used as a basis to synthesise the information from the king crab papers in this thesis. This synthesis and a framework for integrating ecosystem service studies into ecosystem based management will be presented in the synthesis.

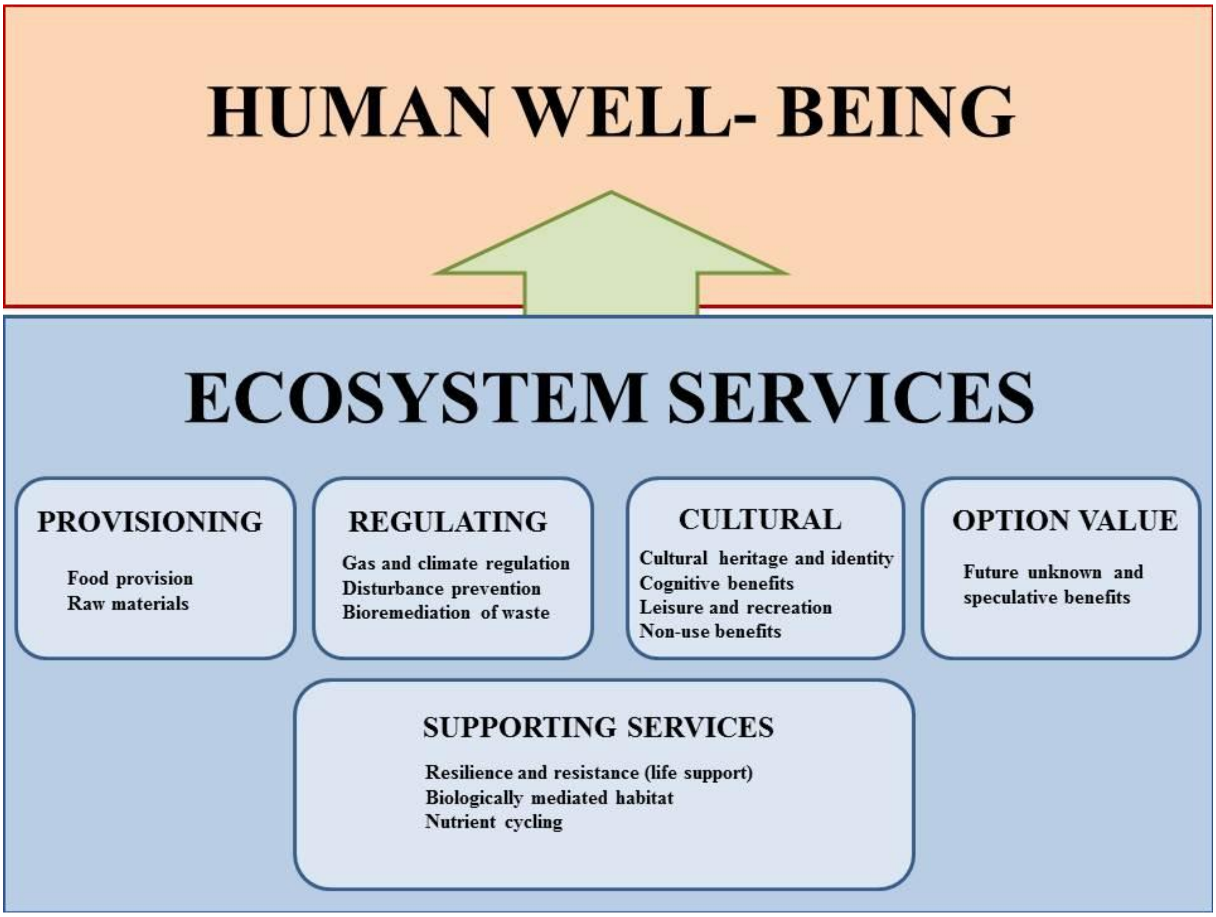

Figure 2: Constituents of ecosystem services as identified in Beaumont, Austen, Atkins et al. (2007), organized according to Millenium Ecosystem Assessment (2005). The term "production services" used in the former is replaced with "provisioning services" to be consistent with the terminology used in MEA.

Summary of papers

Paper 1, 2 and 3 focus on the need to systematise knowledge, both to ensure a common reference framework and understanding of the issue of concern, and as a guide for further research and management. Paper 1 clarifies the terminology used in invasion ecology, separating the use of terms that describe ecological characteristics from those describing social and economic consequences of invasions. Paper 2 and 3 are review papers on respectively, the impact of destructive fishing practices and the Barents Sea red king crab invasion on benthic ecosystems and their services. Paper 2 points out that while protection of habitat for fisheries production is increasingly a focus of management plans, it has been challenging to establish the link between fish population dynamics and the supporting services of habitats. Thus, the indirect negative impact on the fisheries themselves via fishing practices that damage habitats cannot be demonstrated. Loss in future fisheries production is a potential indirect effect of habitat damage, as is reduced fishing efficiency, since habitats may have an aggregating effect on commercial fish.

Paper 3 identifies important factors contributing to the crab establishment in the Barents Sea and synthesise knowledge that can contribute to understanding how it may interact with native biota. It concludes that key elements explaining the crab's success as an invasive species are favourable physical and biological conditions and a generalist diet combined with a low fishing pressure. The review of available literature revealed that while there is limited information of their interactions during earlier life stages, juvenile and particularly adult crabs are better studied. The paper concludes that the king crab has the potential to significantly affect local ecosystems. Reduced benthic diversity and biomass have been observed in invaded areas. Benthic organisms have important functional roles in the system, thus supporting habitat services and nutrient cycling may be affected by the invasion. In addition, provisioning services may be directly impacted through predation on eggs of commercial fish. The paper refers to estimates of carrying capacity of king crabs, but notes that these only consider the capacity of the benthic community to produce biomass, and do not account for other issues such as maintaining biological and structural diversity.

Papers 2 and 3 argue that there is a need to fill the knowledge gaps identified, primarily the link between supporting and provisioning services, in order to justify management measures.

In both cases the provisioning services in terms of food provision is obvious: bottom trawling is often highly efficient and the king crab represents a lucrative fishery. However, while some of the supporting services affected can be identified, how deterioration of these services feed into provisioning services cannot be estimated. In order to motivate protection of habitat from damaging fishing practices, Paper 2 argues that habitat-fisheries connections must be included in stock assessment in order to legitimize habitat protection. Paper 3 identifies areas where more information is needed in order to provide management institutions with information on ecosystem impacts. In both papers fishing practices is the key to protection of benthic ecosystem services. However, while the fisheries is the source of destruction in Paper 2, it is the source of the solution in Paper 3 since fishing is the main tool to limit the growth and spread of the red king crab population.

Papers 4 and 5 discuss how the knowledge gaps identified in Paper 3 can be filled. The former analyses the bio-economically optimal stock size of the king crab, given that it affects human welfare both positively through food provision and negatively. Known costs affecting the profitability of the fishing fleet are those related to bycatch of crabs in traditional fisheries. These are negligible compared to the income of the king crab fishery. To account for impacts on native ecosystems, biodiversity loss is treated as a cost due to negative effects on supporting services. The relationship between alien species abundance and biodiversity loss is likely to be non-linear, thus characterised by thresholds. Non-linear relationships between crab stock size and ecosystem damage were therefore explored. While the exact damage function is not known, the Barents Sea management goal of maintaining the structure of the ecosystem can be used as a threshold point beyond which society has determined that the losses are unacceptable. The analysis showed that when impact on supporting services is included, optimising food production of the king crab is in conflict with this management goal. In addition to illustrating the importance of knowing the carrying capacity of the ecosystem with respect to the crab, it stressed the need to know the carrying capacity of the king crab stock itself. The carrying capacity of the crab is based on the largest estimated stock size of commercial crabs. It does not take into account that the crab is an alien species that is expected to initially overshoot its carrying capacity before a new equilibrium between the crabs and their prey is established. Observed reductions in condition and size in the field (Haugan 2004) suggests the carrying capacity of the king crab stock used in existing population models is too high to secure that the crab is managed at a maximum sustainable yield level.

While stressing the need to establish the relationship between king crab biomass and biodiversity loss, Paper 4 also points to the importance of identifying the range of services the ecosystem provides. Furthermore, the inherent uncertainty of predicting ecosystem effects of alien invasive species calls for inclusion of ethical judgements in the management process in order to establish the socially acceptable level of environmental impact (Perrings and Pearce 1994). The inclusion of stakeholder perceptions in managing the king crab is explored in Paper 5. Stakeholders recognised both positive and negative impacts of the crab on supporting, provisioning and cultural services. Furthermore, people were concerned about impacts on ecosystem services we do not have enough knowledge to value today, or option values. Perceptions differed between people living within the area the crab is managed as a resource, and in the open-access area where the crab's presence is more recent. The former emphasized the crab's contribution to provisioning and cultural services, while the latter stressed negative impacts on option values. However, it was agreed that biodiversity concerns should be central and that further invasion was undesirable because of the impact the crab could have on ecosystem services. The interviews conducted also revealed different perceptions of the term carrying capacity. Some saw benthic organisms as a supporting service to the king crab and a number of respondents expressed a concern that current management ignored the carrying capacity of benthic ecosystems to king crab in setting quotas. Others regarded the benthic ecosystem as a supporting service to the rest of the system, thus focusing on the need to avoid overshooting the carrying capacity of benthic ecosystems.

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PAPER 1

PAPER 2

PAPER 3

PAPER 4

PAPER 5

Synthesis

Table 1 synthesises information on ecosystem services affected by the king crab invasion as identified in Paper 3 and 5. The definitions follows those described in Beaumont, Austen, Atkins et al. (2007). Where information is available additional services to those identified in Paper 3 and 5 are included.

Table 1: Synthesis of ecosystem services affected by red king crab invasion.

Service		**King crab impact**
Provisioning services	Food provision	+ Food (king crab) – Food (lumpsucker, haddock, anglerfish, capelin, herring, cod)
	Raw materials	Unknown
Regulating services	Gas and climate regulation	Unknown
	Disturbance prevention	Unknown
	Bioremediation of waste	- Loss of benthic organisms
Cultural services	Cultural heritage and identity	+ Maintain fishing communities – Loss of traditional fisheries
	Cognitive benefits	+ Understand ecosystems – Loss of baseline
	Leisure and recreation	+ Diving/fishing for king crab – Traditional fishing
	Non-use benefits (bequest and existence values)	Unknown
Option value	Future unknown and speculative benefits	– Impact on ecosystem services
Supporting services	Resilience and resistance	– Biodiversity and functional loss
	Biologically mediated habitat	+ Recovery of kelp – Loss of benthic organisms representing or providing habitat
	Nutrient cycling	+ Enhanced oxygenation at surface – Loss of benthic organisms that contribute to nutrient cycling

Provisioning services

Food provision and raw materials: The king crab represents an important food item, but could have negative impacts on commercial fish through egg predation, bycatch, trophic interactions and competition (Paper 5). Their impact on raw materials, thus marine organisms not used for human consumption, and the potential use of the king crab as raw material has not been a part of the debate. These values can therefore be regarded as option values.

Regulating services

The ability of the king crab to affect the balance and maintenance of the chemical composition of the ocean through their impact on marine living organisms has not been a focus in the scientific or public debate. Benthic organisms have the potential to bury, sequester and process pollutants (Beaumont, Austen, Atkins et al. 2007). Benthic diversity and functional groups providing these services have been negatively affected by the king crab invasion (Oug, Cochrane, Sundet et al. 2010), thus bioremediation of waste could be affected. The role of benthic organisms in gas and climate regulation and disturbance prevention is unknown.

Cultural services

Cultural heritage and identity: As discussed in Paper 4 and 5 the king crab industry is an important basis for securing the economy of small scale fishers and associated fishing communities in this area. These communities have been marked by reduced catches due to reduction in Barents Sea capelin and cod stocks, bankruptcy of production companies (Arbo and Hersoug 1997) and local extinction of coastal cod populations. However, while representing a valuable income and enabling recruitment of young people into the fishing industry, the crab is also a threat to traditional fisheries.

Cognitive benefits: Studying alien invasions can give new insight into how ecosystems function, thus the invasion can be a positive contribution to research. However, a lack of baseline information particularly on the role of benthic communities could also represent an important limitation to understanding these systems and how they may respond to various disturbances (Dayton, Tegner, Edwards et al. 1998; Knowlton and Jackson 2008). This could result in the “shifting baseline syndrome” where management targets are set according to baselines that do not account for human induced changes of marine ecosystems (Pauly 1995).

On the other hand, introduction of new species represents an irreversible process which could lead to the historical baseline being an unachievable management target.

Leisure and recreation: The king crab is promoted in the tourist industry and is also a target for divers. The crab may be in conflict with traditional fisheries as a recreational activity, but it is the commercial fisheries that are the focus of the debate.

Bequest and existence values: As shown in Paper 5 people are concerned about the impact the crab may have on the ecosystem, and this concern could include the ability of future generations to enjoy ecosystem services (bequest value). Existence values, which is the value of organisms in themselves for their own sake, could be important for capturing the intrinsic value of ecosystems (Callicott 2005). Intrinsic values, as oppose to instrumental values that are the target in an ecosystem service approach, have been argued to be the main motivating factor for environmental concern (Hargrove 2000). How the king crab should be managed can also be seen as a moral debate due to the uncertain outcome of the invasion. Sen and Williams (1999) argues that complete information is not required in order to make rational choice. Rather, striving towards complete information has been seen as artificial and theoretically problematic when dealing with moral conflicts. Following this argument, intrinsic values should be in focus when capturing people's environmental concerns. In the king crab debate non-use values have not been an important focus and these were therefore not targeted specifically in this work.

<u>Option value</u>

Paper 5 demonstrated that concerns about the impact on ecosystem services we do not currently know the value of are an important factor determining perceptions on how the king crab should be managed. Paper 3 highlights that the crab may have unknown impacts on supporting services provided by benthic organisms. Many of the services and how they may be impacted by the invasion have not been scientifically confirmed and could therefore be classified as option values. However, Table 1 only summarises the potential impacts identified in Paper 3 and 5, it does not evaluate the probabilities of these events.

<u>Supporting services</u>

Resilience and resistance: Resilience refers to the ability of an ecosystem to return to its original state after disturbance, while resistance is the ability to avoid these changes in the first place (Begon, Harper and Townsend 1996). As discussed under methods, the role of biodiversity in securing the resilience and resistance of ecosystems is debated. Functional diversity has been proposed as an important factor determining the resilience of ecosystems. Biodiversity is likely to play a role in determining the functional diversity of a system since high diversity increases the chance of functional redundancy. However, if all species within a functional group have similar responses to disturbance, high biodiversity will not offer additional protection (Hughes, Bellwood, Folke et al. 2005). Reduced species diversity and biomass has been documented after introduction of the king crab as summarized in Paper 3. Oug, Cochrane, Sundet et al. (2010) concluded that the king crab has reduced the functional diversity of native benthos, but little is known about the implications of these losses in a wider ecosystem context.

Biologically mediated habitat: The ability of the king crab to control sea urchin populations, so that kelp forests can regenerate is discussed both in Paper 3, in terms of scientific evidence, and in Paper 5 on people's perceptions. Kelp forests are important habitat for commercial fish. It has therefore been hypothesized that recovery of kelp beds is a key to recovery of coastal cod populations. Crab predation could be a threat to crucial habitats, including those provided by large epibenthos such as scallop beds. Removal of benthos important for securing the quality of habitats within the sediment has been documented (Oug, Cochrane, Sundet et al. 2010).

Nutrient cycling: Reduced numbers of benthic organisms important for sediment reworking and bio-irrigation that secures oxygenation and solute transport to deeper sediment layers have been observed in Norwegian waters. Removal of these groups may affect degradation of organic matter and regeneration of nutrients. On the other hand, through walking, digging and feeding behaviours, king crab may improve particle mixing and oxygenation of surface sediments (Oug, Cochrane, Sundet et al. 2010).

Discussion

This thesis demonstrates that the answer to how the king crab should be managed in the Barents Sea calls for integration of ecological, social and economic sciences. It also identified some key concepts that need to be clarified in order to evaluate the trade-offs involved. After discussing the main results, a framework for integrating natural and social science in the management process to better account for uncertainty and the range of benefits the ecosystem provides will be presented. The ecosystem based management framework for the Barents Sea will be used as an example of how identification of ecosystem services could contribute into the decision making process.

Papers 2 and 3 identify a number of potential services provided by benthic ecosystems and stress the need for a better understanding particularly of how supporting services contribute to our welfare in order for these to be accounted for in management. Knowledge gaps in our understanding of what enables ecosystems to deliver their services have been identified as an important constraint in integrating an ecosystem service approach into management (Anton, Young, Harrison et al. 2010). The uncertainty associated with scientific understanding and prediction has also been suggested as the main barrier to informing social actions on environmental issues. The response to this has been development of research programmes that aim to reduce uncertainty (Hart and Calhoun 2010). This way of reasoning is reflected in the Barents Sea management plan that emphasises the need for better knowledge of what impacts the overall pressure of all activities in the area may have on the ecosystem (Anonymous 2006).

However, the degree to which filling knowledge gaps reduces uncertainty has been questioned. Ecological research has often revealed that the knowledge gaps are larger than first anticipated and that uncertainty is not necessarily reducible (UNESCO 2005; Hart and Calhoun 2010). Furthermore, as also reflected in Paper 5, ecological information is just one of many aspects stakeholders evaluate when deciding on their preferences for management options. Values, attitudes and belief systems may affect stakeholder perceptions in ways that do not necessarily follow the rationales based on scientific information (Hart and Calhoun 2010). However, judgments made by professionals regarding environmental threats are also affected by values and beliefs (Slimak and Dietz 2006). Furthermore, as stressed in the precautionary principle, all parties affected in decision making should be involved in order to capture the wide range of opinions and values in a society (UNESCO 2005). Thus, the social sciences have an important role to play in formalising these inputs in order to facilitate a balanced debate on how natural resources should be managed.

The interpretation and use of the term carrying capacity turned out to be a central theme in the discussion on how the king crab should be managed (Paper 3, 4 and 5). The different perceptions identified in Paper 5 illustrate this issue well. Stakeholders stressed that the carrying capacity of benthic ecosystems had to be taken into consideration when determining how many king crabs there should be in the Barents Sea. But stakeholders differed in terms of what this would imply depending on what was the focus of their concern. A sustainable management practice was understood as a) a king crab population size that could be supported by the capacity of benthic ecosystems to produce biomass, or b) a king crab population size that did not affect the capacity of benthic ecosystems to provide ecosystem services. This illustrates that perceptions depend on individual objectives and values, as well as what types of ecosystem services people emphasise or are aware of. Methodological considerations did not allow for exploring further to what degree stakeholders related to the various ecosystem services identified in the synthesis. Tools for capturing stakeholder perceptions could, however, benefit from using an ecosystem service framework to discuss impacts. This could contribute to a common understanding of the problem through translation of ecosystem functions into services people can relate to, inform stakeholders about issues that are not apparent and give feedback to scientists on what type of research society demands (Barkmann, Glenk, Keil et al. 2008; Hart and Calhoun 2010) (point 1, Figure 3).

The different perceptions on what it means to account for carrying capacity in king crab management also reflect that as fishers adapt to new conditions, perceptions on what is a well-functioning and productive ecosystem changes. The Barents Sea management plan suggests that there is a baseline state to which the management goal of “maintaining the structure, functioning and productivity of Barents Sea ecosystems” could be compared. This management goal also defines the boundary within which human activities should operate (Anonymous 2006). In their management advice for 2011 on the king crab, Norway’s Institute of Marine Research referred to new research documenting negative impacts on ecosystem functioning (Oug, Cochrane, Sundet et al. 2010) and concluded that in order to maintain the demography and species diversity of benthic communities, the king crab population had to be kept at the lowest level possible (Anonymous 2010). This advice follows the guidelines given in the management plan where the baseline state is determined by reference to a time where the system is perceived to be in a desirable state.

Ecosystems are dynamic, affected by large-scale climatic and oceanographic events and have been altered by humans for centuries (Dayton, Tegner, Edwards et al. 1998; Pitcher and Pauly 1998), including through irreversible events such as introduction of new species. A static world view such as that reflected in the Barents Sea management goal, where anthropogenic pressures such as invasive species represents a threat to the trajectory nature is to follow, has been argued to be in conflict with the dynamic nature of ecosystems. Thus, there are numerous alternative conditions that can be considered natural (Hull and Robertson 2000; Larson 2007). Furthermore, since humans are creatures of nature it has been argued that anthropogenic pressures cannot be disconnected from other factors contributing to ecosystem dynamics (Larson 2007).

Ecologists have a duty to raise concerns about the impact of alien invasive species since they may negatively affect ecosystem functions and thereby represent a threat to the services humans depend on. On the other hand, natural scientists are not necessarily the only holders of the truth when it comes to defining what nature is and should be. There exist many points of views and value criteria for what is natural and healthy (Hull and Robertson 2000; Larson 2007). Stakeholders stressed that biodiversity concerns should be central in managing the king crab and were concerned about the ecological consequences of the invasion (Paper 5). But while there was agreement that it is better to have too few than too many king crabs, current reference points may not necessarily be appropriate in determining the optimal king crab stock. Rather than being static, management goals should adapt to account for the dynamics of both ecological and social systems. Ecosystem service frameworks have the potential to be a common platform for communication between managers, scientists and stakeholders in establishing these “moving target” baselines.

The importance of accounting for uncertainty in determining the socially optimal management strategy was discussed in Papers 4 and 5. Since option values were identified as central in determining stakeholder's perceptions on how the king crab should be managed, Paper 5 argues that these values should explicitly be accounted for when identifying ecosystem services. Translation of ecosystem services through valuation is suggested as a necessity to ensure that the benefits derived from these are recognised (TEEB 2008; Abson and Termansen 2011). Nunes and van den Bergh (2001) argue that valuation studies are only applicable when the change in biodiversity is well defined and not too large. However, option values may be substantial (Balmford, Walpole, ten Brink et al. 2008) and uncertainty related to how humans affect key ecosystem services is an important element in environmental debates. It is also the basis for the precautionary principle that is incorporated into international and national laws on natural resource management (UNESCO 2005).

The trade-off between the king crab as a valuable economic resource versus concerns about unknown impacts on ecosystem services is central in the debate on how the king crab should be managed. This type of trade-off where protection of the ecosystem is less risky, but may result in low economic returns, is inherent in real-world decision making. However, ecosystem service valuation has been criticized for not capturing such issues (Abson and Termansen 2011). Biodiversity has been proposed to represent an insurance value against the uncertain provision of ecosystem services (Baumgartner 2007). However, the idea that the flow of directly used services is a function of changes in supporting ecosystem services, and therefore can be expressed in terms of ecological risk, has been rejected (Abson and Termansen 2011). Risk is a social construct that depend on how an individual assesses the probability of an event and how severe the impacts may be. Scientists can describe possible outcomes, but society through individuals must express their preferences for different levels of risks and economic returns, or values (Elliott 2003; Abson and Termansen 2011).

The discourse analysis in Paper 5 revealed that while there is general support for protecting unknown ecosystem services in the western management region through a decimation fishery, support of such a management strategy in the quota regulated area would require documentation of negative ecosystem effects. That people tend to emphasise losses compared to gains is known from the stated preference literature. This has been explained by people overvaluing goods they possess, have a preference for the current situation, and perceive that losses have a larger impact on utility than gains of the same magnitude (Dupont and Lee 2002). The threat the king crab represents to the ecosystem is unlikely to differ between the two management areas. While the observed spatial difference in support for protecting option values could reflect that people's perceptions on what is a healthy ecosystem has changed according to the new ecological situation as discussed above, this could also illustrate the phenomenon that benefits obtained from taking risk can affect risk perceptions (Slovic, Fischhoff and Lichtenstein 1980).

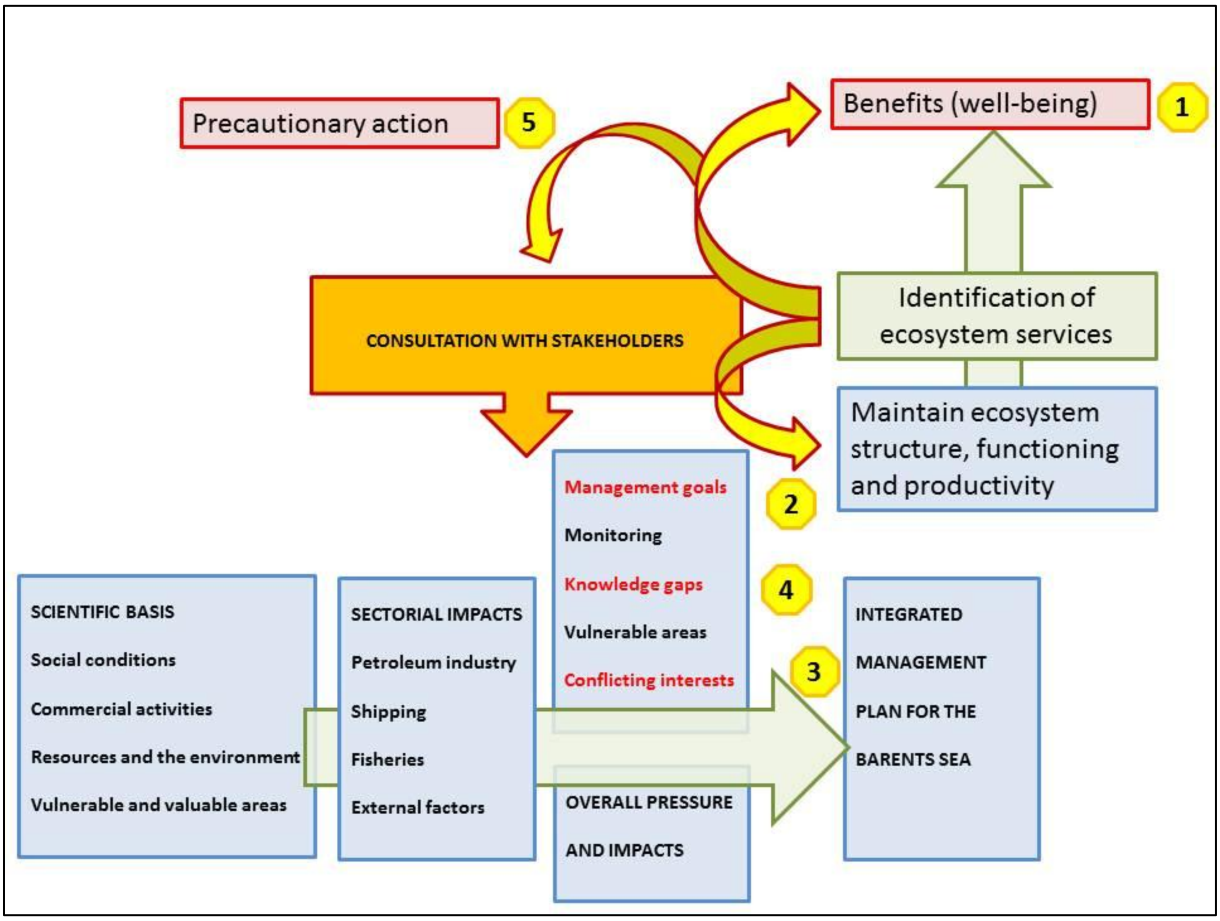
In addition to personal consequences, a number of factors determine how environmental risk is judged including familiarity, how well the consequences are understood, if they are potentially catastrophic and whether there is a latency period (Burger and Gochfeld 1991; Elliott 2003; Slimak and Dietz 2006; Beaumont, Austen, Mangi et al. 2008). To add to the complexity of determining the socially acceptable level of environmental risk, individual choice may be in conflict with that of the society. The issue of legitimacy and representativity needs to be addressed when integrating social perceptions in the management process (van den Hove 2000). It may therefore not be appropriate to aggregate individual perceptions of, and preferences for, risk in order to identify the socially acceptable king crab stock. However, capturing these perceptions and values could contribute to increased awareness of the values and concerns connected to ecosystem services, ensure a common understanding of these and give input on how the precautionary principle may be applied. Furthermore, stakeholder inclusion may improve the legitimacy of the decision making process (van den Hove 2000).

Valuation frameworks have been criticized due to limitations related to translating ecosystem services into monetary units. The sum of the values identified is not equivalent to the value of the total system as a whole. To secure ecosystem functions, the composition of the ecosystem must be maintained. Furthermore, capturing non-market values using stated preference techniques is fraught with difficulties (Nunes and van den Bergh 2001; Jones-Walters and Mulder 2009; Turner, Morse-Jones and Fisher 2010; Abson and Termansen 2011). Thus, in addition to using non-monetary values to complement those captured in economic terms (Abson and Termansen 2011), there should be room in the management process for discussing the trade-off between all services in qualitative terms. While the natural system has been the focus in risk assessment of ecosystem services, factors contributing to sustainable social systems should also be included in risk assessment. The red king crab has improved, and in many cases made it possible to sustain, the livelihood of small-scale fishers by providing an important buffer when the traditional fishery fails (Eldorhagen 2008). The continuation of the quota-regulated management zone despite increased awareness of negative ecological impacts reflects that the importance of the king crab for local fishing communities is recognised. However, the ability of the crab to support these communities could also suggest that attaching local user rights to a resource can be a key to sustaining coastal communities.

Knowledge gaps and the lack of integration of social science aspects have been identified as major limitations to applying an ecosystem service approach to management (Anton, Young, Harrison et al. 2010; Christie 2011). The 2011 white paper giving an update on the Barents Sea management plan rejects the use of valuation tools when facing uncertainties due to knowledge gaps on ecosystem services and methodological issues. Application of the precautionary principle or minimum standards to secure ecosystem services are suggested as alternative decision tools (Anonymous 2011). This reflects the strong position the natural sciences have in setting management targets. As discussed above, it is problematic to have a management system that does not integrate social values and concerns. Furthermore, such a system may lose its legitimacy. While monetizing may not always be appropriate or possible, that does not imply that an ecosystem service approach to management should be rejected.

While ecologists often are driven by a desire to create knowledge that can contribute to improved management of ecosystems, it is increasingly recognised that although this knowledge is necessary, it is not sufficient for improving environmental outcomes (Hart and Calhoun 2010; Christie 2011). Ecosystem service frameworks have the potential to integrate both natural and social science aspects within an adaptive management cycle. This is illustrated using the framework developed for ecosystem management for the Barents Sea presented in blue and orange in Figure 3. The primary goal of applying ecosystem service frameworks is often to identify the range of benefits an ecosystem provides in addition to provisioning services, in order for these to be better accounted for in management (1). Additionally, important knowledge gaps are identified (4). Within an adaptive management framework facilitating dialogue between scientists, stakeholders and decision makers, the discussions on ecosystem services could also give input to the baseline "moving target" management goal (2). Furthermore, while the Barents Sea management plan focuses on reducing conflict between the different industries operating in the area, ecosystem service exercises can help setting the focus on the range of services these industries may be in conflict with (3). Involving stakeholders can contribute to identifying areas of conflict, as well as values and perceptions on how ecosystems contribute to well-being (1) and give feedback on what knowledge gaps stakeholders believe should be prioritised (4). Finally, dialogue assisted using an ecosystem service framework may contribute to a better understanding of how uncertainty should be accounted for and what should be the basis for precautionary action (5).

Figure 3: The Barents Sea ecosystem management framework (blue and orange) and the potential role of identification of ecosystem services (green and yellow). Numbers are referred to in the text.



Conclusion

Application of interdisciplinary frameworks to analyse the red king crab invasion in the Barents Sea has shown that ecological, economic and social sciences have important roles to play in determining how the invasion should be managed. Ecosystem service frameworks are not the only tools that can contribute to a management system that better integrate the different disciplines. However, such frameworks have the potential to create a common platform for discussing the range of services the ecosystem provides and exploring trade-offs between these, including how to deal with uncertainties, different values and ecosystem changes.

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