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Contents

Abstract

ACCESS has developed a framework for Integrated Ecosystem Based Management (IEBM) of the Arctic. This framework takes a holistic system approach for management and aims to account for all aspects of Arctic developments that matter. Its essential role is to help managers deal with systemic and non systemic change aiming toward improved and sustained human well-being. This framework does not present a universal solution to management issues in the Arctic, rather it provides general guidelines to support managers in building their own solutions adapted to their particular problem.

At the core of the framework lies a social-ecological system lens with focus on resilience, the capacity of a system to deal with change and continue to develop. Ecosystem services play a critical role at the base for most human activities and human well-being, some of them being non substitutable. We identified some of these services in the Arctic Ocean for the purpose of ACCESS. In addition we highlight social-ecological system connections between Arctic geophysical and ecological processes, and multiple economic and social sectors. IEBM should build on existing knowledge and tools already available like Marine Spatial Planning, Arctic Resilience Assessment, Sustainability Indicator and use these tools together.

A good overview of the whole system is essential for IEBM and we suggest to use a nested approach where a broad but abstract framework can contain several more or less detailed pieces that can be linked together and turned on or off depending on the needs. ACCESS produced a general model of interactions between different elements of the Arctic system and complements it with several more detailed models of particular interactions. An IEBM of the whole Arctic should also identify how the Arctic interacts with the rest of the world.

Society is better prepared to deal with slow marginal change compared to abrupt and substantial change so the ACCESS framework for IEBM puts particular focus on how to handle abrupt and substantial change, building on results from the 7th Framework program Arctic Tipping Points (e.g. Wassman and Lenton, eds 2012, Crépin et al 2012; Levin et al 2011).

We suggest that an IEBM of the Arctic includes 14 steps divided into categories related to understanding the system, representing/modeling the system, testing the validity of results, identifying potential change and their impacts and finally implementing and testing results in management. We illustrate how most these steps could be approached except for those related to direct implementation of the results into management. I particular we illustrate the advantages of an IEBM approach through 6 hypothetical scenarios of possible climate driven change in the Arctic marine ecosystem. Two of these scenarios focus on changes in zooplankton production and four scenarios on changes in presence of Arctic species like crabs. All scenarios illustrate the potential impacts on the Arctic system using an integrated ecosystem based management approach and show very different outcomes.

Conditions for integrated ecosystem based management in the Arctic

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1 Background

The expansion of human activities into a globalized society, enhancing the material standard of living for a large part of people on Earth, has pushed humanity into a new geological era, the Anthropocene. This process has generated the bulk of the global environmental changes, with potential thresholds and tipping points, which currently challenge the future wellbeing of the human population on Earth (Steffen et al. 2007; Rockström et al. 2009). This expansion has heavily eroded the natural capital of the planet and the flow of goods and services that provides the basis for all socio-economic activities (Millenium Ecosystem Assessment, MA 2005).

The impacts are substantial on all parts of the planet and on the Arctic in particular. Climate change is expected to transform the Arctic Ocean from a year round frozen sea ice to a sea with open waters in the summer and a layer of annual ice in the winter. (ACCESS D1.23, D1.25, Wadhams et al 2011a,b, Wadhams 2012, Stroeve et al 2012a,b, Wang and Overland 2012, Massonet et al 2012) Such dramatic change will have substantial impacts on economic activities, governance, and indigenous and local peoples in the Arctic (ACIA 2004, ACCESS D5.91). The Arctic, particularly its ocean also provides substantial ecosystem services and benefits to humanity outside of the region. The region is essential for regulation of global Earth processes, in particular the climate, making the changes in the Arctic globally relevant (Arctic Council, 2013a). To better grasp the new conditions for policy making in the region, human development and progress must be reconnected to the capacity of the biosphere and essential ecosystem services to be sustained (Folke et al., 2011).

The Arctic Ocean is also substantially influenced by what happens in the rest of the world. In particular, it faces greater temperature increases compared to the Earth as a whole, as the results of the effects of feedbacks and other processes, also referred to as the polar or Arctic amplification (Kattsov et al. 2004). Climate change, the main topic of ACCESS, is just one example of such influence. In addition societies outside the Arctic have strong influence for example through the impacts of globalized markets and Arctic countries' administrations on local populations. Most decisions are taken in the central administrations located outside the Arctic and the Arctic minorities may not be able to influence these much.

In the new context of a globalized and interlinked world, management could increase in efficiency if it takes a systematic approach, viewing the world or some region of the world as one system where all elements interact in a complex way. Such a social-ecological systems view is critical for generating sustainable management strategies in a world of surprises, thresholds, non-linearities and tipping points (Chapin et.al 2010). In this context, the use of an integrated management approach can provide an essential system understanding, highlighting connections between ecosystems, and the economic and social sectors.

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Interconnections within ecosystems is the focus of conventional ecosystem based management strategies (see e.g. Christensen et al. 1996, POC 2003, USCOP 2004, MA 2005, Olsson et al. 2008). Ecosystem based management (EBM) is an environmental management approach that highlights key ecological interactions between biotic and abiotic components of the ecosystems, as well as with humans, rather than considering single issues, species, or ecosystem services in isolation (Christensen et al. 1996, McLeod et al. 2005). A recently published report by the Arctic Council (2013b), proposes recommendation for ecosystem-based management in the Arctic Council, and offers a list of including definitions[3] and essential principles of EBM.

Recognizing that economic, social, cultural, and ecological values ultimately all rely on the sustainability of the ecosystem, EBM poses ecosystem management as the main objective. However, social planners and managers may have many other objectives related to human well-being and development. Hence, it is important to go beyond a traditional definition of ecosystem, recognizing the essential role of ecosystems and the biosphere for human well-being.

The main objective of this deliverable is to develop a framework for integrated ecosystem based management (IEBM) in the Arctic, which could be one way among others to acquire such system approach and implement it in management. The aim of this IEBM is to support management taking into account the crucial role of the ecosystem to provide goods and services, but also all other relevant activities and variables that impact directly or indirectly on human well-being and development in the Arctic. We illustrate how to build such framework using information obtained from the responses to a questionaire that was given to participants of the second ACCESS general assembly in Barcelona 2013. This information was further complemented by results disseminated through the ACCESS project Newsletters, as well as the results from several group exercises with ACCESS researchers during ACCESS meetings. At the very end of the project we were also able to use information available from the ACCESS scientific deliverables and synthesis. We demonstrate possible use of the framework by developping six scenarios of climate induced change in the Arctic ecosystem and speculate how their impacts may cascade through the whole system.

Section 2 of this reports presents a broad framework for integrated ecosystem based management of the Arctic relying on a social-ecological systems view of the Arctic (2.1), with a discussion of possible management objectives and principles (2.2) and the identification of relevant tools and methods potentially useful for integrated ecosystem based management (2.3). Section 3 identifies essential characteristics of the Arctic viewed as a social-ecological system and in relation to climate change. Arctic earth system (3.1) and ecosystem (3.2) form the essential base of the system where economic activities (3.3) and governance (3.4) can then take place. Section 4 illustrates some analysis methods building on an integrated ecosystem based management approach. An overarching analysis based on a simplified overview of how interactions between human actions their ecological and social impacts, governance and the rest of the world can be used to identify so called pathological dynamics, which lead to unwanted trajectories and how these can be overcome (4.1). To complement such analysis it is necessary to look in more detail at certain properties of the social-ecological system and identify specifically how particular connections may play out. Examples of such connections discussed here include the complex relationship between sea

[3] This report collects several definitions from different sources (Arctic council 2013 p 12). For example ecosystem based management is "the comprehensive, integrated management of human activities based on best available scientific and traditional knowledge about the ecosystem and its dynamics, in order to identify and take action on influences that are critical to the health of ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity." (OSPAR)

ice, climate and the world economy (4.2). To illustrate the potential use of integrated ecosystem based management in the context of Arctic climate change we identify six essential elements of uncertainty about climate induced changes in the ecosystem, with regard to zooplankton, invasive species or ocean acidification, and discuss possible outcomes in the whole system based on different scenario assumptions. (5) Finally we discuss and conclude.

2 A framework for integrated ecosystem based management in the Arctic

We suggest that a framework for IEBM should contain a description of the social-ecological system (SES) to be managed (2.1), a set of objectives for management (2.2), and tools and methods to achieve these objectives (2.3).

2.1 The Arctic social-ecological system

The framework for integrated ecosystem based management we propose hinges on a social-ecological systems lens. We highlight system connections, including humans and ecosystems not only within ecosystems and geophysical parts of the system, but also to the economic and social sectors. Such a social-ecological systems view is critical for generating sustainable management strategies in a world of surprises, thresholds, non-linearities and tipping points (Chapin et.al 2010).

Figure 1 illustrates a very general model of the Arctic using a SES lens. Human actions have social impacts and ecological impacts. The ecological impacts can further result in social impacts, and social impacts can trigger change in human actions. Arctic governance sets the rules governing the human actions, but human actions can also impact governance, ideally through the democratic process (Peterson et al, in prep). Further, the rest of the world impacts what happens in the Arctic, and vice versa. Of course these impacts go through a fine web of links between more detailed parts of the system like commodity and service markets, geophysical dynamics, interacting species or regional governance.

Simply put, ecosystem services are the benefits that households, communities, and economies obtain from ecological processes (MA, 2005). This concept facilitates to convey the critical role of ecosystems as they are the base for most human activities and human well-being, providing multiple services, some of which are non-substitutable. Hence they are at the core of the arrow going from ecological impacts to social impacts. The ecosystem service concept was originally developed to increase the communication between ecologists and economists on the importance of the work of nature for human welfare and survival (Gómez-Baggethun et al, 2013) and has grown world-wide as a constructive lens for operationalizing the social-ecological systems approach and to integrate the work of nature into policy and every day decision making (see. e.g. TEEB: www.teebweb.org, NCP: www.naturalcapitalproject.org). The concept of ecosystem services can be very useful to help measure the ecological footprint of human actions, as well as to operationalize the assessment of resilience of a social-ecological system to particular changes. Ecosystem service is also a useful concept to link ecosystem outcome with human health and quality of life. Although the ecosystem service lens has not been readily employed in an Arctic context (see Magnusson et al. 2010 for an exception), it may be particularly beneficial in this context, since increased atmospheric concentrations of greenhouse gases are very likely to have a larger effect on climate in the Arctic than anywhere else on the globe (Kattsov et al. 2004), thus potentially changing the ecosystem service generation, not only for Arctic residents, but also for people much further away for example if aquaculture can expend substantially and thereby provide marine protein feed to the world market. (D3.21[4])

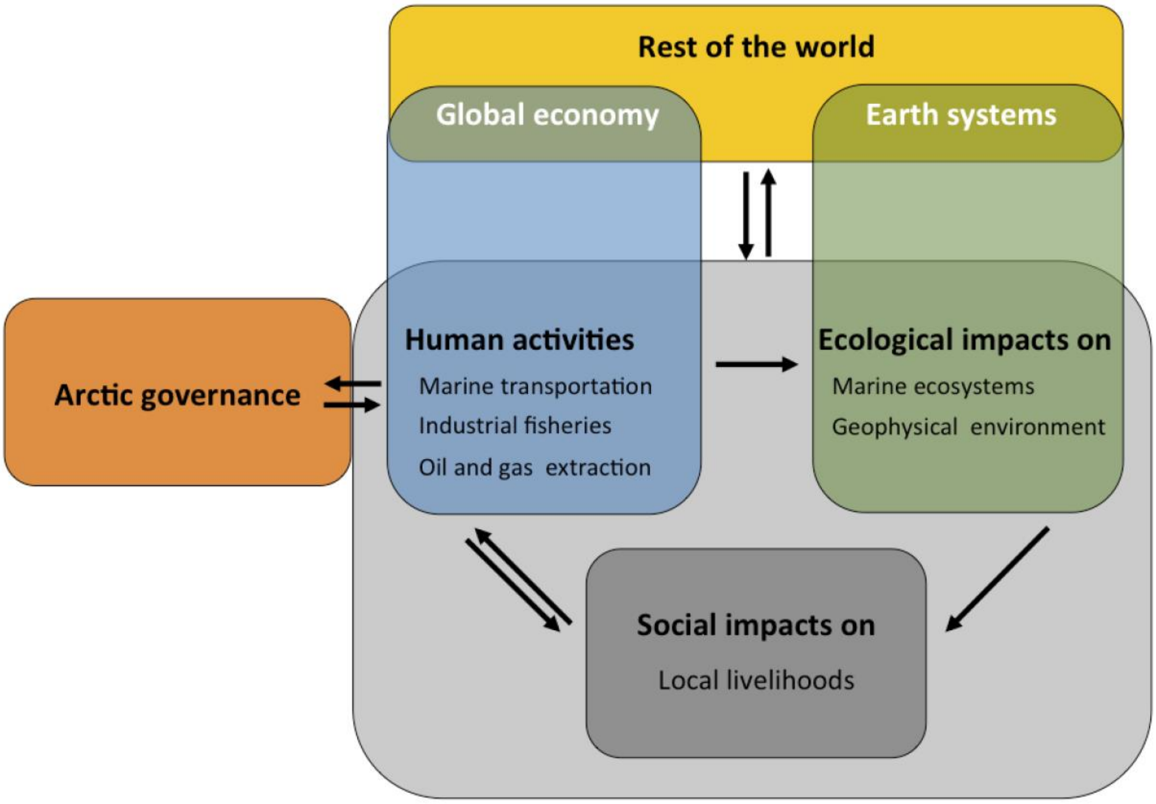

Figure 1: The Arctic social-ecological system. Modified from Peterson et al in prep.

The ecosystem service concept can thus help link potential impacts of climate change to change in human welfare. For this purpose, we start by identifying some key species associated to key ecosystem services underlying major economic activities in the Arctic, such as fisheries, within a social-ecological system context.

In order to develop a good system overview, identifying all relevant connections, it is necessary to depart from a high level of aggregation, including only the most essential aspects. However, a better understanding of particular mechanisms of interactions between different parts of the system may require a high level of details, based on substantial empirical data. Both characteristics trade off against each other because large detailed models become less transparent, take longer time to simulate on a computer and some properties may be technically difficult to accommodate (e.g. non-linear relationships). As a way to reconcile these two essential features of an IEBM we suggest to use a nested approach where a broad and abstract framework can contain several more or less detailed pieces that can be 'turned on or off' depending on the needs.

Table 1 illustrates variables that ACCESS identified as essential in a pan Arctic model depending on the level of aggregation of the model. The level of aggregation chosen and the

[4] Refers to ACCESS deliverable nummer D3.21. The complete reference is available in the reference list.

variables identified as the most relevant are conditional on the management questions that the particular IEBM approach aims to answer.

biophysical realm	geophysical environment	Sea ice thickness
		Sea ice extent
		Length of ice free season
		Frequency of bad weather events
	ecosystem	primary producers
		zooplancton
		fish stocks
		invasive species (crabs)
		marine mammals
social realm	local actors	Indigenous people
		local people
		Arctic workers
		Researchers community
	economic sectors	Fisheries and sea food production
		tourism
		transportation
		resource extraction
governance realm	Institutional actors	Arctic council
		Arctic states
		IP organisations
		EU
	Rules	UNCLOS
		Polar code
		International agreements
		National rules
Rest of the world		

Table 1: Proposed essential nodes for an IEBM model of the Arctic Ocean: each column represents a level of aggregation: high to the left, lower to the right. The rows represent the essential components for the relevant level of aggregation

ACCESS has produced several detailed models that could potentially feed into a broader IEBM framework, provided their underlying assumptions are compatible with the rest of the framework. Table 2 presents an overview of such ACCESS models.

ACCESS Deliverable	Name	Type	Explanation
D1.71 and D1.72	OsloCTM2 model and a Radiative Forcing (RF) model	Models	Studies quantifying impacts on climate and air pollution levels of local Arctic emission sources both for the current and future.
D2.16	ICEROUTE	Model	Traveling time calculation
D2.42	Fuel consumption per ship type and ice conditions	Model	Calculation of fuel consumption
D2.44, D4.52	Model of noise propagation	Model	Modelling of noise pollution in the Arctic from transport and oil industry
D2.52	QND	Model	Model of future Arctic observing system for safe marine transport under changing climate
D2.61	Cost and benefit of Arctic transport	Calculation	Socio-economic costs and benefits of Arctic transports
D2.62	HTM1	Model	Model of Arctic tourism
D3.11	SINMOD + fish component	Model	Evaluates the impacts of warming on Barents sea fisheries based on knowledge about sea ice, currents, primary production and fish dynamics
D3.51	Behavioural experiments	Experiments	Calculation of correlation between different aspects of user behaviour and the resource they exploit derived from lab experiments
D4.11	Impacts of warming on Arctic energy supply	Model	
D4.44	Report on oil flow under ice	Model simulations	Simulations of three kinds of oil related accidents and subsequent transport patterns of the released oil.
D5.81	Marine spatial planning tool	Tool	Tool that can help identify essential spatial interactions
D2.91, D3.71, D4.71	**Indicators for sustainable development**	Tool	

Table 2: Examples of models and tools of ACCESS that could be used in a broader context and linked together to support Integrated Ecosystem Based Management

2.2 Objectives for management and general principles

The reason why people and governance bodies undertake management action is typically that they are unhappy with the current situation and want to change it. For example there may be opportunities to improve the system so that some people's well-being increases. The system may have been malfunctioning to start with due to all kinds of market or governance failures. Classical examples of market failures include externalities, market power[5],

[5] Market power refers here to situations where one actor or a group of actor can influence market outcomes. Examples include monopoly, monopsony, oligopoly, etc.

asymmetric information, and non-convexities.[6] Beside market failures, all kinds of pathological dynamics can occur, where social-ecological features interact with management efforts in a way that consistently leads to management failures and further aggravation of the environmental problem. (Peterson et al in prep). For example, 'long fuse big bang' occurs when time delays and non-linear social-ecological dynamics can produce a dynamic in which slow gradual change leads to noticeable impact only after a long delay, like the impacts of climate change for example. Because impacts will occur in the relatively distant future and has little influence today, the issue does not seem urgent to decision-makers and the public, and there is limited societal support for taking action, especially if the costs of action are high (Peterson et al in prep, Levin et al 2012).

Another typical societal objective may be to maintain as much as possible the resilience of the current system. By resilience we here refer to "social-ecological resilience" as defined by Walker et al. (2004), which is the capacity of a system to deal with change and continue to develop. It is about the capacity to use shocks and disturbances like a financial crisis or climate change to spur renewal and innovative thinking. Resilience is particularly important in systems that can undergo rapid substantial change, like the Arctic Ocean is about to experience. The Arctic Council is currently working on an Arctic Resilience Report, a science-based assessment that aims to better understand the integrated impacts of change in the Arctic. Its goals are to identify the potential for shocks and large shifts in ecosystems services that affect human well-being in the Arctic, analyze how different drivers of change interact in ways that affect the ability of ecosystems and human populations to withstand shocks, adapt or transform and evaluate strategies for governments and communities to adapt.[7] Society may also want to reduce the ecological footprint and ecological debt of humanity, while enhancing resilience, health, and the quality of life of the human population (see e.g. Gómez-Baggethun 2013).

Society's goal could include increasing the welfare of a group or parts of a group, increasing resilience of the managed system to changes, making sure that the current level of welfare can be sustained in the long run, etc. Often multiple objectives are set up, but it can be quite challenging to address multiple objectives at the same time and typically these imply trade-offs. An essential role of an IEBM in that respect could be to help planners deal with change, either by helping them react to upcoming change in an appropriate way (to fulfil their objectives) or trigger some change if the current situation is unsatisfactory. One way to address the need to fulfil multiple objectives could be to define one of these objectives as main objective and define some standards for the other ones. Another way is to use multi criteria analysis. (Gamper and Turcanu 2007)

A tool to facilitate IEBM should provide support for management decisions given the manager's objective and available knowledge. However it is the manager's role to set political priorities and choose accordingly among possible alternatives. Hence an IEBM tool should be politically neutral and decisions made based on its support could differ for decisions makers with different political mandates.

In general, society is better prepared to deal with change that is relatively slow and of incremental nature. Substantial scientific literature supports this kind of decision making and an IEBM framework should build on this. (See e.g. Weitzman, 1974, Anthoff and Hahn 2010, Hepburn 2010, Requate 2005a,b, Ostrom 1990, Sterner and Coria 2012.) Several ACCESS deliverables also deal with more marginal change of that kind. (D3.21, D3.31, D4.11)

[6] See Hepburn 2010 for an overview of classical market failures.
[7] For more details see http://www.arctic-council.org/arr/, retrieved February 1, 2015.

However change can sometimes be abrupt and substantial if the system undergoes a critical transition to another regime. Change can also be due to substantial inherent variations if the system is complex and has some chaotic or highly stochastic patterns. These kinds of change are much more difficult to address for society. Hence ACCESS put focus on how to handle abrupt and substantial change in its framework for IEBM.[8] There is a growing literature on the implication of abrupt change for public management and policy (e.g. Arrow et al 2003, Margolis and Naevdal 2008, Polasky et al 2011, Crépin et al 2012). Crépin and Folke (forthcoming 2015) provides a review of implications for policy and growth of having potential abrupt changes at the planetary scale, that risk shifting the planet out of its current domain of stability called the Holocene. This is highly relevant as climate change is identified as one such potential change (Rockström et al, 2009; Steffen et al 2015) and the Arctic climate has a substantial influence on the geophysical dynamics in the rest of the world.

In particular Crépin and Folke (forthcoming 2015) assert that pervasive uncertainties combined with impacts of abrupt change at planetary scale clearly legitimate using safe standards or precautionary approaches. In particular (following Margolis and Nævdal 2008), information about the risk structure of potential large-scale regime shifts, could help refine policies and tell whether one should set a safe standard or just be precautious. Abrupt change at the planetary scale motivates to limit the biophysical dimension of the human expansion; economic growth should occur in other dimensions instead (Van den Berg and Kallis 2012).

The Arctic is expected to undergo transformations (ACCESS D5.91) likely to impact production costs in several sectors of economic activities (ACCESS D2.61, D2.63, D3.21, D4.11). Such changes could occur rapidly and be substantial (D2.61, D4.11). How would related market be affect? Could traditional policy instruments still be used successfully to regulate such markets? Following Weitzman (1974) a substantial stream of literature asked when it is better to regulate a market using price instruments like taxes, and when it is better to use quantity instruments like quotas or transferable permits systems. The outcome depends on all kinds of different market characteristics, and when abrupt and substantial changes are involved an important aspect is whether or not markets change faster than the physical conditions in the system. Crépin (submitted 2014)

IEBM should use the prevailing goals for management. Typically these goals are set through a democratic process. The IEBM should be able to relate to different possible goals and build on existing knowledge and general management principles that already exist. Special attention should be given to potential abrupt changes because they require particular management tools. An IEBM takes a more holistic view than many other management approaches and has this greater potential to identify abrupt changes and other critical interactions with bearing on management. Next section identifies methods for IEBM.

2.3 Tools and methods for integrated ecosystem based management

We suggest an IEBM that gathers and uses existing knowledge and articulates a portfolio of methods to increase our understanding of the system, using these insights to develop nested models that contribute to evaluate different management options. The IEBM should have a system perspective, with ecosystems as the base for well-being through the generation of ecosystem services, some of them non substitutable. Indeed an ecosystem service lens can help illuminate, trace and quantify the relevant and sometimes complex links between nature's production capacity and human welfare. IEBM should highlight the main set of interactions within an ecosystem, including humans, rather than considering isolated issues,

[8] This research builds further on results from the 7th Framework program Arctic Tipping Points (e.g. Wassman and Lenton 2012, Crépin et al 2012; Levin et al 2012).

species or services. Hence, a focus on social-ecological systems and their resilience, i.e. the extent to which they can maintain structure, function, and identity in the face of disturbance is appropriate.

For this proposed IEBM framework, we focus on economically important species, as this ensures a clear connection to human welfare, and provides a common unit of comparison between different scenarios and alternative management strategies of the complex social-ecological system of the marine Arctic. The change in value may be measured in monetary terms, but could also be measured using alternative units, depending on the context and purpose (D3.71). For other kinds of IEBM it may be more relevant to focus on other kinds of ecosystem services and natural resources.

The methods used to perform IEBM are essential for its success. However there are probably no universal methods rather each particular task of each particular IEBM exercise requires choosing an appropriate method for that particular task. Ideally, existing knowledge and appropriate methods should be used to understand the system, picture it in a simplified way to better analyse it, identify potential change and their impacts, test the validity of the results, and finally test and implement the results in management. These steps are presented in Table 3 with more detail. Importantly, this should be an iterative process of adaptive management type (Walters, 1986, Folke et al 2002).

Understand the system	1. Assess the most essential elements/nodes/variables of the Arctic system. 2. Gain conceptual understanding and map how these elements interact with each other.
Represent/model the system	3. Build and evaluate conceptual models of partial interactions. 4. Calibrate and validate those models using available empirical data 5. Simulate the models
Test validity of results	6. Perform sensitivity analysis and model perturbations, test model's explanatory power against reality. 7. Analyse results and identify need for further research and data gathering.
Identify potential change and their impacts	8. Identify essential assumptions for scenarios of change, i.e. drivers of change (e.g. climate change, management intervention, catastrophe, new policy instrument, etc). 9. Run the models using scenarios assumptions.
Implement and test results in management	10. Identify management goals. 11. Test and evaluate possible management interventions using simulated models. 12. Compare different management interventions with regard to goal fulfilment and other impacts. 13. Test and evaluate possible management interventions on small scale. 14. Implement management intervention on larger scale and evaluate it.

Table 3: Essential elements of an Integrated Ecosystem Based Management

In addition, each of the steps in Table 3 should include a meticulous method discussion to assess the most appropriate method for that particular task given the particular conditions of the studied system, the level of ambition, and known restrictions like the available budget. Tools and methods that can contribute towards an IEBM in the Arctic include marine spatial planning tools (D 5.82), resilience assessments (Walker and Salt 2006; Arctic Council 2013), indicators' sets (D2.91, D3.71, D4.D 5.91), integrated assessments (Brock et al 2013, 2015), behavioural experiments (Lindahl et al 2015), expert elicitation using questionnaires and focus groups, environmental risk assessments, oil spill planning, ship-routing, ice modelling, circulation modelling, and many others.

While all the steps in Table 3 are important, the ACCESS task was to build a framework for IEBM, and we focused therefore on understanding the system (in particular steps 1-2), representing the system (steps 3-5) and identifying potential change and their impacts (steps 8-9). We did not particularly address issues related to testing the validity of the results. Nevertheless some of the cases of more detailed system representation that we refer to in section 4.2 were performed under ACCESS and the scientific articles resulting from this work also discuss results validation in these particular cases (see references in section 4.2). We did not either address the steps related to testing and implementing the results directly in management as this would have required a different mandate and much more time and resources than were available. The following sections highlight and give examples of progress made within task 5.7 of ACCESS to address several essential elements in an IEBM for the Arctic as outlined in Table 3. It is important to note that the work here makes no claim on being in any way exhaustive. Rather they should be seen as first steps and partial contributions to a full scale IEBM. Each section contains an introductory part that refers to the particular methods that we used for the task. We start with the fundamentals - understanding the system.

3 Understanding the system

As highlighted in Table 3 a fundamental building block of an IEBM is a good understanding of the system. Understanding the Arctic system includes assessing the most essential variables of the Arctic system, the underlying characteristics of its constituents (step 1) but also how these are connected and interact with each other (step 2). For these two steps it is particularly important to try to identify also the less obvious but still important variables and connexions. These are essential elements of what is usually referred to as systems thinking, which focuses on the way a system's parts interrelate and evolve over time and within the context of larger systems. Having a system perspective is important when trying to identify unforeseen problems and helps avoiding unintended consequences.

This section outlines a set of important large scale nodes and interactions between current biophysical and socioeconomic processes in the Artic Ocean. The content underlying this section is based on information available from ACCESS deliverables and inputs to the ACCESS synthesis. However this information was only available at the very end of the project so we also relied on different methods of expert knowledge elicitation within the ACCESS consortium. These include answers to a questionaire, information obtained from focus group exercises performed at ACCESS meetings, and results that have been disseminated througout the ACCESS project Newsletters. These methods are explained in more detail in Appendix A.

3.1 The Arctic social-ecological system

In an IEBM the essential nodes should be a nested collection of variables relevant to the management issues to be addressed. Figure 2 illustrates how some of the important variables for the Arctic system that we identified in Table 1 could interact with each other. This is one possible characterization of the Arctic Ocean as a social-ecological system, and provides a holistic view of the Arctic.
For some issues it may be more relevant to look at lower scale and gain a higher level of details, section 4.2 gives some examples. Ideally an IEBM of the Arctic would need to be consistent at all scales and between scales. For example the underlying assumptions made in a model of the links between the geophysical environment, zooplankton, fish and the

fisheries industry (D3.11) should not be in contradiction with the assumptions underlying a model of Arctic energy supply (D4.11) and neither of them should contradict the assumptions in the overall framework that represents how they are linked together (Figure 2). However we did not check for such consistencies here.

Although it is a large region, the Arctic cannot be seen independently of what happens in the rest of the world. Most of the drivers of the recent change in the region are exogenous. Human population has experienced a tremendous change in the 20th century with substantial increases in numbers from below 2 billion at the beginning of the 20th to 7 billion 2012 with projections going to 9-11 billion by mid-century (W. Lutz et al. 2014, UN2012). In addition consumption patterns are also evolving (Kastner et al, 2012) in a way that may drive Arctic change. These factors are represented in yellow in Figure 2 and are likely to be an important source of change in the Arctic trough two channels 1) the global climate change resulting from increased fossil fuel consumption by this growing world population and 2) changes in global market prices of Arctic resources. ACCESS results find that these two drivers of change are likely to have substantial impacts on the Arctic in the coming years (e.g. D2.61, D3.31, and D4.11). We picture climate change to impact primarily the geophysical Arctic system and the ecosystem, while price changes should impact the different sectors of economic activities directly. Any attempt to manage the Arctic system must take this global context into account.

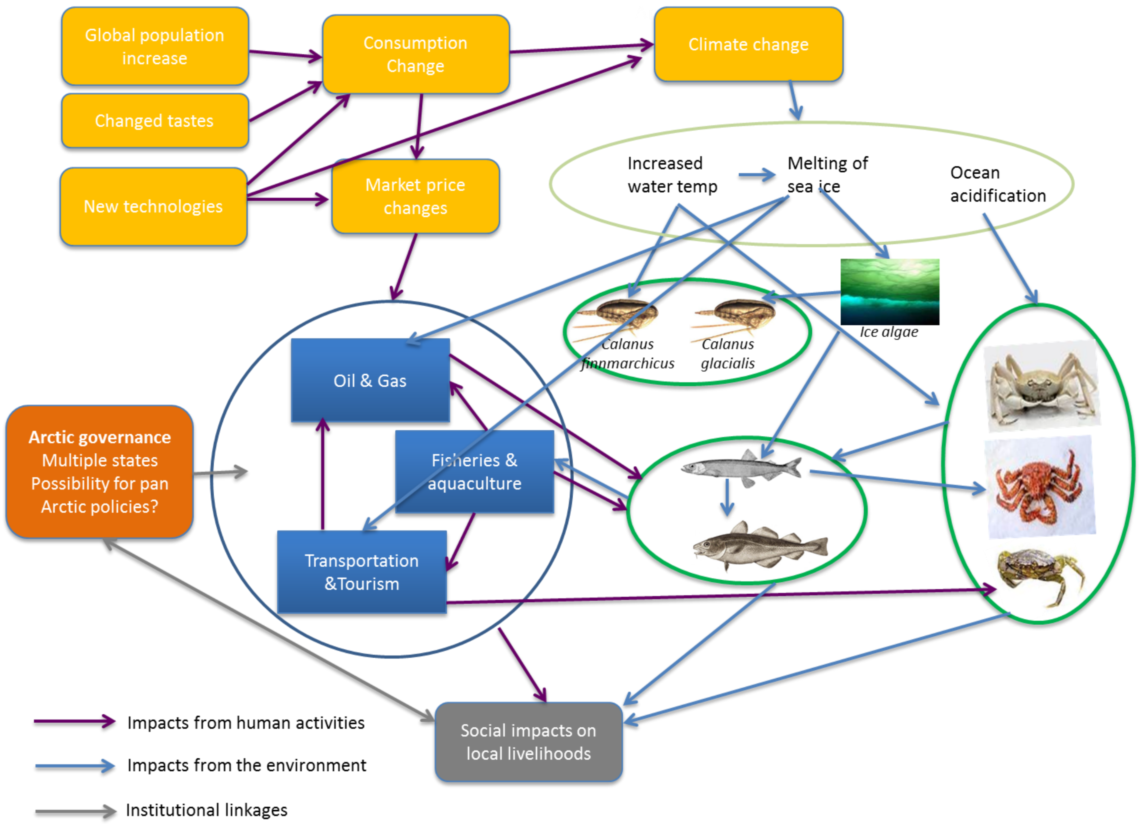

Figure 2: Essential social-ecological connections in the Arctic. Green circles represent natural systems, blue squares Arctic economic sectors, yellow squares, global drivers, orange square governance and grey square social aspects.

The remainder of this section explains in more detail the some broader sets of nodes and their interactions highlighted in Figure 2.

3.2 Geophysical impacts of climate change

ACCESS identified two main channels of impacts of climate change on the Arctic environment: through 1) changed sea ice conditions in the Arctic Sea and 2) changed weather conditions.

Over the last 30 years, the areal extent of summer sea ice has declined at a rate of 11.2% per decade, leading to dramatic sea ice extent minima in 2007 and 2012. Analysis of satellite data by the National Snow and Ice Data Center indicate that the 2012 sea-ice minimum covered only 3.41 million square kilometers, decreasing more than 750,000 square kilometers compared to the previous Arctic sea-ice minimum set in September 2007. An underlying reason for this faster summer ice retreat appears to be a progressive replacement of old and thick sea ice by much thinner and younger ice. Moreover, the 2012 sea-ice minimum was 11.83 million square kilometers less than the sea-ice maximum on 20 March 2012, reflecting the environmental state-change from a polar marine system dominated by old perennial sea ice to a new Arctic Ocean dominated by young first-year sea ice.[9]

The analysis of the influence of the Atlantic water penetrating into the Arctic Ocean via the Barents Sea and the Fram Strait shows that Atlantic water has a direct impact on the thinning of Arctic sea-ice. The impact on Arctic sea-ice of Atlantic water carrying on heat and salt in the so -called Atlantic sector of the Arctic Ocean is demonstrated by several publications (Parkinson et al 2012, Polyakov et al 2012, Vihma et al 2014). Evidence shows that Atlantic water has a direct impact on the thinning of Arctic sea-ice downstream of the Svalbard Archipelago, extending its effects as far as the Severnaya Zemlya Archipelago. Simple lower-end estimates indicate that the recent water warming episode could have contributed up to 150-200 km^3 of sea-ice melt per year, which would constitute about 20% of the total 900 km^3/year negative trend in sea-ice volume since 2004. (D1.34)

Further the number of freezing degree days (FDD) in the Arctic has diminished by more than 2000 between 1980 and 2012, which is equivalent to the sensible heat flux required to form more than a metre of sea-ice thickness. Direct observations of Arctic sea-ice revealed a decrease of about 1 metre of sea-ice thickness over the past 20 to 30 years. This is mainly due to successive winters being milder in recent years and therefore less and less capable of forming thicker ice. Conversely, the number of melting degree days (MDD) increased significantly in the same period, doubling between 2000 and 2012. While both FDD and MDD anomalies are impacting on sea-ice volume, FDD anomalies are impacting more on sea-ice thickness, while MDD anomalies are impacting more on sea-ice extent. However the causes of these anomalies are still unclear. Possible drivers include increasing solar radiation, an increase of long-wave downward radiation due to an increase in greenhouse gases and an increase in warm air convection transporting more equatorial heat towards the poles. (D1.42)

Following the three decades of decline in ice extent and ice thickness, the Arctic sea ice cover today is much more vulnerable to external forcings as compared to earlier times. This is particularly true for extreme weather events like the large Arctic storm that occurred during the first week in August 2012 and led to the new record ice minimum in September 2012.(ACCESS work package 1)

Climate change will undoubtedly have a large impact on the state of the Arctic and in particular the sea ice conditions. Moreover, as the Arctic continues to melt a positive feedback effect between these Arctic changes and global climate change may occur which

[9] ACCESS Newletter 4, and www.nsidc.org.

could have a rebound effect, in terms of impacts on the underlying processes driving climate change. Work done as part of the ACCESS project captured the positive feedback effect associated with decreasing albedo, as more polar ice starts to melt due to global warming or get covered by soot due to increased marine transportation (D2.41).

Links
changes in ice thickness lead to longer ice-free path for transportation
changes in ice extent and less freezing days open possibilities for oil and gas extraction
changes in temperature and salinity affect fisheries through complex ecosystem interactions

3.3 Impacts of climate change on Arctic marine species relevant for fisheries

There are different types of impacts of climate change on species, some are *direct*, such as physical effects caused by change in thermal regimes or salinity, while others are *indirect*, such as the effects of changes in ocean currents and water masses causing the displacement of fish larvae or the loss of large areas of sea ice, resulting in potentially devastating habitat loss for ice-adapted species, including polar bear, seals, walrus, narwhal and some microbial communities. The indirect impacts are often manifested via shifts in competitors, predators, prey, or parasites and diseases (Reist et al. 2006 a,b,c). Many of these shifts are due to change in food sources, which in turn are driven by change in physical parameters, such as sea ice extent or water temperature (Falk-Petersen et al. 2007). Since no species exists in isolation, but interact with other species and the physical environment, a systems view is required to assess the wider range of potential effects of climate change. Because change in food sources, as stated above, is often the cause of shifts, a systems view based on food interactions is useful in this context.

The species addressed here generate ecosystem services within the fisheries sector by being either economically important species (e.g. Atlantic cod and Arctic Char), or key species in the food chain (e.g. *Calanus* spp., Capelin and Herring) (Wassman et al. 2006)), thus underpinning the generation of economically important species, as well as other species. We also identify key invasive species with potential impacts on future generation of ecosystem services in the fisheries sector in the Arctic, under climate change. Figure 3 illustrate the main interactions between Arctic marine species and how they are affects by climate change.

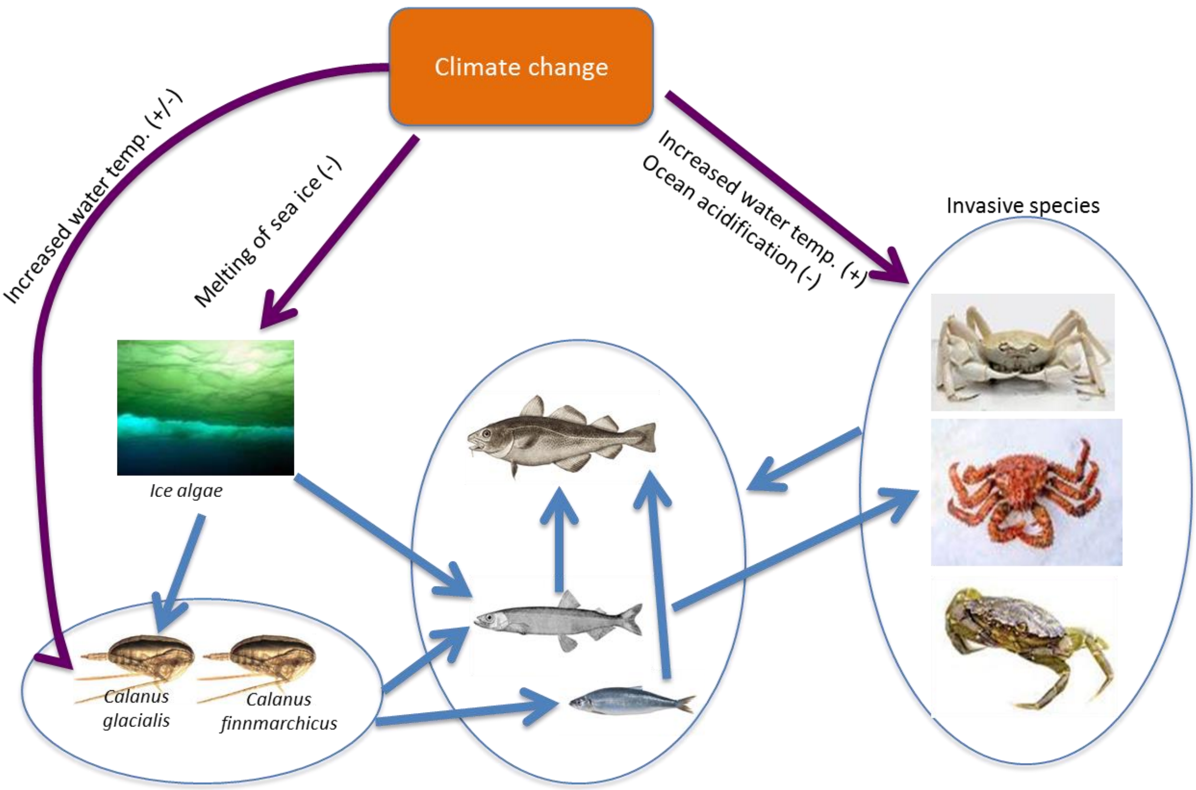

Figure 3: Arctic marine ecosystem and climate change impacts, blue arrows indicate feeding patterns and purple arrows climate change impacts

3.3.1 Native Arctic species

Ice algae, as primary producers, are the base for all other production within the Arctic ecosystem. Reduction in sea ice thickness and coverage area, will lead to earlier ice break-up and onset of the phytoplankton bloom, which is very likely to alter the current primary production regime in the Arctic Ocean (Søreide et al. 2010).

The Arctic grazer *Calanus glacialis* is a zooplankton species feeding on ice algae. It is an essential food source for many economically important fish species in the Arctic and indeed for the entire Arctic marine ecosystem. Among the zooplankton in the Arctic shelf seas *Calanus glacialis* accounts for up to 80% of the biomass (Blachowiak-Samolyk et al., 2008; Søreide et al., 2008). The current ecosystem state is driven by ice floating in from other areas which, as they melt, affect water temperature. When this process stops, due to climate change, there will be a change of state with direct negative impacts on some higher trophic levels, such as sea birds and large predators, since lipid-rich key Arctic grazers, such as the *C. glacialis*, are likely to be replaced by temperate and less lipid-rich organisms such as the *C. finmarchicus* (Falk-Petersen et al., 2007; Steen et al., 2007).

Arctic char populations, an economically important species, will be differentially affected by climate change, mainly through latitudinal and regional effects acting directly upon the fish (e.g., thermal regimes enhancing growth), or indirectly through ecosystem or habitat pathways (e.g., shifts in competitors, predators, prey, or parasites and diseases) (Reist et al.

2006 a,b,c). Effects on chars may range from positive, e.g., enhanced growth, to negative, e.g., shift in balance among or loss of life history types. An additional significant effect from climate change is alteration of habitat quantity (see Prowse et al. 2006) and quality (Wrona et al. 2006, Gantner et al 2010a,b).

Recruitment and growth of *Atlantic cod* are both positively related to temperature (Nakken and Raknes 1987; Sætersdal and Loeng 1987; Ottersen et al. 1994; Ottersen et al. 1998). The direct impacts on the Barents Sea cod fisheries from global warming through water temperatures and other oceanographic changes is likely to be insignificant compared with the normal environmental fluctuations experienced in this area, although increased fluctuations in stock biomass and stock age composition are found (Eide 2008, D3.11). However, the indirect effects (e.g. change in prey, competition, parasites) are less well investigated.

In summer, *Capelin* graze on dense swarms of plankton at the edge of the ice shelf. Larger capelins also eat a great deal of krill and other crustaceans. Whales, seals, cod, squid, mackerel, beluga whales and seabirds all prey on capelin, in particular during its spawning season while the capelin migrates southwards. Capelin distribution and migration is linked with ocean currents and water masses, and the species is thus potentially sensitive to change in these parameters due to climate change.

Capelin is an important forage fish, and is essential as the key food of the Atlantic cod, its main predator (Bogstad et al. 1997; Bogstad et al. 2000)). The northeast Atlantic cod and capelin fisheries therefore are managed using a multispecies approach, developed by the main resource owners Norway and Russia. In some years with large quantities of herring in the Barents Sea, capelin seems to be heavily affected. Probably both food competition and herring feeding on capelin larvae lead to collapses in the capelin stock. However, in some years there has been good recruitment of capelin despite a high herring biomass, suggesting that herring is only one factor influencing capelin dynamics.

Herring is a prominent converter of zooplankton into fish. Herrings consume copepods, arrow worms, pelagic amphipods, mysids and krill in the pelagic zone. They are thus potentially sensitive to change in zooplankton production e.g. different Calanus species. Conversely, they are a central prey item or forage fish for higher trophic levels. Herring recruitment is climate dependent and is favored by inflow of warm water to the Barents Sea (Stephens and Krebs 1986; Sætersdal and Loeng 1987; Hamre 1994; Toresen and Østvedt 2000; Sætre et al. 2002).

3.3.2 Invasive species in the Arctic

Biological invasion is now widely recognized as a factor in the endangerment and extinction of native species, second only to habitat alteration (Lassuy 1995; Wilcove et al 1998). Indeed, many consider invasive species, together with climate change, to be among the most important ecological challenges facing global ecosystems today.

Biological invasions are known from around the globe but are relatively less known or studied in the Arctic. In their analysis of coastal marine invasions, de Rivera et al. (2005) noted a pattern of decreasing diversity and abundance of non-native species with increasing latitude Studies of polar shipping operations have demonstrated that the external hull and ballast tanks of vessels operating in ice-covered waters can support a wide variety of non- native marine organisms (Lewis et al. 2003, Lewis et al. 2004). Ruiz and Hewitt (2009) conclude that “environmental changes may greatly increase invasion opportunity at high northern latitudes due to shipping, mineral exploration, shoreline development, and other human responses”.

One of the invasive species potentially benefitting from increased shipping and transportation is the *European green crab*. This species is a tough euryhaline, i.e. it can tolerate a wide range of salinities and it survives in temperatures of 0 to 30 °C (Cohen et al. 1995). De Rivera et al. (2007a,b) estimated that a suite of marine invasive species, including the European green crab had the potential to expand to sub-Arctic and Arctic waters even under moderate climate change scenarios.

The *Red king crab* was introduced to the Barents Sea by Russian scientists over 40 years ago and has now become a common species in the Barents Sea (WS Tromsö). According to WWF Norway the red king crab's population has increased six fold since 1995 and the current population is estimated to be above 12 million in the Barents Sea alone.

The first specimens of *Snow crabs* were recorded in 1996, in the eastern part of the Barents Sea. Since then it has spread and is now found in most parts of the eastern Barents Sea. According to Russian scientists the snow crab biomass is now approximately ten times higher than the red king crab biomass and, the snow crab is now a major part of the Barents Sea ecosystem, but our knowledge on this new inhabitant is scarce (although see Hjeltsen 2014). The snow crab poses a hug commercial potential, which Norway and Russia are just about to start exploring (Pettersen 2014).

3.4 Main economic activities

3.4.1 Transport & Tourism

Current shipping activity in the central Arctic Ocean is low, but the reduction of sea ice is expected to increase shipping activity. It would seem likely that at least initially (up to 2020) this will be mostly traffic travelling to and from Arctic harbours rather than trans-Arctic between continents.(ACCESS Newsletter 3) As the Arctic appears to be transitioning to seasonal ice cover, the latest Intergovernmental Panel on Climate Change (IPCC) report estimates that by 2050 navigable conditions in the Arctic will be 2-1/2 times longer than today, with 125 days available. The melting of Artic sea ice will also open up new shipping routes which have previously not been available. Increased duration of ice-free waters along the Eurasian coastline preconditions opportunities for more navigation from Europe to Asia. Recent years have witnessed increased use of the Northern Sea Route (NSR) for transit navigation, confirming profitability of cargo transportation to and from Europe and Asia. More cargo transportation, application of flexible rate policies and reduced sea-ice conditions in summer along the NEP contributed to the intensification of transit navigation on this particular route. According to a report by the Russian Government the transport volume along the NSR in 2011 was 5.8-times higher than in 2010. This development requires special attention with regard to the improvement of safety, as well as economic considerations, due to drifting icebergs and ice thickness concerns, among others. Here, monitoring and information dissemination are of key importance and the quality of short (seasonal) and relatively long forecasts of sea ice properties (extent, concentration and thickness) will affect transportation and its safety in the future. This is challenging since sea-ice distribution along the NSR is irregular. (D2.12)

Multi-year experience of navigation in the Arctic seas determines the main variants of the routes[10] at which favourable conditions for shipping can form. ACCESS work shows that under today's changing climate, optimal routes may differ from the standard recommended ones depending on ice and weather conditions. (D2.12)

Together with safety and insurance, travelling time of ships for certain ice conditions is the main factor influencing profitability of transit throught the NEP. Estimates using a travel time model indicate that travel time was longer in 2000 than 2007, especially in summer. However, for some route options, travel time in winter 2007 shows approximately the same time frame. Hence winter sea-ice extent and quality is probably comparable between 2000 and 2007. However the change in quality and extent of the summer sea-ice between 2000 and 2007 is such that in 2007, sea transports can cover substantially more travelled distance without the need for icebreaker assistance compared to 2000. Furthermore, it can be observed that in recent years (since 2007), the operation window for cargo transit shipping can be extended to the freeze-up period (October, November). (D2.16)

Smaller vessels have been navigating the Northwest Passage for decades, but reduced Arctic pack ice has increased accessibility. In September 2013 for the first time a bulk cargo ship passed through the Northwest Passage into Baffin Bay along Greenland's southwest coast. In doing so, it cut about four days and more than 1 000 nautical miles off the usual route through the Panama Canal. Additionaly, it carried 25% more coal since it did not need to factor in the shallow Panama Canal crossing. (D2.71)

A very important global and local environmental aspect related to the increase in marine transportation from melting sea-ice concerns the existence of a positive feedback loop between the two. The feedback comes about from the release of black carbon emissions in shipping. When black carbon is deposited on snow and ice, the soot-covered snow or ice absorbs more sunlight, leading to increase in surface warming. Further, melting will likely imply that more shipping lanes open up leading to an increase in activity thereby closing the feedback loop. It is likely black carbon will be increasingly emitted locally in the Arctic with increasing commercial activities. These emissions are thus of major concern for the speed with which the Artic ice caps melt. The same is also true for troposheric ozone which is formed via chemical reactions of emitted nitrogenoxides and hydrocarbons. Figure 4 illustrates this feedback. (D2.41)

An important outcome of ACCESS analyses is that while emissions from shipping will be the highest in summer, maximum impact is expected to occur in spring (Dalsøren et al. 2013). This is important since, as stated before, sea-ice break up in recent years is ocurring earlier due to a decrease in winter atmospheric cooling, thus making it essential to consider how shipping may accelerate future sea-ice and snow cover melt in the Arctic. This study points out an important contribution from black carbon to Arctic ice reduction in 2030.

Much of the transport activities in the Arctic generate these emissions where approximately 50% are currently connected to the fishing industry (Corbett et al 2010). Increased pollution from tourism has however also been observed. (Ødemark et al 2012;)

ACCESS also considered noise pollution related with increasing marine transportation. It seems that change in the water column temperature in the Arctic region will have impacts on the way sounds propagate. Hence monitoring and mitigation policies and practices should take account of these changes to properly address noise issues to ensure environmental quality in the region. (D2.44).

[10] The main shipping routes in the Arctic are The North East Passage (NEP) along the coasts of Norway, Russia and Alaska and the North West Passage (NWP) along the coast of Canada and Alaska. The Russian section of the NEP is called the Northern Sea Route (NSR).

Arctic shipping and the pollution associated with it will be determined by the interelation of political, economic and technological factors: For example, shipping regulations along the NSR (especially from Russia) will affect the growth of shipping activities and the number of ships crossing the Artic and hence affect pollution, and IMO regulations might affect the types of fuel which can be used in the Artic e.g. low sulphur content fuel in so-called ECAs (emission controlled areas). Policy will thus impact on the technological developments concerning the kind and amount of emissions being released from shipping. Special requirements such as air quality restrictions will perhaps also dampen the attractiveness of NSR for ship operators due to increased costs.

Climate change is also likely to lead to changes in socio-economic activity in the Arctic region, including tourism. Climate change is expected to influence a redistribution of tourists from areas that are becoming increasingly hot to cooler destinations (Hamilton, et al., 2005a,b). Climate change is likely to have various impacts on tourism in the Arctic. They may be contradictory as the Arctic becomes more accessible and less forbidden, while some of its unique characteristics may shift or disappear in a changing climate regime. Such threats may lead to a temporary surge in the number of tourists, who might want to experience the Arctic in its current profile.Ultimately the current patterns of tourism depend crucially on demand, but also on supply and services in terms of tourism sector engagement, accommodation, transport, and other infrastructure, which are influenced locally and as part of national or regional development strategies. (D2.62)

The impact of transport and tourism on fisheries is of great concern. Fisheries, depend on clear, fresh and cold waters. These requirements may be more threatened by continuously occuring and increasing emissions from the transport sector, rather than by potential blow-outs from extraction activities (except the worst case scenarios) Too much fish uptake from tourism could, at the utmost, be a threat to the fishing industry and fish stocks. At a few villages such strains have occured between fishing and tourism[11]. However, there is a good potential for fisheries and tourism to coexist without any substantial conflicts

[11] Reference: answer from questionnaire.

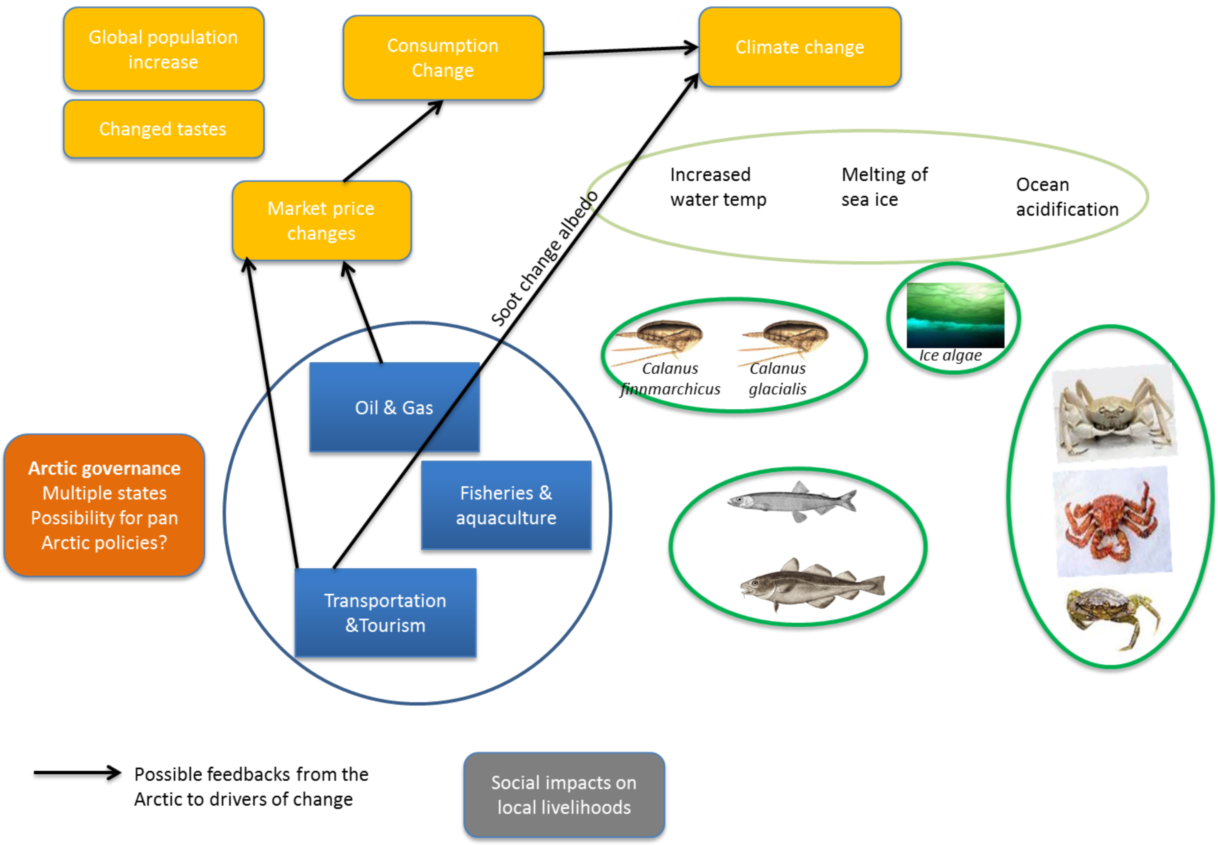

Figure 4: Feedback from changed Arctic activities to global climate change

Links
Transports are positively, affected by climate change
Transports and tourism reinforce climate change trends through black carbon emission and fossil fuels use
Tourism might affect fish stocks negatively if not properly managed

3.4.2 Fisheries and aquaculture

Fisheries is another socio-economic activity in the Artic that will be impacted on by changing sea-ice conditions due to climate change. This involves Arctic fisheries, aquaculture, and the livelihood of communities and economic actors depending of these industries. Climate change may impact on fisheries in a variety of ways in the future, but there still remains significant uncertainity as to how these multiple processes will unravel.

A warmer climate will affect the distribution of warm Atlantic water and seasonal ice cover in the European Arctic (D3.11). This will impact on the primary (phytoplankton) and secondary (zooplankton) production – the basic energy source for the fish populations (see Section 3.3 Impacts of climate change on Arctic marine species relevant for fisheries). Distributional effects seem to have already taken place. In the present climate, highest primary production is found in the Atlantic, where nutrients are easily mixed into the euphotic zone during the early summer. In the northern Barents Sea ice and in the Arctic Ocean the growth rate is reduced in spring due to reduce light penetration into the water column due to the ice cover.

When the ice melts, a strong thermocline is formed that inhibits the nutrients to be mixed into the euphotic zone. Simulations in the ACCESS project reveal that, towards the end of this century a strong increase in primary production is likely to occur in the western Kara Sea and in the Atlantic water that flows along the northern slope of the Barents Sea. Secondary production seems to increase in the Southern Barents Sea, but decrease in the Northern Barents Sea and on the East Greenland shelf as the Northern areas warm. The substantial decrease in zooplankton production in the northern areas is due to increased temperature that is unfavourable for Arctic zooplankton species, but not high enough to enable production by Atlantic species in the Arctic Ocean. The migration of zooplankton will have impacts on fisheries (D3.11).

Impacts on fisheries includes also aquaculture in the Arctic which represents about 2% of worldwide volume. Although small relative to worldwide production, it is still an important economic activity at about the same scale as total production within the European Union. Farming operations are distributed unevenly within the Arctic region, with salmon farming in Norway making up the bulk of the production. There is minor aquaculture production within the Arctic areas in Iceland and Russia, while the small levels of production in Sweden and Finland are mainly outside the Arctic region.

Several abiotic environmental conditions are of fundamental importance for successful aquaculture. Both growth and health of organisms are highly dependent on variables such as temperature, salinity, oxygen concentration and water quality. Physical processes such as waves, currents and ice formation also influence the farming conditions. A number of international studies indicate that these variables and processes to various degrees will be influenced by climate change. Detailed knowledge is limited, which limits our capacity of making predictions about climate change impacts on aquaculture at local and even regional scales. This is due both to the uncertainty in physical climate change and the lack of understanding of the complex causative links between physical processes and aquaculture.

Currently coastal aquaculture expansion in Norway, is limited by access to suitable farming areas. There is considerable uncertainty in the estimates of expected temperature changes, ranging from a rise of 0.5 to 1.7 ° C in about 50 years for the Norwegian Sea., but increased sea temperature could allow for farming in regions that today are not considered economically viable, as well as in areas in Russia, Canada and Alaska. Therefore, considering the temperature factor alone, larger parts of the Arctic would be positively affected for aquaculture.

Disease impacts are harder to predict, but based on experience from other areas, no severe changes should be expected. Climate change models generally predict more frequent and intense storms, including the Arctic region, which would pose a challenge to sea-based fish farming. Moreover, there are still many unknown factors and challenges that relate to conservation issues (e.g. biodiversity conservation, linkages to fisheries), social considerations (other stakeholders and activities), and also shifts at the global level that have implications for fish farming in the Arctic (e.g. feed availability, consumer preferences).

Links
Uncertain, but fisheries likely positively affected by climate change
Aquaculture positively affected by climate change

3.4.3 Resource extraction

Resource extraction of hydrocarbons from the Arctic Ocean is associated with risks and opportunities. Oil spills in the Arctic Ocean are of serious concern, especially as the potential for large-scale energy exploitation increases in response to sea-ice decreases. An important discussion revolves around whether or not oil and gas extraction should be allowed in certain fishing areas, especially in Lofoten/Vesterålen area which is a spawning ground of one of the largest and most important fish stocks. Oil spills risks harming vulnerable ecosystems, which are the base for other socio-economic sectors such as fisheries and tourism.

It is generally accepted that open-ocean oil spill models are well established and perform well in open-ocean conditions. However modelling of oil flow in the presence of sea ice is more uncertain. Within the ACCESS project an under ice oil trajectory model has been developed based on a high-resolution 3-D dataset of the ice bottom, thus overcoming the inadequacies of previous under-ice oil spill models. This model was grounded on empirical assessment of the differences in oil movement on different types of ice (D5.91, D4.44).

Apart from oil spills, environmental concerns resulting from resource extraction also involve air and noise pollution. Concerning air pollution, large enhancements of the concentrations of hydrocarbons, sulfur dioxide, volatile aerosols and other components occur in the vicinity of the oil and gas extraction facilities. The expected future increase of transpolar shipping and hydrocarbon resource extraction will have a significant impact on the atmospheric composition in the northern polar region. At present, the distribution of chemical species and aerosols is mainly affected by a few Arctic pollution sources and the import of biomass burning emissions from northern mid-latitudes. (D4.53)

Resource extraction facilities in the Arctic will also cause an increase in acoustic noise within the water column itself, which can cause problems to marine mammals. (D4.51, D4.52)

Links
Resource extraction positively affected by climate change
Reinforce increase in marine transport
Risk for tourism

3.5 Governance

The changing conditions in the Arctic also pose challenges for governance. Today different hierarchical levels of regulation, ranging from regional to national and international, operate in the Arctic, resulting in multilateral and national agreements, with hard and soft laws, guidelines and recommendations. The ACCESS project has identified gaps in governance. One key issue of great importance for the future governance of the Arctic is the creation of a unified observation system for the Arctic. Today, funding mechanisms and governance are mainly regional leaving coordination fragmented (D5.11). Other gaps include a lack of regional fisheries management systems, gaps in the developing IMO polar code with respect to climate change effects, and a fragmented aproach to regulations for the resource extraction industry. In particular, the vast majority of texts and instruments examined fail to address the effects on legislation, agreements and guidelines that extend across diverse jurisdictions, with interplay among institutions that have yet to be defined. (D5.11)

The oil and gas extraction sector overlaps significantly with the shipping and marine transport sectors, and much of the current legislation, as well as soft law and guidelines are intimately integrated with the transportation regulations. The long list of local threats, which are likely to develop acutely in relation to the increase in shipping, includes the risk of accidents and spills, accumulation of black soot, transport of alien species, choke-points issues, and search and rescue challenges. Much of the regulations of Arctic Shipping has so far been developed by the Arctic Council (AMSA-Report) and the International Maritime Organization (IMO), such as the mandatory Polar Code (2014).

Regulation regarding fisheries is scattered and combined of different national legislations, complemented with several bilateral agreements. For fisheries, there is a lack of a strong commercial industrial focus in the Arctic Ocean, but some areas – such as the Barents Sea – enjoy a significant level of fishing activities. And aquaculture is a prominent and growing industry in the region. Transboundary stock distributions, and/or developing management practices present ongoing challenges. (D5.11)

A review of Arctic literature indicates few documents addressing the important issue of marine infrastructure that is required to support even today's levels of Arctic marine use. One of the key studies from the Arctic Council, the Arctic Marine Shipping Assessment (AMSA[12]), presents a fundamental review of the infrastructure deficit today in the Arctic. AMSA results have been used as a baseline for initiating a comprehensive ACCESS survey on current and future marine infrastructure requirements. The development and design of icebreaking ships and offshore structures in Arctic Regions is also important for avoiding the danger of oil spills (D2.15, D2.52, D4.21, D4.22). There is a need and a demand from different economic sectors and other stakeholders for the development of 'Escape, Evacuation and Rescue' facilities. Within the ACCESS project this recognition led to the concept of a "common use" infrastructure for multiple industries. Such a configuration could maximise the use of the remote and very expensive infrastructure and minimise the impact on the fragile Arctic environment. (D5.91)

Local and indigenous people's livelihoods in the Arctic are affected, not only by climate change (e.g. reindear hearding areas,D5.61), but also through governance changes associated with the economic sectors mentioned above (e.g. through fishery quotas and potential bans on seal hunting). While ethnic-tourism may bring financial benefits, an increase in tourism also causes damages on the environment.

Field work done within ACCESS to assess local perception of large-scale changes in the Arctic reveals that high variability of opinions, even within the same economic sector. One example is the increase in alien species populations in the Barents Sea, like the King Crab, which may be considered as a burden by one group within the fisheris sector, and as an asset by another one. This species may bring new opportunities for tourist activities (King Crab safari), as well as fishing and farming. However, it may be considered as an invasive species with negative impacts on native fish, and on the coastal ecosystem. Interestingly, in the local perception there is no direct cause-and-effect linkage between climate and the changes in the Barents Sea (D3.41, D3.42)

4 Representing and modelling the system

Once essential nodes and interactions of the social-ecological system have been identified, the next step of an IEBM will require a more careful understanding of the system's strength, weaknesses and dynamics. This step thus requires a more careful representation and modelling of the system. Ideally one would like to be able to exactly characterise the relationship between the nodes for example in a system of mathematical equations that

[12] http://www.pame.is/index.php/projects/arctic-marine-shipping/amsa

would explain how different variables influence each other as a function of time and space (Brock et al 2013, 2015 provide some example). However, often it is only possible to indicate the direction of the relationships, and maybe a relative order of magnitude. When the system is large, having many nodes, conceptual models may be imperative in order to gain deeper understanding. Conceptual models may also be useful in understanding how the system parts are nested within the larger system. An IEBM of the whole Arctic should thus identify how the Arctic as a whole interacts with the rest of the world, which is illustrated in Figure 2. If the ambition is to build an exact mathematical model of these interactions, it will be necessary to somehow quantify the different interactions. Sometimes such estimates can be available from the literature, however in most cases these need to be assessed. Ways to do so include among other methods translating existing estimates from another system to fit the actual object of study, performing statistical analysis of correlation and causality, and performing controlled experiments to see how changing particular properties affect the final outcome.

Modelling is a delicate task and managers should be aware that each particular restriction or assumption they make in their modelling activities can also have substantial impact on the outcome. For example Crépin and Graβ (in prep) show that three different models of the exact same social ecological system, an optimized fishery where fish interact with bottom vegetation and floating vegetation, could provide quite different management recommendation depending on the level of detail of the particular model (1, 2 or 3 different state variables).
Before building complex models it is useful to have an overarching representation of the system. One simple way of doing this is by highlighting how the major elements of the system interact. An attempt to do so for the Arctic system can be seen in Table 4, which indicates some relevant interactions based on ACCESS expert elicitation (Appendix A), exercises during the ACCESS courses, ACCESS deliverables, ACCESS synthesis exercises, and some available publications.

This section provides examples of two distinct ways to represent and model Arctic connections within the context of an IEBM. First, section 4.1 takes a holistic perspective and presents a diagnosis of potential governance/management issues based on the pathological dynamics framework (Peterson et al in prep). An attempt to understand the system by means of an already existing framework in this way reveals new characteristics of the system and thus constitutes an alternative representation. Second, section 4.2 present more detailed studies of some particular connections performed under ACCESS, which relate to modelling parts of the system (steps 3-5 in Table 3) and also testing of the validity of results (steps 6-7 in Table 3).

	Geophysical environment	Marine ecosystem	Fisheries	HC extraction	Shipping and tourism	Local people	Governance	Rest of the world
Geophysical environment		Change (+/-?) in water salinity affect primary production and fishes | Increased ocean acidification impact on crustaceans | Reduced sea-ice extent and duration, affects phyto and zooplankton cycles	Lower ice extent increase potential zones of fisheries	Lower ice extent increase possibilities for energy extraction | Increased icing as closed ice cover / ice recedes (?)	Lower ice thickness increase transportation & tourism / longer seasons of navigation | Artic persived pristiness attracts tourism	Change in cultural meaning for indigenous peoples	Climate change impacts increase pressure on more unified governance for the Arctic	Ice melting leads to sea level rise | Impacts for climate change in the Arctic incentivize regulation in rest of the world
Marine ecosystem			Fish stocks depend on marine primary productions		Artic persived pristiness attracts tourism		Transboundary nature of marine ecosystems requires international governance (given condition?)	
Fisheries						Fisheries are an important source of income for local people	Negative changes in fisheries put pressure on governance	Important for global food security
HC extraction		HC extraction increases pressure (risks?) on marine ecosystem | Oil and wind platforms provide hard structure facilitating (?) invasive species movement, negatively affecting the ecosystem	Competition or cooperation for transport routes and infrastructures?		Competition or cooperation for transport routes and infrastructures? | Increase marine transportation due to HC extraction, damages tourism due to increased risks	Important source of income for local people (?) | Negative effects (risks?) on local livelihoods and economies	Probably oil/gas still source of conflicts outside EEZs?	(Still too expensive to have an impact on global price) | New source of HC, enables continued CO2 emissions**
Shipping and tourism	Increased transportation leads to more black carbon depositation	Invasive species increase with more maritime transportation | Transportation increases pressure (risks?) on marine ecosystem | Tourism increase pressure on fish stocks	Competition or cooperation for transport routes and infrastructures?	Competition or cooperation for transport routes and infrastructures? | Synergies in infrastructure development (also: SAR)**	Increase marine transportation due to trade routes, damages tourism due to increased risks	Source of income and activities? | Negative impacts on local/indigenous communities (?) | SAR / Telecom (?)	Increased traffic demands regulations and management (?)	Increased transportation increases CO2 emissions** (Or shorter routes reduce CO2 emissions?)
Local people		Local people also use the marine ecosystems (?)					How can minorities influence Arctic governance? | Inclusion of 'traditional knowledge' in policy making (?)	
Governance	Monitoring for appropriate implementations and Indicators	Ecosystem management and tools tailored for the Arctic | Monitoring for appropriate implementations and Indicators	Regional management system | Monitoring for appropriate implementations and Indicators	Polar code | Standarising national regulations on hydrocarbons | Port of refuge to minimize environmental damage from potential off-shore spill | Monitoring for appropriate implementations and Indicators	Polar code | Monitoring for appropriate implementations and Indicators	Indigenous people affected by different levels of governance (?) | How to compensate subsistance harvesters without conventional monetary methods? | How to document cultural resources to protect them from damage or loot, without taking away its secrecy?		Potential considerations of fisheries regulations elsewhere in the world?
Rest of the world	Global climate change is driver of changes in Arctic geophysical environment	Global sources of pollution affect Arctic marine ecosystems?	Global demand for fish drives fisheries companies into the Arctic	Global demand for HC drives extractive companies into the Arctic	Global interest in new shipping routes and Aarctic tourism	Global diffusion of values and ideas incluences local people	International conflicts over different topics can affect negotiations on the Arctic	

** **Potential reinforcing feedback**
positive effect
negative effect
mixed or unclear effects
needs clarification
posed as question
governance need
governance already developed

Table 4: Interactions: how elements in columns affect elements in row.

4.1 Representing the system - analysis of Arctic interaction using the pathological dynamics framework

Peterson et al (in prep) identified six archetypical ‘pathological dynamics’ at the global scale that could trigger hard to solve global environmental problems. Here we use the framework they developed as a diagnostic tool with suggested remedies for possible unexpected problems that could emerge in the Arctic. The definitions of the six pathological dynamics presented here come from Peterson et al (in prep), while the analysis of the Arctic case using these definitions is original ACCESS work. We revisit these dynamics in the light of two potential problems with pan Arctic implications: reinforcing feedback mechanisms in the Arctic that worsen the effects of anthropogenic climate change and an increased risk of substantial loss of marine biodiversity.

4.1.1 Long fuse big bang

Non-linear social-ecological dynamics can imply that gradual change unexpectedly lead to abrupt substantial impacts after a long time delay. Once these impacts have manifested, time delays and nonlinearities make it extremely difficult to address the issue. To avoid negative outcomes management actions must be taken long before problems become evident. Ignorance of future consequences is not the prime problem of this dynamic – rather the issue does not seem urgent to decision-makers and the public, and there is limited societal support for taking action, especially if the costs of that action are high.

Arctic climate change leading to melting of summer sea ice seems a textbook example for such long fuse big bang dynamics. Moreover, in the Arctic a further complicating issue is that the long-term impacts are of mixed character. There are substantial advantages of melting summer ice for most economic activities, like resource exploitation and transportation (D5.91), while the impacts on fisheries are less clear (D3.11, D3.31), and some other consequences such as the albedo effect, and the release of methane due to melting permafrost in the sea bottom could turn out to have really undesirable impacts on global human wellbeing (Rachold et al 2007, D5.91). The causes of climate change are almost entirely external to the Arctic region. In addition since greenhouse gases accumulate gradually and their effects come with lags, even if the causes of climate change would cease immediately, the Arctic will still be committed to substantial changes due to the lagged impacts of climate change (Arctic Council 2013).
Changes in marine ecological communities (food web and ecosystem composition) in response to geophysical changes associated with climate change (e.g. sea-ice and water temperature), are uncertain but with potentially big implications. These implications could come first as a consequence of a result from gradual climate change but also because the populations of invasive species might have been rising “in the shadow”, and only now when their numbers are large they have been detected. Multiple important processes and factors are undergoing change in the Arctic due to climate change and their interconnections must also be considered. These processes include impact of phyto and zooplankton population on primary productivity; water salinity on primary production; acidification on calcifying; and extension of fishing grounds. Figure 5 illustrates this case.

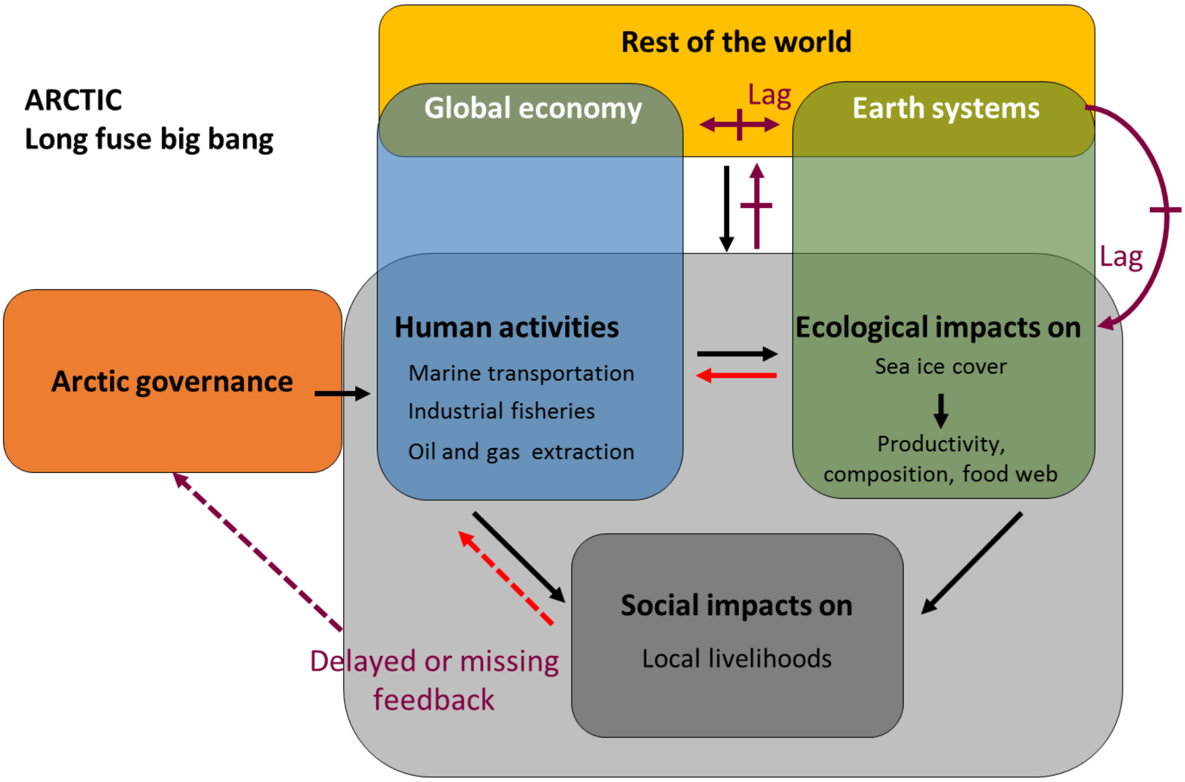

Figure 5: Arctic long fuse big bang

4.1.2 Rapid social-ecological evolution

This pathological dynamic emerges when dynamic feedbacks within social-ecological systems occur more rapidly than governance or management can respond. Novelty, rapid change, and self-organization are key features, often amplified through trade and population movements which increase the social and ecological connectivity of the world. The central challenge in this dynamic is to manage the speed of social-ecological innovation, and improve the rate and ability of social-ecological systems to adapt to rapid change.

The recent years of rapid melting of summer sea ice, opening new shipping routes much earlier than previously planned, illustrate the pace at which transport entrepreneurs are ready to seize these new opportunities. Huge populations of different alien crabs have been found in Arctic waters, and increased global shipping through Arctic routes is/will augment the speed of this process even more. However despite its state of fragmentation across different regions and countries, Arctic governance was able to mobilize in a relatively quick enough fashion, putting in place a Polar code and a search and rescue agreement partly in response to the coming changes (D5.11, D5.91). This indicates that this pathological dynamic may not necessarily be a big problem regarding the specific issue of Arctic marine transportation under climate change. Further development in that direction and implementation of the regulations by national states could maybe help address this pathology in a successful way. Figure 6 illustrates this pathological dynamic in an Arctic context.

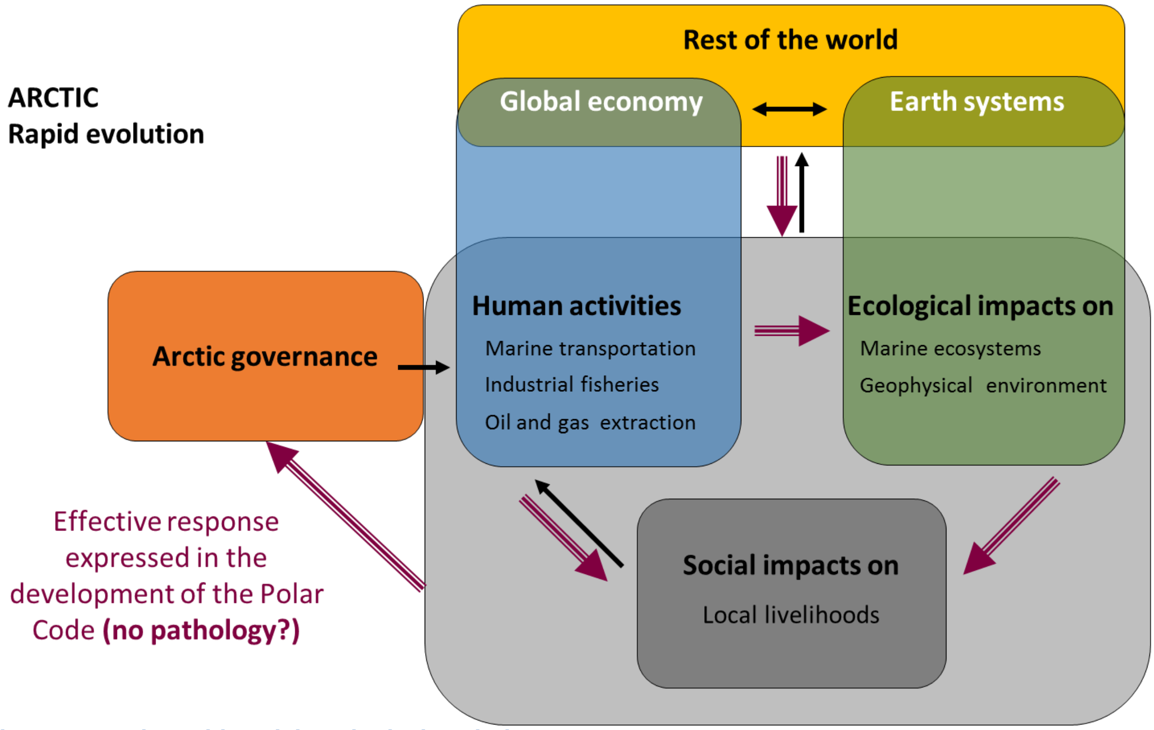

Figure 6: Arctic rapid social-ecological evolution

4.1.3 Unforeseen processes

This pathology focuses on the difficultly of governing or managing complex social-ecological dynamics in which some important processes may be unknown, and novel processes may emerge. This pathological dynamic occurs when institutions are unable to anticipate or recognize novel ecological or social processes.

The Arctic has received relatively little research attention, compared to other areas of the world, particularly from an integrated systems perspective. The rough climatic conditions make it very challenging for research. The Arctic data collected is typically available in rather short time series and collected in few and easier to access places. In addition, the current scientific knowledge about the Arctic is fragmented with low interactions between different disciplines and countries. For example, substantial amount of research results conducted in Russia are not available to the rest of the global scientific community due to language issues. There is also a mismatch of scale between geophysical research, often conducted at the pan Arctic scale, and social research performed at local community scale. In the face of rapid climate change, the lack of systemic understanding implies that there is a big potential for surprises in the Arctic. These surprises could occur as a direct consequence of climate change for example like the discovery of huge methane reserves under permafrost in the Arctic seabed (Rachold et al 2007). Other surprises could occur as consequences of changed activities. For examples the increase of invasive species following increased transportation in the Arctic could lead to substantial surprises if these species interact in unexpected ways in their new environment, creating substantial change.

This pathological dynamic is difficult to address because we don't know in advance what is going to be surprising. However, more research and systematic data gathering increase the chance to discover potential surprises. In addition it is essential to learn more about how all the parts of a particular system interact. This requires more holistic system approaches like those suggested in this framework for IEBM. In particular it is essential that experts in changes related to natural systems and experts in changes related to people and societies start working much more together in an integrated way. This includes joint research projects where they discuss problems jointly from start not only delivering data to each other. Figure 7 illustrates problematic links related to unforeseen processes in an Arctic context.

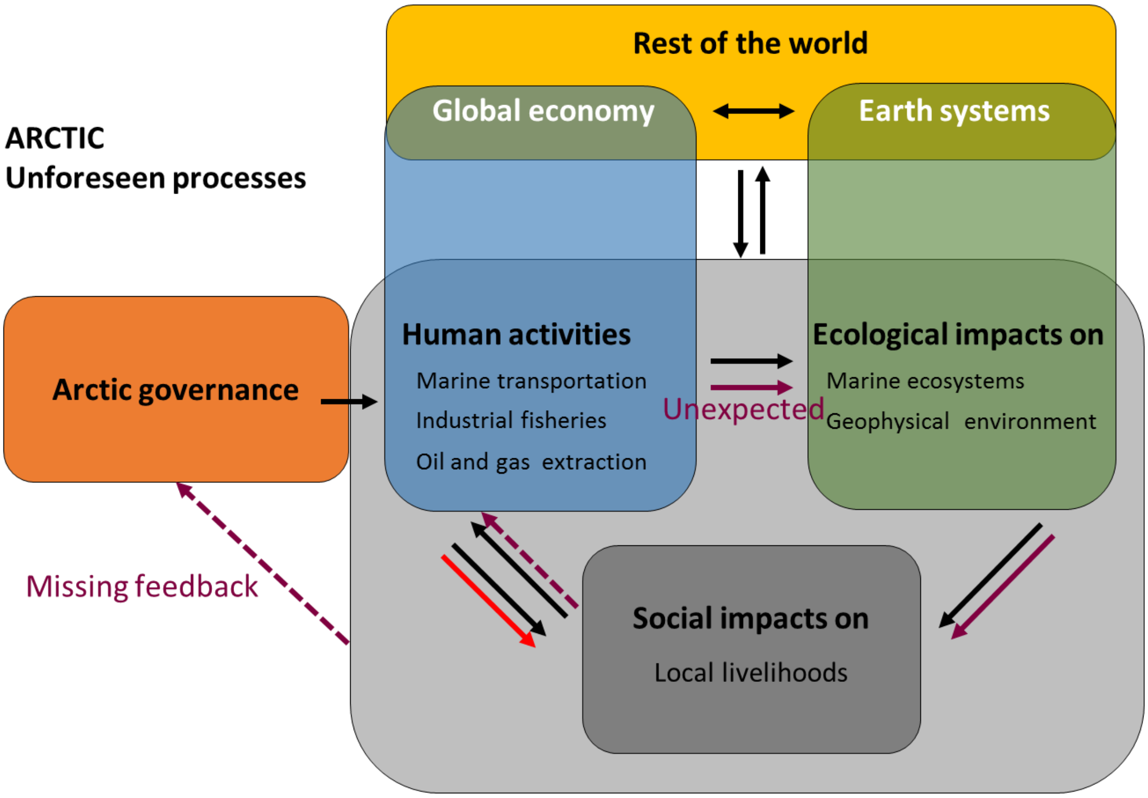

Figure 7: Arctic unforeseen process

4.1.4 Unrecognized spatial connections

Unrecognized spatial connections are a particular type of unforeseen processes that link parts of ecosystems and societies in unexpected ways, sometimes even located far from each other. These are connections between the social and ecological components of the system that governing institutions do not recognize and address. The key challenge of this dynamic is improving society's capacity to effectively address long distance spatial connections and anticipating new connections arising from human activities. Examples of such connections in the Arctic could be the opening of new sea routes due to climate change, which leads to far distance transportations of organisms (e.g. green crabs), or air and water pollution spreading to new environments. Within the Arctic region, harsh climate and difficult living conditions have kept such connections to a minimum level. Current development with increased transportation but also changing patterns of water transportation (from ice drifting to pure sea water currents in some periods), increased potential for communication through satellite and Internet are likely to increase the emergence of such surprises. See Figure 8 for an illustration.

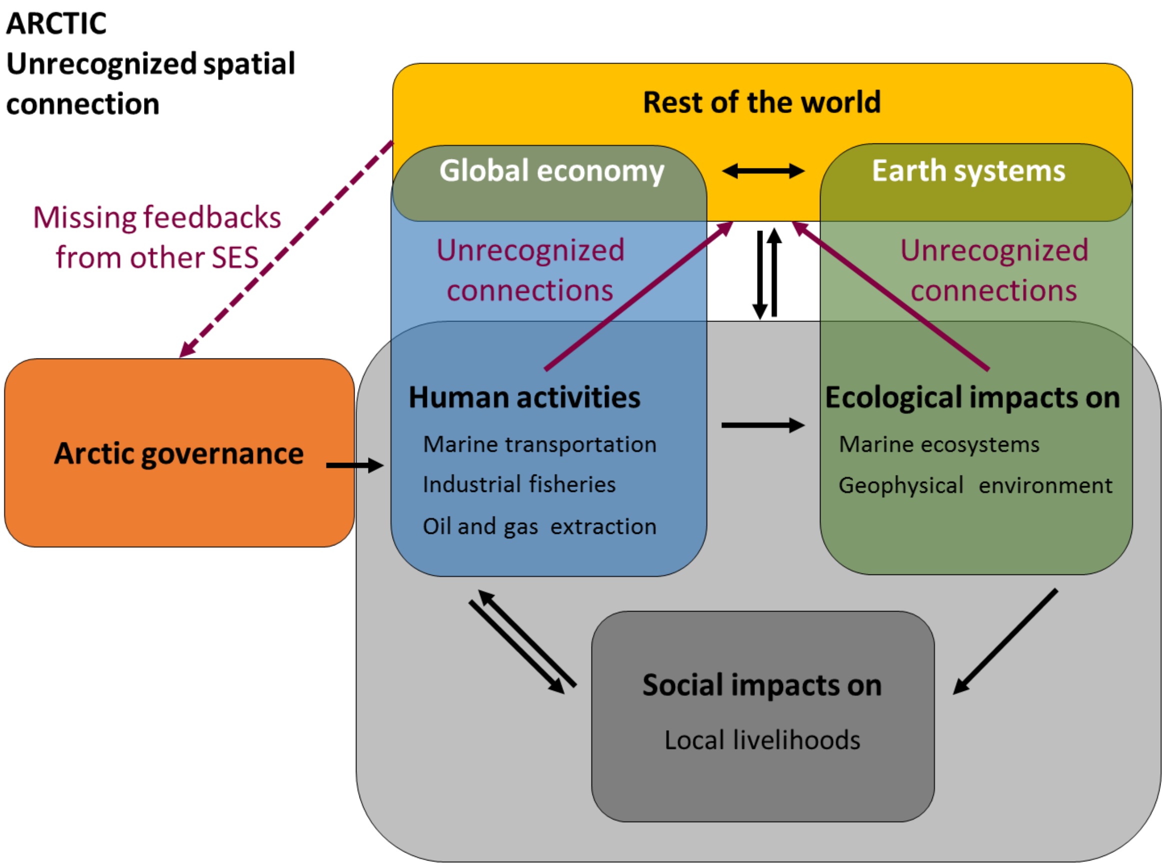

Figure 8: Arctic unrecognized spatial connections

4.1.5 Commons dilemma

This occurs when individual decisions based on personal preferences lead to degradation of a shared resource, so that the net outcome for the community overall is not as beneficial as it could be. This pathological dynamic is especially apparent in problems such as climate change, overfishing deep-water stocks, and eutrophication (Sandler 2004). The central challenge regarding this dynamic is to adjust individual costs and benefits, so that the choices that individuals make better align with the outcomes that are best for the community overall.

The Arctic Ocean is shared by several countries and could thus be particularly vulnerable to the pathological dynamics of commons dilemmas. However current regulations in place imply that most of the Arctic Ocean and seabed are the responsibilities of individual countries (EEZ zone, etc.). Although there are some loopholes still (D5.91; D5.11) and problematic areas under sea ice and it is unclear whether the resources potentially available there are valuable enough to trigger a commons dilemma. The most problematic commons dilemmas in the Arctic are rather likely to occur locally as a consequence of insufficient national governance in some countries. Figure 9 illustrates this.

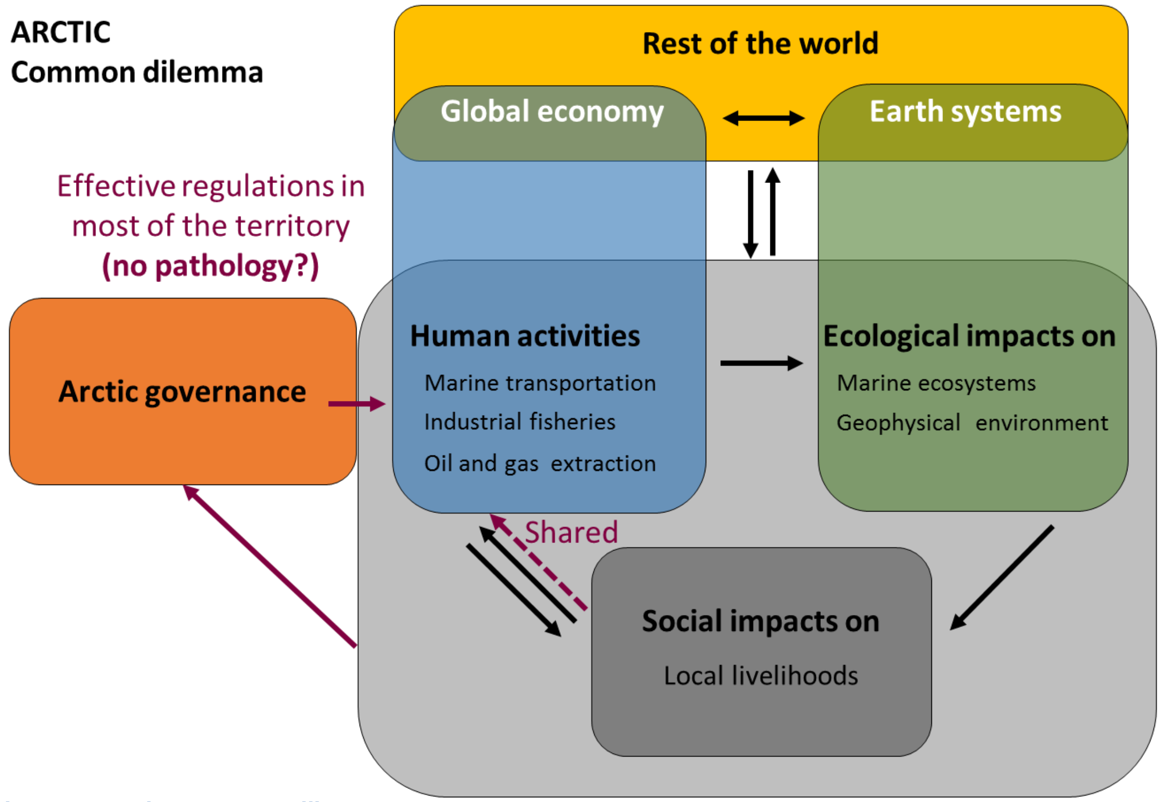

Figure 9: Arctic commons dilemma

4.1.6 Institutional rigidity

Institutional rigidity is a situation such that socio-political lock-ins and vested interests suppress institutional change. Such pathology can develop when powerful institutions inhibit the creation of new governance alternatives through political, market or informal means (Gunderson et al. 1995). Institutional rigidity is a form of government failure because rigidity prevents changes that could increase the net social benefits of current policies (Anthoff and Hahn, 2010). Such failures may occur when regulators do not have incentives to pursue efficient policies, they lack knowledge or information, or enforcement is difficult (Anthoff and Hahn, 2010).

The Arctic is particularly vulnerable to institutional rigidity because of its current fragmented governance situation. Most of the Arctic territories fall under national jurisdictions and are often peripheral regions within those nations (e.g. USA, Russia, and Denmark). Hence Arctic institutional change is likely to have low priority within each nation. In addition, pan Arctic governance change would require diplomatic mobilisation of multiple actors with probably quite different agendas. (D5.11) However, recent agreements on the Polar code and strategies for search and rescue indicate an ambition to adapt current governance to the changing situation. Figure 10 illustrates this case.

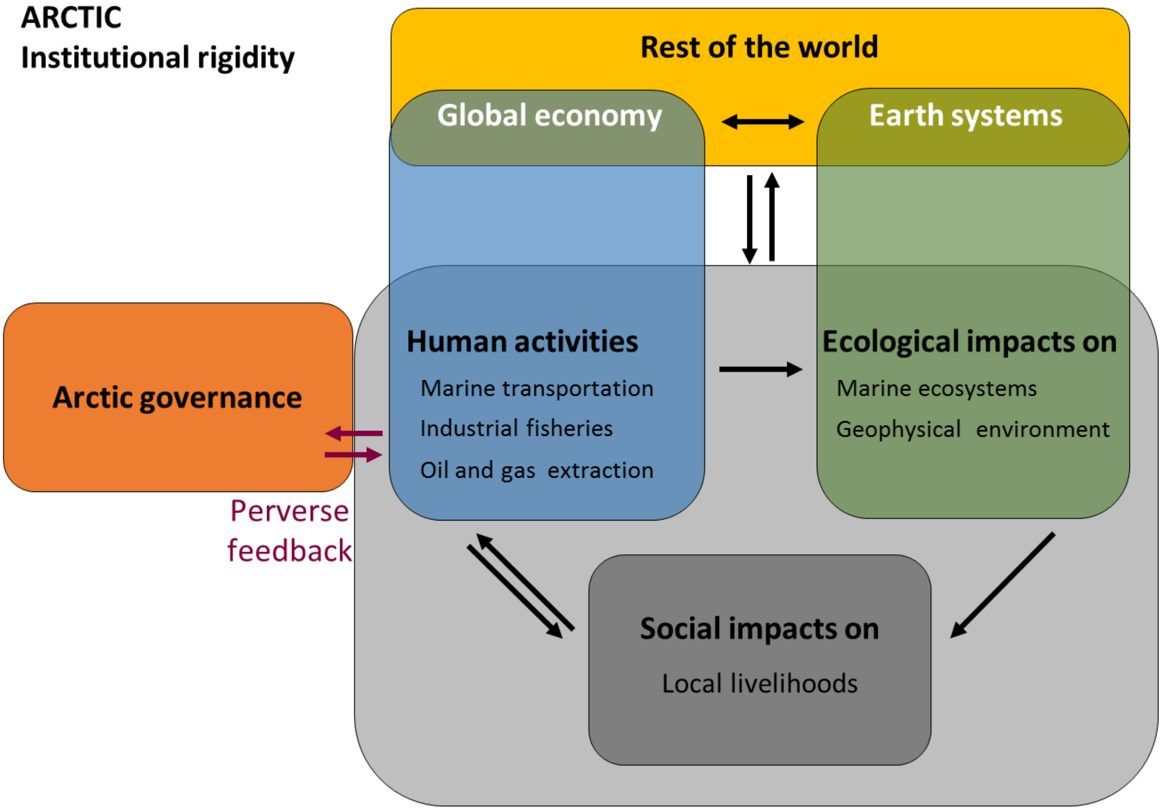

Figure 10: Arctic institutional rigidity

Some interesting insights come up from this rather rudimentary analysis of these six pathological dynamics applied to an Arctic context. The Arctic region is obviously a complex system with substantial elements of all the pathological dynamics identified in Peterson et al (in prep). The profound long fuse big bang nature of Arctic climate change leading to an imminent melting of the Arctic summer sea ice puts substantial pressure on governance institutions to deal with change. Meanwhile, the delayed nature of the phenomenon also provides time to prepare to these upcoming problems. Institutions turn up to have some flexibility and foresight so that they actually can take the opportunity to try to address the problems before they become acute. This seems to have been the case regarding transportation, search and rescue, and also fisheries issues, where recent governance development has allowed dealing with upcoming climate change impacts (D5.11). Hence from this analysis it seems likely that persevering on current paths of more organised Arctic governance may help address several of these dynamics in a promising way. The most serious remaining potential pathologies related to the Arctic are linked to the high level of risk associated with the substantial change that is coming up in the Arctic. Changing a huge system, where most of the connections are still largely unknown is much more likely to create surprises than small changes in an already known system. Such surprises are particularly likely to occur as consequences of unforeseen processes (Figure 7) and unrecognized spatial connections (Figure 8). Hence society should increase its preparedness to surprises (Crépin et al 2012) and should also simultaneously aim to increase system knowledge through more Arctic research aiming at such interactions. The ACCESS project is one such endeavour and so is the Arctic Resilience Report, but there needs to be more.

4.2 Modelling the system - detailed study of particular interactions

Cross-scale perspectives are highly relevant in an IEBM approach and while a system overview is valuable to provide a holistic perspective, it is also essential to go deeper into some details that are pertinent for the analysis. ACCESS performed many such detailed analysis that could be used for this purpose. For example the ACCESS deliverable D3.11 provides a more detailed estimation of the economic impacts of global warming on fisheries using a model focussing on the links between fisheries and the Arctic marine ecosystem highlighting the impacts of climate change through sea currents and primary producers in the ecosystem. Another example is deliverable D 4.11 models the impacts of Arctic energy supply. It does so by coupling two models. The COLUMBUS model of the Cologne Institute for Energy Economics (EWI) is a long-run, partial equilibrium model that allows the simulation of different scenarios of the global natural gas market up to 2040, while taking into account global interdependencies. This model is fed with Arctic data from IMPaC (IMPaC 2012) on investment and production technologies and costs. The COLUMBUS model output is information about production viability and quantity that formed the basis for data on Arctic Gas and Arctic Oil sectors that ACCESS then added into the Dynamic Applied Regional Trade (DART) model using a compatible format. This model represents worldwide production and consumption behaviour, interactions between production sector, CO2 emissions etc. For further details see D 4.11.

This section illustrates in more detail some ways to model particular system parts through two examples of more detailed studies: integrated assessment models that study the global impacts of climate change and incorporate the role of the Arctic in this global perspective (4.2.1) and experiments aiming to understand collective human behaviour in response to change in the resource they manage (4.2.2).

Several other ACCESS deliverables not reported in detail here would of course also help contribute pieces in the puzzle and contribute to a more complete framework for integrated ecosystem based management of the Arctic. Some of them are referred to in Table 2. For example D3.11 models the interactions between sea ice, water currents, zooplanktons and fish and assesses potential responses from fishermen to climate induced changes in the fish stocks due to climate change. Likewise, D4.11 builds an economic model of oil and gas extraction and pictures how resource extraction is linked to cost patterns in the resource, available technology and global development in energy markets.

4.2.1 The role of the Arctic in integrated assessment models

Integrated assessment models (IAMs) are useful tools when studying how particular Arctic phenomena relate to climate change and human development. Such models can be analysed and included as an integral part of an integrated ecosystem based management. These models have for a long time been popular tools for studying economic issues related to climate change. The models can be used for policy evaluation and policy optimization. Models for policy optimization, which search for the optimal set of policies to tackle climate change, are the most common form of models used by economists working on climate change. The main advantage of IAMs over pure climate models is that they combine geophysical, ecological, and socio-economic aspects of climate change in a closed system which allows researcher to assess the many interactions between them. So far these models have however paid little attention to the role of the Arctic for global climate change.

ACCESS work made an attempt to address this gap and produced two articles on the topic (Brock et.al 2013,2015). These articles pay particular attention to the potential for tipping points and spatial aspects related to climate change and the Arctic. They extend existing IAMs and simulate them to show how accounting for melting Arctic sea ice may impact on the design and timing of optimal carbon taxes, which are differentiated across space.

Brock et.al (2015) explore optimal mitigation policies through the lens of a latitude dependent energy balance climate model. The climate model pictures a polar ice cap in the form of an iceline, which can change endogenously in response to temperature changes. The mechanism is that shrinking polar ice caps create some kind of positive feedback loop due to the reduced albedo which follows from loss of ice covered surface. In IAMs this variation of the polar ice cap can be associated with the idea of damage or impact reservoir being a finite source of climate related damage/impacts, which can affect the economy only to the extent that there is still some ice is left that can melt. Brock et al (2015) capture this idea by coupling the climate model with an economic growth model, which combines two sources of economic impact mechanisms, the conventional direct climate impact and the reservoir type impact due to the endogenous change in the ice cap.
This set up results in multiple steady states and so-called Skiba points, situations where at least two alternatives are available, which bring the same level of welfare to society. The resulting optimal mitigation policies are then U-shaped, which contrast with the traditional result where optimal mitigation policies start with a carbon low tax level, which ramps up as time passes.. The results are also confirmed in a modified version of the well-known IAM called DICE (Nordhaus, 2007). Hence due to melting sea ice and depending on the strength of this feedback, the optimal tax rate may be high at first and then falling over time

Much in the same spirit, melting Arctic sea ice may also impact on the degree of spatial differentiation that would characterize optimal tax rates. This occurs when taking into account how future warming impacts on the process of polar amplification[13] Brock et.al (2013) develop a general equilibrium model of the world economy, featuring a two-dimensional energy balance climate model with heat diffusion and anthropogenic forcing driven by global fossil fuel use across the sphere of the Earth. They introduce an endogenous temperature function that depends on location into the standard IAM framework. Thus damage become location dependent as well because they can result from local temperature anomalies. They solve a fictive social planner's problem and characterize the competitive equilibrium for two alternative scenarios with different degrees of market integration. Brock et al (2013) define the spatial characteristics of optimal taxes on fossil fuel use and how one may implement the planning solution. The results suggest that if international transfers across locations are not implementable then optimal taxes will in general be spatially non-homogeneous and may be higher in polar regions compared to regions closer to the equator. They also show that the degree of spatial differentiation of optimal taxes depend on heat transportation and polar amplification.
Brock et al's (2013) two-dimensional energy balance model can be used for analytical derivations and numerical simulations to study the welfare impact of thermal transport across latitudes.
Both these articles have thus shown that by extending the standard IAM framework to include also the process of Arctic warming changes policy decisions also at the global scale. These insights as such are thus important considerations which should be accounted for in the design of an integrated ecosystem based management framework.

[13] Polar amplification refers to the observation that any change in the net radiation balance (for example greenhouse intensification) tends to generate a larger change in temperature near the poles compared to the average of the planet. (Lee 2014)

4.2.2 Users' behavioural response to change in resources

Large uncertainties surround the impacts of climate change on fish stocks, which are likely to influence the way in which fishing activities and consequently fish stocks respond to changes in geophysical conditions, management or economic factors. In particular large and abrupt changes like the ones we may experience in the Arctic could be challenging for management (Crépin et al 2012). Furthermore such changes may trigger particular behaviour among resource users, which management must account for to be successful. Hence ACCESS explored patterns of behavioural responses among fishers to potential abrupt changes in the availability of fish.
A series of experiments were designed to identify how different characteristics like resource renewal patterns, levels of uncertainty and different kinds of policies (quotas, information) influenced the group behaviour of resource users. The experiments were supplemented with post experiment questionnaires and a small survey among arctic fishermen (for more details about methodological approach see D3.51.)

The results suggest that users will manage the resource stock more efficiently (i.e. closer to the maximum sustainable yield) when confronted with a potential abrupt drop in availability compared to a resource that does not entail such a potential shift (Lindahl et al, 2014 submitted). However the magnitude of this effect varied depending on the likelihood of the shift. For example users managed the stock more efficiently if they knew that their harvesting could trigger an abrupt change with 50% risk compared to only 10%. (Schill et al 2015 in press). Further they would over-exploit significantly less if the information about such abrupt change was presented using tables *and* graphs showing the growth rate of the fish stock for different stock sizes compared to only tables (Lindahl et al, 2015a in prep; D3.51)

We have also compared how well a group of resource users manages to sustain a natural resource with a potential drop in growth rate depending on whether the use of the resource is regulated using a quota system or not. Even here the difference in resource use is significant. A resource regulated using a quota system will be associated with more under-exploitation (provided the quota is set at an efficient rate of harvest). It seems that such a regulation can erode cooperation and lead to more overexploitation in the long run (Lindahl et al 2015a in prep, D3.51)

We tested the effect of a sudden increase in demand manifested as an increase in fish price after some periods. We found a statistically significant difference between the change in price treatment and the no change treatment, which indicated that just the anticipation of a change influenced behavior rather than realized changes themselves. (Lindahl et al 2015b in prep, D3.51)

The results suggest that the threat of a significant reduction of the resource renewal rate, triggered better communication within the group, and consequently, more knowledge sharing and cooperation. This work has important policy implications and identifies how some policy instruments perform differently depending on likely future scenarios about abundance of different fish species, their reproduction dynamics, market condition (e.g. market prices) and regulations, as well as the resource users' capacity and willingness to communicate with each other. For example we find evidence that quotas may undermine cooperation in the fisheries sector and that pedagogic information about abrupt change may trigger collective action toward a common desirable outcome.

5 Identify potential change and their impacts

As indicated in Table 3 another important step (8) of an IEBM assessment is to identify essential assumptions for scenarios of change in the Arctic. Here, it is crucial to find out how scenarios will impact on essential ecosystem services in order to find out the full range of impacts of potential changes. First the scenarios should identify the main drivers of change (e.g. climate change, management intervention, catastrophe, new policy instrument, etc) and what potential impacts may arise from these drivers and the system's response to these drivers. For example the species of the Arctic Ocean, interacting with each other and the physical environment generate the ecosystem services on which many economic activities rely. Hence it is of interest to assess the impact of climate change on them in order to identify potential future change in ecosystem service generation in the Arctic Ocean. Using a systems perspective and an ecosystem service lens to assess potential impacts of climate change helps identify different potential scenarios of change and identify knowledge gaps that need to be addressed to aim for a sustainable management of Arctic fisheries.

Scenarios can only be built once the system is well understood and represented conceptually possibly with calibrated models, which have been tested using empirical data. Here models are important since they may be useful ways of implementing the scenarios and identifying outcomes. In this section we identify such scenarios of change based on altered Arctic ecosystems. The IEBM approach is particularly relevant when studying phenomena and situations where large uncertainties prevail. We exemplify the advantages of an IEBM approach for studying the very uncertain impacts of climate change on the Arctic marine ecosystem and analyse the potential economic and social impacts that these may have. In this section we identify some important ecosystem services produced within the Arctic Ocean and present six hypothetical scenarios of possible change in the Arctic marine ecosystem driven by climate change. Two of these scenarios focus on changes in zooplankton production and four scenarios on changes in presence of Arctic species like crabs.

	Ecosystem services			
Species	**Supporting**	**Provisioning**	**Regulating**	**Cultural**
Zoo plankton (Calanus glacialis)	Major food source in the Arctic food chain			
Zoo plankton (Calanus finmarchicus)	Important food source			
Capelin	Important food source especially for arctic cod	Economic species		Fishing culture
Atlantic cod		Economic species		
Herring	Food source for fish higher in the trophic levels	Economic species		Fishing culture
Arctic Char		Economic species		Fishing culture
Red king crab		Economic species		
Snow crab		Potential economic species		

Table 5: Identified ecosystem services linked to specific species based on MA (2005)

Based on the Millennium Ecosystem Assessment ecosystem service classification (MA 2005), we have analyzed the different species addressed in this article using an ecosystem service lens. Table 5 illustrates the results of this study.

Although the *direct* impacts on cod fisheries and other Arctic species, from global warming through changes in water temperatures and other oceanographic changes are likely to be less significant than normal environmental fluctuations, in e.g. the Barents Sea and different management regimes is stated to be of significantly more importance to the economic performance of the fishery industry in the Barents Sea for the next 25 years than the impacts of climate change (Eide 2008, D3.11, D3.31), the *indirect* impacts may not be. The northeast Atlantic cod and capelin fisheries are managed using a multispecies approach, developed by the main resource owners Norway and Russia, since they are so closely connected in the food web. But what are the potential impacts on the production of both cod and capelin if there were to be a substantial change in the access to Arctic grazers, such as the *Calanus glacialis,* who is a main food source for the capelin?

At least two major potential impacts of climate change on the Arctic zooplankton community are worthy of further investigation in the context of sustainable cod and capelin management: First is the potential mismatch between the two peaks on primary production by ice algae, and the reproductive cycle of key Arctic grazers such as the *C. glacialis* (Søreide et al. 2010), resulting from the reduction in sea ice thickness and coverage area. The second one is the potential switch from *C. glacialis* to the less lipid-rich Atlantic grazer *C. finnmarchicus*, due to competitive advantages of the latter species under climate change. According to a model simulation of climate change scenarios (Ellingsen et al. 2008), Atlantic zooplankton species increased approximately 20% and became more abundant in the east, while the Arctic zooplankton biomass decreased 50%, causing the total simulated production to decrease. Herring, another economically important species, is an effective converter of zooplankton into fish, and is thus also potentially sensitive to change in zooplankton production. Furthermore, herring is favored by inflow of warm water to the Barents Sea (Stephens and Krebs 1986; Sætersdal and Loeng 1987; Hamre 1994; Toresen and Østvedt 2000; Sætre et al. 2002), and since young herrings predate on capelin larvae, a potentially significant effect on these populations associated to climate change might take place. Table 6 and Table 7 illustrate the rationale behind two possible scenarios of zooplankton change.

<table>
<tr><th colspan="3">Scenario 1. Decrease in zooplankton production, (Calanus glacialis) due to mismatch</th></tr>
<tr><td colspan="2">Background information</td><td>Reference</td></tr>
<tr><td colspan="2">The arctic grazer Calanus glacialis is an essential food source for many economically important fish species in the Arctic and indeed for the entire Arctic marine ecosystem. Among the zooplankton in the arctic shelf seas Calanus glacialis accounts for up to 80% of the biomass.</td><td>Blachowiak-Samolyk et al., 2008, Søreide et al. 2010</td></tr>
<tr><td colspan="2">Ice algae is a key food source for Calanus glacialis, among many other species.</td><td>Søreide et al. 2010</td></tr>
<tr><td colspan="2">There is a potential mismatch between the two primary production peaks of ice algae and the reproductive cycle of Calanus glacialis, due to the reduction in sea ice thickness and cover area driven by climate change.</td><td>Søreide et al. 2010</td></tr>
<tr><td colspan="3">IEBM lens</td></tr>
<tr><td>Insights</td><td colspan="2">Due to the mismatch there could be a potential reduction in the biomass of Calanus glacialis, which in turn may affect fish production.</td></tr>
<tr><td>Key research questions?</td><td colspan="2">What is the quantitative impact on zooplankton production of a potential mismatch?
What is the quantitative impact on fish production of a potential mismatch?
What are the potential economic implications for the fisheries sector?
Does this change also impact on crabs, and if so how and how much? Could crab fisheries replace traditional fisheries if there is a substantial drop in fish?
How does this affect local livelihoods, indigenous peoples and the local fisheries industries?
Are there potential global repercussions?</td></tr>
</table>

Table 6: Scenario 1, decrease in zooplankton

Scenario 2. Decrease in *Calanus glacialis* in favor of *Calanus finnmarchicus*		
Background information		Reference
The arctic grazer *Calanus glacialis* is an essential food source for many economically important fish species in the Arctic.		Blachowiak-Samolyk et al., 2008; Søreide et al., 2008
Calanus finnmarchicus is less lipid rich than *Calanus glacialis*		Søreide 2008
According to a model simulation of climate change scenarios in the Barents Sea, the Atlantic zooplankton species *Calanus finnmarchicus* increased approximately 20% and became more abundant in the east, while the Arctic zooplankton biomass (including *Calanus glacialis*) decreased 50%, causing the total simulated production to decrease.		Ellingsen et al. (2008)
IEBM lens		
Insights	There will potentially be a reduction in the quantity and quality of zooplankton available for fish production in the Barents Sea	
Key research questions?	What are the implications of the reduction in quantity of zooplankton for fish production? What are the implications of the reduction in quality of zooplankton for fish production? What are the potential economic implications for the fisheries sector? Does this change also impact on crabs, and if so how and how much? Does the planktons vulnerability against pollution differ, and if so how? How does this affect local livelihoods, indigenous peoples and the local fisheries industries? Are there potential global repercussions?	

Table 7: Scenario 2, decrease in Calanus glacialis in favour of Calanus finnmarchicus

An IEBM perspective on these scenarios helps provide the “key research questions” associated with each scenario. Furthermore a full scale IEBM would provide substantial support to also answer those questions in a way that also incorporate aspects that may be relevant but less obvious. For example would fish feeding to a larger extent on *Calanus finnmarchicus* respond in a different way to potential oil spills compared to fish feeding mostly on *Calanus glacialis*?Several crab species have or are becoming dominant species in the Arctic marine ecosystem. The European green crab will potentially benefit from increased shipping and transportation in the Arctic. The green crab has also been estimated to have the potential to expand to sub-Arctic and Arctic waters even under moderate climate change scenarios (De Rivera et al. 2007). Also, it has been shown that conditions under which species can reproduce are more relevant in estimating establishment potential than physiological tolerances. Based on this assumption Ware et al. (2014) predicted that by the end of the century, maximum sea surface temperatures in areas like Svalbard are predicted to rise beyond 10°C (12.5°C), thus rendering a number of non-indigenous species, including the European green crab*,* able to reproduce there. What are the potential implications for Arctic ecosystems of crossing that temperature threshold, in combination with increased shipping? Table 9 illustrates a possible scenario of change related to the European green crab.

The red king crab is another introduced species, which has grown to be of great economic importance in parts of the Arctic. The population of red king crab supports a valuable fishery in the Barents Sea, representing an ex-vessel value of 150 million NOK in 2011 (Hjelstedt 2012). However, it has also been confirmed that the benthic communities in northern Norway and the Kola Peninsula in Russia are facing significant disturbance from the red king crab (Joergensen and Primicerio 2007). In order to estimate the total economical impact of the red king crab on the Arctic social-ecological system, both the pros and the cons of the crab on the Arctic ecosystem must be assessed. This, apart from the profits of catching and selling the crabs, also entails assessing the connection between the destruction of benthic communities by the red king crab and the production of other economically important species, such as the capelin, since concern has been expressed about the predation on capelin eggs by the red king crab (Mikkelsen 2013). Table 8 illustrates a scenario where the red king crab increases substantially, Table 9 emphasizes an increase of the European green crab while Table 10 focuses on snow crabs.

Scenario 3. Increase in red king crab (*Paralithodes camtschaticus)* (biomass and expansion)	
Background information	**Reference**
The red king crab benefits from increased water temperatures in the Arctic	
The red king crab predates on capelin larvae	Mikkelsen 2013
Capelin is a key food species for other economically important fish species, e.g. cod	
IEBM lens	
Insights	An increase in the biomass of red king crabs, due to increased water temperature, can potentially reduce capelin production and thus also impact on the production of other fish species e.g. cod.
Key research questions?	What are the implications of a potential increase and spread of red king crab in the Arctic in the context of capelin production? What are the implications of a potential decrease in capelin production on the production of other economically important fish species, e.g. cod? What are the potential economic implications for the fisheries sector of cod and capelin? What are the implications for the co-management strategies of the cod and capelin fisheries? How does this affect local livelihoods, indigenous peoples and the local fisheries industries? Are those activities resilient to such change and could they seize the opportunity to produce King Crab instead? Are there potential global repercussions?

Table 8: Scenario 3, increase in red king crab

Scenario 4. Increase of the European green crab (C. maenas)	
Background information	**Reference**
The European green crab is one of the species potentially benefitting from increased shipping and transportation in the Arctic.	Roman and Palumbi (2004)
The green crab has been estimated to have the potential to expand to sub-Arctic and Arctic waters even under moderate climate change scenarios.	De Rivera et al. (2007)
The green crab needs a water temperature above 10°C to reproduce.	
The minimum water temperature for successful green crab reproduction is being approached in many places in the Arctic due to climate change.	
IEBM lens	
Insights	Suitable areas for the European green crab are likely to expand in the Arctic due to increased shipping in combination with increased water temperatures, approaching minimum temperature for green crab reproduction. In many places European green crab is considered as a nuisance.
Key research questions?	What are the potential impacts of a spread of the green crab to new areas? What are the implications for other crab species and for fish species? What are the potential economic implications for the fisheries sector of cod and capelin? How does this affect local livelihoods, indigenous peoples and the local fisheries industries? Are those activities resilient to such change? Are there potential global repercussions?

Table 9: Scenario 4, increase in European green crab

<table>
<tr><th colspan="3">Scenario 5 Continued increase in snow crab (Chionoecetes bairdi)</th></tr>
<tr><td colspan="2">Background information</td><td>Reference</td></tr>
<tr><td colspan="2">There are ten times more snow crabs in the Barents Sea than red king crabs</td><td></td></tr>
<tr><td colspan="2">A large stock of Snow crabs could have a significant influence on the bottom communities where they forage – whether “good” or “bad” from the human point of view is difficult to predict.</td><td></td></tr>
<tr><td colspan="2">Snow crabs does not seem to compete with fish for food and does not compete with the red king crab</td><td></td></tr>
<tr><td colspan="2">The snow crab is food for cod</td><td></td></tr>
<tr><td colspan="3">IEBM lens</td></tr>
<tr><td>Insights</td><td colspan="2">The snow crab has the potential to become an important economic species in the Arctic, but there are significant knowledge gaps on the impact of snow crabs on the Arctic ecosystem. Snow crab fisheries will potentially be of economic importance. Russia will start up a snow crab fishery 2014.</td></tr>
<tr><td>Key research questions?</td><td colspan="2">What impacts on the Arctic marine ecosystem can the snow crab have?
What impact on bottom communities can a high density of snow crabs have?
Can the snow crab become a significant food source for cod?
Can a market for snow crab fishery develop?
How does snow crab impact on local communities</td></tr>
</table>

Table 10: Scenario 5, increase in snow crab

Ocean acidification is another process that only recently has been shown to have potentially great impact on a multitude of marine species. The oceans have turned 30% more acidic since the beginning of the Industrial Revolution (NOAA 2010). Besides increased acidity of the ocean, this also entails other changes in the sea’s chemistry, such as robbing the water of important minerals that marine creatures need to grow, especially those with shells. Long et al. (2013) determined the effects of long-term exposure to near-future levels of ocean acidification on the growth, condition, calcification, and survival of juvenile red king crabs (*Paralithodes camtschaticus*), and Tanner crabs (snow crabs, *Chionoecetes bairdi*) and found that both species survival decreased with pH, with 100% mortality of red king crabs occurring after 95 days in pH 7.5 water. More research is needed to add the potential effects of ocean acidification to the already complex context of climate change in the Arctic marine ecosystems, especially in the context of crustaceans. However Table 11: Scenario 6 makes an attempt to identify a scenario of increased ocean acidification.

Scenario 6. Decrease in crab populations (red king crab and snow crab) due to ocean acidification	
Background information	**Reference**
Red king crab fisheries are economically important in the Arctic	Hjelstedt (2012)
Snow crab fisheries will potentially be of economic importance. Russia will start up a snow crab fishery 2014. There is now ten times as much snow crab than king crab in the Barents Sea	
The oceans have grown 30 percent more acidic since the beginning of the Industrial Revolution. Ocean acidification not only entails that the oceans become more acidic, but it also changes the sea's chemistry in other ways, such as robbing the water of important minerals that marine creatures need to grow, especially those with shells.	NOAA (2010)
The effects of long-term exposure to near-future levels of ocean acidification on the growth, condition, calcification, and survival of juvenile red king crabs (*Paralithodes camtschaticus*), and Tanner crabs ((snow crabs), (*Chionoecetes bairdi*))was examined and it was found that both species, survival decreased with pH, with 100% mortality of red king crabs occurring after 95 days in pH 7.5 water	Long et al. (2013)
IEBM lens	
Insights	There can be a potential reduction in crab production (snow crab and red king crab) due to increased ocean acidification.
Key research questions?	How large can the impact of ocean acidification on crab production be? What can the economic implication of crab fisheries be? What are the implications for future management strategies for fisheries in the Arctic?

Table 11: Scenario 6

All scenarios illustrate the potential impacts on the Arctic system using an integrated ecosystem based management approach, they all picture very different very different outcomes. How can society deal with so different possible outcomes and a rather uncertain future? Although these scenarios differ substantially and uncertainty regarding which one may dominate in the future is enormous, it is possible to draw some general conclusions. For example, for society these scenarios amount to a limited range of impacts of concern to people. The main impacts occur on fisheries, and hence it is essential that the fisheries industry develops resilient strategies to deal with three main possible alternatives: 1) an increase in fish, 2) an increase in crabs associated with a decrease in fish, and 3) a decrease of both kinds of species.

Hence local fishers and the regional fishery industry in general should probably improve preparedness to be able to fish, use and trade other species than cod and capelin. Flexibility regarding the species to catch is likely to be critical for sustained food production in the Arctic. In the worst case scenario, where most wild species would decrease, aquaculture may be an alternative livelihood and potential for food production. However this requires that feed is available, which may be a problem if fish stocks are decreasing. This also requires that aquaculture production is able to provide good growing conditions for the cultivated species even in a new ocean environment with warmer and potentially more acid water. (See D3.21 for more details on aquaculture in the Arctic)

The Arctic marine ecosystem is used to rapid and substantial change and is likely to be quite resilient to direct impacts of Arctic climate change. Local fishers are well used to these large variations as well and are likely to adapt to the new conditions. However the changing conditions put substantial pressure on the system which may then become more vulnerable to other disturbances than the direct impacts from climate change. Examples of such disturbances include major oil spills (from tankers or from platforms), increased noise and chemical pollution from transportation, increased pollution run off from rivers and new infrastructure.

While the Arctic ecosystem is likely to cope relatively well with each of these disturbances individually, the capacity to cope with several of these disturbances simultaneously is difficult to assess. Current trends indicate that the current basin of attraction of the Arctic system is being eroded. The picture that appears is that of substantial pressures that may generate other pressures creating a reinforcing feedback loop of rapid change.

IEBM should then account for such kinds of dynamics in steps 10-12 and provide management strategies that can properly address the risks of abrupt changes that these reinforcing feedback loops may create (see Crépin et al 2012 and Crépin 2014 for suggestions).

6. Conclusions

Human activities in the Arctic depend to a large extend on its bio-geophysical environment, which is likely to experience substantial impacts from climate change in the next years. Planning and sustainably managing Arctic activities requires then to encompass both direct and indirect effects of climate change on the production of natural resources and services from marine ecosystems of the Arctic. A social-ecological systems perspective could support such task. By assessing the impacts of climate change on basic physical parameters, such as light, temperature, salinity and nutrient availability, within a food web and ecosystem services framework, the potential change in benefits from Arctic ecosystems and the impact on various economic sectors, can be more readily identified and assessed. The social-ecological system approach facilitates the identification of trade-offs and synergies towards a sustainable management of the Arctic as a whole. This report presents a framework for IEBM of the Arctic Ocean that builds on such perspective.

The framework itself contains three important elements: 1) An evaluation of how to represent the Arctic social-ecological system, in which we opt for a nested approach containing a holistic part (coarse representation of the whole Arctic) complemented with more detailed partial models to shed light on specific processes within the Arctic social-ecological system. 2) An assessment of objectives and general principles for management, which acknowledges the need to recognize and properly represent uncertainties, and builds on substantial existing literature focusing on market failure and dynamics, where social-ecological features interact in a problematic way, and how to address these issues. 3) An identification of tools and methods that could serve an IEBM, where several existing methods are acknowledged and combined and five main steps are suggested to perform an IEBM. These steps are understand the system, represent/model the system, test model validity, identify potential change and their impacts and implement results in management. Each of these steps is specified further.

This report also exemplifies in more details some important steps related to building an IEBM of the Arctic. In particular we used several methods of expert elicitation (questionnaire, focus group discussions, and literature study of ACCESS newsletters and deliverables) to provide an overview of the main Arctic dynamics and their interactions as one particular way to better understand the Arctic system. It is important to note that the particular representation we choose is likely to be biased toward the topics that the ACCESS consortium prioritized at the stage of the proposal. The Arctic Resilience Report (Arctic Council, 2013 and forthcoming) makes another and quite different attempt to understand the Arctic system based on a more bottom-up approach where available knowledge and case studies, rather than predefined topics, steer the focus of attention. A fruitful avenue for further development of this particular step of an IEBM would be to combine the more bottom-up approach of the Arctic Council with the top-down perspective taken by ACCESS. Both have advantages and drawbacks, and combining them would benefit from including a more open elicitation process with a well thought predefined framework that helps identify possible lacunae and important areas which have not been studied yet because of missing expertise.

We used the better understanding gained from the ACCESS project to discuss alternative ways to represent the Arctic system. As first example we take a holistic approach focusing on so called “pathological dynamics” (Peterson et al in prep), which are problematic connections between different parts of the system. These connections could be problematic because they are too slow or too fast, or connect only some parts of the system together while missing to connect other parts, thereby providing spurious incentives for resource use. We also illustrate two examples of more detailed connections studied under ACCESS: the role of the Arctic ice cap and spatial differentiation in IAMs, and the role of users’ behavioural responses to climate and policy change. A further development of this particular work should include an assessment of the compatibility of the different models with each other and the development of a computational framework that allows to ‘turn on and off’ different parts of the models depending on the needs. However it is important to keep track of the particular limitations of each model and avoid building a big black box where it becomes difficult to discern causal processes. In this respect, a nested approach has the advantage of making it easier to highlight the particular dynamics in each part of the system, and identify those parts that are driving the main dynamics for each relevant topic of study.

Finally, we use our system knowledge and representation to discuss six possible scenarios of changes in the marine ecosystem. These scenarios cover changes in zooplankton (*Calanus* species) distribution and abundance, changes in abundance of different crab species, and increased ocean acidification. The scenarios present stories of possible future outcome and questions that become relevant under those particular outcomes. We do not assess the likelihood of each particular scenario, nor do we assess all the particular consequences that each scenario would have. A further development of this work would include a more systematic assessment of the consequences of each scenario for each particular economic sector, and an attempt to rank theses scenarios according to their likelihood. It may be useful to systematically identify additional particular scenarios that also deserve attention.

We did not address at all the steps related to implementation in management of potential policies to address particular problems. While existing literature provides substantial knowledge for how to move forward with different policy responses, it is still rather unclear how to deal with abrupt, substantial and surprising changes, which are more and more likely to occur in a period of global climate change (Crépin et al, 2012).

The exercise of proposing a framework for IEBM is based to a large extent on existing methods, which we refer to in different parts of this report. However we also had to develop our own methods sometimes when the existing methods we knew of were not entirely satisfactory to complete the task. A full scale IEBM plan for the Arctic would require much more time and resources, and should build on the Marine Spatial Planning tool (D5.82) and the indicators for sustainable development (D2.91, D3.71, D4.71) developed within ACCESS. The tools could be used individually but the most of their potential can be released if they are used and further developed in an interactive way. For example, the indicator system proposed can be set up and developed to follow how essential variables of the Arctic social-ecological system perform toward particular targets. The indicator system (D5.91) may help identify unsustainable trajectories, but also inform about the system's resilience towards some types of changes. However it is unlikely that the best response to change and unwanted trajectories can be identified by just looking at indicators. To such end it may be useful to also look at the marine spatial planning tool (ACCESS D5.82) and the framework for IEBM at hand to identify possible policy responses and incentive structures, as well as further refining the set of indicators to monitor. A further development of these management tools after the completion of the ACCESS project is likely to be of substantial value for management at multiple levels.

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ACCESS Deliverables cited

D1.23	Report on analysed data from IMBs
D1.25	Completed analysis on previous submarine voyages and delivery of report on single-beam thickness distributions from submarine , fed to WP1 modelling, WP2-4 for reduced ice assessment
D1.34	Report from AARI on analysis of recent oceanographic voyages in Russian Arctic
D1.42	Monthly evolution of the FDD integrated all over the Arctic and redistributed over subarctic areas for each year
D1.71	Radiative forcing estimates for perturbation in the Arctic of short lived climate compounds
D1.72	Model output from CTM studies of the impact of composition changes from changes in emission
D2.12	Navigation efficiency on NSR and in difficult shipping zones as effected by Climate Change
D2.16	Report presenting results of ICEROUTE calculations of traveling time for different scenarios and routes on NSR and NWSR in past, present, and future
D2.41	Air pollution and surface deposition related to present and future Arctic shipping
D2.42	Calculation of fuel consumption per mile for various ship types and ice conditions in past, present and in future
D2.44	Noise propagation from commercial fishing and vessel traffic in the Arctic today and in the future
D2.52	QND analysis of future Arctic Observing System for safe marine transport under changing climate
D2.61	Socio-economic costs and benefits of Arctic transport
D2.62	Results of downscaled and adjusted HTM 1,4 model runs under various tourism scenarios of socio-economic and climate change
D2.63	Comparison of transport costs and time for sailing from Kirkenes to Yokohama via Northern Sea Route
D2.71	Evaluation of ACCESS Arctic shipping research in view of a shipping company
D2.91	Indicators for sustainable development of Marine Transport and Tourism in the Arctic
D3.11	Economic impacts of global warming on fisheries

D3.21 MS.3.21	Climate change and Arctic aquaculture Aquaculture in the Arctic - A review
D3.31	Market responses to climate change
D3.41	Economic settings, societal and cultural priorities in the fishery and aquaculture sectors Past and present impact of biophysical changes on fisheries
D3.42	International and national fishery management, adaptation practices and strategies to climate-related changes in fisheries
D3.51	Results from field experiments in the Arctic
D3.71	Indicators for sustainable development in the Arctic fisheries sector
D4.11	The impact of Arctic energy supply
D4.21	Report on fixed as well as floating offshore structure concepts
D4.22	Report on the use of subsea systems
D4.44	Report on oil flow under ice
D4.51	Interactive noise maps of exploration/ exploitation sites
D4.52	Simulator of the effects of noise from oil industry operations on marine mammals
D4.53	Emissions of a large set of atmospheric compounds in gas/oil extraction facilities
D4.71	Indicators for sustainable development
D5.11	Analysis and synthesis of extant and developing regulatory frameworks
D5.61	Operational conditions of an effective participation of Arctic indigenous people in the future Arctic governance
D5.81	Development of Marine Spatial Planning concept and principal framework
D5.82	Final test and delivery of Marine Spatial Planning tool
D5.91	Report on Cross-sectoral synthesis of economic policy and governance options for sustainable development.

Appendix A: Expert knowledge elicitation

A questionnaire (Appendix C) was distributed by email to all researchers participating in ACCESS ahead of the second ACCESS general assembly in Barcelona March 2013. The answers were collected by e-mail and on paper at the general assembly itself and respondents were given incentives to respond in the form of a surprise (some chocolate bars) handed out at the general assembly,

The respondents were asked to answer three questions in relation to their ongoing activities within the ACCESS project:

1. Which fields within ACCESS (fisheries, oil and gas, climate, transport and tourism, governance) are you familiar with either through your research or in some other way? Specify in which way.
2. Which activities within your field(s) of expertise above affect other fields, and how (please give references if you have any)?
3. Which activities in other fields affect your field(s), and how (please give references if you have any)?

In total 65 questionaires were given to the participants of which 30 were returned. This is a very low response rate. However, among the respondents we obtained responses from all key sources, such as work package leaders and similar.

In addition we organised group sessions at the ACCESS general assemblies in Barcelona (March 2013, Appendix B) and Cambridge (March 2014) and organised two workshops in Bremen (September 2013) and Stockholm (September 2014). During these sessions participants had the opportunity to identify and discuss several possible interactions between ACCESS sectors of activities so called cross sectoral interactions. They were asked to suggest potential interactions on post it papers that they could stick on a big chart of interactions (See Table 4). We also benefitted from the exercises performed by students at two graduate courses organized by the ACCESS consortium (Bremen, september 2013, D6.251 and Stockholm September 2014, D6.253)

All these activities helped us identify essential variables and build a picture of their possible interactions (Figure 2).

Appendix B: Instructions to break out groups at the ACCESS general assembly, Barcelona March 2013.

Instructions for break out group 1:
Establishment of infrastructure in the Arctic Ocean (e.g. Oil platforms, aquaculture)

Your group should discuss cross-sectoral questions related to the establishment of infrastructures in the Arctic Ocean, in particular oil platforms, aquacultures and other infrastructures related to resource extraction. You should discuss aspects concerning impacts from and to the environment as well as social, political and economic aspects. To guide the discussion you could address some of the sub questions below or discuss other aspects that the group finds relevant to the topic.

The group leader is responsible for moving the discussion forward, in addition we suggest that you take 2 minutes to identify the following roles in the group:
- a note-keeper who documents the discussion
- a time keeper who manages time to make sure you can to address all the relevant aspects
- a rapporteur who will shortly present the results of your discussion at the plenary session tomorrow morning.

To help you address as much as possible during the short time period that you have we suggest that you use some of the following techniques, which are not exclusive:
- You can split into smaller groups for part of the time to address different questions
- You can collect people's ideas on stickers that you together organize and group
- You can do short roundtables so that everybody is given a chance to shortly express their view on the topic
- Etc.

What guidelines could ACCESS produce regarding establishment and management of infrastructures in the Arctic Ocean?

Reflections on the following issues (suggestions for smaller break out groups maybe) may help come up with such guidelines:

a. What is the environmental impact of such infrastructures? How is it affected by the particular characteristics of the Arctic environment? Which of those characteristics are the most relevant?
b. What are the potential impacts of these infrastructures on other economic activities? (Are there particularly important regions for these activities? What are the needs for infrastructure on land? What are the profit margins of such activities in this environment?)
c. Are the current rules and regulations regarding establishment, management and contingency planning sufficient?
d. Will climate change trigger the need for changes in existing rules and institutional settings? Is there need for contingency planning in case of accidents? In which regions will new opportunities occur due to climate change?

Instructions for break out group 2: Arctic Marine transportation

Your group should discuss cross-sectoral questions related to Arctic marine transportation including for example goods transportation through the Arctic, fishing boats going for harvest, transportation of oil and minerals from the Arctic, tourism cruising. You should discuss aspects concerning impacts from and to the environment as well as social, political and economic aspects. To guide the discussion you could address some of the sub questions below or discuss other aspects that the group finds relevant to the topic.

The group leader is responsible for moving the discussion forward, in addition we suggest that you take 2 minutes to identify the following roles in the group:

- a note-keeper who documents the discussion
- a time keeper who manages time to make sure you can to address all the relevant aspects
- a rapporteur who will shortly present the results of your discussion at the plenary session tomorrow morning.

To help you address as much as possible during the short time period that you have we suggest that you use some of the following techniques, which are not exclusive:

- You can split into smaller groups for part of the time to address different questions
- You can collect people's ideas on sheets of paper that you together organize and group
- You can do short roundtables so that everybody is given a chance to shortly express their view on the topic
- Etc.

What guidelines could ACCESS produce regarding marine transportation in the Arctic Ocean?

Reflections on the following issues (suggestions for smaller break out groups maybe) may help come up with such guidelines:

e. What is the environmental impact of marine transportation? How is it affected by the particular characteristics of the Arctic environment? Which of those characteristics are the most relevant?
f. What are the potential impacts on other economic activities? Will there be competition or synergies between transports trough the Arctic and transports of Arctic goods to outside markets?
g. Are the current rules and regulations regarding establishment, management and contingency planning sufficient?
h. Will climate change trigger the need for changes in existing rules and institutional settings? Is there need for contingency planning in case of accidents? In which regions will new opportunities occur due to climate change?

Instructions for break out group 3:
Sustainable use of resources and services from Arctic ecosystems

Your group should discuss cross-sectoral questions related to sustainable use of resources and services from Arctic ecosystems including fisheries and tourism. You should discuss aspects concerning impacts from and to the environment as well as social, political and economic aspects. To guide the discussion you could address some of the sub questions below or discuss other aspects that the group finds relevant to the topic.

The group leader is responsible for moving the discussion forward, in addition we suggest that you take 2 minutes to identify the following roles in the group:

- a note-keeper who documents the discussion
- a time keeper who manages time to make sure you can to address all the relevant aspects
- a rapporteur who will shortly present the results of your discussion at the plenary session tomorrow morning.

To help you address as much as possible during the short time period that you have we suggest that you use some of the following techniques, which are not exclusive:

- You can split into smaller groups for part of the time to address different questions
- You can collect people's ideas on stickers that you together organize and group
- You can do short roundtables so that everybody is given a chance to shortly express their view on the topic
- Etc.

How can we continue to use and benefit from Arctic marine resources and ecosystem services in a sustainable way? Can ACCESS produce guidelines?

i. Are there institutional challenges for sustainable use? (e.g. collective access to the resource which is hard to restrict)
j. What are the economic challenges? (profit margins, quotas constraints, fuel cost, salaries, etc.)
k. How is climate change expected to impact on these activities?
    i. Direct impacts (weather changes, ice melting, etc.)
    ii. Indirect ecosystem impacts (changes in habitats, species migrations, regime shifts (tipping points)
    iii. Indirect economic impact (increased demand for fish from the "last" productive stock, substantial global population increase, tec.
l. Will these changes trigger the need for changes in existing rules and institutional settings?

Appendix C: Questionnaire given at the ACCESS general assembly in Barcelona, March 2013

Questionnaire

Purpose: Identifying links/flows/connections between the different sectors included in ACCESS, to contribute to the construction of a social-ecological systems framework. A deliverable to be provided by WP5

Question 1:
Which sectors within ACCESS (fisheries, oil and gas, climate, transport and tourism, governance) are you familiar with?

Question 2:
*Which activities in **your** sector(s) affect **other** sectors, and how (please give references if you have any)?*

Question 3:
*Which activities in **other** sectors affect **your** sector(s), and how (please give references if you have any)?*

Thank you!

Turn please

Please fill in your name and e-mail address, in case we need to contact you for further clarifications and/or questions

Name: ____

E-mail address: _____________________________________

The information will be treated anonymously and the only persons having access to names will be Anne-Sophie Crépin, Åsa Gren and Gustav Engström. If you have any questions, please feel free to contact us at:
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Thank you again for your contribution!

Anne-Sophie Crépin, Åsa Gren and Gustav Engström